

44th Solid Mechanics Conference

Book of Abstracts

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September 7–10, 2026
Kraków, Poland

44th Solid Mechanics Conference



Book of Abstracts

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and

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and

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Preface

This volume of electronic proceedings contains abstracts of contributions accepted for presentation at the 44th Solid Mechanics Conference SolMech 2026, held in Kraków on September 7–10, 2026.

The Solid Mechanics Conferences are a series of biennial international meetings which have been organized by the Institute of Fundamental Technological Research of the Polish Academy of Sciences (IPPT PAN) since 1953. They aim at facilitating discussions on research topics in solid mechanics, maintaining high scientific standards and providing a friendly atmosphere. This time, the Conference is hosted and co-organized by the Cracow University of Technology.

This 44th edition of the Conference brings together more than 270 participants from 27 European and non-European countries, with nearly 40% of attendees coming from outside of Poland. The scientific programme features more than 245 presentations organized within 15 thematic sessions, including 8 invited plenary lectures and 25 keynote lectures. Approximately 60 presentations are delivered by PhD students, reflecting the strong commitment of the organizers to support early-career researchers.

The plenary speakers are internationally recognized leaders in their respective fields. The list of keynote speakers in the thematic sessions comprises both internationally recognized senior scientists with established expertise across the various fields of solid mechanics and outstanding early-career researchers who have already demonstrated scientific excellence. Notably, three keynote lectures are delivered by recipients of the Professor Michał Życzkowski Prize for Outstanding Young Scientists, awarded by the Committee for Mechanics of the Polish Academy of Sciences during the two years preceding the Conference. Overall, the composition of the thematic sessions reflects the scientific vitality of solid mechanics, as well as the strength, diversity and generational renewal of the research community, demonstrating the field's potential for future development.

On behalf of the Scientific and Organizing Committees of the 44th Solid Mechanics Conference SolMech 2026 we would like to thank all presenters of plenary, keynote and standard papers for their contributions to the meeting. Moreover, we would like to express gratitude to the organizers of the thematic sessions, and to all people and institutions supporting the organization of SolMech 2026. We wish all participants inspiring discussions and enjoyable time in Kraków.

Katarzyna Kowalczyk-Gajewska

Jerzy Pamin

Chair and Co-chair of SolMech 2026

Thematic Sessions and Their Organizers

TS1: Advanced continuum theories

W. Sumelka (*Poland*), Ł. Madej (*Poland*), G.Z. Voyiadjis (*USA*), Y. Sun (*China*), J. Lian (*Germany*)

TS2: Atomistic and nanoscale modelling

M. Giersig (*Poland*), K. Kempa (*USA*), M.J. Naughton (*USA*), D. Carnahan (*USA*)

TS3: Biomechanics and biomaterials

G. Milewski (*Poland*), E. Majchrzak (*Poland*)

TS4: Computational and experimental mechanics in engineering applications

P. Baranowski (*Poland*), K. Jamroziak (*Poland*), J. Małachowski (*Poland*), P. Sielicki (*Poland*)

TS5: Computer methods in solid mechanics

W. Cecot (*Poland*), W. Rachowicz (*Poland*), R. Sauer (*Poland*), G. Zboiński (*Poland*)

TS6: Contact and interface mechanics

F.M. Andrade Pires (*Portugal*), A. Javili (*Turkey*), S. Stupkiewicz (*Poland*)

TS7: Experimental mechanics

Z.L. Kowalewski (*Poland*), S.D. Pastramă (*Romania*), A.M. Pascu (*Romania*)

TS8: Geomechanics and granular materials

J. Tejchman (*Poland*), W. Wu (*Austria*)

TS9: Mechanics of advanced materials and smart structures

E. Pieczyska (*Poland*), D. Jarząbek (*Poland*), A.D. Lantada (*Spain*)

TS10: Micromechanics of heterogeneous and multi-component materials

K. Kowalczyk-Gajewska (*Poland*), S. Mercier (*France*), G. Vadillo (*Spain*), A. Srivastava (*USA*)

TS11: Multiphysics and coupled problems

J. Rojek (*Poland*), Ł. Figiel (*UK*), B. Peters (*Lithuania*)

TS12: Nonlinear dynamics, structural control and monitoring

J. Hou (*China*), Ł. Jankowski (*Poland*), K. Kęcik (*Poland*), K. Mendrok (*Poland*), P. Perlikowski (*Poland*)

TS13: Plasticity, damage and fracture mechanics

R. Kouhia (*Finland*), A. Menzel (*Germany/Sweden*), J. Pamin (*Poland*), H. Petryk (*Poland*), B. Skoczeń (*Poland*)

TS14: Structural optimization and optimum material design

B. Błachowski (*Poland*), M. Bruggi (*Italy*), T. Lewiński (*Poland*)

TS15: Shells, plates, and lattices as macroscopic or microscopic structures

M. Kuczma (*Poland*), N. Fantuzzi (*Italy*), M. Guminiak (*Poland*), M. Kamiński (*Poland*), P. Wriggers (*Germany*)

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Invited Plenary Lectures

New measurement strategies for data-driven mechanics

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KEYWORDS: *X-ray diffraction, High-speed tomography, Machine Learning.*

There has been explosive growth in numerical, data-driven approaches to various problems in the mechanics of materials. These data-driven methods are data-hungry, but traditional measurement protocols are inherently data-poor. Consequently, most studies using these data-driven methods have relied on synthetic data. This dearth of measurement techniques presents opportunities to transform laboratory-based methods, making them better suited to emerging data-driven methodologies in mechanics. We first give a brief overview of emerging laboratory techniques that enable observations that were hitherto considered nearly impossible, at least in a laboratory setting. These methods include (i) dynamic tomography to enable 3D visualisation of high-speed deformations [1], (ii) digital volume correlation in nominally homogeneous materials [2], and (iii) democratising synchrotron technologies to allow the measurements of local stresses within statically indeterminate specimens via energy-dispersive diffraction measurements.

These and other new laboratory measurement methods provide new observations and large datasets. But how can they be used in the data-driven mechanics discovery of constitutive behaviour? Broadly, the constitutive model discovery approaches fall into two categories: (i) supervised models that require data in the form of stress-strain pairs and (ii) unsupervised models that require no stress data but only full-field displacement and global force data. Energy-dispersive measurements provide fully labelled stress-strain pairs for supervised constitutive model discovery. Using these measurements, we shall demonstrate the learning of the plasticity models for Ti64 from a single tensile test on a simple notched specimen. Remarkably, the model indicates that simple J2 plasticity is not sufficient to accurately model the plastic response of Ti64- while this is, of course, known in the literature, those inferences were obtained using multiple different complex specimens designed with significant a priori knowledge of the material response. These new measurement techniques offer the potential to quickly learn complex constitutive responses and may lead to the discovery of new physics.

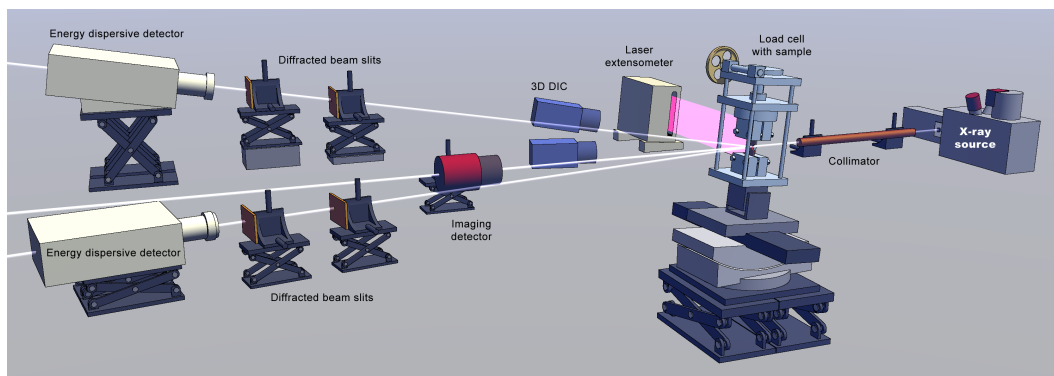


Figure 1. Democratisation of synchrotron-based X-ray diffraction for laboratory-scale property measurements

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[1] I. Grega, W. Whitney and V.S. Deshpande (2025), *High-speed X-ray tomography for 4D imaging*, **Proceedings of the National Academy of Sciences**, 122, e2521089122.

[2] Z. Wang, S. Das, A. Joshi, A.J.D. Shaikeea and V.S. Deshpande (2024), 3D observations provide striking findings in rubber elasticity, **Proceedings of the National Academy of Sciences**, 121 (24), e2404205121.

Advances in the micromorphic homogenization of dynamical metamaterials

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The engineering design and analysis of high-tech systems calls for reliable and accurate methods that adequately capture the mechanics of the underlying constituting materials. This tends to be particularly complex for highly heterogeneous materials, for which a rich class of homogenization methods has been developed to condense all the small-scale fluctuations in an effective continuum that can be solved at the engineering level. Within this class, computational homogenization serves as a highly accurate two-scale coupling of complex nonlinear materials. Amongst others, this homogenization method has been successfully applied to mechanical, thermal and electromagnetic problems, but its application to metamaterials remains a challenge. Metamaterials are characterized by tailored microstructures that entail a dominant emergent effect at the macro-scale. This contribution focuses on the advanced homogenization and model reduction of dynamical metamaterials, leading to a micromorphic-like continuum.

Dynamical metamaterials, mitigating waves, are instrumental for inhibiting sound and vibration transmission in a targeted frequency range. As a point of departure, the original computational homogenization scheme applicable to elastic resonant acoustic metamaterials will be outlined [1]. Exploiting linearity of the problem, a closed form micromorphic continuum homogenization approach for this class of materials is obtained. The resulting dispersion spectra are shown to be accurately captured, which enables direct solutions of initial boundary value problems as required for engineering design problems at the macro-scale [2]. Next, the method will be extended to viscoelastic metamaterials, whereby the damping effects in the solid are modeled using the Kelvin-Voigt constitutive behavior [3, 4]. Finally, a solid-fluid metamaterial is considered, for which an elastic Biot continuum is recovered at the macroscale with micromorphic enrichment variables representing the inertia of the local structure resonance.

- [1] A. Sridhar, V.G. Kouznetsova, M.G.D. Geers, Homogenization of locally resonant acoustic metamaterials towards an emergent enriched continuum, *Comp. Mech.* **57**, 423–435, 2016. <https://doi.org/10.1007/s00466-015-1254-y>
- [2] R. Liupekevicus, J.A.W. van Dommelen, M.G.D. Geers, V.G. Kouznetsova, An efficient multiscale method for subwavelength transient analysis of acoustic metamaterials, *Phil. Trans. Royal Society A* **382**(2279), article 20230368, 2024. <https://doi.org/10.1098/rsta.2023.0368>
- [3] R. Liupekevicus, J.A.W. van Dommelen, M.G.D. Geers, V.G. Kouznetsova, Transient computational homogenization of heterogeneous poroelastic media with local resonances, *Int. Jnl. Num. Meth. Engng. Solids* **125**(18), 2024. <https://doi.org/10.1002/nme.7505>
- [4] R. Liupekevicus, J.A.W. van Dommelen, M.G.D. Geers, V.G. Kouznetsova, Equivalent continuum for viscoelastic metamaterials, *Comp. Meth. Appl. Mech. Engng.* **445**, article 118160, 2025. <https://doi.org/10.1016/j.cma.2025.118160>

Compressive Behavior and Crushing of Foams: Experiments and Modeling

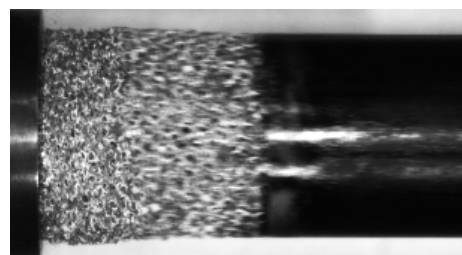
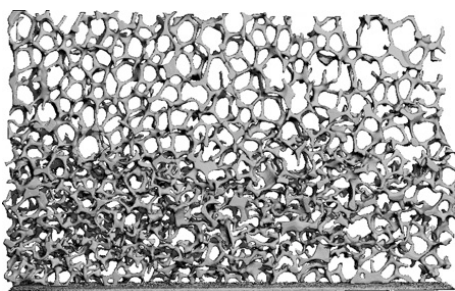
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KEYWORDS: *Foam Crushing, Quasi-static, Propagating Instability, Impact/Shock.*

Lightweight cellular materials such as foams exhibit excellent energy absorption characteristics and are widely used for impact mitigation in a variety of applications. This lecture presents results from combined experimental and analytical efforts that investigate the crushing behavior of Al-alloy open-cell foams under quasi-static uniaxial and triaxial loadings and under impact. The foam microstructure is established using X-ray tomography including the cell and ligament morphology. The compressive force-displacement response exhibits an initial stiff branch, followed by an extended load plateau during which localized cell crushing progressively spreads throughout the specimen. When most of the cells are crushed the densified material stiffens again. Foam crushing is simulated using micromechanically accurate models. Skeletal random models generated from soap froth using the *Surface Evolver* software are dressed with solid to match the material distribution and relative density of actual foams. The ligaments are modeled as shear-deformable beams with variable cross sections discretized with beam elements in LS-DYNA, while the Al-alloy is modeled as elastic-plastic. Such models are shown to reproduce all aspects of quasi-static crushing faithfully, including the initiation of instability, its localization, the subsequent propagation and the densification stage. This modeling framework is used to crush model foams in a true triaxial loading apparatus. The recorded responses are shown to exhibit the same three-deformation regimes characterized by stress plateaus and localized crushing. The results of such discrete models are subsequently used to calibrate a pressure sensitive constitutive model with a partially softening material response. It is demonstrated that such a homogenized solid, introduced in finite element analyses of triaxial crushing, can reproduce the responses and localized crushing observed in the discrete models.

Under impact at velocities higher than 50 m/s, the foams develop nearly planar shocks that propagate at well-defined velocities, crushing the specimen. The shock-impact speed and the densification strain-impact speed representations of the Hugoniot were both extracted directly from high-speed images recorded during the impact. The compaction energy dissipation across the shock was found to increase with impact speed and to be significantly greater than the corresponding quasi-static one. Similar discrete foam models used in impact simulations are found to capture accurately the dynamic crushing behavior observed experimentally. That is, limited inertial effects are present below a critical speed, and shock formation above it. In the shock regime, the models reproduce the force acting at the two ends, the shock front velocity and energy absorbed.



Fast Fourier Transform (FFT)-based models for microstructure/property relationships of polycrystalline materials

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Crystal plasticity (CP) are well-established models, used, e.g., in scale-bridging applications to obtain microstructure-sensitive mechanical response of polycrystalline materials. These models require a proper consideration of the single crystal deformation mechanisms, a representative description of the microstructure, and an appropriate scheme to connect the microstates with the macroscopic response. FFT-based methods, originally proposed by Moulinec and Suquet for composites [1] and extended to polycrystals [2] (our most recent formulation, including non-local large-strain elasto-viscoplasticity reported in [3]) are attractive due to their higher efficiency compared with CP-Finite Elements, and their direct use of voxelized microstructural images. In this talk, we will report recent progress on FFT-based polycrystal plasticity, with emphasis in novel implementations, including strain-gradient plasticity, achieving geometric accuracy working with voxelized images, non-periodic extensions, and dynamic effects. We will show applications of these methods to: micromechanics of nano-metallic laminates, wave propagation in heterogeneous materials, multiscale coupling with Lagrangian hydrocodes, integration with 3-D characterization methods, and use for training and validation of machine-learning methods.

- [1] H. Moulinec, P. Suquet, A numerical method for computing the overall response of nonlinear composites with complex microstructure, *Comput. Methods Appl. Mech. Eng.* **157**(1–2), 69–94, 1998. [https://doi.org/10.1016/S0045-7825\(97\)00218-1](https://doi.org/10.1016/S0045-7825(97)00218-1)
- [2] R.A. Lebensohn, N-site modelling of a 3D viscoplastic polycrystal using Fast Fourier Transform, *Acta Mater.* **49**(14), 2723–2737, 2001. [https://doi.org/10.1016/S1359-6454\(01\)00172-0](https://doi.org/10.1016/S1359-6454(01)00172-0)
- [3] M. Zecevic, R.A. Lebensohn, L. Capolungo, Non-local large-strain FFT-based formulation and its application to interface-dominated plasticity of nanometallic laminates, *J. Mech. Phys. Solids* **173**, 105187, 2023. <https://doi.org/10.1016/j.jmps.2022.105187>

Micromechanics: The “Strength” of Miniaturized Testing

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The continued miniaturization of engineering systems and the increasing complexity of multimaterial architectures demand characterization approaches capable of resolving mechanical behavior at the length scales where deformation, damage, and failure originate. Conventional testing methods often fail to capture the localized phenomena governing performance, particularly when the representative volume approaches the characteristic dimensions of the microstructure and pronounced size effects emerge. This presentation highlights recent advances in quantitative small-scale mechanical testing and nanomechanical characterization that enable direct correlations between processing, local microstructure, and performance, going well beyond investigating the “smaller is stronger” paradigm. Emphasis is placed on distinguishing intrinsic material behavior from testing artifacts and on establishing robust constitutive descriptions for microscale materials and device components. By integrating advanced microstructural characterization with micromechanical testing, this framework provides powerful tools for accelerated process optimization, root-cause failure analysis, and predictive lifetime assessment across a broad range of material systems and applications. Ultimately, the talk demonstrates how miniaturized testing has evolved from a characterization technique into a quantitative diagnostic methodology, revealing that the reliability and functionality of advanced materials are fundamentally governed by local mechanical behavior across multiple length scales.

Modelling electrical conductivity across scales

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KEYWORDS: *homogenisation, thermo-electric conductors, Joule heating, cohesive-zone model, size effects.*

Motivated by the effects induced by grain boundaries and microcracks on effective electrical properties, the focus of this contribution is on the development of generalised computational multiscale formulations for electrical conductors. In line with classic energy-based approaches for bulk material, it is shown that effective electrical conductivity tensors can be condensed from the underlying microstructure. Thereby, special emphasis is placed on asymptotic expansions and Hill-Mandel-type multiscale techniques. Their usefulness is demonstrated by consideration of experimental investigations. Extending the established multiscale description of electrical conductors, grain boundaries together with related strong discontinuities in the microscale fields are elaborated. This allows for a comprehensive analysis of the Andrews method, which is established as the key materials science approach to study grain boundary resistivity and its effect on the effective electrical properties of polycrystalline materials. Particularly, the applicability as well as the limitations of the Andrews method are addressed. In general, material interfaces occur at different length scales – electrically conductive adhesives being a typical example of, e.g., macroscale interfaces. Such adhesives are key elements of electronic packages used in, e.g., communication and computing applications, with their distinct properties induced by the underlying multiscale nature. Considering appropriate scale-bridging relations, these macroscale composite interphases are approximated as zero-thickness cohesive interfaces. The proposed framework thereby generalises classic phenomenological traction-separation approaches by relating the apparent electro-mechanical interface response to the underlying microstructure.

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- [1] D. Güzel, D. Wiedemann, T. Kaiser, and A. Menzel. On dissipative effects in thermo-electrically coupled systems: Hill-Mandel-type homogenisation, asymptotic expansions and two-scale convergence. *J. Mech. Phys. Solids*, 208:106427, 2026. doi:10.1016/j.jmps.2025.106427.
- [2] D. Güzel, T. Kaiser, and A. Menzel. A computational multiscale approach towards the modelling of microstructures with material interfaces in electrical conductors. *Math. Mech. Solids*, 30(2):247–266, 2025. doi:10.1177/10812865231202721.
- [3] D. Güzel, T. Kaiser, H. Bishara, G. Dehm, and A. Menzel. Revisiting Andrews method and grain boundary resistivity from a computational multiscale perspective. *Mech. Mat.*, 198:105115, 2024. doi:10.1016/j.mechmat.2024.105115.
- [4] T. Kaiser, G. Dehm, C. Kirchlechner, A. Menzel, and H. Bishara. Probing porosity in metals by electrical conductivity: Nanoscale experiments and multiscale simulations. *Euro. J. Mech. A/Solids*, 97:104777, 2023. doi:10.1016/j.euromechsol.2022.104777.
- [5] T. Kaiser and A. Menzel. Fundamentals of electro-mechanically coupled cohesive zone formulations for electrical conductors. *Comput. Mech.*, 68:51–67, 2021. doi:10.1007/s00466-021-02019-z.

From fundamental principles to mechanics near absolute zero

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KEYWORDS: *Cryogenics, Weakly Excited Lattice, Dissipative Phenomena, Fundamental Principles.*

Cryogenics was born in Kraków in 1883, when Karol Olszewski, an outstanding chemist, carried out – together with the physicist Zygmunt Wróblewski – the first successful liquefaction of air. Nowadays, attaining temperatures close to absolute zero is relatively standard, although it still requires sophisticated and complex equipment. In the vicinity of absolute zero, the thermal conductivity, thermal expansion coefficient, and specific heat of metals and their alloys all tend toward zero. This behaviour is fully consistent with the third law of thermodynamics, which states that the entropy of a perfect crystal at absolute zero is equal to zero. It is well known that heat transport in a crystal lattice is governed by two fundamental mechanisms: phonon transport and free-electron transport. At extremely low temperatures, the contribution of lattice quantum vibrations (phonons) is limited to acoustic modes and can be described as the total energy of the lattice, represented by the sum of the energies of all harmonic oscillators. The excess lattice energy above zero vibrations is proportional to the fourth power of temperature; consequently, the specific heat – expressed as the derivative of lattice energy with respect to temperature – is proportional to the third power of temperature. As the specific heat approaches zero with decreasing temperature, the derivative of temperature with respect to heat (dT/dQ) tends to infinity. Therefore, near absolute zero, even an arbitrarily small dissipation of energy can produce a significant increase in temperature. In the present paper, several dissipative phenomena occurring in crystal lattice at very low temperatures are discussed, including intermittent plastic flow [1], plastic strain-induced phase transformations, the evolution of microdamage, fracture [2], as well as creep mechanisms. Intermittent plastic flow represents an oscillatory mode of plastic deformation that occurs below a critical temperature: T_0 for materials with high stacking fault energy (HSFE) and T_1 for materials with low stacking fault energy (LSFE). Plastic flow in metastable materials, such as stainless steels, at extremely low temperatures is usually accompanied by a dynamic evolution of the microstructure resulting from plastic strain-induced fcc–bcc phase transformation. Ductile damage and fracture are key issues for metastable materials operating at extremely low temperatures. A broad class of these materials, particularly stainless steels, exhibits clear evidence of ductile fracture. Moreover, extensive studies of the long-term creep behaviour of metals and alloys at cryogenic temperatures clearly indicate that creep occurs even at temperatures approaching absolute zero (liquid helium, 4.2 K). To explain the background of these phenomena, the behaviour of liquid and superfluid helium – the only element that remains in a liquid state down to absolute zero – is examined, with particular emphasis on phase transitions. Heat transport across the solid–fluid boundary and its influence on lattice-related dissipative phenomena are also illustrated and discussed. All of these effects are considered in the context of the fundamental principles of mechanics and thermodynamics.

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- [1] K. Nalepka, B. Skoczeń, R. Schmidt, W. Zwolińska-Faryj, E. Schmidt, R. Chulist, *Int. Journ. of Plasticity*, **177**, 103994, 2024. <https://doi.org/10.1016/j.ijplas.2024.103994>
- [2] R. Schmidt, E. Schmidt, B. Skoczeń, *Int. Journ. of Plasticity* **187**, 104273, 2025. <https://doi.org/10.1016/j.ijplas.2025.104273>

Diffuse-interface modelling of microstructure evolution at micro- and macro-scale

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KEYWORDS: *interfaces, instabilities, shape memory alloys, deformation twinning, phase-field method.*

Formation and evolution of microstructure is a common feature in displacive transformations such as martensitic transformation and deformation twinning. It is accompanied by nucleation, propagation and annihilation of interfaces, either direct phase and twin boundaries or microstructured interfaces such as austenite–twinned martensite interfaces. These phenomena are particularly important in the case of shape memory alloys (SMAs), in which martensitic transformation is the main mechanism responsible for their functional properties, in particular for the shape memory effect and pseudoelasticity. In deformation twinning, the associated microstructure evolution is typically coupled with dislocation slip, and from the modelling point of view, the strong coupling between the two mechanisms of plastic deformation constitutes an additional challenge.

The phase-field method is a powerful computational tool for spatially-resolved modelling of microstructure evolution. Its essence lies in treating the interfaces as diffuse. This is achieved by introducing a continuous phase variable, called the order parameter, so that interface tracing is avoided and computations can be performed on a fixed computational grid. On the other hand, the need for accurate resolution of the diffuse interfaces requires the computational grid to be sufficiently fine with respect to the interface thickness.

At a higher scale, the stress-induced transformation in polycrystalline SMAs often proceeds in a heterogeneous manner, through the propagation of macroscopic transformation fronts that separate transformed and untransformed areas of the sample and often resemble Lüders bands, although more complex patterns are also observed. This is particularly true for NiTi subjected to tension-dominated loading. The associated instabilities result from a non-monotonic (up-down-up) intrinsic stress–strain response. A possible approach to modelling related phenomena is to introduce some kind of gradient enhancement into the model. As a result, the macroscopic transformation front is modelled as a diffuse interface, and the computational framework bears some similarity to the phase-field method. This approach has been used in our recent work on the modelling propagating instabilities and transformation patterns in pseudoelastic NiTi.

The talk will summarize our recent results on diffuse interface modelling of martensitic transformation in SMAs [1], deformation twinning in magnesium [2, 3], both within the phase-field framework, and transformation patterns in polycrystalline NiTi within the framework of gradient-enhanced pseudoelasticity [4, 5].

- [1] M. Rezaee-Hajidehi, K. Tüma, S. Stupkiewicz, Indentation-induced martensitic transformation in SMAs: Insights from phase-field simulations, *Int. J. Mech. Sci.* **245**, 108100, 2023.
- [2] M. Rezaee-Hajidehi, P. Sadowski, S. Stupkiewicz, Deformation twinning as a displacive transformation: Finite-strain phase-field model of coupled twinning and crystal plasticity, *J. Mech. Phys. Solids* **163**, 104885, 2022.
- [3] M. Rezaee-Hajidehi, P. Sadowski, S. Stupkiewicz, Indentation-induced deformation twinning in magnesium: Phase-field modeling of microstructure evolution and size effects, *J. Magn. Alloys* **13**, 1721, 2025.
- [4] M. Rezaee-Hajidehi, S. Stupkiewicz, Predicting transformation patterns in pseudoelastic NiTi tubes under proportional axial-torsion loading, *Int. J. Solids Struct.* **281**, 112436, 2023.
- [5] A. Ahadi, E. Sarvari, J. Frenzel, G. Eggeler, S. Stupkiewicz, M. Rezaee-Hajidehi, Size-dependent transformation patterns in NiTi tubes under tension and bending: Stereo digital image correlation experiments and modeling, *J. Mech. Phys. Solids* **206**, 106413, 2026.

Session TS1

Advanced continuum theories

Nonlocally Regularised Stress-Fractional Plasticity Model Considering Fabric Anisotropy

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KEYWORDS: *Nonlocal Regularization, Fractional Plasticity, Fabric Anisotropy, Numerical Methods.*

Stress-Fractional and non-orthogonal plasticity models are capable of capturing the state-dependent nonassociated behaviour of soil without using additional plastic potential or even state index in some circumstances; however, their performances in finite element analysis involving softening and strain localization can be highly sensitive to mesh discretization, thereby compromising the reliability and accuracy of the results. To this end, a nonlocal regularised two-surface stress-fractional plasticity model is proposed, where a basic simplification criterion for the practical modelling in general stress condition is suggested. Given the critical role of plastic volumetric strain in simulating strain softening, its evolution is assumed to be governed by increments at both local and neighbouring integration points. The regularization method is implemented via a user-defined subroutines using an explicit stress integration scheme, where the nonlocal model is applied to simulate boundary value problems involving over-consolidated clay under biaxial compression, cut slope, and strip footing bearing capacity. When compared to the original model, the nonlocal model substantially reduces mesh sensitivity in the load-displacement response and produces more consistent soil failure patterns, validating the effectiveness of the nonlocal approach.

- [1] W. Sumelka, M. and Nowak. Non - normality and induced plastic anisotropy under fractional plastic flow rule: a numerical study. *International Journal for Numerical and Analytical Methods in Geomechanics*, Vol. 40(5), pp. 651-675, 2016.
- [2] Y. Sun, Y. Gao, and Q. Zhu. Fractional order plasticity modelling of state-dependent behaviour of granular soils without using plastic potential. *International Journal of Plasticity*, Vol. 102, pp. 53-69, 2018.

Geometrical description of stress and strain tensor and its relation to material effort hypotheses

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KEYWORDS: *Stress tensor, Geometrical representation, Material effort hypotheses.*

A stress and strain tensor may be presented as a surface delimited by vectors located at angles α_1 , α_2 , α_3 in relation to axes x, y, z (Eq. 1). Geometrically, it outlines a domain and results from the loading. Therefore, its geometrical presentation may be used for comparison of various loading patterns. Quantities like volume, surface area, cross-section area, or circumference of the cross section are the obvious options. This study presents basic cases of uniaxial, biaxial, triaxial tension and pure shear for an isotropic solid body. The first part describes analysis of the stress cases, while the other involves analysis of strain cases. Particular cases of pure shear and uniaxial tension proved to be most interesting. It is worth mentioning that in case of stress analysis this approach does not involve any material features, whereas for strain, Poisson's ratio contributes this material property into consideration. For the first time this approach was presented by the author in 2022 [1]. In Figure 1 there is an example of the stress domain for uni-axial tension, placed in a sphere of the points for the tri-axial tension. Next to it, its isometric view of half the domain with some geometrical quantities calculated is shown. The basic equation for normal stress is presented below (Eq.1) with principal stresses utilised.

$$\sigma_\mu = \sigma_1 \cos^2(\alpha_1) + \sigma_2 \cos^2(\alpha_2) + \sigma_3 \cos^2(\alpha_3) \quad (1)$$

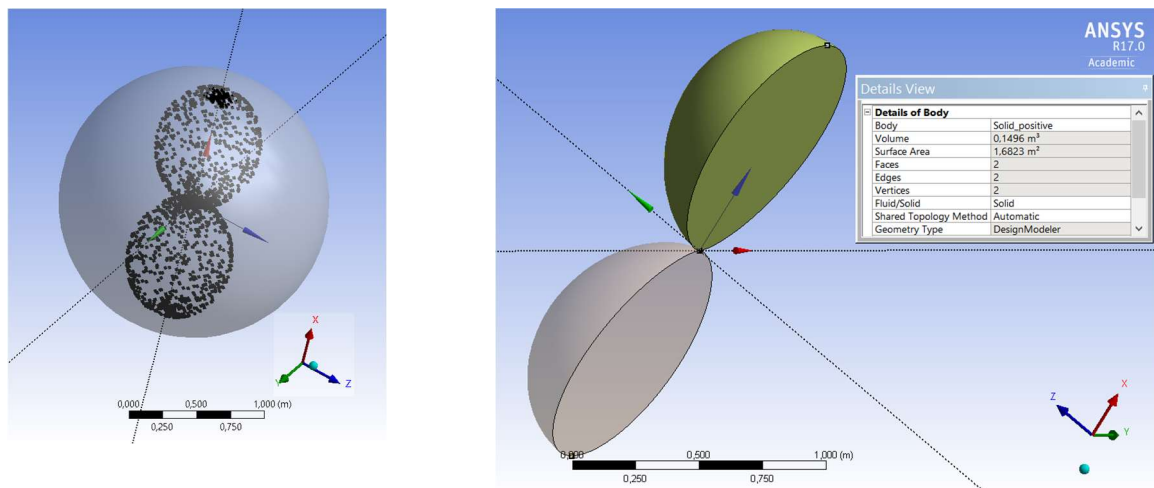


Figure 1. Clouds of points referring to normal stress tensor for uniaxial tension inside a sphere of triaxial tension [1].

The discussed approach has proved to be feasible in typical comparisons between pure shear and uniaxial tension, and biaxial tension as well. One of the discussed geometrical quantity namely, the circumference of the cross sections of the domains fits well with the Huber-Misses criterion for material's failure.

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[1] K. Waclawiak, *EngTrans.* **70**(2), 183-199, 2022. <https://doi.org/10.24423/EngTrans.1311.20220602>

A Universal Laplace Transform–Based Algorithm for the Analysis of Statically Indeterminate Bending Beams Including Shear Deformation Effects in the Vlasov–Timoshenko Model

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KEYWORDS: *Vlasov–Timoshenko beam theory, Laplace transform, Shear deformation, Structural analysis algorithm.*

This contribution outlines a unified analytical framework based on a Laplace-transform approach for the static analysis of prismatic bending beams across multiple classical and extended beam models. Starting from the full Timoshenko theory [1], the governing equation is systematically reduced to the Euler–Bernoulli model [2] as a limiting case of vanishing shear deformation. The formulation also incorporates a Vlasov warping correction for asymmetric cross-sections, enabling the analysis of beams lacking geometric symmetry and exhibiting warping-related stiffness effects.

The study addresses various static load types, including concentrated forces, bending moments, distributed loads, and beams reinforced with two internal stiffeners. All computations are performed in the Laplace domain using a single governing equation, even for multi-span or piecewise-loaded beams, and inverse transformation yields closed-form deflection fields.

To assess the influence of support spacing on the agreement between the Timoshenko, Euler–Bernoulli and Vlasov-corrected models, an experimental campaign was conducted in which beam deflections were measured at several points and compared with analytical predictions for varying support configurations. The results identify the ranges of beam slenderness and support geometry for which shear deformation, warping stiffness, or classical bending assumptions dominate.

The main novelty lies in solving multi-span and irregularly supported beams using a single closed-form Laplace-space formulation. The algorithm includes (i) system release from supports, (ii) transformation of loading to the Laplace domain, (iii) analytical solution in Laplace space, (iv) inverse transformation to the physical domain, (v) enforcement of boundary and intermediate support conditions, and (vi) computation of deflections, slopes, bending moments, shear forces, and reactions, enabling efficient treatment of beams with multiple supports, non-classical stiffness features, and non-uniform loading patterns.

- [1] S.P. Timoshenko, On the correction for shear of the differential equation for transverse vibrations of prismatic bars, *Philosophical Magazine, Series 6, Vol. 41(244)*, pp. 744–746, 1921. <https://doi.org/10.1080/14786442108636264>
- [2] T. Haukaas, “Euler–Bernoulli Beams,” University of British Columbia, 2026. Available online: <https://civil-terje.sites.olt.ubc.ca/files/2026/02/Euler-Bernoulli-Beams.pdf>

Some Results and Unusual Consequences of Elasticity without Hooke's law

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KEYWORDS: *Non-Hookean infinitesimal elasticity, non-linear small strain response, Poisson's ratio, hyperelastic isotropic model, aerogels, metamaterials*

Hookean elasticity is based on a linear relation between stresses and strains, which is reasonable for the most of solids at small deformations. In turn, linearity justifies the superposition principle leading to the classical generalized Hooke law. One of its well-known thermodynamical consequences is that for isotropic materials Poisson's ratio lies within the interval $[-1, 0.5]$. In this contribution, we propose a hyperelastic isotropic material model based on a positive-definite strain energy function (see [1] for more details). The stress-strain response of the model is non-linear even at infinitesimal deformations and cannot thus be linearized. As a result, the superposition principle does not apply, and the generalized Hooke law is not valid even at small strains. In this case, one can speak about non-Hookean infinitesimal elasticity. A further unusual feature of this material model is that Poisson's ratio can be smaller than -1 or greater than 0.5 in full agreement with the laws of thermodynamics. For example, in the latter case volume of a specimen monotonically decreases under uniaxial tension, which is rather unusual. The proposed model is verified in various deformations states such as uniaxial tension/compression, simple shear and pure dilation and demonstrates plausible and stable response.

[1] M. Itskov, *ResearchGate* (preprint), 2026. <https://doi.org/10.13140/RG.2.2.12123.22562>

Non-local space-fractional model for complex planar bar-type structures analysis

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KEYWORDS: *non-local models, fractional calculus, fractional mechanics, space-fractional truss, discrete model, statics analysis*

Modern mechanical systems, widely deployed across diverse engineering and technological applications, increasingly integrate nanoelectromechanical systems (NEMS) and microelectromechanical systems (MEMS). At these characteristic length scales, the inherently discrete and atomistic nature of matter does not fit the classical theories of continuum mechanics, which assume purely local constitutive behavior. They are therefore inadequate for precise modeling and predictive analysis in these applications.

A wide range of nonlocal phenomenological models have been developed to capture size-dependent and scale-related effects, including integral-type theories, general nonlocal theories, strain-gradient theories, and micropolar theories, among others. However, in the present work the analysis is conducted within the framework of the Fractional Continuum Mechanics (FCM) model [1].

The primary objective of the present study is to quantify changes in the global structural response resulting from microstructural modifications in selected members. It has been demonstrated that the microstructure governs the nonlocal behavior of the material [3] modeled using the fractional model. Consequently, the parameters of this model can be adjusted to represent microstructural alterations. In this work, various configurations of fractional order of material α and characteristic length scale ℓ_f for individual structural members are examined, with particular emphasis on their influence on the global response and the emergence of unexpected asymmetry. Additionally, due to the complex and computationally demanding nature of the numerical solution of fractional calculus cite szajek-2019, a multilevel framework is proposed that employs fractional bar reduction as a surrogate model [4].

The proposed procedure was assessed using full-scale models of truss-like structures that explicitly account for local effects. The findings unambiguously demonstrate the impact of microstructural characteristics on the global structural response, including the emergence of asymmetric deformation in geometrically symmetric models under symmetric loading and boundary conditions.

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- [1] Sumelka, W., "Thermoelasticity in the Framework of the Fractional Continuum Mechanics, Journal of Thermal Stresses, Vol., 37/61, pp. 678–706, 2014.
- [2] Szajek K., Sumelka W., *Identification of mechanical properties of 1D deteriorated non-local bodies*, Structural and Multidisciplinary Optimization, Vol., 59/1, pp. 185-200, 2019.
- [3] Szajek K., Sumelka W., *Discrete mass-spring structure identification in nonlocal continuum space-fractional model*, The European Physical Journal Plus, Vol., 134 (9), pp. 448, 2019.
- [4] Szajek K., Sumelka W., *Surrogate model for statics of fractional thin bar element and its equivalence with mass-spring metamaterial*, Scientific Reports, Vol., 15/1, pp.39114, 2025.

First- and Second-Order Strain-Gradient Materials in the Light of Singular Wave Analysis

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KEYWORDS: *first-order gradient materials, second-order gradient materials, singular waves, acceleration waves, constitutive equations, strain-gradient continua.*

This paper investigates first- and second-order strain-gradient materials by means of nonlinear wave dynamics, using singular shock and acceleration waves to characterize admissible constitutive equations. The framework focuses on one-dimensional continua, where the state is described by the stress $\sigma(x, t)$, the strain $\varepsilon(x, t)$, and the velocity $v(x, t)$, subject to the momentum equation $\rho v_t = \sigma_x$, the kinematic relation $\varepsilon_t = v_x$, and a general constitutive equation

$$F(\sigma, \varepsilon, \sigma_x, \sigma_t, \varepsilon_x, \varepsilon_t) = 0$$

or

$$G(\sigma, \varepsilon, \sigma_x, \sigma_t, \sigma_{xx}, \sigma_{xt}, \sigma_{tt}, \varepsilon_{xx}, \varepsilon_{xt}, \varepsilon_{tt}) = 0$$

in the second-gradient case.

In the method of singular wave analysis, a material initially in a uniform physical state is disturbed at one point, and the resulting disturbance propagates along a wave front $\phi(x, t) = \text{const}$ with speed $c = -\phi_t/\phi_x$. Using Hadamard's jump relations, the paper distinguishes between first-order (shock) waves, second-order (acceleration) waves, and third-order (higher-gradient) waves, where the jumps vanish up to a given order of derivatives but reappear at the next order. This classification allows the derivation of compatibility conditions on the wave amplitude moduli μ, κ, ν and the propagation speed c from the governing equations.

For second-order waves, the analysis yields a third-degree polynomial in the wave speed c of the form

$$\rho \frac{\partial F}{\partial \sigma_t} c^3 - \rho \frac{\partial F}{\partial \sigma_x} c^2 + \frac{\partial F}{\partial \varepsilon_t} c - \frac{\partial F}{\partial \varepsilon_x} = 0.$$

For third-order (second-gradient) waves, the compatibility analysis is extended to second-order spatial and temporal derivatives, leading to a fourth-degree polynomial

$$2\rho \frac{\partial G}{\partial \sigma_{tt}} c^4 - \rho \frac{\partial G}{\partial \sigma_{xt}} c^3 + \left(\rho \frac{\partial G}{\partial \sigma_{xx}} + \frac{\partial G}{\partial \varepsilon_{tt}} \right) c^2 - \frac{\partial G}{\partial \varepsilon_{xt}} c + \frac{\partial G}{\partial \varepsilon_{xx}} = 0.$$

The work thus provides a systematic way to deduce admissible first- and second-order gradient constitutive equations from the structure of second- and third-order singular waves, linking the non-local nature of gradient materials to the dynamics of disturbance propagation in a unified framework.

[1] Gy. Béda, *Nonlinear Anal.* **30**, 397–407, 1997.

[2] Gy. Béda, P. B. Béda, *Proc. Estonian Acad. Sci.* **8**(2), 101–111, 1999.

[3] Gy. Béda, *Int. Appl. Mech.* **10**, 136–143, 2010.

Study of the temperature effect in fractional thermoelasticity at micro- nano scale

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KEYWORDS: Fractional Calculus; Thermoelasticity; Scale Effect; Nonlocal Theory; Temperature Variation, Young Modulus

Traditional continuum models are insufficient for accurately depicting thermoelastic behavior at micro- and nano-scales, where size-dependent effects become significant. Long-range interactions at these scales strongly influence the thermomechanical response of structural systems. A novel method for simulating such nonlocal phenomena is space-fractional continuum mechanics, which uses fractional calculus. Space-fractional models can effectively represent size-dependent mechanical responses, but their application to thermoelastic problems remains constrained. A space-fractional thermoelastic framework for analyzing beam structures at the micro- and nano-scales has been described in this work. By accounting for temperature-dependent material characteristics, thermal effects are incorporated, enabling the examination of the impact of temperature changes on structural response within a coherent continuum framework. The impacts of Young's modulus, material grain size, and fractional order under various temperature conditions and boundary conditions are assessed through a parametric study. Overall, the suggested model advances our understanding of thermomechanical behavior at small scales and provides a useful framework for the study and design of micro- and nanoscale systems, such as MEMS and NEMS devices, where thermal effects are crucial.

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- [1] Stempin, P., and W. Sumelka. "Space-fractional Euler-Bernoulli beam model-Theory and identification for silver nanobeam bending." *International Journal of Mechanical Sciences* 186 (2020): 105902.
- [2] Wojciech Sumelka. "Thermoelasticity in the Framework of the Fractional Continuum Mechanics." *Journal of Thermal Stresses* 37, no. 6 (2014): 678-706.

Evaluation of Cellular Automata–Based Static Recrystallization Model Capabilities supported by Parallel Execution

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KEYWORDS: *Cellular automata, static recrystallization, OpenMP, c++.*

The evolution of material microstructure in metallic materials plays a crucial role in determining the final exploitation properties of the manufactured components. However, accurate numerical modeling of phenomena responsible for microstructure evolution requires the use of large computational domains to properly capture grain morphology and their representative interactions. Therefore, simulations of microstructural phenomena, such as static recrystallization (SRX), are computationally demanding and often limited by execution time when implemented on fine-resolution computational domains. However, this high computational cost can be significantly reduced by applying parallelization strategies, either through GPU computation [1] or distributed computing techniques that decompose the computational domain across multiple CPU processing units [2,3].

Therefore, this work investigates the use of advanced parallelization techniques to accelerate a cellular automata (CA) based model of static recrystallization. The study focuses on data-parallel approaches in which computations for individual CA cells are performed independently in multiple computing threads. Particular attention is given to the most time-consuming parts of the algorithm, including the grain growth phase, space update procedures, and nucleation processes, which dominate the overall simulation time. The application of shared-memory parallelization using technologies such as OpenMP, DPC++, or the newer C++ standard enables relatively straightforward adaptation of an existing sequential code to a multithreaded version by parallelizing loops that iterate over the CA space. This approach allows efficient utilisation of modern multicore processors without fundamental modifications to the underlying physical model, thus maintaining the model's predictive capabilities. Computational experiments demonstrate that, for sufficiently large problem sizes, significant reductions in execution time can be achieved, especially for the most computationally intensive stages of the algorithm.

ACKNOWLEDGEMENT: M.S. and S.S. acknowledge financial assistance of the National Science Centre project No. 2024/55/D/ST8/00192.

- [1] A. Giordano, A. De Rango, D. D'ambrosio, M. Gil, D. Macri, X. Martorell, R. Rongo, G. Utrera, G. Mendicino, W. Spataro, Cellular Automata on a Multi-GPU Architecture: A Technical Overview, in: Proceedings - 2024 32nd Euromicro International Conference on Parallel, Distributed and Network-Based Processing, PDP 2024, 2024, 253–259. <https://doi.org/10.1109/PDP62718.2024.00042>.
- [2] M. Sitko, Q. Chao, J. Wang, K. Perzynski, K. Muszka, L. Madej, Comput. Mater. Sci. 172, 2020, 109283. <https://doi.org/10.1016/j.commatsci.2019.109283>.
- [3] Y. Lian, S. Lin, W. Yan, W.K. Liu, G.J. Wagner, Comput. Mech. 61, 543–558, 2018. <https://doi.org/10.1007/s00466-017-1535-8>.

Fractional evolution of damage anisotropy in anisotropic hyperelasticity: theory and validation for roofing felts

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KEYWORDS: *damage anisotropy, anisotropic hyperelasticity, fractional calculus, roofing felts.*

This contribution presents a constitutive framework for finite-strain materials in which elastic anisotropy and damage anisotropy are described independently within anisotropic hyperelasticity. Two structural tensors are introduced: one for the directional elastic response and one for the evolving directional damage state. The free-energy function is decomposed into an undamaged hyperelastic part and a damage-related energy loss part, which provides an objective and thermodynamically admissible description. The main novelty is a time-stress-fractional evolution law for anisotropic damage. The direction of damage growth is determined by a Riesz-Caputo fractional derivative with respect to the stress state, while the temporal history of damage can be represented by a Caputo fractional derivative with respect to time. As a result, the model can capture both stress-induced directional effects and memory in damage evolution. Because the evolution equations do not admit a general closed-form solution, a numerical approximation is derived and prepared for implementation in an Abaqus subroutine. The formulation is then examined through a parametric study for an isotropic hyperelastic solid and validated against uniaxial tension tests for roofing felts, which exhibit pronounced elastic and damage anisotropy due to orthogonal fibre reinforcement. The results show that the proposed approach can reproduce finite-strain behaviour together with direction-dependent degradation, making it a promising tool for anisotropically damaged hyperelastic materials.

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- [1] B. Luczak, W. Sumelka, A. Wypych, *Materials* 14(22), 6907, 2021. <https://doi.org/10.3390/ma14226907>
- [2] W. Sumelka, G.Z. Voyiadjis, *Int. J. Solids Struct.* 124, 151-160, 2017. <https://doi.org/10.1016/j.ijsolstr.2017.06.017>

Cobalt Nanorods Buckling within Nonlocal Eringen Elasticity Theory: Numerical and Experimental Approach

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KEYWORDS: *nonlocal elasticity theory; nanorods; post-buckling behavior.*

This study examines the post-buckling response of compressed nanorods using Eringen's nonlocal elasticity theory. We develop a nonlocal elastica model for a compressed nanorod based on the moment-curvature relation and the corresponding equilibrium equations. The boundary conditions are chosen to reflect those used in experiments on nanowires. The resulting nonlinear boundary-value problem is solved numerically with a shooting method, which makes it possible to compare the classical Euler elastica with its nonlocal extension and to evaluate the influence of the nonlocal parameter on the structural response. In particular, the simulations are used to observe how variations in the nonlocal parameter affect the post-buckling shape, as well as the value and location of the maximum deflection along the nanowire's axis. The shooting method was chosen because of its numerical stability and robustness when dealing with high order nonlinear differential equations containing trigonometric terms and variable coefficients. The effects of the scale parameter, slenderness ratio and boundary conditions on buckling behavior are very carefully examined.

The model was developed to match as closely as possible the conditions of the in-situ SEM compression experiments performed with a flat-punch nanoindenter. In those tests, SEM image sequences were used to track cobalt nanowire deflection in the post-buckling regime, providing the basis for fitting the nonlocal parameter in the model, for given values of the initial angle and bifurcation mode. The sensitivity of the elastica shape to variations in the nonlocal parameter is evident. The numerical results clearly show that even relatively small changes in the nonlocal parameter can lead to noticeable differences in the predicted post-buckling configuration of the nanorod, including the location and value of the maximum deflection. It can also be observed that the higher the value of the initial angle is, the greater the difference between the Euler-Bernoulli theory and the nonlocal Eringen theory. A similar conclusion can be drawn by considering the bifurcation mode value – the higher the mode value is, the greater the difference in the results. Likewise, higher buckling modes are associated with more pronounced discrepancies between the two models, suggesting that nonlocal effects become increasingly important for more complex deformation patterns.

On this basis, we conclude that selecting an appropriate value of the nonlocal parameter is not just a technical detail, but a key step in obtaining realistic predictions for a given material system. In particular, for larger initial imperfections, the nonlocal model departs more strongly from the classical Euler–Bernoulli prediction, which indicates that geometric imperfections amplify nonlocal effects. These studies showed overall agreement with elastica-based predictions, but also highlighted the influence of geometric parameters and the need to account for realistic support conditions at the nanoscale. Overall, the findings support future comparisons with nanoscale experiments and may help in identifying appropriate nonlocal parameter values and experimentally realistic boundary conditions for slender nanostructures.

Session TS2

Atomistic and nanoscale modelling

Why nanostructures are different?

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KEYWORDS: *Nanostructures, Moire bilayers, correlated electron-ion dynamics, anharmonicity.*

In my talk I will give a general introduction to vibrational properties, and their coupling to electron liquid, in nanostructures. In the first part I wish to provide a brief and accessible explanation on what happens when a characteristic size of a device reaches an order of nanometers. I shall introduce concepts such as energy level quantization, surface-to-volume ratio, anharmonicity and non-adiabaticity to discuss their implications and range of applicability. To be specific I shall focus on one- and two-dimensional systems where collective phenomena definitely determine the physics of the material. These are the systems that are at present at the forefront of materials science such as nanotubes, nanorods, stepped surfaces, but also topological states on crystal dislocations. One particular example that I will explore in more detail are Moire bi-layers.

The reason why Moire bi-layers are special is because at a finite twist angle, in a single sample one obtains a set of atoms with varying degrees of anharmonicity and non-adiabaticity. Indeed, several exotic orderings have been detected in this platform within the last decade of intense research, which has lead to numerous publications in the highest level journals. Thus, in the second part of my talk I will show how to incorporate such extraordinary lattice dynamics within a full microscopic quantum mechanical description: the method of effective correlated electron-ion dynamics (ECEID). I will present the ECEID equation (together with a sketch of their derivation) and compare the results with simpler methods for instance Ehrenfest dynamics.

In the last part of my talk I will show how these microscopic results can be employed into a field theoretical description of nanostructures at the mesoscopic scale. It is at this scale that the collective phenomena play a crucial role and ought to be captured. In this way measurable quantities can be obtained. Overall, the aim of this talk is to show that a description of materials that include the quantum mechanical effects is entirely possible already with a current state of knowledge. Importantly, up to large extend it does not require a heavy numerical effort, but it is a description that uses analytical methods.

ACKNOWLEDGEMENT:

I acknowledge collaboration with my PhD student Shaswati Mandal on a part of the ECEID computations, and interesting discussions on numerical implementations with prof Wacław Kuś and prof. Tadeusz Burczynski. We acknowledge financial support of NCN under OPUS grant no.2021/43/B/ST8/03207

Influence of Mn on Plastic Deformation in Polycrystalline α -Ti–Mn Alloys

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KEYWORDS: *Molecular dynamics simulations, tensile tests, mechanical properties.*

Titanium alloys are widely used in aerospace, biomedical, and energy applications owing to their high specific strength, corrosion resistance, and biocompatibility. In order to investigate the influence of the manganese on the mechanisms of plastic deformation in polycrystalline α -phase Ti–Mn alloys we have performed a series of molecular dynamics simulations for uniaxial tensile tests at 300K and 10^9s^{-1} strain rate for Ti–2at%Mn, Ti–4at%Mn, as well as pure Ti and analyzed the results.

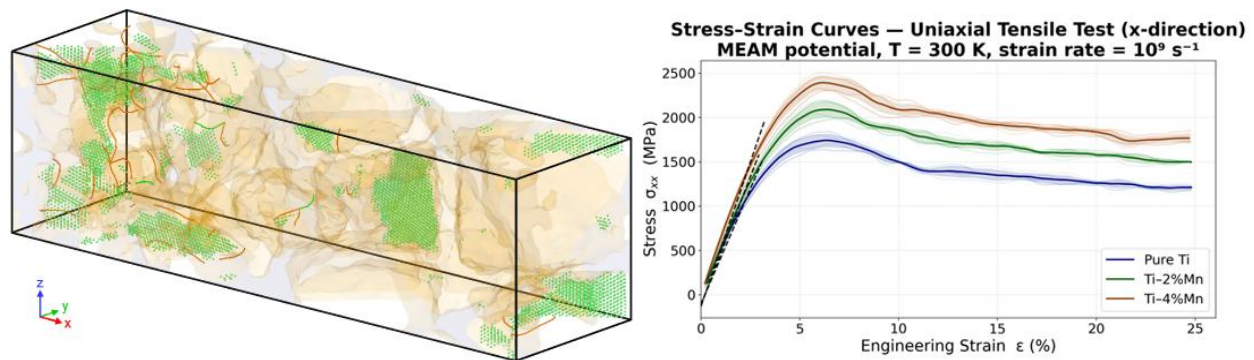


Figure 1. Example of simulated cell after tensile test, as well as stress-strain curves for pure Ti, Ti–2Mn and Ti–4Mn.

In pure Ti, plastic deformation is mediated mainly by the growth of the grain boundaries, reaching 56at% at the end of strain test, compared to 46% in Ti–2Mn and 39% in Ti–4Mn at.%. Apart from the grain boundary growth, a different mechanism of deformation is occurring inside the grains. When strain is applied, stacking faults are formed (which in HCP material are planes ordered as FCC), limited inside the grain by the $1/3\langle 1-100 \rangle$ -type edge dislocations, or by the grain boundaries. Under further application of strain, three different options are possible. (i) Two $1/3\langle 1-100 \rangle$ -type dislocations surrounding a stacking fault form one $1/3\langle 11-20 \rangle$ -type dislocation, that is terminated on the grain boundaries, following the balance of energies, e.g. $1/3[-1010]-1/3[1-100]=1/3[-2110]$. This leads to a decrease in the percentage of FCC atoms. (ii) Stacking fault is absorbed into the grain boundary, leading to a decrease in the density of $1/3\langle 11-20 \rangle$ -type dislocations. (iii) Stacking faults grow until they fully terminate on the grain boundaries and either stabilize or split the grain in two. Stacking faults form in every sample of every alloy, but in alloys with Mn, their number and size are increased. As such, a clear trend is observed: increasing Mn content leads to higher resistance to deformation, as reflected in the stress–strain response. At the atomic scale, plastic deformation is governed by dislocation nucleation and their subsequent interactions. The addition of Mn modifies the local atomic environment, hindering dislocation mobility and contributing to the observed strengthening.

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The Influence of Kinks in Edge Dislocations of bcc Fe on the Acoustic Softening Effect

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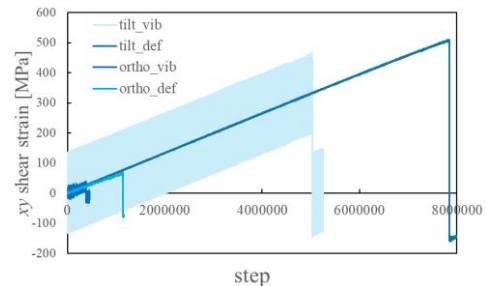
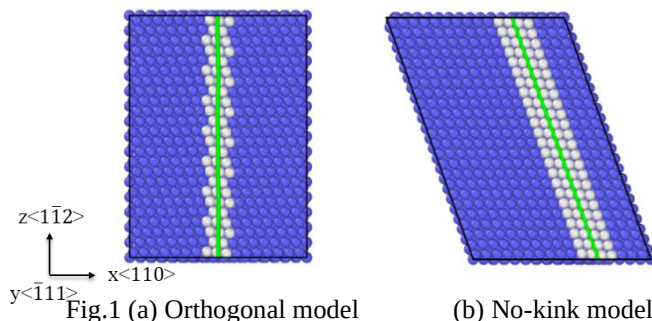
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KEYWORDS: *Acoustic Softening, Edge Dislocation, Molecular Dynamics, Ultrasonic Vibration, Kink.*

There is an effect called the ultrasonic vibration-assisted forming effect. It is a phenomenon, in which the flow stress decreases intensely when ultrasonic vibration is superimposed during the plastic deformation. It includes three effects, which are the “Stress superposition effect”, “Residual effect” and “Acoustic softening effect”. This study focuses on the acoustic softening effect. Asazuma elucidated that the atomic density difference resulting from extra atomic planes affects the interatomic potential, leading to an imbalance in atomic mobility; this promotes slip and gives rise to acoustic softening [1]. However, in that study, the edge dislocations contained kinks, and the effect of these kinks remains unclear. The aim of this study is to elucidate the influence of kinks in edge dislocations on the ultrasonic softening effect by comparing the yield stress, the interatomic potentials, and the kinetic states of atoms, which take account of their orientation.

The molecular dynamics simulations were conducted by LAMMPS [2] using the edge dislocation inserted model shown in Figure 1. Two types of models are created: a tilted model and an orthogonal model. The orthogonal model size is $40.8\text{\AA} \times 88.8\text{\AA} \times 56.0\text{\AA}$ and it contains 17424 atoms. Also, the no-kink model is tilted by $19.2\text{\AA}$ in the xz direction to satisfy periodic boundary conditions. In this model, slip direction $\langle 111 \rangle$ adopted to the x direction, and slip plane (110) to xz plane. xy shear and ultrasonic vibrations that proportional to the normal yield stress were applied to both models. The stress-time curves are displayed in Figure 2. The yield stress of the orthogonal model decreased from 68 MPa to 40 MPa. Furthermore, the yield stress of the tilted model decreased from 510 MPa to 460 MPa. These results indicate that the kink caused a significant reduction in yield stress. It was also found that acoustic softening effects were increased efficiency by four times due to the kinks.



- [1] Akari Asazuma and Shuichi Arikawa, Absorption of ultrasonic vibration energy by dislocations in body-centered cubic iron: a mechanistic study using molecular dynamics simulations, 2026. <https://link.springer.com/article/10.1007/s10853-026-12331-9>
- [2] LAMMPS Molecular Dynamics Simulator: <https://lammps.sandia.gov>

Nanoscale Modelling of New 2D Materials

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KEYWORDS: 2D Materials, Interatomic Potentials, Nanoscale Modelling, Moire Pattern, AI Algorithms.

2D materials play important role in engineering applications and the problem how to design new ones based on atomistic and nanoscale modelling is the subject of the paper.

The following problems are considered:

- for 2D Materials with p-orbitals, (graphene analogues), i.e. the case of materials where valence electrons are well spread as they reside on weakly correlated p-orbitals, we shall inquire how does the change of constituents towards heavier atoms affect structural properties;
- for 2D Materials with d-orbitals we shall explore whether our relatively simple method can be extended to capture systems with electrons correlations.

The main goal is to find stable arrangements of selected atoms of carbon, molybdenum, silicon and tin under certain imposed conditions. The total potential energy of an atomic system is minimized by AI in the form of a hybrid parallel evolutionary algorithm.

In the case of carbon a discrete atomic model and interactions between atoms are modeled using the AIREBO potential. The parallel approach used in computations allows significant reduction of computation time. Validation of the obtained results of new 2D graphene allotropes obtained using the described methodology is presented, along with their mechanical properties [1,2].

Apart from graphene one of the most prominent 2D material is the Single-Layered Molybdenum Disulfide (SLMoS₂), which reveals polymorphism at the nano-level. The paper presents optimization technique which allows to obtain SLMoS₂ heterostructures with desired mechanical properties. The behavior and energy of the atoms is determined by the REAX-FF potential. Examples of such periodic SLMoS₂ 2H/1T heterostructures are presented with corresponding mechanical properties [3].

The ability of various interatomic potentials to reproduce the properties of silicene and tin, that is, 2D single-layer silicon and the stanene (2D tin), polymorphs are also examined [4], [5].

Finally, we present also mesoscopic scale superstructures, as a new tool to tailor properties of 2D materials. The simplest example here is Moire pattern in bi-layers, a generator of which is presented.

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- [1] A. Mrozek, W. Kuś, T. Burczyński, *Computational Materials Science*, Vol.106, pp.161-169, **2015**.
- [2] M. Maździarz., A. Mrozek , W. Kuś, T. Burczyński, *Materials Chemistry and Physics*, Vol.202, pp.7-14, **2017**.
- [3] W. Kuś, J. Akhter Mohammed., T. Burczyński, *Materials*, ISSN: 1996-1944, Vol.15, No.8 (2812), pp.1-9, **2022**.
- [4] M. Maździarz, *Beilstein J. Nanotechnol.* **2023**, 14, 574–585.
- [5] M. Maździarz, *Journal of Computational Chemistry*, **2025**; 46:e70032 1 of 12.

Atomistic reconstruction of dislocation sets based on tensor algebra of lattice distortion fields

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KEYWORDS: *Dislocation Network, Atomistic Models, Preprocessing, Lattice Distortion, Tensor Fields*

Atomistic models of dislocations are often obtained by means of elastic-plastic relaxation of a perfect crystal lattice subjected to external loading. Another method, widely used in ab-initio modeling, is based on insertion of single dislocations into the perfect lattice. In such a case, the analytic formulas for displacement vector field inserting a single dislocation into elastic continuum are used. As of yet, the methods mentioned above do not give possibility for emerging the atomistic models of arbitrary chosen networks of dislocations. Among others, this problem concerns reconstruction the sets of dislocations observed by means of high resolution transmission electron microscopy. In this talk we discuss a deterministic method of obtaining atomistic models of dislocation networks. The method is based on a tensor algebra of elemental lattice distortion tensor fields used to subsequent insertion of single dislocations into deformed crystal lattice.

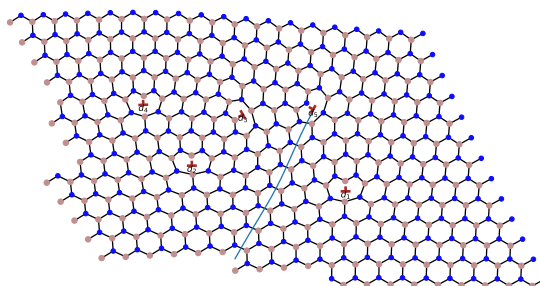


Figure 1. Preprocessed GaN lattice and glide plane along which the 5-th dislocation has been inserted[1].

Contrary to the linear-strain and linear-rotation measures, a lattice distortion tensor is the correct tensor measure of finite deformation. Thus, many different tensor fields of finite strain and finite rotation can be extracted uniquely from such a distortion field [2]. This enables a preprocessing of atomistic models of dislocations in terms of finite deformation approach. A method presented here links: (i) the analytic formulas for lattice distortions derived from the linear theory of dislocations, (ii) a tensor algebra of distortion fields, and (iii) the atom-by-atom reconstruction of a network of dislocation cores into crystal lattice (see Fig. 1). Configurations of atoms obtained in this way satisfy the stress equilibrium condition in terms of the linear theory of elasticity. On the other hand, the spatial Burgers vectors of dislocations are stretched and rotated to each other according to the finite deformation theory. Such obtained the resultant network of dislocations can be used next as the input data for the ab-initio and/or molecular dynamics programs to find a low energy configuration of atoms corresponding to a given interatomic potential.

[1] P. Jarosik, WURTZITE, <https://github.com/pjarosik/wurtzite>.

[2] P. Dłużewski K. Napleka, *CAMES* **32**(4), 367-383, 2025. <https://doi.org/10.24423/comes.2025.1963>.

Session TS3

Biomechanics and biomaterials

In Silico simulations of functionally graded tricuspid artificial aortic valves

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KEYWORDS: *Aortic Valves, Ogden model, FEM, FGM.*

Cardiovascular diseases are the leading cause of death worldwide. Among them, aortic valve (AV) disorders characterized by abnormal function manifesting as regurgitation or limited leaflets movement become more prominent [1]. Current treatment methods involving the implantation of an artificial valve, despite continuous advances in engineering and medical sciences, are still far from achieving an optimal solution in terms of balancing the implant's cyclic deformation with its fatigue strength. The aim of this study was to investigate the effect of using functionally graded materials (FGM) on the working cycle of the considered synthetic tricuspid AV geometries. A homogeneous reference AV model was also considered [see Fig. 1a]. Using ANSYS Mechanical software (ANSYS Inc., US) and the finite element method (FEM), dynamic simulations were performed under loading conditions corresponding to the isovolumetric contraction phase of the left ventricle with a maximum pressure of 120 [mmHg] and an aortic pressure of 80 [mmHg] [2]. Four conical curve-based rho-driven leaflet geometric variants were considered, with the coefficient ranging from 0.3 to 0.6. Using experimental data obtained from mSLA printed resins, hyperelastic material models were adopted, to which a second-order Ogden model was fitted. Within each geometry, the structure was divided into 4, 6, and 8 sections with varying mechanical properties, assuming a stepwise reduction in material stiffness along the free-edge direction of the valve leaflets [see Fig. 1b].

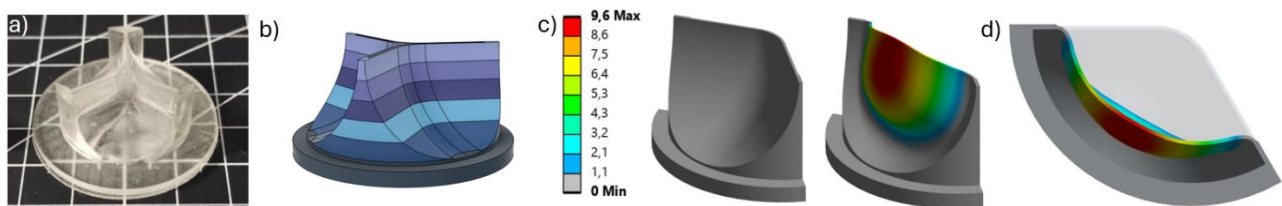


Figure 1. a) 3D-printed homogeneous AV. b) 0.4-rho AV model with six material sections. c) Total deformation [mm] of a one-third section before and after loading (isometric view). d) Top view of the deformation field.

The results of the simulations allowed the estimation of equivalent stress values, leaflet's buckling pressure as well as the displacements of the elements [see Fig. 1c, d], thereby enabling the calculation of both, the cross-sectional areas of the valve at the characteristic points required for Gorlin's equation and the assessment using clinically applied indicators. An additional outcome of this work is the development of a framework that provides a way to tailor the properties of the functionally graded material along the structure to achieve more balanced ratio between the strength of synthetic AVs and their ability to undergo elastic deformation.

ACKNOWLEDGEMENT: Presented research is an extension of the FutureLab PK founded project nr 187.

- [1] S. Parness, J. T. Womble, T. E. Hester, P. Tasoudis, A. E. Merlo, Aortic Valve Replacement in the Current Era, J. Clin. Med. 14(5), 1447, 2025. <https://doi.org/10.3390/jcm14051447>
- [2] D. LaFlamme, Cardiology: A Practical Handbook, Editions Frison-Roche, Paris, France, 2nd Edition, 2020

Influence of Material Heterogeneity on the Numerical Prediction of the Mechanical Response of an L5 Vertebra

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KEYWORDS: *finite element method, material heterogeneity, vertebral mechanics, numerical prediction, computational biomechanics*

Accurate numerical prediction of vertebral mechanical response depends strongly on the adopted constitutive assumptions and representation of material heterogeneity. Simplified homogeneous material models can potentially affecting the reliability of stress and deformation predictions. The present study investigates the influence of material heterogeneity on the numerical response of an L5 vertebra model under compressive loading.

A three-dimensional finite element model of the L5 vertebra was developed, with geometry based on a commercial anatomical model from Sawbones® (see Fig. 1). Three material modeling strategies were considered: (i) a homogeneous isotropic model with uniform elastic properties defined as a volume-weighted average of the properties of cortical and trabecular bone, (ii) a region-based heterogeneous isotropic model distinguishing cortical and trabecular bone with different constant elastic parameters, and (iii) a region-based heterogeneous orthotropic model assigning direction-dependent properties to cortical and trabecular regions. Quasi-static axial compression was applied to evaluate global stiffness, displacement fields, and stress distribution patterns.

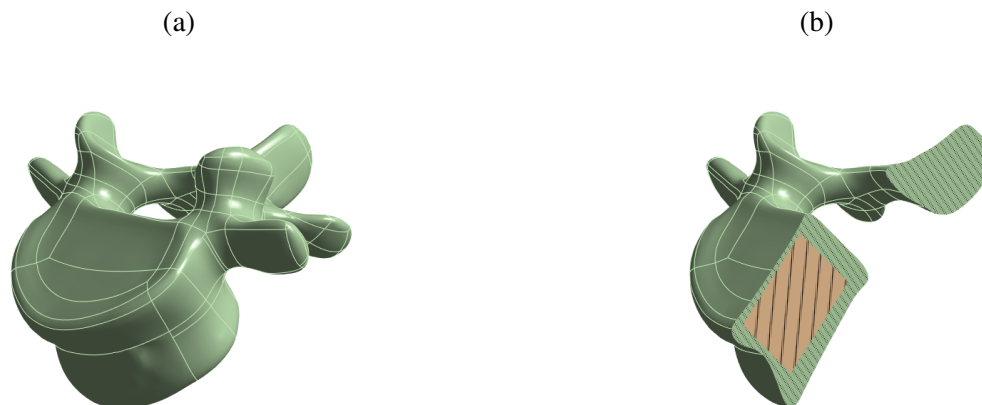


Figure 1: Finite element model of the L5 vertebra: (a) overall geometry, (b) cross-section highlighting cortical (green) and trabecular (orange) regions.

The preliminary results indicate that introducing material heterogeneity and orthotropic behavior affects both local stress concentrations and predicted structural stiffness. Although the overall load–displacement response remains qualitatively similar across all models, the heterogeneous isotropic and orthotropic formulations predict higher stress levels and larger deformations compared to the homogeneous model.

These findings demonstrate the sensitivity of vertebral finite element simulations to constitutive modeling assumptions and emphasize the importance of appropriate representation of tissue heterogeneity and anisotropy for reliable numerical prediction. The study contributes to assessing the impact of model simplifications in computational analyses of spinal biomechanics and constitutes a preliminary numerical investigation of the influence of material heterogeneity on vertebral mechanical response.

Modelling of Heat and Mass Transfer during Cryopreservation in Biological Sample Treated as Homogeneous and Porous Material with Uncertainty

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KEYWORDS: *Heat Transfer, Mass Transfer, Interval numbers, Diffusion coefficient, Numerical Methods.*

Porous materials are composed of a solid matrix and pores containing a fluid. One of the key properties of a porous medium is porosity, defined as the ratio of the pore volume to the total volume of the material. Biological tissues consist of cells separated by pores through which, for example, nutrients are transported. Therefore, it is appropriate to model them not only as homogeneous materials, but also as porous ones [1].

Biological systems can be analysed in the context of various phenomena, including cryopreservation, which involves storing biological material at low temperatures. The mathematical model considers, among other things, heat and mass transfer [2]. Thermal processes are governed by heat conduction and blood perfusion (blood convection), while mass transfer occurs as a result of diffusion associated with the movement of cryoprotectants (CPAs) or nutrients through the pores [1].

Heat transfer is described by the Fourier equation, whereas mass transfer is governed by a diffusion equation based on Fick's law. The phenomena are coupled, as the diffusion coefficient appearing in the mass transfer equation depends on temperature. The diffusion coefficient is defined in three different ways: (1) using the Einstein–Stokes equation, (2) the Arrhenius expression, and (3) a formulation accounting for the porous structure of the material. The first two approaches treat the biological sample as homogeneous, whereas the third one accounts for its porous structure [3].

Furthermore, the parameters of biological models are determined experimentally, and may therefore be subject to uncertainty. Such uncertainty can be analysed using probabilistic or non-probabilistic methods. Non-probabilistic approaches include, for example, the theory of interval numbers, defined by lower and upper bounds specifying the range of possible values [4].

This article presents a mathematical and numerical model of coupled heat and mass transfer during the cryopreservation of biological material. The tissue is modelled as both a homogeneous and a porous medium; in the former case, uncertain parameters are introduced using interval numbers.

ACKNOWLEDGEMENT: The research was partially funded from financial resources from the statutory subsidy of the Faculty of Mechanical Engineering, Silesian University of Technology, in 2026.

- [1] A.-R. A. Khaled and K. Vafai, The role of porous media in modeling flow and heat transfer in biological tissues, *Int. J. Heat Mass Transf.* **46**(26), 4989-5003, 2003. [https://doi.org/10.1016/S0017-9310\(03\)00301-6](https://doi.org/10.1016/S0017-9310(03)00301-6)
- [2] K. A. Jungare, R. Radha, and D. Sreekanth, Cryopreservation of biological samples – A short review, *Mater. Today Proc.* **51**, 1637-1641, 2022. <https://doi.org/10.1016/j.matpr.2021.11.203>
- [3] A. Skorupa and A. Piasecka-Belkhat, Analysis of Cryoprotectant Concentration During Cryopreservation in Articular Cartilage Sample Using Homogeneous and Porous Material Models, *Ann. Biomed. Eng.* **54**, 804–812, 2026. <https://doi.org/10.1007/s10439-025-03925-6>
- [4] C. Wang and H. G. Matthies, Coupled fuzzy-interval model and method for structural response analysis with non-probabilistic hybrid uncertainties, *Fuzzy Sets Syst.* **417**, 171–189, 2021. <https://doi.org/10.1016/j.fss.2020.06.002>

The influence of strain rate on the viscoelastic properties of duck oesophageal tissue

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KEYWORDS: *Oesophageal tissue, mechanical response, stress relaxation, numerical model, viscoelastic modelling.*

The oesophagus is an organ with a complex tissue structure, exhibiting nonlinear and viscoelastic mechanical behaviour. This response arises from the presence of structural components with distinct properties and their mutual interactions. Understanding the stress relaxation behaviour of oesophageal tissue is of particular importance in the context of developing biomechanically justified elongation methods used in the treatment of long-gap oesophageal atresia.

The aim of this study was to experimentally characterise the stress relaxation behaviour of oesophageal tissue and to develop and validate a numerical model capable of reproducing its time-dependent mechanical response under different strain rates.

The study was conducted on oesophageal tissue obtained from Pekin ducks ($n = 5$ per strain rate). Specimens were subjected to stress relaxation tests at strain rates of 1, 2.5, 5, and 10%/s, with loading corresponding to a stress level of 0.5 MPa and a relaxation period of 1.3 h. The material behaviour was described using a Yeoh hyperelastic model combined with a three-term Prony series. The model parameters were identified based on fitting to experimental data and subsequently implemented in finite element simulations (ANSYS, Transient Structural). Two approaches were considered: a direct approach using parameters fitted independently for each strain rate, and a normalized approach in which the material parameters were defined as functions of strain rate.

A close agreement was observed between the experimental and numerical results for all analysed strain rates (Figure 1). The RMSE values ranged from 0.003 to 0.009 MPa, with NRMSE below 3.5%, and the coefficient of determination (R^2) exceeding 0.96. The normalized model, incorporating the strain rate dependence of the material parameters, also accurately reproduced the stress relaxation behaviour.

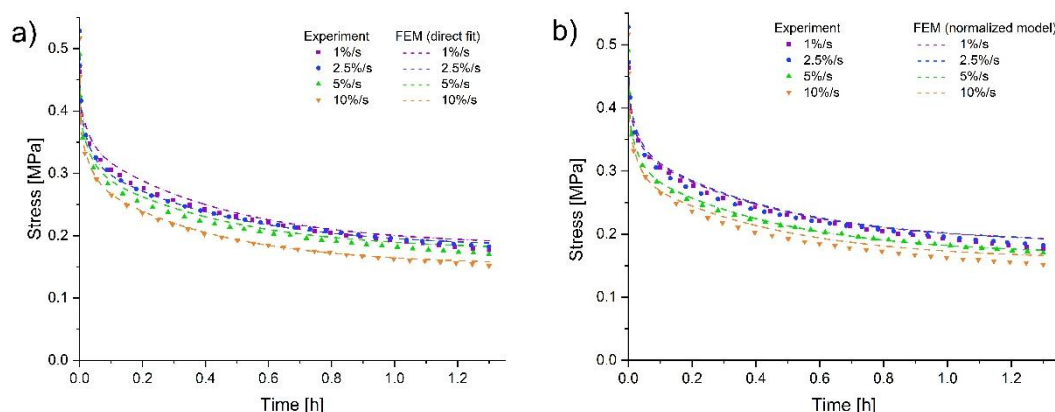


Figure 1. Comparison of experimental and numerical stress relaxation results: (a) direct model, (b) normalized model.

Influence of UV Crosslinking Time on the Mechanical Properties and Degradation of GelMA Hydrogels

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KEYWORDS: *GelMA hydrogels, degradation, mechanical properties*

Gelatin methacryloyl (GelMA) is widely used in biomedical engineering due to its biocompatibility and tunable mechanical properties. Precise control of both mechanical behavior and degradation is crucial for tissue engineering applications. However, the effect of photo-crosslinking parameters is still not fully understood. In this study, synthesized GelMA hydrogels were UV-crosslinked for 60, 90, and 120 s. Mechanical properties were evaluated using biaxial tensile testing, enabling the determination of Young's modulus and stress-strain behavior in two directions. Degradation was assessed under physiological conditions based on mass loss and changes in material stability [1], [2].

The results showed that increasing crosslinking time significantly improved mechanical properties. When comparing samples crosslinked for 60 s and 120 s, the median Young's modulus increased by over 600% in the X-direction and over 720% in the Y-direction. This was accompanied by higher maximum stress and an approximately 35% decrease in maximum strain. Degradation exhibited a two-stage behavior, with a rapid initial mass loss (~30% after 1 h), followed by a slower increase to ~45% after 24 h, ~55% after 72 h, and ~75% after 168 h, at which point the sample lost its structural integrity. (Fig. 1, example for the 90 s group). Hydrogels crosslinked for 60 s lost structural integrity after prolonged incubation, whereas samples crosslinked for 120 s remained stable and more resistant to degradation due to higher crosslinking density.

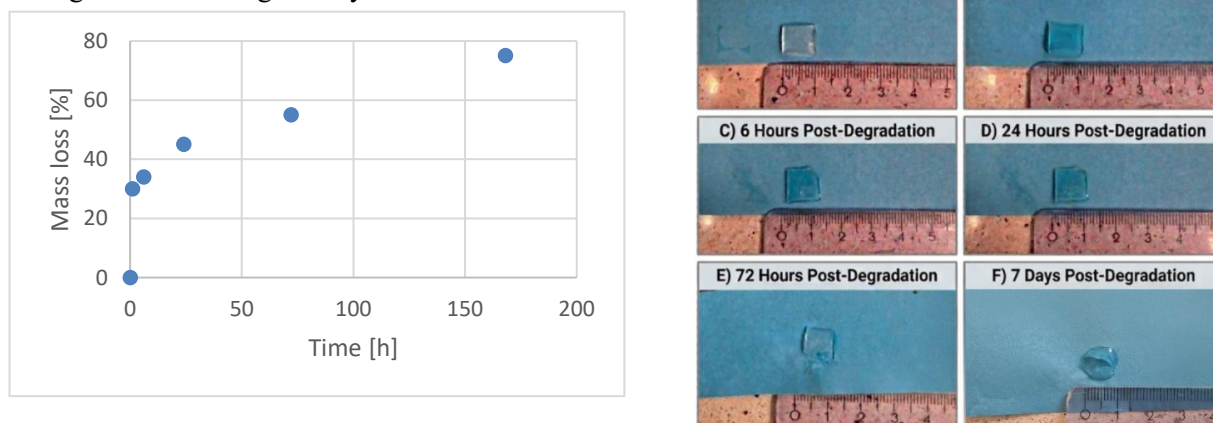


Figure 1 Degradation of GelMA hydrogels crosslinked for 90 s: mass loss over time (left) and representative images of samples after 0, 1, 6, 24, and 72 h of degradation (right).

These findings demonstrate that photocrosslinking time plays a key role in controlling both the mechanical properties and degradation behavior of GelMA hydrogels, which is important for the design of materials for biomedical applications.

- [1] K. Yue, G. Trujillo-de Santiago, M. M. Alvarez, A. Tamayol, N. Annabi, and A. Khademhosseini, "Synthesis, properties, and biomedical applications of gelatin methacryloyl (GelMA) hydrogels," Dec. 2015, *Elsevier Ltd.* doi: 10.1016/j.biomaterials.2015.08.045.
- [2] S. Zigon-Branc *et al.*, "Impact of Hydrogel Stiffness on Differentiation of Human Adipose-Derived Stem Cell Microspheroids," *Tissue Eng. Part A*, vol. 25, pp. 1369–1380, Oct. 2019, doi: 10.1089/ten.tea.2018.0237.

Epithelium and 2D Crystal

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KEYWORDS: *Lewis' Laws, Euler's Law, Dislocations, Cell Divisions, Energy, Tissue Stationary State.*

Epithelium is one of the most important tissues in the body, whether animal or plant. Externally, epithelial tissue presents a mosaic of densely packed polygonal cells. There are 4-, 5-, 6-, 7-, 8-, and 9-gons. Hexagonal cells constitute approximately 50% of the total, pentagonal and heptagonal cells approximately 45%, and the remaining 5% are tetragons, octagons, and 9-gons. A graph of the frequency of polygons versus the number of angles produces a curve that deviates slightly from the normal distribution. If only 5-, 6-, and 7-gons are considered, the proportions of polygons in the epithelium resemble those in an intermediate stage of hexatic transformation.

There is an analogy between epithelium and 2D crystal. The dense packing of cells in a single-layer epithelium and atoms in a 2D crystal, which is revealed by the honeycomb arrangement. More over, the lattice defects in both are similar. The difference is that in the 2D crystal, only pairs of 5- and 7-gons (5|7 dislocations) appear.

F.T. Lewis discovered laws of epithelial cell behaviour [1]. The first law states that the average number of cell sides is 6. Strictly speaking, this is a corollary of Euler's law for polygons. The second Lewis law states that the surface area S of a n -sided cell is proportional to the number $(n - 2)$, i.e., $S = C(n - 2)$, where C is a constant. The mathematical proof of this law uses Euler's polygon theorem and the principle of maximum entropy [2]. Therefore, it is also valid for 2D crystals. This allows us to estimate the relative changes in the lengths of the polygon sides. We have $a_5/a = 1.06$ and $a_7/a = 0.95$, where a_5 and a_7 are the lengths of the sides, and a is the length of the 6-gon side. Knowing these relative lengths and assuming the interaction potential of the crystal atoms, we can determine, for example, the dislocation energy.

Unlike a crystal, epithelial cells can undergo division. The mother cell loses its "identity" and its n sides are distributed between two daughter cells, and some of its neighbours gain new edges (because the new edge of the daughter cells touches them). Lewis' third law states that the average number of sides of dividing cells is 7. The question arises as to how the proportions of the polygons in the tissue are preserved. We consider the system of equations $df/dt = \lambda g$, $dg/dt = \mu f$ (f – number of 5|7 pairs, g – number of 6-gons, t – time, λ and μ – constants) whose solutions, asymptotically in t , yield constant proportion $f/g = \sqrt{\lambda/\mu}$.

- [1] F.T. Lewis, *The correlation between cell division and the shapes and sizes of prismatic cells in the epidermis of Cucumis*, The Anatomical Record, **38**, 341–376, 1928.
- [2] N. Rivier, A. Lissowski, *On the correlation between sizes and shapes of cells in epithelial mosaics*, Journal of Physics A: Mathematical and General, **15**(3), L143, 1982.

Problems with Designing of Medical Equipment for Young Patients

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KEYWORDS: *Rehabilitation equipment, Young patients, Small-scale production, Additively manufactured components, Mass-produced components.*

Recently, there has been a growing demand for rehabilitation equipment for children. This is due to road accidents, disabilities, and, above all, armed conflicts, in which civilians, including children are the victims. In its 2022 report [1], UNICEF summarizes that over 104,100 children were killed or injured between 2005 and 2020. However, the organization emphasizes that these figures are underreported. This is due to limited access to victims, lack of safety, and the shame, pain, and fear experienced by victims, which often hinder the reporting, documentation, and verification of serious violations of children's rights in situations of armed conflict. Since 2020, further conflicts have emerged around the world, resulting in an increase in these statistics. Long-term use of equipment requires adapting it to the developing body. Responding to such changes should be relatively quick to avoid interruptions in rehabilitation or to keep it as short as possible. Discontinuing exercise can result in a reversal of previously achieved results and progress. An important aspect is the ability to relatively quickly produce small-scale components. Solutions that can be applied to a variety of patients are a good direction. While this is possible in some cases, it is not always possible. There are patients who require personalized device adaptation. It is then necessary to use technology that allows for relatively easy changes and relatively rapid production. The possibility of rehabilitation in a center located as close to the patient as possible reduces the material and psychological costs incurred by the patient and their family. Aspects that have been marginalized for some time in the design process include aesthetic values and the possibility of external personalization dictated by the patient. Prolonged, repeated repetitions of, for example, an exercise can lead to fatigue and withdrawal. In rehabilitation, the patient's consistency and determination are often crucial. The ability to choose options provides a sense of agency. We are more likely to use devices we have chosen ourselves or have had an influence on their appearance. Allowing a child to choose the color or texture can enhance the experience of using the equipment.

The problems presented above were observed when designing personalized medical equipment for a young patient. Two cases will be discussed in more detail. The aim was to propose a solution that would be adapted to the developing organism. It combines readily available, mass-produced components with additively manufactured components, which are relatively well-suited for small-scale production. Such components offer the potential for aesthetic personalization. Another project addressed the issue of a prosthesis designed for soccer. This approach was aimed at activating individuals after limb amputation. This is an important aspect – improving quality of life. As in the previous case, the proposed solution utilizes both mass-produced and additively manufactured components. In summary, the most important problems related to the design of rehabilitation equipment for young patients will be presented, along with possible solutions using available resources.

[1] 25 years of children and armed conflict: taking action to protect children in war, ©United Nations Children's Fund (UNICEF) June 2022;

Peridynamic Modeling of Adaptive Remodeling

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KEYWORDS: *Peridynamics, adaptive remodeling, nonlocal modeling, strain energy density*

This work presents a bond-based peridynamic formulation of an adaptive remodeling model for density evolution. The study investigates how the nonlocal character of peridynamics affects the numerical response and the evolving density distribution in benchmark problems commonly analysed with the finite element method. The density update follows the approach of Weinans et al. [1]:

$$\Delta \rho_i = C \left(\frac{SED_i}{\rho_i} - k \right) \quad (1)$$

where C is the rate parameter and k denotes the homeostatic set-point. The remodeling stimulus is defined by the strain energy density SED_i obtained from the nonlocal peridynamic solution. The implementation is developed within the open-source PeriLab framework [2] and is based on the theory introduced by Silling [3].

The analysed cases consider a 2D plate subjected to linearly varying loading. The study examines the influence of the nonlocal interaction radius, the stiffness averaging rule, and the evolution parameters. Particular attention is paid to numerical challenges related to the nonlocal formulation, including the sensitivity of the energy field and the stability of the evolving response. Preliminary results indicate that both the nonlocal modeling choices and the evolution parameters strongly affect the smoothness of the obtained fields and the emerging density patterns. The presented work is part of an ongoing study aimed at establishing a robust peridynamic framework for remodeling-driven structural evolution.

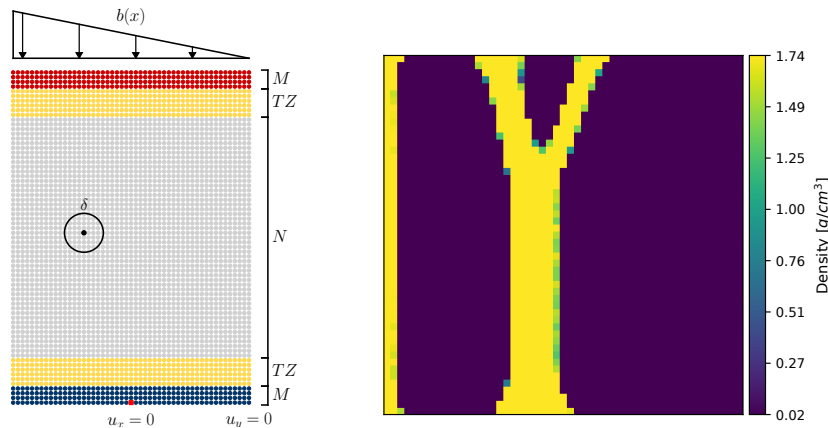


Figure 1: Left: analysed problem setup. Right: representative converged density distribution for one analysed parameter set.

- [1] H. Weinans, R. Huiskes, H.J. Grootenboer, *J. Biomech.* **25**(12), 1425–1441, 1992. [https://doi.org/10.1016/0021-9290\(92\)90056-7](https://doi.org/10.1016/0021-9290(92)90056-7)
- [2] C. Willberg, J.-T. Hesse, A. Pernatii, *SoftwareX* **26**, 101700, 2024. <https://doi.org/10.1016/j.softx.2024.101700>
- [3] S.A. Silling, *J. Mech. Phys. Solids* **48**(1), 175–209, 2000. [https://doi.org/10.1016/S0022-5096\(99\)00029-0](https://doi.org/10.1016/S0022-5096(99)00029-0)

Sensitivity of Mechanically Admissible Squat Motion to Joint Moment Capacity Distribution

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KEYWORDS: *Biomechanics, Constrained Optimization, Elasto-Plastic Joints, Human Motion, Load Transfer.*

This contribution presents a computational framework for analyzing the sensitivity of mechanically admissible squat motion to the distribution of joint moment capacities. The approach builds upon a previously developed model of load-constrained motion reconstruction, in which human movement is represented as the solution of a constrained optimization problem.

A three-dimensional multi-segment rigid-body system is considered, including feet, shanks, thighs, pelvis, and torso. Joint behavior is modeled using smooth elasto-plastic rotational elements with bounded moment capacity. A reference squat trajectory is first generated kinematically, and subsequently corrected by solving a frame-wise optimization problem subject to geometric and mechanical constraints.

The problem is formulated as minimization of the total mechanical cost [1,2],

$$J(\mathbf{q}) = \frac{1}{2}(\mathbf{q} - \mathbf{q}_{ref})^T \mathbf{K}(\mathbf{q} - \mathbf{q}_{ref}) + \sum_i \Psi_i(\Delta\theta_i) + W_{ext},$$

where the first term enforces trajectory tracking, the second term represents joint-level elasto-plastic energy contributions, and the last term accounts for external loading due to the barbell.

A parametric study is performed by varying the critical moment capacities assigned to individual joints while maintaining identical external loading conditions. The results demonstrate that the admissible squat posture is strongly governed by the relative distribution of joint strength, leading to systematic changes in pelvis backshift, torso inclination, and redistribution of rotational demand between lower-limb joints.

The study shows that squat technique should be interpreted not only as a response to external load but also as a consequence of internal mechanical capacity constraints, providing a consistent framework for analyzing strength-dependent movement adaptations.

- [1] K. Nowak, A. Szymczak-Graczyk, A., Cornaggia, T. Garbowski, Appl. Sci. **16**(8), 4010, 2026. <https://doi.org/10.3390/app16084010>
- [2] K. Nowak, A. Szymczak-Graczyk, A., Cornaggia, T. Garbowski, BioEng. **13**(5), 485, 2026. <https://doi.org/10.3390/bioengineering13050485>

Quasi-static problems of the coupled linear theory of elastic nanomaterials with triple porosity

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KEYWORDS: *Triple porosity, Elastic nanomaterials, Quasi-static theory, Fundamental solution, Boundary value problems.*

Abstract

This paper considers the coupled linear quasi-static theory of elasticity for nanomaterials with triple porosity. The model combines Darcy's law with the concept of volume fractions corresponding to three levels of pore networks, namely macro-, meso- and micropores. The governing system of equations are formulated in terms of the displacement vector, the changes of pore volume fractions, and the fluid pressures in the three pore systems. By combining the constitutive relations, equilibrium equations, and fluid mass conservation laws, a general three-dimensional system of field equations is obtained for triple-porosity elastic nanomaterials.

Assuming harmonic time dependence, the governing equations are reduced to a system of partial differential equations with constant coefficients describing steady vibrations. An appropriate matrix differential operator is introduced, and the system is written in operator form for a nine-component vector function. Within this framework, the fundamental solution of the steady vibration system is constructed explicitly. The fundamental matrix is represented in terms of elementary functions, and its main properties are established, including the structure of singularities, behavior near the origin, and regularity away from the singular point.

The internal and external basic boundary value problems describing steady vibrations within this theory are formulated for regular vector functions, where the unknowns are the displacement vector field, the changes of pore volume fractions, and the fluid pressures in the three pore systems. Green's first identity is derived and used to prove uniqueness theorems for classical solutions. Green's second identity is obtained in operator form, and Green's third identity gives integral representations of solutions through surface and volume potentials constructed with the fundamental matrix.

In the analysis, surface potentials, both single-layer and double-layer, as well as volume potentials are introduced, and their basic properties are examined. A set of relevant singular integral operators is constructed, for which Noether-type theorems are shown to hold. The symbolic determinants and indices associated with these operators are explicitly computed. The boundary value problems are then transformed into equivalent systems of singular integral equations. Ultimately, by applying the potential method, the boundary integral equation approach, and the theory of singular integral equations, the existence of classical solutions to all formulated boundary value problems is rigorously established.

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Quaternary-Ammonium Urethane Dimethacrylate Dental Composite for Long-Lasting Restorations

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KEYWORDS: *Dental composites, antimicrobial polymers, quaternary ammonium dimethacrylate, microhardness, sustainable dentistry.*

Failures at the tooth-restoration interface remain the dominant reason for replacement of resin-based composite restorations, with recurrent caries accounting for a significant portion of clinical failures. Each replacement cycle generates particulate waste derived from crosslinked polymer matrices and inorganic fillers, which is released into the environment and accumulates as persistent microplastic waste. Extending the service life of composite restorations therefore has implications that extend beyond clinical performance, directly contributing to material sustainability and waste-reduction strategies in modern dentistry.

Recent efforts have introduced antimicrobial agents into resin matrices to suppress biofilm formation at restoration interfaces. Among the explored efforts, covalently bonded quaternary ammonium dimethacrylate monomers (QADMs) have provided sustained antimicrobial action [1][2]. Regardless of these encouraging findings at the monomer level, relatively few investigations have reported on fully formulated antimicrobial resin composites, limiting insights into material design and clinical translation.

In this work, the gap is addressed through the development of a novel QAUDMA-based composite containing an antimicrobial monomer synthesized via a modified Menshutkin reaction and incorporated into a conventional resin matrix at 40 wt.%, followed by the addition of mineral-based inorganic fillers according to a typical formulation design. Initial mechanical performance was assessed using Vickers microhardness testing under a load of 1 N and a dwell time of 15 s. The experimental composite exhibited microhardness similar to the control composite without the antimicrobial monomer, which suggest that the incorporation of the antimicrobial monomer did not affect the composite's initial surface characteristics.

Future investigations are focused on a comprehensive assessment of mechanical, physicochemical, and antimicrobial performance to determine whether QAUDMA-based composites can be a clinically durable approach to extending the longevity of dental restorations while contributing to sustainability goals in dentistry.

- [1] P. Drejka, P. Kula, and I. Barszczewska-Rybarek, "Novel Quaternary Ammonium Urethane-Dimethacrylates for Copolymers with Low Water Sorption and Solubility," *Mol. Basel Switz.*, vol. 30, no. 4, p. 769, Feb. 2025, <https://www.doi.org/10.3390/molecules30040769>.
- [2] J. E. Ampah-Essel, I. Barszczewska-Rybarek, P. Drejka, and G. Chladek, "Quaternary Ammonium Dimethacrylates as an Additive in Dental Composite Resins: A Review of Their Antimicrobial, Mechanical, and Physicochemical Properties," *Materials*, vol. 18, no. 21, p. 4844, Jan. 2025, <https://www.doi.org/10.3390/ma18214844>.

Session TS4

**Computational and experimental mechanics
in engineering applications**

A Unified Physics-Based Framework for Incremental Modelling of Residual Stress in History-Dependent Manufacturing Processes

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KEYWORDS : *Residual stress, Analytical modelling, Load path, Incremental plasticity, history-dependent manufacturing processes, Laser powder bed fusion*

ABSTRACT: Residual stress plays a fundamental role in determining the structural integrity, dimensional accuracy, and fatigue performance of manufactured components. Depending on the manufacturing process, it evolves under thermal loading, mechanical loading, or their coupled interaction, making its prediction a major challenge in manufacturing science. While experimental characterization is costly and finite element analysis is computationally expensive for predictive applications, this keynote lecture presents an incremental physics-based analytical framework for predicting residual stress evolution by accounting for the entire loading history through sequential thermo-mechanical analysis. Owing to its general formulation, the framework is applicable to a broad range of manufacturing processes, including laser powder bed fusion, machining, burnishing, shot peening, and laser shock peening. The proposed methodology is demonstrated and verified through pulsed laser powder bed fusion as a representative case study, where the predicted residual stresses show good agreement with X-ray diffraction measurements.

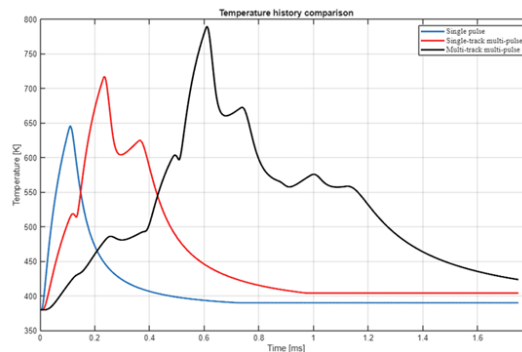


Figure 1: Temperature history as load path for single-pulse, multi-pulse single track and multi-pulse multi-track pulsed laser powder bed fusion

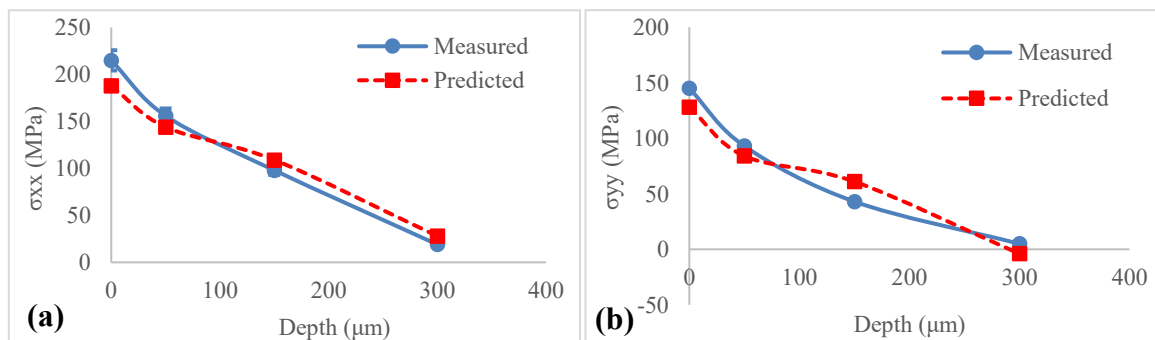


Figure 2: Distribution of residual stress in (a) track direction (b) hatch direction

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Studies of energy absorption of TPMS structures manufactured via EBM from Ti6Al4V

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KEYWORDS: EBM, additive manufacturing, TPMS structure, energy absorption, numerical modelling.

Cellular structures are the subject of many research works due to their high capacity to absorption mechanical energy. These meta-materials have been classified into two main groups: 2D and 3D [1]. One of the example of spatial 3D structures is Triply Periodic Minimal Surface (TPMS), which has been widely studied over last years with the most well-known architectures like diamond and gyroid structures [2].

In the present paper, the EBM method was used to produce specimens of TPMS structures, which were subsequently subjected to uniaxial compression tests under quasi-static loading conditions in order to characterize their deformation behavior and energy absorption capacity. Moreover, the material model calibration was performed in the LS-DYNA numerical environment based on the results of quasi-static uniaxial tensile tests conducted on dog-bone specimens. The purpose of this paper is to present the results of experimental and numerical studies of TPMS structures manufactured using EBM technology from Ti6Al4V titanium alloy and tested under quasi-static compression conditions for different wall thicknesses. The obtained results constitute a starting point for assessing the potential use of this type of structure as an element of a ballistic panel.

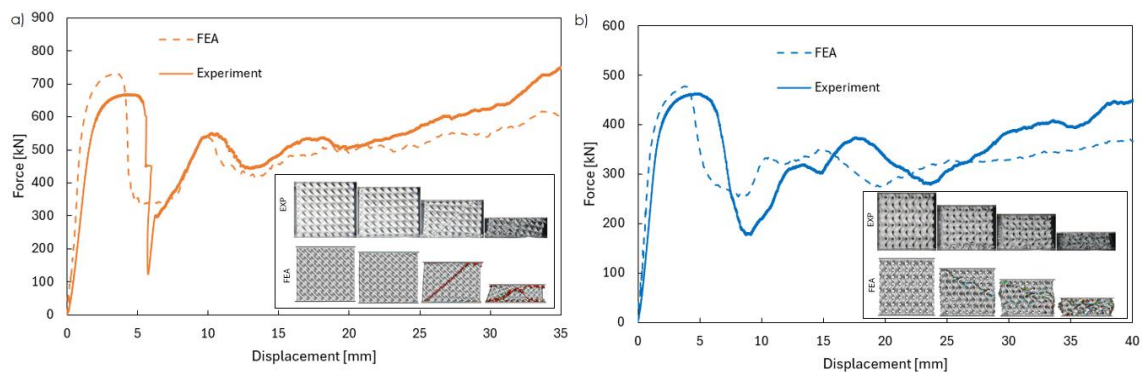


Figure 1. Deformation force vs. displacement curves from experimental test and simulations: a) Diamond structure, b) Gyroid structure.

The developed LS-DYNA numerical model accurately reproduced experimental behavior, with an overall discrepancy between numerical predictions and experiments within 6–10% for SEA. From the conducted studies it was demonstrated that gyroid structures shows progressive folding and stable plateau behavior, while diamond structures exhibits higher stiffness and peak force associated with shear-band dominated collapse. Furthermore, diamond architectures gave approximately 8% higher SEA than gyroid structures at comparable relative densities.

ACKNOWLEDGEMENT:

The research was supported by the Military University of Technology under the research grant no: UGB: 000009-W100-22 and with the support of the Interdisciplinary center for Mathematical and Computational Modeling (ICM) of the University of Warsaw, under grant no GBE84-20. The numerical models were prepared using Altair® HyperMesh software and computed with Ansys LS-Dyna software.

[1] Y. Hanfeng, Z. Wenzheng, Z. Liangcong, M. Fanbo, L. Jie, W. Guilin, *Compos. Struct.*, Volume 304, 2023. <https://doi.org/10.1016/j.compstruct.2022.116397>

[2] Z. Dong, X. Zhao X, *Eng. Regen.* 2(8), 2021, <https://doi.org/10.1016/j.engreg.2021.09.004>.

Multiscale Modelling of Physical Vapor Deposition for Semiconductor Thin Films: From Reactor Dynamics to Nanoscale Feature Evolution

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KEYWORDS: *Physical Vapor Deposition, PVD, Direct Simulation Monte Carlo, Multiscale Simulation.*

Physical Vapor Deposition (PVD) is an essential industrial process characterised by the physical sputtering of a target material and the subsequent deposition of the particles onto a substrate, such as a semiconductor wafer. This technique allows for the precise control of composition, thickness, and microstructure of the deposited materials.

The optimisation of semiconductor thin films necessitates a comprehensive understanding of how macro-scale operational parameters ultimately determine the final deposited film properties. This requires a computational framework capable of resolving phenomena across an enormous dynamic range, linking the ~ 50 cm scale of the entire deposition chamber (where boundary conditions are applied) through the ~ 1 mm shadow mask structural dimensions and further down to feature level of ~ 50 nm, where deposition spots evolve. This endeavour involves bridging approximately 9 orders of magnitude in volume.

In this talk a multiscale simulation framework (Fig. 1 left) that connects the scale of the deposition chamber with the feature scale will be presented, explicitly accounting for shadowing effects and the role of the background gas (Fig. 1 right). Rarefied transport is modelled using Direct Simulation Monte Carlo (DSMC) to obtain energy- and angle-resolved particle fluxes at the substrate, which then serve as boundary conditions for level-set based feature-scale simulations. The framework is used to analyse not only local deposition profiles and step coverage, but also the spatial evolution of film composition across the wafer and within individual features.

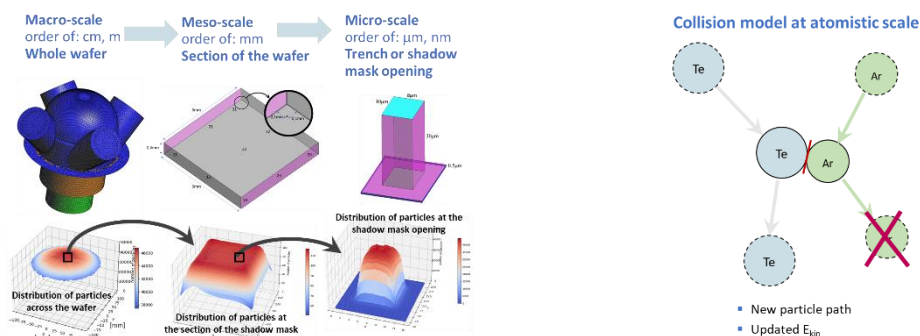


Figure 1. A multiscale simulation framework for PVD process modelling (left) and a collision model between material particles and background gas molecules (right).

ACKNOWLEDGEMENT: The authors gratefully acknowledge the financial support provided by the Sächsische Aufbaubank (SAB) and the European Union for funding this research project.

- [1] E. E. Lorenz et al., Film Growth from Particle Raytracing: A Simulation Method for Vapor Deposition Processes with Changing Surface Topographies, IEEE Materials for Advanced Metallization Conference, Dresden, Germany, 2023, pp. 1-3, doi: 10.1109/IITC/MAM57687.2023.10154705
- [2] J. Gehre, Coupling between stochastic particle transport models and topographic thin film growth, Master thesis, Chemnitz University of Technology, 2022.

FE model for creep buckling modelling of Al–SiC composite beam

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KEYWORDS: *Buckling, Al–SiC composite, Creep, Numerical Model.*

The paper presents the finite element beam model applied on creep buckling simulation of a functionally graded Al–SiC composite with a spatially varying volume fraction. The creep parameters of the material were taken from available experimental studies on Al–SiC composites and described using the Norton–Baley creep law. Available experimental data were interpolated to obtain continuous creep parameters corresponding to the specific Al–SiC volume fraction distribution considered in this work. An original Fortran code was developed to simulate the creep buckling behaviour. A numerical algorithm using one-dimensional spatial beam finite element is developed. The corresponding equilibrium equations are formulated in the framework of co-rotational description. Results were compared, for validation purposes, with those obtained from FEMAP (see Fig. 1). The critical creep buckling times were determined for different beam structural geometries as well as for several loading conditions.

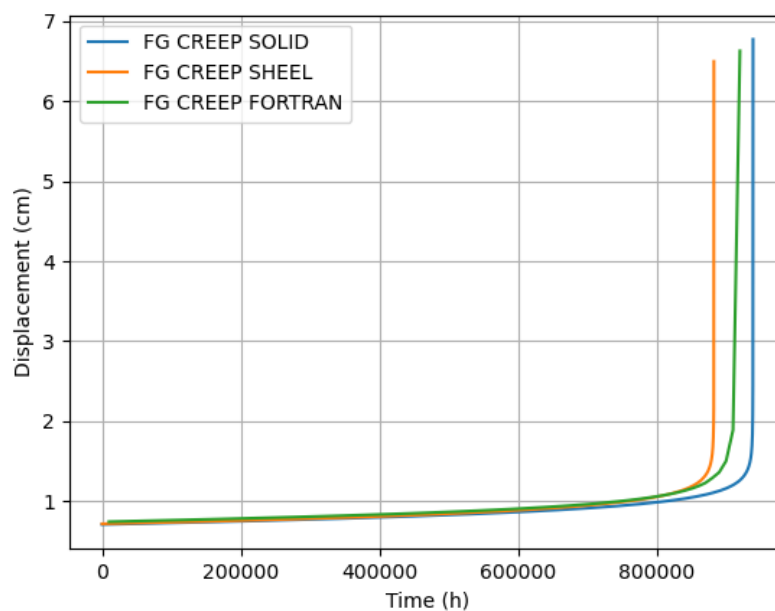


Figure 1. Critical buckling time for axially loaded cantilever.

ACKNOWLEDGEMENT: The work was supported by the Croatian Science Foundation under the project number HRZZ-IP-2024-05-6868. Also, this work was funded by the European Union – NextGenerationEU – MIZGRED – uniri-iz-25-233 and COBEAMSTAB-uniri-iz-25-95

- [1] S. Golmakaniyoon, F. Akhlaghi, *Comp. Mat. Sci.* 121, 182–190, 2016. <https://doi.org/10.1016/j.commatsci.2016.04.038>
- [2] D. Lanc, G. Turkalj, J. Brnić, *Commun. Numer. Meth. Engng.* 24, 989–1008, 2008. <https://onlinelibrary.wiley.com/doi/pdf/10.1002/cnm.1004>
- [3] D. Lanc, TP. Vo, G. Turkalj, J. Lee, *Thin-Wall. Struct.* 86, 148–156, 2015. <https://doi.org/10.1016/j.tws.2014.10.006>

Development of a strain sensor using mechanoluminescence for multiaxial stress measurement

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KEYWORDS: *Mechanoluminescence, 3D printing, Sensor, Multiaxial stress, FEM analysis*

Mechanoluminescence refers to the phenomenon in which a material emits light in response to externally applied strain [1][2]. The aim of this study is to develop a multiaxial stress sensor capable of identifying the loading direction applied to mechanical components by using a mechanoluminescent material. To achieve this purpose, we focused on the stress concentration generated around circular holes. In this study, a circular plate with multiple holes was fabricated using a stereolithography 3D printer, and a sensor prototype was produced by coating its surface with mechanoluminescent paint (see Fig. 1). Tensile loads were applied from various directions, and the resulting luminescence intensity was quantified. The results demonstrated that the desired sensing characteristics can be achieved using a disk-shaped structure containing multiple circular holes. Furthermore, we developed an image analysis technique based on the commercial finite element software Marc Mentat 2023 (MSC Software Corporation). Simulation results confirmed that this method can successfully identify both the direction and magnitude of the applied load.

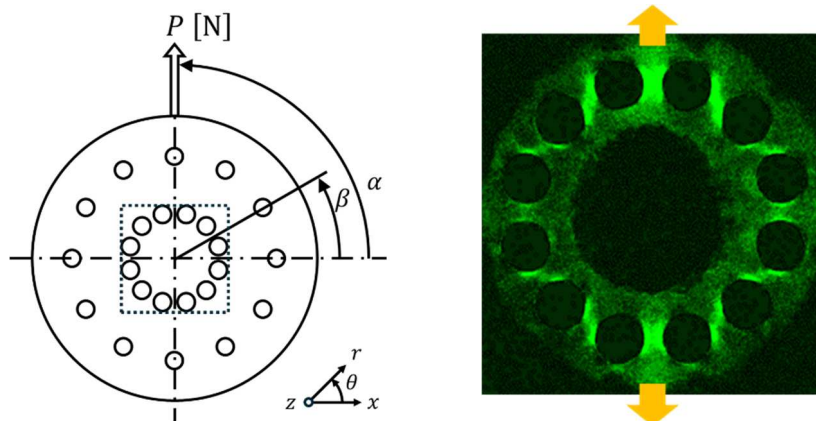


Figure 1. Proposed model (left) and the resulting mechanoluminescence within the dotted area (right).

- [1] S. A. Fartode, A. P. Fartode, T. R. Shelke, S. J. Dhoble, “A comprehensive study of mechanoluminescence: a review”, *Journal of Optics*, 2025: DOI /10.1007/s12596-025-02519-8.
- [2] X. Yang, T. Wang, L. Zhao, X. Xu, “Recent progress in mechanoluminescence for multi-dimensional stress monitoring”, *Advanced Science*, Vol. 13 (2026): DOI 10.1002/advs.202519938.

Thermo-mechanical analysis of the white-topping slab with long-term monitoring data

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KEYWORDS: *Thermal analysis, elastic thermo-mechanics, coupled FEA, long-term monitoring.*

White-topping represents a pavement rehabilitation technique with a thin cement concrete overlay. The paper summarizes thermo-mechanical analysis of a single slab $1750 \times 2000 \times 140$ mm over deteriorated asphalt concrete pavement [1]. A non-stationary heat transport is weakly coupled with elastic material model, supplemented with constant mechanical elements to capture slab warping. The results show that traffic loading solely acting on the slab induces principal tensile stresses of up to 2.4 MPa. Summer characteristic thermal cycle induces up to 1.6 MPa (see Fig. 1). The combination of temperature cycles with traffic yields up to 4.1 MPa, indicating cracking, concrete softening and fatigue phenomena.

The monitored data over five years comprised six pairs of vibrating wire strain gauges, twelve thermal gauges, ambient air temperature, solar radiation and three inductive gages monitoring concrete separation from underlying asphalt concrete. Unsymmetrical temperature differences across the thickness were measured and simulated, owing to much higher heat flow from solar radiation than from night cooling. After four years, moisture-induced warping seems already stabilized at the curvature of 2.5 km^{-1} . Continuous separation of the slab from asphalt concrete has been measured and stabilized at a gap of 0.3 mm after two years. The experimental data served for calibration and successful validation of the thermo-mechanical model.

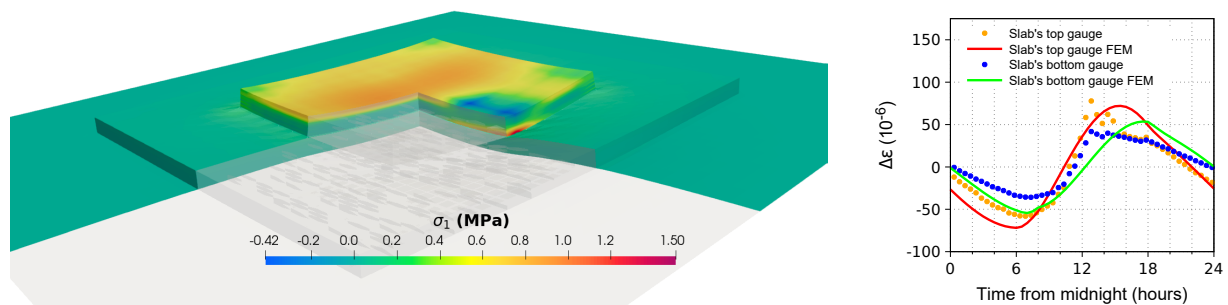


Figure 1. Thermo-mechanical analysis (left) and strain validation during summer cycles (right).

ACKNOWLEDGEMENT: The research was co-funded by the European Union under the project INODIN, no. CZ.02.01.01/00/23_020/0008487 and from the Czech Science Foundation under the project number 25-15501S.

[1] B. Slánský, L. Vysloužil, P. Bijok, V.Šmilauer, R. Hela, R., *The First Whitetopping in the Czech Republic*, National Report of the 6th FiB Congress, Oslo, 2022.

Development of an AE Waveform Simulation Method Using Experimentally Determined Sensor Responses

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KEYWORDS: *Acoustic emission (AE), Elastic wave simulation, 3D-FDTD, Piezoelectric sensor, Sensor response, Resonance*

An Acoustic emission (AE) is a nondestructive evaluation technique that detects transient elastic waves generated by crack initiation, propagation, friction, and other damage-related phenomena in materials and structures. Resonant AE sensors using piezoelectric elements are widely employed due to their high sensitivity; however, the detected waveforms are significantly distorted by resonance and the frequency-dependent response of the sensor, making direct comparison with simulated waveforms difficult. To address this issue, methods that experimentally characterize the sensor response and incorporate it into simulated AE waveforms have been investigated [1]. In AE measurements, the detected waveform $W(t)$ can be expressed as

$$W(t) = S(t) * T(t) * R(t) \quad (1)$$

here $*$ denotes convolution, $S(t)$ is the source waveform, $T(t)$ represents wave propagation characteristics in the material, and $R(t)$ is the sensor response. In contrast, 3D-FDTD simulations provide only $S(t)*T(t)$, as they do not include the sensor response. Consequently, simulations alone cannot accurately reproduce experimentally measured waveforms. In this study, the sensor response $R(t)$ was identified from experimental and simulated waveforms and incorporated into other simulated waveforms shown in Fig.1. As a result, the reproduced waveforms showed significantly improved agreement with experimental measurements compared with those obtained using simulation alone. Furthermore, regularization was introduced into the response identification process to stabilize the solution and enhance reproducibility. The proposed method demonstrated superior performance compared with conventional sensor response characterization approaches.

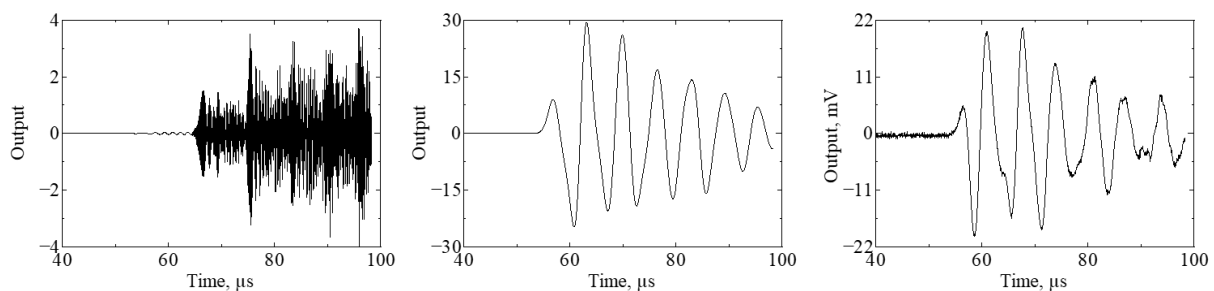


Figure 1. Comparison of waveforms obtained using different approaches: (left) 3D-FDTD simulation alone; (center) waveform reproduced using the proposed method; (right) waveform experimentally measured with a resonant AE sensor.

- [1] K. Arakawa and T. Matsuo, “Acoustic Emission Pattern Recognition Method Utilizing Elastic Wave Simulation”, *Materials Transactions*, Vol. 58, No. 10 (2017), pp. 1411-1417.

The numerical analysis and experimental tests of the rotational connection stiffness between the purlin and the truss top chord

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KEYWORDS: *Connection Stiffness, Structural Stability, Truss, Brace.*

The paper is focused to the study of the rotational connection stiffness between the purlin and the top chord of a flat truss. The steel light trusses can be characterized by high stiffness and load-bearing capacity, but only in their plane. In each case the roof bracing system have to be design to ensure the structural stability out of the truss plane [1, 2]. The guidelines for the design of the roof cross braces can be found in the European standards [3]. The stiffness of the connection mentioned above can have a significant impact on the truss buckling load, especially in case of wind loading which can cause compression in the bottom chord [1].

In the present research the connection stiffness between the purlin (which is usually the part of the bracing system) and the truss top chord was taken into consideration for the structure without any additional braces located at the bottom chord. Based on the numerical analysis results (linear buckling analysis) performed for the shell model of the truss the relation between the buckling load (upward wind loading) and the described connection stiffness was found. Furthermore, the connection between the part of the purlin and the part of the top chord was tested experimentally. In this case, the prototype test stand was used to subject the bending load to the described element connection. As the result the relative rotation between the purlin and the top chord was found. On this basis the rotational connection stiffness was determined. Two different types of structural connection between separate steel profiles used in reality (purlin and the top chord) were taken into account. Also the comparison between the nonlinear static analysis results (geometric and material nonlinearity) performed for the shell model of the structural connection and the experimental test results was presented.

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[1] A. Biegus, “Trapezoidal sheet as a bracing preventing flat trusses from out-of-plane buckling”, Archives of Civil and Mechanical Engineering, vol. 15, no. 3, pp. 735–741, 2015.
<https://doi.org/10.1016/j.acme.2014.08.007>.

[2] M. Gajdzicki, J. Goczek, “Numerical simulation to determine torsional restraint of cold-formed Z purlin”, Proc. International Conference on Metal Structures, Wrocław, 2011, pp. 424–433.

[3] PN-EN 1993-1-1, Eurocode 3: Design of steel structures – Part 1-1: General rules and rules for buildings, 2005.

Predicting irradiation hardening and microstructural evolution in irradiated Eurofer97: a nanoindentation study supported by CPFEM and TEM

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KEYWORDS: *RAFM steels, Nanoindentation, Ion irradiation, Crystal Plasticity FEM.*

Reduced activation ferritic/martensitic (RAFM) steels are the main candidates for the construction of structural components in future fusion and Gen IV nuclear reactors. To ensure safe and stable reactor employment, RAFM-based materials require efficient methods for their characterization under harsh operational conditions. Constantly exposed to neutron irradiation, their mechanical properties degrade and may lead to component failure. However, neutron irradiation for research purposes is an expensive and time-consuming process, so it becomes a major limiting factor in steadily investigating its effects and delivering new research data. Hence, a safer, faster, and cheaper solution of ion irradiation as a tool for surrogating the neutron damage is becoming more and more popular. As ions are characterized by their penetrating ability, the introduced damage is non-uniformly distributed and densely accumulated on the sub-surface. To correctly estimate their impact, the nanoindentation technique is widely applied. The presented study demonstrates the development process of a semi-empirical approach [1] to effectively interconnect the ion and neutron radiation-induced hardening in RAFM steels, introduced in a range of irradiation conditions. The applied set of tools, based on nanoindentation and tensile tests, as well as their simulations using crystal plasticity finite element method, allows us to extract the irradiation effect on the material law, and accurately reproduce the experimental data. Ultimately, the analysis performed on an ion-irradiated specimen can provide the macroscale (neutron irradiated) yield stress values in a range of dpa doses, which accurately correlate with the literature. The complementary investigations of the microstructural evolution done by focused ion milling and transmission electron microscopy are compared with their computational analogue to confirm the predictive capability of the method. Globally, the presented research is aimed at the establishment and validation of the computationally experimental procedure to precisely deduce the temperature-dependent irradiation hardening in metallic materials for nuclear applications.

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[1] T. Khvan, L. Noels, D. Terentyev, E. Corniani, P. Hähner, C.-C. Chang, J. Mater. Res. Technol 38, 5780–5796, 2025. <https://doi.org/10.1016/j.jmrt.2025.08.235>

Numerical Framework for Evaluating Debris Loads on Underground Structures

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KEYWORDS: *Progressive collapse, Debris loads, Underground structures, Numerical simulations*

This paper presents a comprehensive methodology for analyzing static loads acting on underground structures due to debris accumulation following the progressive collapse of above-ground, multi-story reinforced concrete buildings. A large set of frame-slab type structures was parametrically generated and numerically collapsed using Abaqus/Explicit. The simulations accurately reflect real-world rubble behavior by selecting optimal debris element sizes and distributions. Figure 1 shows an example of the collapse process of a 16-story building. It can be observed that the majority of debris fragments accumulate in the zone near the base of the building and in the surrounding area.

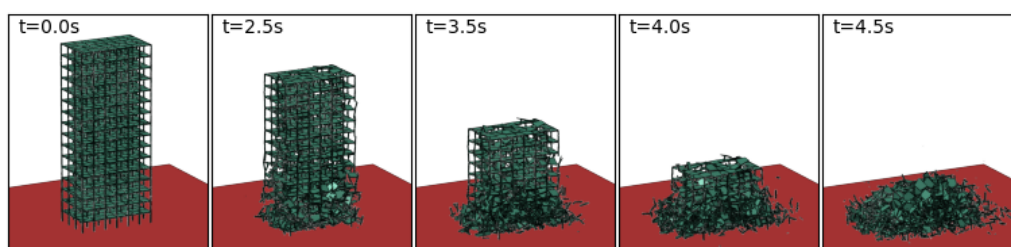


Figure 1. Snapshots of the 16-story building collapse process. Each columns shows selected frames in time.

The presented cases were further compared with the Polish notional guidelines to assess the dependence of rubble-induced pressure on building height. Figure 2 shows the obtained results, where it is clearly visible that the numerical simulations predict lower pressure values for each case compared to the notional guidelines.

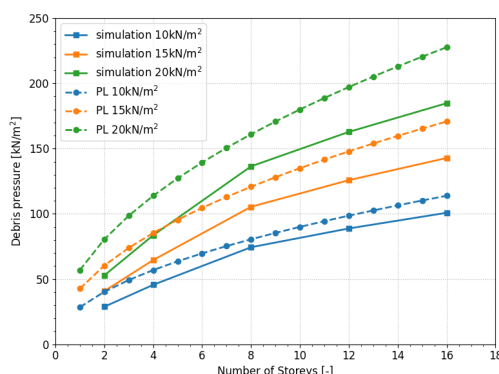


Figure 2. Comparison of obtained loads according to PL notional guidelines.

The results provide a robust foundation for ongoing updates of the international guidelines addressing rubble-induced static loads on buried structures, particularly in the context of progressive collapse or warfare scenarios.

Stochastic Analysis of Deflection Response of RC Beam Strengthened with CFRP Materials

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KEYWORDS: RC beams, CFRP materials, carbon strips, Finite Element Method, Semi-Analytical Probabilistic Analysis, Stochastic Perturbation Technique, Monte Carlo Simulations.

This paper presents an analysis of the deflection state of the Reinforced Concrete (RC) simply supported beam strengthened with Carbon Fiber Reinforced Polymer (CFRP) [1, 2] strips in a random approach. In the deterministic analysis, the Finite Element Method (FEM) with 2D elements and the Concrete Damage Plasticity (CDP) model for concrete [3], taking into account cracking phenomena, are used. Random analysis is based on FEM [4]. In the current work three independent approaches were adopted: Semi-Analytical Method (SAM), Stochastic Perturbation Technique (SPT), and Monte Carlo simulation (MCS). These three approaches have already been used in previous works, e.g. [5, 6]. A normal Gaussian probability density distribution was assumed for each of the design parameters. It is also assumed that the selected design parameter varies discretely and regularly from its lowest to its highest value. For each such value of the design parameter, the deflection at a selected point on the beam cross-section is calculated. Since the Gaussian probability density function is continuous and smooth, fitting curves based on a finite number of deterministic solutions must be established. These functions will be used primarily in a semi-analytical approach and will also serve as a stochastic basis for the MCS to determine random moments, with the expected value of the structural response being the most important. Probabilistic moments will be defined in the form of curves (for SAM and SPT) or a set of points (for MCS), as a function of the coefficient of variation of the design parameter. Additionally, in a semi-analytical approach, one can easily define random moments as a function of two variables – the mean value and the standard deviation of the design parameter, and determine the so-called random response surfaces of the structure. Finally, by determining the so-called random entropy it will be possible to estimate the so-called measures of structural reliability expressed e.g. by the index First-Order Reliability Method (FORM).

- [1] R. Kotynia, *FRP composites for flexural strengthening of concrete structures. Theory, testing, design*, Łódź University of Technology Press, Poland, 2019
- [2] M. Hammad, A. Bahrami, S.A. Khokhar, R.A. Khushnood, *A State-of-the-Art Review on Structural Strengthening Techniques with FRPs: Effectiveness, Shortcomings, and Future Research Directions*, Materials, 17(6), 1408, 2024, <https://doi.org/10.3390/ma17061408>
- [3] I. Jankowiak, *Analysis of RC beams strengthened by CFRP strips – experimental and FEA study*, Archives of Civil and Mechanical Engineering 12, 376–388, 2012
- [4] G. Stefanou, *The stochastic finite element method: Past, present and future*, Computer Methods in Applied Mechanics and Engineering, 198, 1031–1051, 2008.
- [5] M. Kamiński, *The Stochastic Perturbation Method for Computational Mechanics*, Wiley: Chichester; 2013
- [6] M. Kamiński, M. Przychodzki, M. Łasecka-Plura, M. Guminiak, A. Lenartowicz, *Random eigenvibrations of beams with viscoelastic layers*, Journal of Theoretical and Applied Mechanics 62(4), 763–767, 2024

The effect of knot location on the load-bearing capacity of reclaimed timber beams

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KEYWORDS: *Reclaimed timber, Finite element method, Four-point bending, knot.*

Reclaimed timber is increasingly used in structural applications due to sustainability considerations and the growing demand for circular construction practices. However, its structural performance remains difficult to assess due to natural heterogeneity and the presence of defects such as knots, which significantly influence mechanical behaviour. Existing grading approaches, including visual sorting methods, already recognize the importance of knot size as a key parameter affecting timber classification and strength [1]. Nevertheless, the influence of knot location within structural elements remains less clearly quantified.

This study investigates the effect of knot location on the load-bearing capacity of timber beams subjected to four-point bending. An experimental campaign is conducted to determine the modulus of elasticity (MoE) and modulus of rupture (MoR) of reclaimed timber elements. A representative example of the failure mode observed during testing is shown in Fig. 1. The obtained results serve as a reference for the development and validation of a numerical modelling framework.

In parallel, a finite element model is being developed in Abaqus to simulate the bending response of timber beams. At the current stage, the model reproduces the behaviour of defect-free beams in the linear elastic range. The ongoing work focuses on incorporating knots as localized material disturbances, represented through variations in density, fibre orientation, or local stiffness reduction. The failure criterion is defined based on reaching a critical stress level, with consideration of appropriate strength hypotheses.

The proposed approach is intended to enable a parametric analysis of the influence of knot position and characteristics on beam capacity. Ultimately, the framework will be extended to include geometrically accurate models derived from three-dimensional scans of real timber elements, following previous work on lidar-based assessment of reclaimed timber [2]. This will allow for more reliable prediction of structural performance based on actual material geometry.

The presented work constitutes an initial step toward integrating experimental testing, numerical modelling, and advanced imaging techniques for the assessment of reclaimed timber structures.

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- [1] D.F. Llana, G. Turk, C. Osuna-Sequera, G. Íñiguez-González, Recovered timber grading system. In 14th World Conference on Timber Engineering. Curran Associates, 2025. <https://doi.org/10.52202/080513-0424>
- [2] J. Pełczyński, K. Ostapska, P. Arendt, Reclaimed timber assessment supported by lidar scanning. In 14th World Conference on Timber Engineering. Curran Associates, 2025. <https://doi.org/10.52202/080513-0148>

Modeling the kinematics of material flow in the cutting process as a basis for optimizing tool geometry to limit the formation of burrs on the cut surface of components

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KEYWORDS: *Cutting process, Modeling, FEM, Tool geometry.*

The paper presents the results of physical modeling and numerical simulations of the mechanical cutting process, focused on analyzing the kinematics of material flow and identifying factors affecting the quality of the cut surface. It was demonstrated that in complex metal forming processes, characterized by multiple degrees of freedom of the material, an intuitive approach to tool design is insufficient, and that visualization and process modeling play a key role.

Physical modeling enabled the identification of regions of strong geometric and material nonlinearities depending on the geometry of the cutting tool. A simulation model of the cutting process was developed, allowing for the analysis of displacement, strain, and stress states as a function of time, taking into account load history as well as variable process parameters such as tool geometry, friction conditions, and material properties.

The conducted analyses showed a significant influence of cutting tool geometry on the mechanics of material flow, including the formation of sticking and sliding zones, areas of deformation, and the energy consumption of the process. Conditions for process realization were determined that enable the reduction of cutting resistance and unfavorable phenomena such as excessive material hardening or the formation of flash.

Based on the obtained results, directions for optimizing the geometry of cutting tools were proposed, enabling the reduction of burr formation and improvement of the cut surface quality of metallic materials. The research results provide a basis for the development of new tool designs and can be applied in the design of cutting technological processes with increased efficiency and product quality.

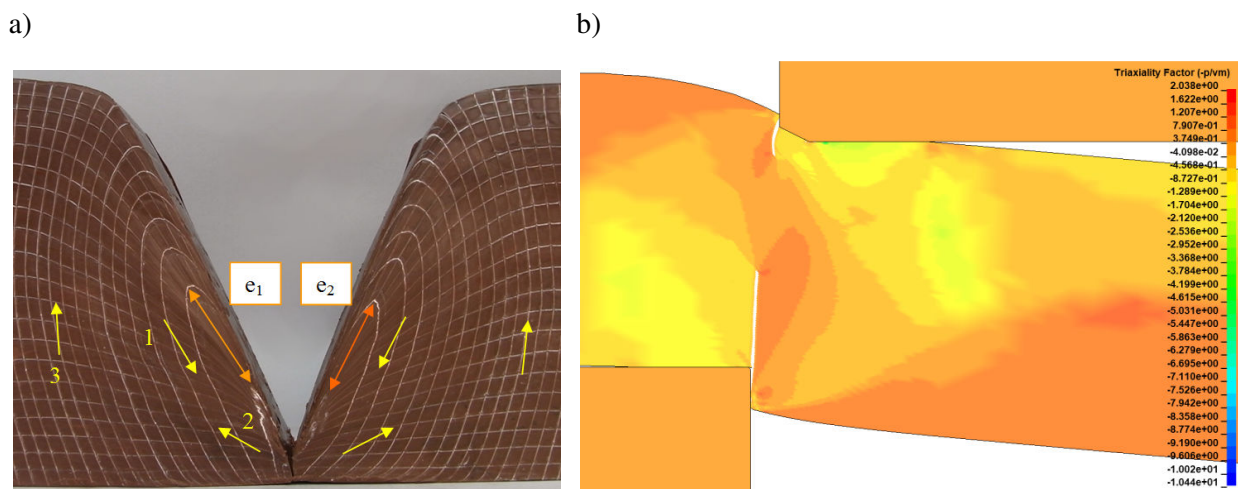


Figure 1. Example of physical modeling of cutting process (a), numerical modeling (b)

Modelling and tension regulation of a 12 rod hanger system in CHP plants

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KEYWORDS: *CHP plants, rod tension, Finite Element Method, Reinforcement Learning*

Steam furnaces, which are utilized in combined heat and power plants (CHP), are typically suspended using complex hanger rod systems consisting of numerous vertical rods [1]. During the operation of such plants the distribution of tension in rods tend to vary over time and as such it is essential to monitor and adjust it on a regular basis, in order to ensure the reliable operation of the furnace [2].

Figure 1 shows a typical 12 rod hanger system of a furnace front wall with tension distribution obtained from measurement performed at an CHP plant. In this work, the numerical modelling of such a system is presented using both finite element method and analytical equations. Additionally, possible tension regulation of such a system is proposed, employing optimization techniques and reinforcement learning methods.

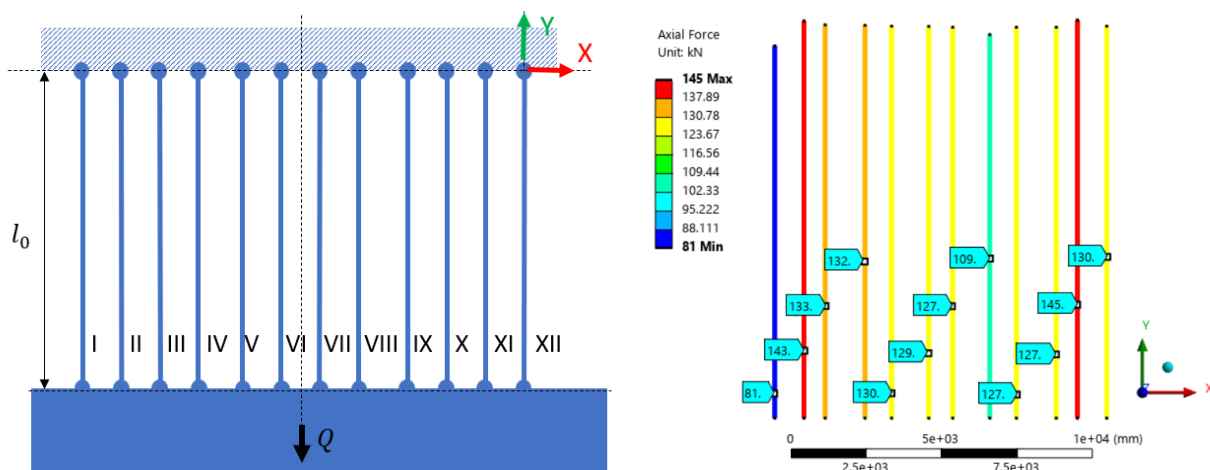


Figure 1. 12 rod hanger model of a front furnace wall (left); tension distribution from experimental data (right)

ACKNOWLEDGEMENT: This work has been supported by the National Centre for Research and Development through Grant No 0317/L-14/2023, „MASy 2.0: system for Monitoring and Adjusting the tenSion force in hanger rods of power boiler”

- [1] P. Duda, Ł. Felkowski, A. Duda, 2024. Analysis of the Impact of Forces in Hanger Rods on Power Boiler Operation. Applied Sciences 14, 5720.
- [2] Ł. Felkowski, 2020. Metody oceny stanu cieplno-wytrzymałościowego elementów kotła energetycznego, PhD Thesis (in Polish).

On the equivalent stiffness in cryogenic tensile testing: FEM–DIC coupled identification approach

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KEYWORDS: *system stiffness; Digital Image Correlation (DIC); finite element modelling (FEM); cryogenic tensile testing; plastic flow instability*

Material testing at low temperatures is typically conducted in accordance with established standards and procedures [1]. However, the mechanical compliance of the testing system remains insufficiently quantified. In particular, the stiffness of the testing machine and the overall experimental set-up can significantly affect the measured response. This influence becomes especially pronounced under discontinuous plastic flow instability (DPF), where the dynamic interaction between the specimen and the extensometer plays a critical role [2].

In this study, the equivalent stiffness of a cryogenic material testing setup (Fig. 1) is determined using a multi-approach methodology. The stiffness is evaluated through analytical formulations, finite element modelling (FEM), and experimental measurements based on Digital Image Correlation (DIC). The developed approaches are compared and validated to ensure consistency and reliability of the obtained results.

Subsequently, the identified equivalent stiffness is incorporated into the analysis of tensile tests to assess its influence on the dynamic response of the specimen–extensometer system and on its impact of material characterization. The obtained results indicate that the extensometer geometry significantly influences the measured response, highlighting the importance of its appropriate selection. Alternatively, this effect can be mitigated by increasing the overall stiffness of the testing system.

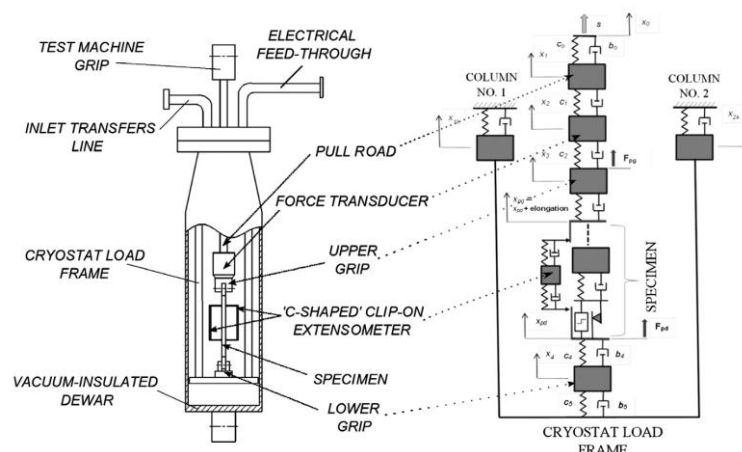


Figure 1. Schematic view of the experimental set-up (left) and extensometer (right) [2].

ACKNOWLEDGEMENT: This work has been supported by the National Science Centre through the Grant No 2023/51/D/ST8/02370.

[1] ISO 6892-3:2015, Metallic materials — Tensile testing Part 3: Method of test at low temperature

[2] J. Tabin, M. Pracik, Methods for identifying dynamic parameters of clip-on extensometer–specimen structure in tensile tests, Measurement, Volume 63, 2015, Pages 176-186, ISSN 0263-224.

Three-Dimensional Elasticity Analysis of Sandwich Laminated Finite Shell with FG Core by Numerical Integration Approach

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KEYWORDS : *Sandwich laminates, functionally graded core, three-dimensional elasticity analysis, numerical integration technique.*

Sandwich panel are widely employed in engineering applications such as aerospace, construction, and transportation, where high strength-to-weight and stiffness-to-weight ratios are essential. A critical issue in such structures is delamination between the core and face-sheets, primarily caused due to the mis-match in their material properties. Previous studies indicate that the resistance to delamination can be enhanced by tailoring the material properties of the core. Consequently, the concept of functionally graded (FG) materials has gained significant attention in sandwich panel design.

Accurate evaluation of stresses, particularly transverse stresses responsible for delamination, is crucial for reliable structural assessment. Classical theories often fail to capture these stresses with sufficient accuracy, whereas three-dimensional (3-D) elasticity theories account for the complete stress state. In this study, a 3-D elasticity-based solution is developed using a numerical integration approach for the bending analysis of a finite sandwich laminated circular cylindrical shell with a FG orthotropic core.

The core material properties are assumed to vary exponentially in a symmetric manner with respect to the shell mid-surface, while the face sheets are considered homogeneous. Continuity of material properties is maintained at the interfaces. The proposed formulation employs a mixed approach, enabling the simultaneous evaluation of displacements and stresses with equal accuracy. The method utilizes the full set of 3-D elasticity equations without introducing simplifying assumptions, and the solution is obtained through an efficient numerical integration technique. The proposed method offers a valuable tool in advancing the understanding and analysis of laminated sandwich composite shell structures.

- [1] Ren, J. G. "Exact solutions for laminated composite cylindrical shells in cylindrical bending." *Composites Science and Technology*, 29: 169–187, 1987. [https://doi.org/10.1016/0266-3538\(87\)90069-8](https://doi.org/10.1016/0266-3538(87)90069-8).

Numerical Prediction of Yield Surface Evolution in LENS-Manufactured Inconel 625 under Sequential Multiaxial Probing: A UMAT-Based Approach

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KEYWORDS: Yield Surface, Szczepiński Yield Function, Kinematic Hardening, Multiaxial Probing.

Numerical modelling of yield surface evolution under non-proportional multiaxial loading is critical for the structural integrity assessment of high-performance engineering components. Nickel-based superalloys such as Inconel 625, fabricated by Laser Engineered Net Shaping (LENS), inherently develop a columnar grain microstructure that introduces pronounced crystallographic anisotropy and direction-dependent plastic flow behaviour [1]. Such orientation-dependent mechanical responses remain beyond the predictive capability of conventional uniaxial characterisation approaches. To capture the anisotropic yielding phenomenon of LENS-fabricated Inconel 625 thin-walled tubular specimens, a dedicated UMAT-subroutine is implemented in ABAQUS, enabling simulation of the initial yield surface under sequential biaxial tension-torsion loading at a 0.01% plastic offset strain criterion. The UMAT integrates the Szczepiński anisotropic yield criterion coupled with the Armstrong-Frederick nonlinear kinematic hardening law to capture path-dependent back-stress evolution. Across all loading paths, the simulation demonstrates excellent agreement with the experimentally fitted yield locus. A mean angular deviation of $|\Delta\alpha| = 0.51^\circ$ with every path within $\pm 1.5^\circ$ confirms directional accuracy, while a mean radial deviation of $|\Delta r| = 2.41\%$ ($< \pm 5\%$) validates magnitude reliability. Additionally, Szczepiński function values are consistent within $f(\sigma, \tau) \in [0.90, 1.10]$ confirms accuracy. The antisymmetric angular deviation pattern of positive back-stress overshoot in 2nd and 4th quadrants constitutes direct numerical validation of kinematic behaviour and the Bauschinger effect under sequential non-proportional loading.

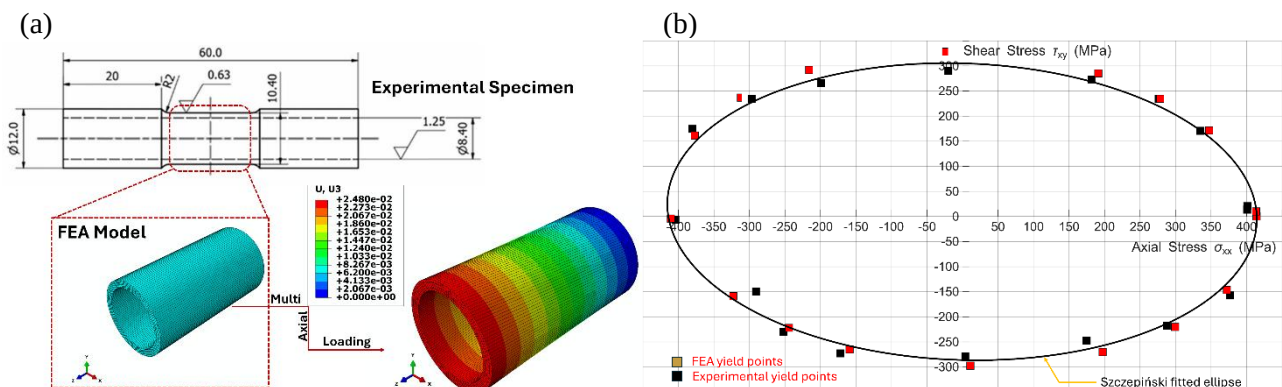


Figure 1. (a) Specimen geometry and discretised computational domain showing contour of deformed model, (b) Experimental and finite element simulated yield points at 0.01% offset strain with fitted Szczepiński ellipse.

ACKNOWLEDGEMENT This work was funded by National Science Centre, Poland through the grant no. 2023/51/B/ST8/01751.

[1] H. Przygucki, V.P. Dubey, T. Durejko, D. Przygucka, Z.L. Kowalewski, S. Jóźwiak, M. Kopec, Int. J. Adv. Manuf. Technol. (2026). <https://doi.org/10.1007/s00170-026-17839-7>

Investigation of stress relief holes geometry by means of machine learning and digital image correlation methods

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KEYWORDS: *Machine Learning, Digital Image Correlation, Stress Relief Holes, Stress Concentration, Optimization, Finite Element Method.*

Fatigue of materials and structural elements has major influence on design and safety of machines and its components. One of the most important factor affecting the fatigue life is the stress concentration, which appears in the surroundings of notches and openings of various kinds. It is the common knowledge that such stress concentration can be reduced by different technological operations or structure modifications. One of these methods is the application of the stress relief holes (SRH), which reduce the stress concentration in a meaning way. The main problem of this approach is the determination of the optimal configuration of SRH (i.e. size and location). In this research the machine learning is applied for optimization of geometrical parameters of the applied stress relief holes.

Here, the input data required for machine learning analyses is prepared by means of numerical analyses, namely finite element (FE) calculations. The obtained optimal configurations are the starting point for preparation of samples for experimental studies. The experimental research is made with the use of the contactless method – digital image correlation (DIC), which is the well-established method for analysis of deformation and strains. The DIC method is used for evaluation of introduction of SRH effectiveness, which is illustrated by the reduction of the strains around the notches and by comparison of numerical FE results and experimental ones [1, 2].

- [1] P.J. Romanowicz, B. Szybiński, M. Wygoda, Fracture Mechanism of Adhesive Layers in Fatigue-Loaded Steel Structures Reinforced by the CFRP Overlays, *Appl. Sci.* 2025, 15(7), 3435; <https://doi.org/10.3390/app15073435>.
- [2] P.J. Romanowicz, B. Szybiński, M. Wygoda, Assessment of Digital Image Correlation Effectiveness and Quality in Determination of Surface Strains of Hybrid Steel/Composite Structures, *Materials* 2024, 17(14), 3561; <https://doi.org/10.3390/ma17143561>.

Prediction of Surface Quality in Roller Burnishing Processes Using FEM-Based Applications

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KEYWORDS: *Numerical Analysis, Surface Quality Forecasting, Burnishing Rolling.*

Applications developed in FEM systems enable comprehensive time-dependent analysis of deformation states (displacements and strains) and stresses occurring in an object composed of a workpiece and a burnishing tool. They allow flexible modification of model parameters such as geometry, loading conditions (e.g., indentation depth), friction conditions, process time, and material properties (including nonlinear plasticity models dependent on strain and strain rate). The application developed by the author meet advanced practical requirements and can be successfully used for simulating real burnishing processes. Increasing technical and economic demands, along with the development of new materials, necessitate the creation of new theoretical models and their implementation in numerical software. These applications are used for modeling and simulation of burnishing processes. The model assumes a three-dimensional state of stresses and strains. The applications enable full analysis for a wide range of input data, including: arbitrary geometry of the workpiece (e.g., shaft, sleeve, cone) and tool (e.g., sphere, polyhedron), various materials with complex plastic behavior models, diverse surface geometries resulting from prior machining processes, deviations and surface irregularities with defined profiles, different friction conditions in the contact zone, arbitrary tool displacements over time, arbitrary initial and boundary conditions.

The first step involves defining the geometry of the workpiece and the tool. The analyses primarily use three-dimensional models, assuming the tool to be either rigid or elastic. The simulation program allows the introduction of various surface profiles, including different angles and deviations of surface irregularities. An important feature of the application is the ease of modifying geometry, refining the mesh, and optimizing the model, which enables accurate representation of real burnishing process conditions. To confirm these capabilities, both experimental studies and numerical analyses were carried out. They involved surfaces prepared for burnishing by turning, made of C45 steel, characterized by surface irregularities with different apex angle θ , while the spacing of the irregularities was $s=1$ mm.

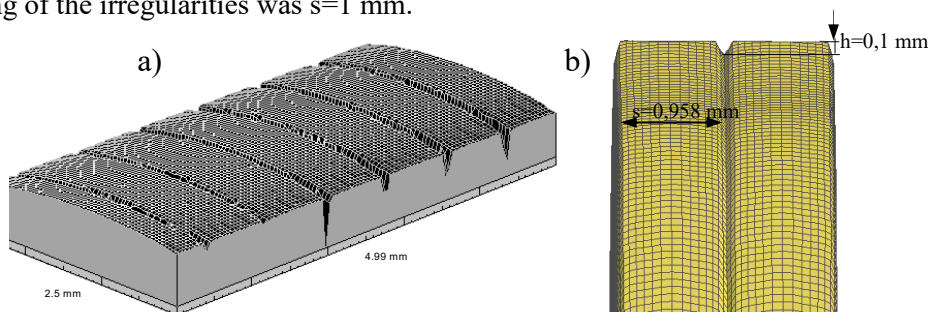


Figure 1. Continuous axonometric view of the surface after burnishing with visible secondary indentations (a), computer simulation result (b).

- [1] Jerez-Mesa, R.; Travieso-Rodriguez, J.A.; Lluma, J.; López de Lacalle, L.N. Numerical–experimental approach for ball burnishing process on complex surfaces. *Precision Engineering*, 2021, 67, 231–243
- [2] Kluz, R.; Antosz, K.; Trzepieciniski, T.; Bucior, M. Modelling the Influence of Slide Burnishing Parameters on the Surface Roughness of Shafts Made of 42CrMo4 Heat-Treatable Steel. *Materials* 2021, 14, 1175. <https://doi.org/10.3390/ma14051175>.

A Novel Three-Element Column–Slab Connection System with Variable Centre of Rotation for Reinforced Concrete Structures

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KEYWORDS: *column–slab connection, variable centre of rotation, punching shear, semi-rigid joint, reinforced concrete, finite element method, structural optimisation*

This paper presents the concept and ongoing development of a column–slab connection system for reinforced concrete structures, based on a three-element mechanism with pinned joints. In conventional solutions, loads transferred from a slab to a column never pass precisely through the column axis, generating unavoidable eccentric loading. This eccentricity demands additional reinforcement steel and concrete volume beyond what purely axial assumptions would require, increasing both material consumption and construction cost.

The proposed system redistributes the support reaction along three distinct load paths: a vertically acting compressed element and two inclined tension members connected via pins. This arrangement creates a connection with a variable centre of rotation, enabling controlled force flow, reduction of bending moments, and optimisation of connection stiffness in response to varying load conditions.

The overall project encompasses four objectives: (1) formulation of mathematical models to determine optimal connection geometry, (2) design of numerical models (3) assessment of economic and environmental benefits.

The work presented here covers the research completed prior to the conference, which includes four stages. At first, a systematic literature review was conducted using Scopus, Web of Science, and Google Scholar, focusing on punching shear, unbalanced moment transfer, semi-rigid connections, and variable-centre-of-rotation concepts. A structured comparison of existing column–slab joint solutions was compiled, with identification of key research gaps. Second, a Python-based optimisation program was developed to systematically explore the parameter space and identify geometries that maximise load-bearing capacity while minimising material use. Fourth, a 2D finite element model was built in Autodesk Robot / ANSYS to validate the analytical algorithm. Bending moments and internal forces obtained from the FEM model were compared against Python program outputs, and a comparative analysis against reference cases — classical pinned and rigid connections — was performed to quantify moment and force reductions achieved by the proposed system.

The expected outcomes of the full project include design criteria for structural engineers (equations, geometric parameter ranges, and sample construction drawings), a validated experimental and numerical dataset for future research.

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Low-Velocity Impact Cracks in Glass and Laminated Glass Based on Peridynamics

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KEYWORDS: *Glass, Laminated glass, Impact, Crack, Peridynamics.*

Glass is commonly used in building and daily life. However, due to its brittle property, its use needs carefully considered. To improve this property, safety glass or laminated glass is popular in buildings, vehicle engineering and aviation industry. To safely use these two types of materials, their ability to suffer the impact of foreign object is major topic. The object of this work to invest the low-velocity impact of these two materials by both experiment and simulation approaches. In the experiment, the free fall of a small object with the mass of 618 g was executed under different heights to create the impact cracks on both the glass and the laminated glass. In the simulation approach, the peridynamic finite element method was selected to create the cracks during the impact. Figure 1(a) compares the fracture pattern of glass under the impact energy of 3 Joules. The measured force with respect time and the simulation result are compared in Fig. 1(b). Under the same impact energy, the crack pattern of the laminated glass is compared in Fig. 2(a), and the comparison between the experiment and the simulation is shown in Fig. 2(b). These comparison indicates the good results from the peridynamic finite element method.

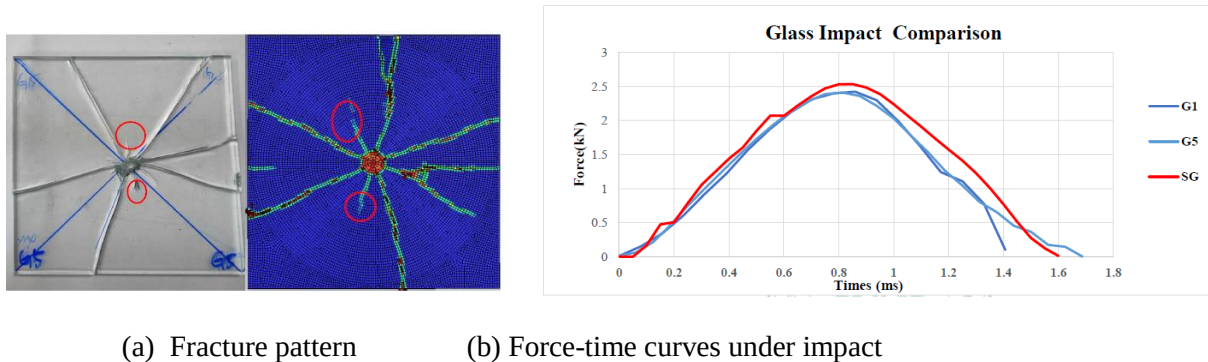


Figure 1. Fracture pattern and force-time curve of glass under impact.

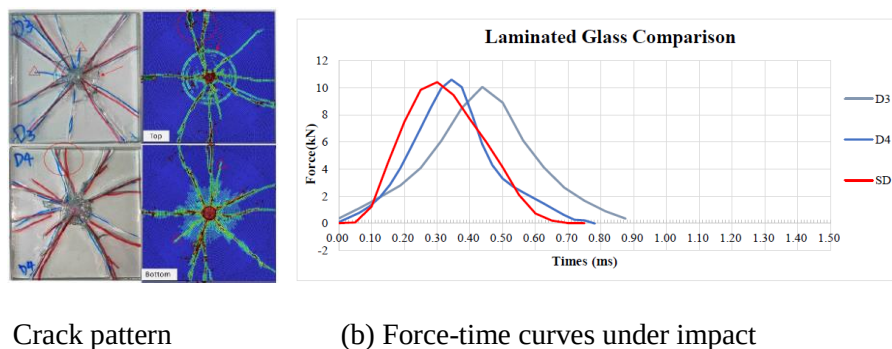


Figure 2. Crack pattern and force-time curve of laminated glass under impact.

ACKNOWLEDGEMENT: The funding from NSTC 114-2221-E-224-036 is appreciated.

Analysis of the Vibration Isolation Performance of an Active Suspension System Designed for a Child Car Seat

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KEYWORDS: *Active Suspension; Vibration Isolation; Child Car Seat; PMSM Actuator; Field-Oriented Control; SEAT Index*

The aim of the study is to analyse the vibration damping properties of an active suspension system designed for a child car seat that is designed to reduce the impact of vertical accelerations on the child's body during vehicle travel. The motivation for undertaking this research is the absence of vibration isolation solutions dedicated to this group of users, despite the well-documented sensitivity of children to vibrations in the frequency range of 4–10 Hz [1-3]. The proposed system extends a previously developed passive suspension by introducing an active actuator in order to improve vibration reduction under varying operating conditions. The actuator is implemented using a permanent magnet synchronous motor (PMSM) controlled with a field-oriented control (FOC) strategy [4]. A physical and mathematical model of the suspension system was developed in the MATLAB/Simulink environment. The model includes passive suspension components as well as an active control force generated by the electric drive. The control algorithm determines the desired actuator force based on the displacement of the isolated mass and the relative displacement of the suspension system. To evaluate the vibration isolation performance, the SEAT coefficient and the relative displacement RS were used as optimisation criteria. A multi-objective optimisation procedure was applied to determine the optimal control parameters and to identify Pareto-optimal solutions representing a compromise between vibration reduction and allowable suspension stroke. The dynamic response of the system was analysed using broadband excitation representing road-induced vibrations in the frequency range typical for vehicle operation. The obtained results indicate that the application of active control significantly improves the vibration isolation performance of the suspension system. The proposed approach enables effective reduction of vibration transmissibility while maintaining acceptable values of relative displacement. The developed model also allows investigation of the influence of control parameters on the dynamic behaviour of the system. The presented results provide a basis for further experimental validation and future development of actively controlled suspension systems for child car seats.

[1] Giacomini J. Absorbed power of small children. *Clinical Biomechanics* 20, 2005.

[2] Bai X., et al. On 4-degree-of-freedom biodynamic models of seated occupants: Lumped-parameter modeling, *Journal of Sound and Vibration*, 2017.

[3] ISO 2631-1: 1997 Mechanical vibration and shock. Evaluation of human exposure to whole –body vibration.

[4] Maciejewski I. et al. Vibration control of an active horizontal seat suspension with a permanent magnet synchronous motor, *Journal of Sound and Vibration* 488 (2020) 115655

A Finite Element Model for Buckling Analysis of Composite Beams

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KEYWORDS: *Thin-Walled, Angle-Ply Laminate, Beam Model, Buckling.*

This study presents an enhanced stability analysis based on a shear-deformable beam formulation for laminated composite beam-like structures with thin-walled cross-sections. Each cross-sectional wall is modeled as a thin, symmetric angle-ply laminate. The governing equilibrium equations for a straight beam element are obtained using the principle of virtual work within a Lagrangian framework, incorporating Hooke's law and a nonlinear displacement field that accounts for restrained warping and large rotational effects in thin-walled sections.

The proposed formulation incorporates shear deformation effects through the Timoshenko–Ehrenfest theory to describe non-uniform bending behavior and the modified Vlasov theory to model non-uniform torsion. In addition, an advanced shear-deformable beam formulation is introduced to capture shear-induced coupling between bending–bending and bending–warping torsional responses. These coupling phenomena are particularly pronounced in beams with asymmetric cross-sections, where the principal bending axes do not align with the shear axes. The beam members are assumed to be straight and prismatic, and the applied external loads are considered static and conservative.

The element's geometric stiffness matrix is derived from a nonlinear displacement field of the cross-section, incorporating second-order displacement terms to represent large rotational effects. This formulation enables the evaluation of the incremental geometric potential associated with semitangential moments arising from internal bending and torsional actions, thereby ensuring equilibrium of moments at joints connecting beam members with differing spatial orientations.

A locking-free, super-convergent beam element is achieved by employing cubic interpolation functions for transverse displacements and twist rotations, together with mutually dependent quadratic interpolation functions for slopes and the warping parameter. This interpolation strategy accurately captures shear-deformable behavior without the need for reduced integration schemes to mitigate shear-locking issues.

To determine properties of a laminated thin-walled cross-section, a separate numerical model is developed. The cross-sectional properties are weighted by using three distinct reference moduli: the longitudinal modulus, which governs properties related to the coupling between normal stress forces and normal strains, including area, moments of inertia, area moments, sectorial inertial moments, and sectorial area moments; the shear modulus, which governs the torsional moment of inertia and shear coefficients; and the coupling modulus, which governs the coupling between the normal and shear strains. All cross-sectional properties are defined with reference to the midline of each branch of the cross-section.

ACKNOWLEDGEMENT: This work was supported by the Croatian Science Foundation under the project number [HRZZ-IP-2024-05-6868]. This work was Funded by the European Union – NextGenerationEU under project numbers (uniri-mz-25-3; uniri-iz-25-95 and uniri-iz-25-233).



Prediction of residual compressive strength of normal concrete exposed to elevated temperatures

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KEYWORDS: *Residual compressive strength, Elevated temperature, Concrete, Machine learning, Design-code equations.*

Predicting the residual compressive strength of concrete after exposure to elevated temperatures is essential for post-fire safety assessment. However, this task remains difficult because the degradation of concrete strength is nonlinear, scattered, and strongly affected by testing conditions. Existing empirical and design-code equations usually rely on simplified assumptions and limited datasets, which may restrict their accuracy when applied to broad experimental databases. This study presents a comparative data-driven framework for predicting the residual compressive strength of normal concrete exposed to elevated temperatures. A database of 700 experimental results collected from 67 published studies was used. Exposure temperature and compressive strength at ambient conditions were selected as input variables because they are widely reported in the literature and are commonly used in design-code formulations. Seven predictive models were developed and evaluated, including multiple linear regression (MLR), support vector regression (SVR), k-nearest neighbor (KNN), random forest (RF), extreme gradient boosting regression (XGBR), gene expression programming (GEP), and multi-expression programming (MEP). The models were assessed using statistical error metrics, regression analysis, sensitivity analysis, and comparison with existing empirical and code-based equations. The results showed that ensemble learning models such as RF and XGBR provided the most accurate and stable predictions. In particular, XGBR achieved the best testing performance, with a test RMSE of 3.57 MPa and R^2 of 0.914. RF also showed strong predictive capability and stable generalization. In contrast, MLR and several existing equations were less effective in capturing the nonlinear strength degradation at high temperatures. Among the symbolic models, GEP showed better generalization than MEP and provided an explicit analytical relation for practical estimation. Sensitivity analysis confirmed that exposure temperature was the dominant variable, while ambient compressive strength had a secondary influence. Overall, the findings indicate that ensemble models are suitable for accurate prediction, whereas GEP can support transparent engineering assessment through an explicit formulation.

Session TS5

Computer methods in solid mechanics

Collocation-Based Robust Variational Physics-Informed Neural Networks (CRVPINNs)

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KEYWORDS: *Physics-Informed Neural Networks, Collocation Methods, Robust Discrete Formulations.*

Physics-informed Neural Networks (PINNs) have been introduced by G. Karniadakis [1] as a way to apply Deep Learning methods to solving partial differential equations (PDEs). Unlike the more common data-driven approaches, PINNs operate by minimizing a loss function based on the residual of the strong formulation of the PDE, evaluated on a set of collocation points. Because of that, PINNs fail to provide accurate solutions in some problems with low regularity of the data, since the solution only makes sense in a variational form. A natural way to overcome this limitation is to build the loss function using the residual of the variational formulation of the underlying PDE – an approach known as Variational PINN (VPINN) [2].

While the VPINNs have been successfully applied in a number of areas, they have a considerable drawback in that the loss is sensible to the choice of basis functions, and may not be robust, that is, the loss value can tend to zero, while the true error in a relevant Sobolev norm does not. To mitigate that problem, Robust Variational PINN (RVPINN) has been proposed [3], which follows the core ideas introduced in Minimum Residual (MinRes) methods. The RVPINN loss function is constructed as the dual norm of the residual of the variational (Petrov-Galerkin) form of a PDE. As long as the variational formulation satisfies the assumptions of the Babuška theorem (continuity and inf-sup stability of the bilinear form), such loss function constitutes an efficient and reliable estimator of the true error. More precisely, the norm of the true error is bounded from below and above (up to an oscillation term) by the square of the loss.

Unfortunately, to compute the weak residuals, RVPINNs require expensive numerical integration. We proposed an alternative combining their robustness with the efficiency of standard PINN – Collocation-based Robust Variational PINN (RVPINN) [3]. The continuous spatial domain and integral forms are replaced with a discrete set of collocation points and discrete weak formulation, mimicking the properties of the continuous, Sobolev space-based theory, similar to the finite difference method. The result is a robust loss function, which does not require integration.

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- [1] M. Raissi, P. Perdikaris, G.E. Karniadakis, *J. Comput. Phys.* 378 (2019) 686–707. <https://doi.org/10.1016/j.jcp.2018.10.045>
- [2] E. Kharazmi, Z. Zhang, G.E. Karniadakis, Variational physics-informed neural networks for solving partial differential equations, 2019, arXiv:1912.00873.
- [3] S. Rojas, P. Maczuga, J. Muñoz-Matute, D. Pardo, M. Paszyński, Robust Variational Physics-Informed Neural Networks, *Computer Methods in Applied Mechanics and Engineering* 425 (May 2024): 116904. <https://doi.org/10.1016/j.cma.2024.116904>
- [4] M. Łoś, T. Służalec, P. Maczuga, A. Vilkha, C. Uriarte, M. Paszyński, Collocation-based robust variational physics-informed neural networks (CRVPINNs), *Computers & Structures* 316, 107839 (2025). <https://doi.org/10.1016/j.compstruc.2025.107839>

Fast Numerical Method Based on Discrete Sine and Cosine Transforms for Wave Propagation in Heterogeneous Media

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Keywords: *FFT-based Methods, Non Periodic Boundary Conditions, Discrete Sine-Cosine Transforms.*

FFT-based numerical methods, introduced by Moulinec and Suquet [1], are now a class of highly efficient solvers in computational micromechanics. Their success relies on their simplicity of implementation and their low computational cost, of order $O(N \log N)$, which is significantly lower than that of approaches based on the assembly and inversion of global matrices. However, the representation of fields using Fourier series inherently implies periodic boundary conditions. This limits their application to problems where more realistic boundary conditions are required, such as non-periodic microstructures or transient problems. Extending these methods to non-periodic frameworks is therefore a major scientific challenge.

Recent works [2] have extended these methods [1] to non-periodic boundary conditions using a decomposition of the solution field into a term satisfying the boundary conditions and a second term, referred to as a fluctuation, described by sine and cosine series and vanishing at the boundaries. This approach allows one to move beyond the strictly periodic framework and has enabled the solution of elasticity problems [3] for microstructures subjected to Dirichlet and Neumann boundary conditions.

In this work, this framework [2] is used to develop solvers for mechanical problems involving microstructures subjected to non-periodic boundary conditions. Starting from the classical elasticity formulation [3], an implicit method is proposed for elastodynamic problems with stress wave propagation in heterogeneous media, based on the approach developed in [2] and on a Newmark- β time discretization, following [4]. The method is validated using analytical solutions in both homogeneous and heterogeneous cases. It is then applied to study wave propagation in polycrystalline media with different levels of anisotropy and compared with a reference finite element solution.

- [1] H. Moulinec, P. Suquet, A numerical method for computing the overall response of nonlinear composites with complex microstructure, *Comput. Methods Appl. Mech. Eng.* 157, 69–94,
[https://doi.org/10.1016/S0045-7825\(97\)00218-1](https://doi.org/10.1016/S0045-7825(97)00218-1).
- [2] J. Paux, L. Morin, L. Gélébart, A Discrete Sine-Cosine Transforms Galerkin Method for the Conductivity of Heterogeneous Materials With Mixed Dirichlet/Neumann Boundary Conditions, *Int. J. Numer. Methods Eng.* 126 (1) e7615,
<https://doi.org/10.1002/nme.7615>.
- [3] J. Paux, L. Morin, L. Gélébart, A. M. Amadou Sanoko, A discrete sine–cosine based method for the elasticity of heterogeneous materials with arbitrary boundary conditions, *Comput. Methods Appl. Mech. Eng.* 433,
<https://doi.org/10.1016/j.cma.2024.117488>.
- [4] R. Sancho, V. Rey-de Pedraza, P. Lafourcade, R. A. Lebensohn, J. Segurado, An implicit FFT-based method for wave propagation in elastic heterogeneous media, *Comput. Methods Appl. Mech. Eng.* 404, 115772,
<https://doi.org/10.1016/j.cma.2022.115772>.

Numerical Homogenization in Viscoelastic Analysis

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KEYWORDS: *Numerical Homogenization, Finite Element Method, Viscoelasticity, Asphalt Concrete.*

The leading role of heterogeneous materials used in civil engineering requires dedicated numerical methods for detailed analysis of their behavior. The Finite Element Method (FEM) is used in our research as the general tool for numerical analysis. Due to the heterogeneity of the analyzed domain and the physical nonlinearity (observed mainly within the matrix phase), the straightforward approach is rather ineffective. In our ongoing research, the numerical homogenization is developed. As the test material, asphalt concrete is considered.

A number of homogenization methods based on the Representative Volume Element (RVE) can be found in the literature [1-3]. For the purposes of this research, the numerical homogenization approach presented in [4] is adopted. Based on the high-quality image and its further processing, the asphalt concrete specimen with the underlying microstructure is reconstructed. In this research, the analysis is limited to the 2D case with two phases distinguished, i.e. the aggregate and the mastic. The reconstructed microstructure is accounted for at the RVE level and the effective tensors of material parameters are subsequently evaluated. The main idea of the proposed approach is to avoid time consuming evaluation of the tangent matrices resulting from the transient problem. Instead, the inelastic strain evolution contributes to the load vector. As a result, the effective stiffness matrices of macroscale elements remain the same for the whole time-stepping algorithm. Moreover, the nonlinear strain evolution needs to be analyzed, accounting for the microstructure solely at the RVE level. The averaged inelastic strain is transferred to the corresponding Gauss point.

The obtained numerical results confirm the applicability of the proposed approach. One can observe a substantial reduction of the number of degrees of freedom compared to the straightforward analysis carried out using the overkill mesh. On the other hand, the additional modeling error introduced by the homogenization is kept at the acceptable level of several percent (measured in L2 norm).

The proposed framework can be further generalized to the 3D case with the microstructure reconstructed using e.g. the X-ray computed tomography. Also, a number of nonlinear material models can be easily incorporated at the RVE level to increase the applicability of the developed approach.

- [1] I. Özdemir, W. Brekelmans, M. Geers, *Int. J. Numer. Methods Eng.* 73, 185-204, 2008. <https://doi.org/10.1002/nme.2068>
- [2] M. Hain, P. Wriggers, *Comput. Mech.* 42, 197–212, 2008. <https://doi.org/10.1007/s00466-007-0211-9>
- [3] I. Temizer, P. Wriggers, *Comput. Methods Appl. Mech. Eng.* 198, 495–510, 2008. <https://doi.org/10.1016/j.cma.2008.08.018>
- [4] M. Klimczak, M. Oleksy, *J. Theor. Appl. Mech.* 62, 351–364, 2024. <https://doi.org/10.15632/jtam-pl/185459>

Numerical Modelling of Transient Heat Transfer in an Axisymmetric Cylindrical Container with Phase Change Materials

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KEYWORDS: *Heat Transfer, Phase Change Materials, Finite Difference Method, Cold Chain Transport.*

The paper concerns numerical modelling of transient heat transfer in a cylindrical container used for vaccine transport, with the application of phase change materials (PCMs). The considered system consists of a multilayer structure including an insulating layer, an ice domain and an additional PCM layer. The role of the PCM is to stabilize temperature and prevent vaccine freezing. Due to the geometry, the problem is formulated in an axisymmetric coordinate system.

The mathematical model is based on the heat conduction equation in cylindrical coordinates

$$c\rho \frac{\partial T(r, z, t)}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left(\lambda r \frac{\partial T(r, z, t)}{\partial r} \right) + \frac{\partial}{\partial z} \left(\lambda \frac{\partial T(r, z, t)}{\partial z} \right). \quad (1)$$

Thermophysical parameters depend on temperature, and the phase change process is described using the apparent heat capacity approach. Heat transfer in the domain is assumed to be conductive, while appropriate boundary conditions, including convection and radiation, are imposed on the outer surfaces.

In contrast to the reference model based on the finite element method [1], the present study applies the finite difference method (FDM), formulated directly in cylindrical coordinates [2]. This formulation enables efficient numerical implementation and reduces computational cost.

Calculations are performed for selected geometric parameters, including the thickness of insulation, ice and PCM layers. The analysis focuses on the influence of the additional PCM layer on temperature distribution in the storage region, particularly in the range required for safe vaccine transport (2–8°C). The numerical results are analysed with respect to data reported in the literature [1]. The obtained agreement confirms the correctness of the model and the suitability of the FDM approach for this type of problem.

The results show that the application of an additional PCM layer significantly improves thermal conditions and extends the safe storage time. The developed model can be used in further analysis and optimization of thermal systems applied in cold chain transport.

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- [1] S. Ayala-Zambrano, R. Jackel, G.L. Gutiérrez-Urueta, A. Ramos Blanco, C. Monreal Jiménez, Parametric optimization of cylindrical vaccine transport containers with dual phase change materials to prevent vaccine freezing and heat damage using artificial neural networks, *Journal of Energy Storage*, 109, 115239, 2025. <https://doi.org/10.1016/j.est.2024.115239>
- [2] A. Piasecka-Belkhat, A. Skorupa, Application of interval arithmetic in numerical modeling of cryopreservation process during cryoprotectant loading to microchamber, *Numerical Heat Transfer, Part A: Applications*, 84, 83–101, 2023. <https://doi.org/10.1080/10407782.2022.2105078>

Numerical Comparison of Selected Methods for Modelling Phase Change in Heat Transfer Problems

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KEYWORDS: *Heat Transfer, Phase Change Materials, Finite Difference Method, Effective Heat Capacity, Enthalpy Method.*

The study concerns numerical modelling of transient heat transfer in a multilayer system containing a phase change material (PCM) layer. Particular attention is devoted to the analysis of selected methods for modelling the phase change process. The governing equation is solved using the finite difference method. The mathematical model is based on the one-dimensional heat conduction equation

$$c\rho \frac{\partial T(x,t)}{\partial t} = \frac{\partial}{\partial x} \left(\lambda \frac{\partial T(x,t)}{\partial x} \right). \quad (1)$$

In the case of the PCM layer, thermophysical parameters are temperature-dependent, and the phase change process is taken into account. The phase change is described using two approaches: the effective heat capacity method and the enthalpy method [1, 2]. In the enthalpy approach, the enthalpy is defined for the PCM and includes latent heat effects.

Calculations are carried out for a multilayer roof system containing a PCM panel. The influence of the applied modelling approach on the temperature distribution in the system is analysed. The comparison is performed under identical boundary and initial conditions.

The numerical results are compared with experimental data reported in the literature [1]. The obtained agreement confirms the correctness of the model and the suitability of the applied approaches. The differences between the considered methods are particularly visible in the phase change interval, where the distribution of latent heat affects the temperature evolution.

The results indicate that both approaches enable effective modelling of the phase change process. The enthalpy method provides a continuous representation of thermophysical properties, while the effective heat capacity approach offers a simpler and computationally efficient formulation. The comparison allows for the assessment of accuracy and computational efficiency of the considered methods.

ACKNOWLEDGEMENT: The authors gratefully acknowledge the financial support provided by the Faculty of Mechanical Engineering, Silesian University of Technology, in 2026.

- [1] A. Pasupathy, R. Velraj, Effect of double layer phase change material in building roof for year round thermal management, *Energy Build.* 40, 193–203, 2008.
<https://doi.org/10.1016/j.enbuild.2007.02.016>
- [2] K.S. Reddy, V. Mudgal, T.K. Mallick, Thermal performance analysis of multi-phase change material layer-integrated building roofs for energy efficiency in built-environment, *Energies* 10, 2017.
<https://doi.org/10.3390/en10091367>

Comparative Study of Numerical and Analytical Solutions for an Elastic Half-Space under Rectangular Loading

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KEYWORDS: *Schleicher–Love Problem, Rectangular Loading, Infinite Elements, Numerical Solution.*

This work addresses the classical Schleicher-Love problem of an elastic, isotropic half-space subjected to a uniform vertical load applied over a rectangular area. While the theoretical foundation for such contact problems dates back to the Boussinesq solution, obtaining explicit analytical formulas for displacements throughout the 3D domain remains complex. This study utilizes the recent analytical solutions [1], which provide explicit formulas for the displacement components at any point in the half-space.

The primary objective of this research is to perform a comparison between analytical solutions and numerical results obtained through the Finite Element Method (FEM) using Abaqus. The study focuses on three key modeling aspects: the influence of mesh refinement on solution accuracy, a comparison between fixed boundary conditions and the use of infinite elements, and the evaluation of convergence behavior.

Preliminary results are presented in Fig.1 for a model utilizing infinite elements at the boundary with a progressively refined mesh, where the element size h ranges from 1 to $\frac{1}{8}$ of the characteristic length. The results show good convergence in the energy norm, while the displacement field exhibits poor convergence. This occurs because the formulation with infinite elements does not fully constrain rigid body modes, leading to a constant shift in displacement field. The magnitude of this shift was observed to vary depending on the configuration of the infinite elements. Possible improvements to this problem will be discussed.

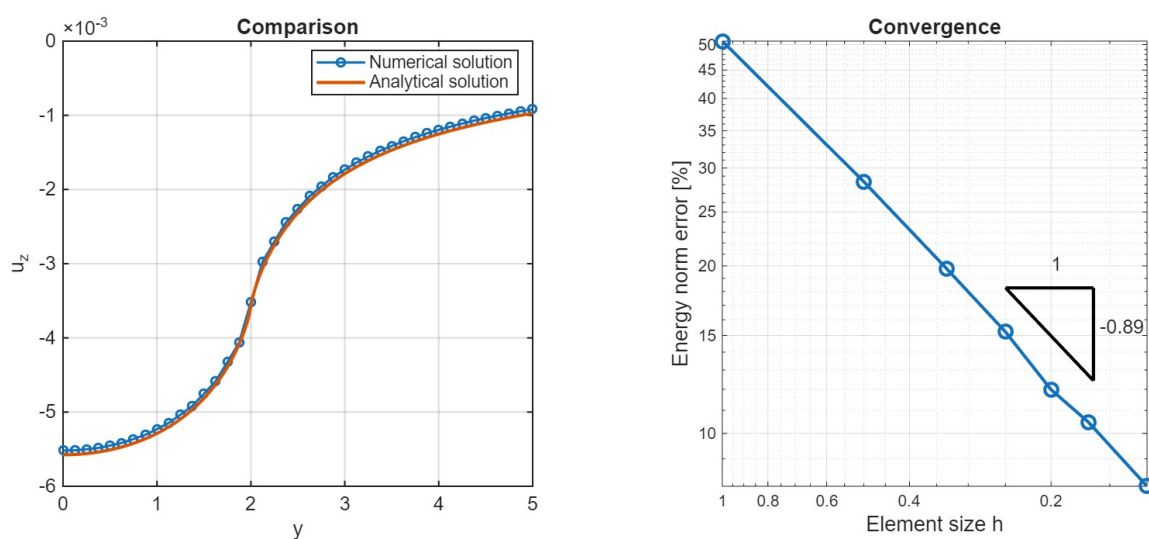


Figure 1: Left: comparison of vertical displacement u_z along the y -axis between analytical and numerical solutions. Right: convergence in the energy norm measured in $5 \times 5 \times 5$ domain of the characteristic length of the rectangular load.

[1] M. Nagirniak, *ZAMM* **106**(1), e70310, 2026. <https://doi.org/10.1002/zamm.70310>

A Novel Approach for Impact Load Identification Based on The Cuckoo Optimization Algorithm

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KEYWORDS: *Inverse Problem, Impact Load, Gyro Sensor, Generalized Inverse Matrix, Cuckoo Optimization.*

Ensuring the safety and reliability of structures requires accurate identification of both the magnitude and location of impact loads. In this presentation, we propose a method for estimating these quantities using the Cuckoo Optimization Algorithm (COA) [1] (see Fig. 1). Assuming that the structure undergoes elastic deformation, the temporal variations in the rotational angles measured by wireless gyroscopic sensors mounted on the surface are related to the impact loads through a response matrix equation. The impact location is determined using the COA, while the magnitude of the impact load is computed using the Moore–Penrose generalized inverse [2].

The proposed approach enables efficient identification of both the time history and the location of impact loads without the need for a large number of sensors. To verify its effectiveness, the method was applied to impact problems involving a simply supported beam and a plate. The results confirm that the proposed method can accurately estimate both the magnitude and the location of the applied impact load in these cases.

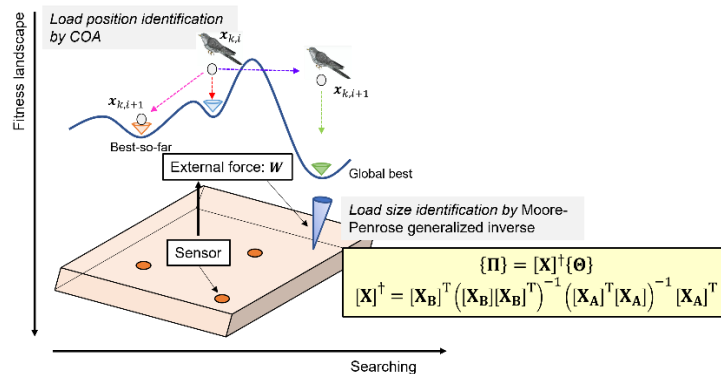


Figure 1. Overview of the proposed load identification method, which uses COA to search for the load position in the fitness landscape and the Moore-Penrose generalized inverse to estimate the load magnitude.

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- [1] R. N. Mategna, *Phys. Rev. E*, **49** (5), 4677-4683, 1994. <https://doi.org/10.1103/PhysRevE.49.4677>.
- [2] M. A. Rakha, *Appl. Math. Comput.*, **158** (1), 185-200, 2004. <https://doi.org/10.1016/j.amc.2003.09.004>.

Improved Evolutionary Algorithms and MFDM Applied to Large Non-linear Optimization Problems of Mechanics

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KEYWORDS: *Evolutionary Algorithms, MFDM, Non-linear Constrained Optimization.*

Improved Evolutionary Algorithms (EA) applied to a wide class of large non-linear constrained optimization problems are considered in this paper. The long-term objective of this research is a significant acceleration of the EA based solution approach and its application to chosen engineering problems of mechanics, including residual stress analysis. In the problems considered, a function given in the discrete form, e.g. expressed in terms of its nodal values, is sought. In order to obtain discrete formulation, any discretization method may be applied, including Meshless Finite Difference Methods (MFDM) [3, 4] considered here.

The standard EA are understood here as real-value coded Genetic Algorithms using three operators: selection, crossover, and mutation [1]. Dedicated approach proposed includes several additional speed-up techniques, namely: smoothing and balancing, step-by-step mesh refinement, a posteriori solution error analysis combined with non-standard parallel computations, estimation of the convergence point of population, efficient constraint handling techniques, and population averaging [5]. These very general ideas may be applied in many ways. Recent advances in development of all proposed techniques, including searching of the most efficient combinations and numerous parameters, are considered here.

Presented is the efficiency analysis of all speed-up techniques proposed. Simple but demanding benchmark problems are used, including residual stress analysis in chosen elastic-perfectly plastic bodies under various cyclic loadings [2], and problems resulting from the Physically Based Approximation (PBA) of experimental and/or numerical data. Such approximation may simultaneously use all information available for the problem considered: all experimental data obtained by means of various measurement techniques, their statistics, as well as theoretical and/or heuristic knowledge. Chosen benchmark boundary value elliptic problems, with various geometrical shapes are considered as well. All these benchmarks allow to choose almost any number of decision variables involved. The largest executed numerical tests involved more than 3000 decision variables. Results obtained indicate a possibility of practical application of the improved EA to the large optimization problems considered. Each one of the techniques considered allowed for significant acceleration of computations. The final engineering objective of this research includes real complex problems, e.g. residual stress analysis in railroad rails, and vehicle wheels.

- [1] A.P. Engelbrecht, *Computational intelligence: an introduction*, Wiley, Chichester, 2007. <https://doi.org/10.1002/9780470512517>
- [2] R. Hill, *The Mathematical Theory of Plasticity*, Oxford University Press, online, 1998. <https://doi.org/10.1093/oso/9780198503675.001.0001>
- [3] T. Liszka, J. Orkisz, *Comp. & Struct.* 11, 83–95, 1980. [https://doi.org/10.1016/0045-7949\(80\)90149-2](https://doi.org/10.1016/0045-7949(80)90149-2)
- [4] S. Milewski, *Eng. A. Bound. El.* 131, 100–117, 2021. <https://doi.org/10.1016/j.enganabound.2021.06.010>
- [5] J. Orkisz, M. Glowacki, *IEEE Symp. Series on Comp. Intelligence 2017 - Proceedings*, 1698–1702, 2017. <https://doi.org/10.1109/SSCI.2017.8285212>

Soft Boundary Conditions in the Reissner–Mindlin Plate Analysis by the Equilibrium Finite Element Method

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KEYWORDS: *Reissner–Mindlin Plate, Stress-Based FEM, Soft Boundary Conditions.*

In the equilibrium finite element approach to the analysis of the Reissner–Mindlin plate, bending and twisting moments, along with shear forces, are expressed in terms of first and second derivatives of the Southwell stress vector function [1]. The boundary conditions then take the form of linear constraints on the degrees of freedom at nodes located along the plate boundary.

The statically admissible solution of the Reissner–Mindlin plate, obtained using the Hsieh–Clough–Tocher (HCT) element presented in [1], yields excellent results for hard (2D) boundary conditions. Unfortunately, this approach suffers from over-constraining when soft (3D) boundary conditions are applied, as the number of required constraints exceeds the number of degrees of freedom associated with these conditions.

To overcome this difficulty, an additional term related to bending and twisting moments has been introduced in the present formulation. This modification makes it possible to impose independent constraints on the three stress resultants—namely, the bending moment M_n , the twisting moment M_{ns} , and the transverse shear force Q_n —defined with respect to the local coordinate system ns , associated with the plate boundary.

Two C^1 triangular elements were used in computations: the HCT element with 36 degrees of freedom and cubic interpolation functions, and the Argyris element with 63 degrees of freedom and fifth-degree shape functions. Elements with smooth shape functions are required because the shear forces, represented by second derivatives of the stress function, contribute to the strain energy.

The HCT element allows for the representation of an arbitrary parabolic distribution of bending and twisting moments along the edge and a linear distribution of the shearing force. The Argyris element enables the application of boundary conditions with bending and twisting moments following a quartic polynomial distribution and a cubic distribution of the shearing force.

The results obtained using the equilibrium FEM are dual to those derived from the kinematically admissible approach, which provides bounds on the exact value of the strain energy. The duality can be readily exploited to estimate the error of the approximate solution using Synge's method [2].

- [1] Z. Więckowski, P. Świątkiewicz, Equilibrium-Based Finite Element Analysis of the Reissner–Mindlin Plate Bending Problem, *Materials* **18**(21), 4969, 2025. <https://doi.org/10.3390/ma18214969>
- [2] J.L. Synge, *The Hypercircle in Mathematical Physics*. Cambridge: Cambridge University Press, 1957.

Evaluation of Field Intensity Factors in 3D Potential and Elasticity Problems

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KEYWORDS: *Field Intensity Factors, Hypersingular Boundary Integral Equation, Monomial Asymptotics, Tangent-Plane Approach, Extrapolation.*

In material science and fracture mechanics, accurate evaluation of extremal, rather than average, values of physical fields is of prime significance. This requires studying high physical fields near edges of open surfaces, which are sources of unfavorable effects such as potential discharge, static fracture, fatigue, etc. Their strength is characterized by the field intensity factors (FIFs). The tail distributions of FIFs define the probability of rare high values, and serve to assign safety factors for a given fracture risk. To the date, FIFs are calculated mostly for 2D problems. In 3D, they are found for planar crack and for the axisymmetric spherical cap-like crack. Extensions to arbitrary open curvilinear surfaces have been hampered by the difficulties, involved by the need to solve 3D hypersingular boundary integral equation with the density, whose asymptotics defines the FIF. Nowadays, the *tangent-plane approach* (TPA) opens a possibility to remove the difficulties [1]. Our *objective* is to employ the new options for developing accurate and efficient method of FIF evaluation at edges of open surfaces in 3D. We reach the goal due to the improvements sketched below.

We consider an open surface, at which a physical field U is discontinuous. The edge contour is assumed to be a smooth curve. Then the field discontinuity ΔU near an edge point x has the monomial asymptotics

$$\Delta U(s) = K(x)s^{\alpha(x)} \quad (1)$$

where s is the distance to the edge point, measured in the cross-section normal to the contour; K is actually the FIF at this point; $\alpha(x)$ is the known exponent (usually, $\alpha = 1/2$). We account for the *asymptotics* (1) in approximation of the density ΔU . This significantly increases its accuracy at a vicinity of the edge.

Yet, the improved approximation of ΔU requires appropriate adaptation of the TPA to the monomial asymptotics (1). We performed the needed *modification* by complementing the TPA with the corrective terms derived. The modification drastically improves the accuracy of the density ΔU near the edge.

Furthermore, by (1), the FIF is defined as the limit of the ratio $K(x_j) = \lim_{s_j \rightarrow 0} [\Delta U(x(s_j))/s_j^{\alpha(x)}]$, in which both numerator and denominator go to zero. Consequently, with decreasing distance s_j , the relative error of conventional finding FIF via a single value of the pseudo-FIF $K_p(x_j) = \Delta U(x(s_j))/s_j^{\alpha(x)}$ unavoidably goes to infinity. To prevent the loss of the accuracy, we have designed *extrapolation formulae* of order $m > 0$, which employ $m + 1$ values of the pseudo-FIFs at $m + 1$ different distances from the edge. They provide notably better accuracy of FIFs, than the conventional calculations, corresponding to $m = 0$.

Summarizing, the objective to develop a universal method for accurate evaluation of FIFs in 3D potential and elasticity problems is reached by combining the three improvements briefly reported above. These are: (i) accounting for the *monomial asymptotics*; (ii) appropriate *modification* of the TPA, and (iii) *extrapolation formulae* of higher orders. Numerical results for a number of examples confirm that the method suggested provides accurate and computationally efficient evaluation of FIFs.

- [1] A. Linkov, E. Rejwer-Kosińska, L. Rybarska-Rusinek, *Eng. Anal. Bound. Elem.* **179**, Part B, 106394, 2025. <https://doi.org/10.1016/j.enganabound.2025.106394>

Numerical Anisotropy in Finite Elements: Where It Comes From and How to Eliminate It

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KEYWORDS: *Numerical Anisotropy, FEM, Spline-Based Approximation, Numerical Band Gaps.*

Accurate numerical modelling of wave propagation remains a challenge in computational mechanics, as spatial discretization may introduce artificial dispersion and anisotropy that are not present in the underlying physical system. Even for isotropic materials, finite element (FE) models may exhibit direction-dependent wave speeds and, more critically, frequency ranges in which wave propagation is completely suppressed. We adopted a broader definition of numerical anisotropy that includes not only directional variations of phase and group velocities, but also the presence of directional numerical frequency band gaps. From the perspective of wave modelling, such band gaps represent an extreme manifestation of anisotropy, as they completely eliminate wave propagation in parts of the angular spectrum.

The study focuses on three formulations: classical finite elements (FEM), time-domain spectral finite elements (TD-SFEM), and a class of spline-based finite elements (spFEM) developed by the authors [1]. Dispersion relations are obtained by combining the finite element formulation with Bloch–Floquet theory, allowing the analysis of the complete angular-frequency behaviour of the discretized system.

The results show that classical formulations of FEM and TD-SFEM exhibit pronounced numerical anisotropy, including directional band gaps which significantly limit their applicability in wave propagation problems. In contrast, the proposed spline-based formulation eliminates numerical frequency band gaps and substantially reduces directional dependence of wave velocities. As a consequence, a much larger portion of the numerical spectrum becomes usable, leading to a more efficient use of degrees of freedom.

Time-domain simulations of wave propagation confirm these observations. While standard formulations exhibit direction-dependent distortion and suppression of wave fronts, the spline-based model maintains stable and nearly isotropic propagation over a wide frequency range. Even near the upper limit of its applicability, the observed deviations remain small and systematic, without the abrupt breakdown associated with band-gap formation.

The presented results demonstrate that elimination of numerical band gaps is a key to improve the reliability and efficiency of finite element models for wave propagation. The proposed spline-based formulation provides a promising alternative to standard approaches, particularly in applications requiring accurate broadband simulations.

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- [1] A. Żak and W. Waszkowiak. A spline-based FE approach to modelling of high frequency dynamics of 1-d structures. *Comput. Math. Appl.*, 2021, 104: 14-33.

Analysis of Heating Processes in Domain of Double-Layered Thin Metal Films Using a Hyperbolic Two-Temperature Model

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KEYWORDS: *Double-Layered Thin Metal Films, Hyperbolic Two-Temperature Model, Laser Pulse, Finite Difference Method.*

The heating of thin double-layered (gold-copper, gold-chromium) film that has been exposed to an ultra-short laser pulse is considered. The system of equations determining the electron and lattice temperatures, as well as the dependences between the intensities of the heat fluxes and the temperature gradients in which the phase lag appears, for the first and second layer, respectively, provide the mathematical foundation for the description of this process (a hyperbolic two-temperature model) [1]. In the first version, a condition of perfect contact at the interface of layers was assumed, while in the second version, a condition of imperfect contact was adopted. A no-flux condition was accepted on the external surfaces. The initial condition is also known.

The main goal of the work is the correct wording of the mathematical form of ideal and imperfect contact conditions for hyperbolic two-temperature model presented here. In literature, the conditions of ideal or imperfect contact corresponding to the macroscopic Fourier model is most often applied, which does not take into account the relaxation time of free electrons in metals and the relaxation time in phonon collisions.

The finite difference method's implicit scheme is used to solve the issue [2]. Comparisons were made between the solutions obtained using the hyperbolic and parabolic models (Figure 1) and on this basis appropriate conclusions were formulated.

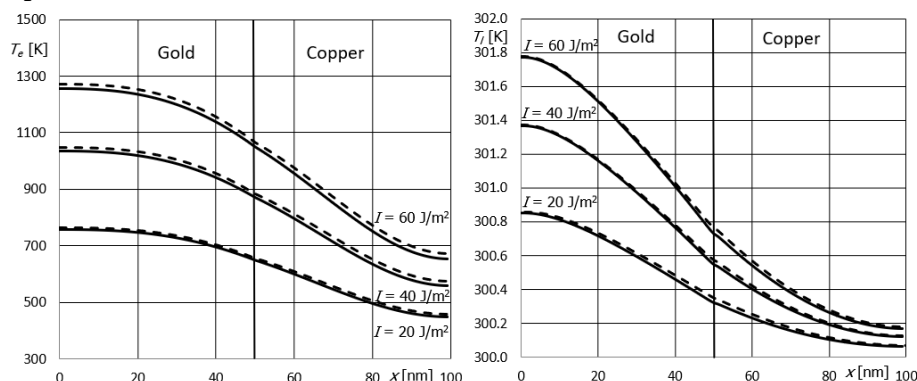


Figure 1. The distribution of temperature of: a) electrons, and b) lattice after 0.3 ps, $t_p = 0.1$ ps for hyperbolic ideal contact condition (solid lines) and parabolic ideal contact condition (dashed lines)

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[1] Z.M. Zhang, Nano/Microscale Heat Transfer, McGraw-Hill, New York, 2007

[2] J.Dziatkiewicz, E.Majchrzak, *JTAM*, **62** (2), 405-413, 2024. <https://doi.org/10.15632/jtam-pl/185352>

Nonlinear Dynamic Analysis of Progressive Destruction, Leveling and Repair of Multi-Story Buildings

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KEYWORDS: *Nonlinear Dynamics, Plastic Flow Theory, Finite Element Method, Damage Mechanics.*

The behaviour of structures of multi-story buildings under extreme loads arising from strong seismicity, gas explosions, drone impacts, artillery shell impacts, etc., is considered. At the first stage, the problem of progressive destruction is solved, and the proposed approach, unlike conventional methods, allows us to instantly or gradually remove the finite elements of not only spatial frames, but also finite elements of any type, including fragments of load-bearing walls and staircase-elevator blocks modelled by the finite elements of plane shells [1]. The proposed technique for adding and removing auxiliary supports, based on the method of time-dependent penalty parameters, as well as adding finite elements, allows us to simulate the leveling of a structure that has significant deformations and the replacement of destroyed finite elements with new, undamaged ones [2].

The finite element library includes quadrilateral and triangular Mindlin-Reissner finite elements, as well as a space frame finite element. In reinforced concrete, reinforcement is modeled as inclusions. For concrete, the plastic flow theory is applied, and the yield surface is assumed to be a non-circular Geniev paraboloid. In the hardening zone, the yield surface expands, and in the softening zone, it contracts. When the limiting deformations are exceeded, the destruction of concrete is modeled using the damage parameter. For steel, the von Mises plastic flow theory with kinematic hardening is adopted. When the limiting deformations are exceeded, the failure of the reinforcement is also modeled using the damage parameter. The calculation is carried out according to a deformable scheme – after each converged time step, the nodal coordinates are updated using nodal displacements.

As a result, we obtain the Cauchy problem:

$$\mathbf{M}(t)\ddot{\mathbf{u}} + \frac{d\mathbf{M}}{dt}\dot{\mathbf{u}} + \mathbf{C}\dot{\mathbf{u}} + \mathbf{f}^{int}(\mathbf{u}, t) + \mathbf{\Gamma}(t)\mathbf{u} = \mathbf{f}^{stat} + \mathbf{f}^{dyn}(t) + \mathbf{\Gamma}(t)\hat{\mathbf{u}}(t) \quad (1)$$

$$\mathbf{u}(0) = \mathbf{u}_0, \quad \dot{\mathbf{u}}(0) = \mathbf{v}_0$$

Here $\mathbf{u}$ is the vector of nodal displacements, $\mathbf{M}$ and $\mathbf{C}$ are the mass matrix and dissipation matrix, $\mathbf{f}^{int}(\mathbf{u}, t)$ is a nonlinear operator returning the vector of internal forces, $\mathbf{\Gamma}(t)$ is the diagonal matrix of penalty parameters, $\mathbf{f}^{stat}$ is the vector of static loads, $\mathbf{f}^{dyn}(t)$ is the vector of dynamic loads, $\hat{\mathbf{u}}(t)$ is the vector of imposed displacements. The derivative $\frac{d\mathbf{M}}{dt}$ appeared because the mass matrix changes over time when finite elements are removed/added. The Cauchy problem is solved numerically using the implicit α -HHT method. Details are presented in [1, 2].

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- [1] S. Fialko. Progressive Collapse Analysis on Multicore Computers Using Nonlinear Dynamic Approach, Comp. Assist. Methods Eng. Sci. **31**(4), 449–486, 2024. <https://doi.org/10.24423/comes.2024.1641>
- [2] S. Fialko. Finite Element Modeling of Collapse, Leveling and Repair of Multi-Storey Buildings Exposed to Extreme Impacts, Comput. Struct. **325**, 1 – 10, 2026. <https://doi.org/10.1016/j.compstruc.2026.108197>

Finite Element Modeling of Torsion in Functionally Graded Shafts

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KEYWORDS: *Torsion, Saint-Venant, FEM, Warping, Shear Stress*

This study investigates the Saint-Venant torsion of functionally graded (FGM) shafts using the Finite Element Method. For the purpose of this research, numerical models of shafts with circular, elliptical, equilateral triangular, and square cross-sections were developed. A functional material gradation was applied radially from the geometric center to the outer boundary, transitioning from an aluminum (Al) core to a titanium (Ti) surface. The effective material properties were evaluated using the Mori-Tanaka micromechanical model. Two distinct gradient modeling techniques were employed and compared: a conventional discrete layer-wise gradation and a novel approach utilizing a continuous field variable interpolated directly from nodes to Gauss integration points. Boundary conditions consistent with Saint-Venant free torsion theory [1] were applied, allowing for the unconstrained warping of the non-circular cross-sections. To prevent rigid body motion without overconstraining the model, a weak springs algorithm was implemented, yielding negligible reaction forces on the order of 10^{-14} N. Figure 1 shows a concept of the shaft material gradation using: a), d) the discrete layer-wise method, and b), c) the continuous method.



Figure 1. Material gradation in various cross sections using different modeling methods.

The effective material properties were evaluated using the Mori-Tanaka [2] homogenization, governed by:

$$G^{MT} = G_1 + \frac{V_f(G_2 - G_1)G_1}{(1 - V_f)(G_2 - G_1)\beta_1 + G_1}, \beta_1 = \frac{6(K_1 + 2G_1)}{5(3K_1 + 4G_1)}. \quad (1)$$

The model incorporates the reinforcement volume fraction V_f [0-1], alongside the shear and bulk moduli of Al and Ti. High-fidelity results are ensured via rigorous strain energy-based mesh convergence and GCI calculations. Subjecting the shafts to ± 1 Nm torsional moments, the study evaluates the impact of Al/Ti gradation on cross-sectional warping and resultant shear stress distribution, using a homogeneous aluminum shaft as a baseline. Figure 2 shows results of u_z displacement for triangular cross-section.

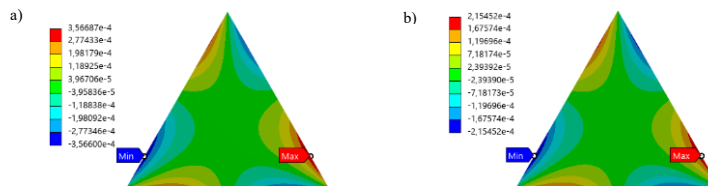


Figure 2. Results of u_z displacement for triangular cross-section, a) aluminium, b) Al/Ti FGM.

- [1] De Saint-Venant, A. J. C. B. (1856). Mémoire sur la torsion des prismes. *Mémoires présentés par divers savants à l'Académie des Sciences*, 14, 233-560.
- [2] Mori, Tanaka, and Kohichi Tanaka. "Average stress in matrix and average elastic energy of materials with misfitting inclusions." *Acta Metallurgica* 21.5 (1973): 571-574.

Exact Geometric Representation of Curved Domains in Discontinuous Galerkin Method

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KEYWORDS: *Discontinuous Galerkin Method, Polygonal Meshes, Curved Domains.*

This work presents the formulation and analysis of a Discontinuous Galerkin Method (DGM) for second-order boundary value problems defined on two-dimensional domains with curved boundaries. The method is developed within a broken-Sobolev-space framework over meshes composed of convex polygonal finite elements. In DGM, the underlying function space is discontinuous across the mesh skeleton in the infinite-dimensional setting, and this discontinuity is inherited by the corresponding finite-dimensional approximation space. Within the infinite-dimensional space, we identify the subspace consisting of continuous functions that satisfy homogeneous Dirichlet boundary conditions. In the finite setting, we determine the subspace that minimizes both the interelement discontinuities and the deviation from homogeneous Dirichlet boundary conditions [1].

In contrast to the standard FEM, the basis functions in the DGM are defined independently on each finite element, and therefore do not depend on the element's shape. Then, a wide range of basis functions can be employed, and polygonal finite elements of arbitrary geometry may be used. In particular, elements with curved edges can be incorporated to accurately represent the curved outer boundary of the computational domain. For numerical integration, each polygonal element is subdivided into triangles, to which suitable quadrature schemes are applied. Standard numerical integration rules are used for triangles with straight edges. When a triangle possesses one curved edge, integration is performed using a scaled boundary approach [2]. The outer boundary of the domain must be described analytically by a parameterized function. This parametrization is then transferred to the polygonal edges aligned with the outer boundary in order to curve those edges and to generate the corresponding numerical integration schemes for both the curved elements and the curved portions of the external boundary.

It is well known property of higher-order finite element approximations yield higher convergence rates, allowing significantly improved accuracy with comparatively fewer degrees of freedom than low-order elements. However, when the boundary of the domain is curved, small elements must often be used to faithfully recover the geometry, which diminishes the advantages of high-order elements. The approach adopted in this research enables the use of relatively large finite elements while providing an exact representation of the domain geometry. Under these conditions, the size of the finite elements is determined solely by the need to reduce the approximation error of the numerical solution, rather than by geometric constraints.

The capabilities of the method are demonstrated through a series of numerical examples. These include benchmark Poisson problems featuring highly irregular solutions on strongly curved domains. In addition, the method is applied to the Stokes problem that combines the velocity and pressure fields. The presented examples illustrate the flexibility of the approach and its numerical robustness, even for high-order approximations.

- [1] J. Jaśkowiec and N. Sukumar, *Int. J. Numer. Methods Eng.* **125**(12), e7472, 2024. <https://doi.org/10.1002/nme.7472>
- [2] E.B. Chin and N. Sukumar, *Comput. Methods Appl. Mech. Engrg.* **380**, 113796, 2021. <https://doi.org/10.1016/j.cma.2021.113796>

MsFEM Supported by an Artificial Neural Network

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KEYWORDS: *MsFEM Upscaling, Prolongation Matrix, Physics Informed Neural Networks.*

The Multiscale Finite Element Method (MsFEM), originally proposed three decades ago [1] and further developed in subsequent years, e.g., [2], is an efficient framework for multiscale analysis. In this approach, computations are performed at the macroscale while properly accounting for material properties and physical phenomena occurring at the microscale.

The core idea of MsFEM is the construction of special shape functions associated with coarse finite elements. These shape functions are computed offline by employing a fine-scale discretization within each coarse-mesh element and solving an auxiliary boundary value problem defined on the element domain. The resulting solution provides the degrees of freedom of the approximated shape functions, which constitute the columns of the prolongation matrix mapping degrees of freedom from the coarse grid to the fine grid. Through the Galerkin coarsening procedure, this prolongation matrix enables the computation of coarse-scale element matrices that incorporate the effects of heterogeneous material microstructures.

In certain applications, such as microstructure optimization [3], it is necessary to compute the prolongation matrix multiple times for a single element. To enhance the efficiency of such analyses, we propose the use of artificial neural networks. The training inputs include material properties as well as arbitrary spatial distributions of components within the microstructure. Once trained, the neural network enables efficient evaluation of prolongation matrices without the need to repeatedly solve auxiliary boundary value problems. This approach is inspired by the application of artificial neural networks, known as Physics-Informed Neural Networks [4], to the direct (non-multiscale) solution of boundary value problems. Our preliminary results obtained for the Laplace problem with two materials distributed in a piecewise-constant manner confirm the potential of enhancing MsFEM through the use of artificial neural networks.

- [1] T. Hou and X. Wu, A Multiscale Finite Element Method for Elliptic Problems in Composite Materials and Porous Media. *J. Comput. Phys.* **134**, 169–189, 1997.
- [2] M. Oleksy, W. Cecot, W. Rachowicz, M. Nessel, An improved Multiscale FEM for the Free Vibrations of Heterogeneous Solids. *Comput. Math. Appl.* **110**, 110–122, 2022.
- [3] H Liu and Y. Wang and H. Zong and M. Wang, Efficient Structure Topology Optimization by Using the Multiscale Finite Element Method. *Struct. Multidiscip. Optim.* **58**, 1411–1430, 2018.
- [4] S. Roy, C. Annavarapu, P. Roy, D. M. Valiveti, Physics-informed Neural Networks for Heterogeneous Poroelastic Media. *Int. J. Comput. Method Eng. Sci. Mech.* **26**, 187–207, 2024.

Reduced Finite Element Modelling of Rivetted Joints Using Semi-Empirical Formulations

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KEYWORDS: *Riveted Joints, Semi-empirical Formulation, Finite Element Modelling, Shear Compliance, Fastener Stiffness, Numerical Methods.*

Critical structural components in the various industries are connected via flanges using riveted joints, which offer superior shear strength compared to bolts, making them well-suited for load-bearing applications. Despite their geometrically simple shape, the stress behavior of rivets is complex due to assembly-specific features such as preload, interference fit, and the use of sealing elements or adhesives [1]. This complexity makes it impractical to model rivets with solid finite elements. To address this, rivets are commonly represented as mesh-independent point fastener elements in finite element models. Existing approaches in the literature — including formulations by Huth, Boeing, Douglas, Tate & Rosenfeld, and Grumman — estimate fastener shear compliance using semi-empirical expressions derived from test data [2]. However, these formulations may vary and can be difficult to choose for specific systems.

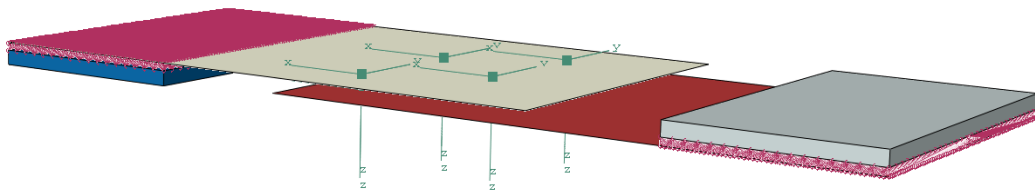


Figure 1. Reduced riveted joint FEA model in ABAQUS.

In this study, a new semi-empirical shear compliance formulation was developed using tensile test data obtained from riveted plate specimens covering a range of plate thicknesses and rivet diameters. The base term structure of the formulation was adopted from existing literature formulations such as Huth, Boeing, and Douglas, utilizing fundamental terms of the form $(t/d)^{0.8}/E_t$, $1/tE$, $1/(tE_f)$, $1/(dE_f)$ and similar expressions. The iterative finite element models employed shell elements for plates with contact definitions. Shear compliance values were extracted iteratively from global stiffness measurements, and multiple regression techniques — including least squares, weighted least squares, regularized least squares, and PCA-based order reduction — were applied to determine the formulation coefficients. A three-term model was selected by balancing prediction error and condition number stability.

Finite element analyses using the new formulation were compared against rigid fastener modeling and existing literature formulations. The results demonstrate that the new formulation correctly predicts failure modes and produces structural responses consistent with the actual assembly behavior — an outcome not reliably achieved with rigid modeling approaches.

- [1] Vivio, F., Fanelli, P. & Ferracci, M., Experimental characterization and numerical simulation of riveted lap-shear joints using Rivet Element., *Int. J. Adv. Struct. Eng.* 10, 37–47 (2018). <https://doi.org/10.1007/s40091-017-0176-7>
- [2] Jarfall, L., Shear loaded fastener installations., *Int. J. Veh. Des.* 7(4–5), 337–380 (1986), <https://doi.org/10.1504/IJVD.1986.061155>

Total and Modelling Error Estimation for the 3D-Based Hierarchical First-Order Shell Models

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KEYWORDS: *Error Estimation, Equilibrated Residual Method, Total Error, Modelling Error, Hierarchical Modelling, First-Order Shell Models.*

In the case of thin-walled structures, error-controlled adaptive finite element (FE) analysis requires estimation of the total, approximation and modelling errors, in contrast to 3D-elasticity where only approximation error is required. The approximation and modelling error estimators control the p - and q -adaptivity in the longitudinal and transverse directions of the shell (or plate) structures, respectively. Here, p and q represent longitudinal and transverse approximation orders within adaptive shell finite elements. In this work, the order q characterizes also the order ($I \equiv q$) of the 3D-based hierarchical shell models MI . These 3D-based models apply through-thickness shell degrees of freedom (dofs), instead of mid-surface dofs of the conventional hierarchical shell models.

The applied equilibrated residual method (ERM) of approximation error estimation have been presented in [1] and [2] for the general elliptic and specific 3D-elasticity problems, respectively. The ERM approximation error estimation for the conventional and 3D-based hierarchical ($q \geq 1$) shell models MI ($I \equiv q$) has been proposed in [3] and [4], respectively. Application of the last two approaches to the total and modelling error estimation is possible for higher-order and first-order models ($q \geq 1$). However, the first-order hierarchical model ($I \equiv q = 1$) suffers from the improper solution limit and has to be replaced with the first-order ($q = 1$) Reissner-Mindlin (RM) model of the correct solution limit. Unfortunately, direct application of ERM to the total and modelling error estimation for this model does not lead to the correct estimation results as this model is not a regular member of the hierarchy of models MI . In this work, we show how to resolve the problem of incorrect total and modelling error estimation results for the RM model. Note that the approximation error estimation for this model is presented in [5].

One of the elements of ERM are local (element) problems, the solution of which leads to element error indicators. The removal of the incorrect estimation of the total and modelling errors for the RM model requires modification of these local problem through energy projection of the work of the RM-based inter-element forces of the element so as the local problem solution moves from the incorrect solution space to the projected solution space closer energetically to the MI solution space. The projection can be applied to Neumann and Dirichlet (with 6 rigid body vertex displacement constraints) genuine local problems or tuned both Neumann and Dirichlet problems with 18 vertex displacement constraints. We also show that the first-order hierarchical model MI ($I \equiv q = 1$) requires energy projection of the 18 vertex constraints in the Neumann and Dirichlet problems, so as the local problem solution moves from the incorrect solution space to the MI ($I \equiv q \geq 2$) correct space. Error estimation effectivity indices are used to demonstrate effectiveness of the proposed approaches.

- [1] M. Ainsworth, J.T. Oden, *Comput. Math. Appl.* **25**(2), 101–113, 1993. DOI: 10.1016/0898-1221(93)90184-7
- [2] M. Ainsworth, J.T. Oden, W. Wu, *Appl. Numer. Math.* **14**, 23–55, 1994. DOI: 10.1016/0168-9274(94)90017-5
- [3] J.T. Oden, J.R. Cho, *Comput. Meth. Appl. Mech. Eng.* **136**, 317–345, 1996. DOI: 10.1016/0045-7825(95)00986-8
- [4] G. Zboiński, *Comput. Meth. Appl. Mech. Eng.* **267**, 531–565, 2013. DOI: 10.1016/j.cma.2013.08.018
- [5] G. Zboiński, *A posteriori error estimation for hp -approximation of the 3D-based first-order shell model. Part I. Theoretical aspects*, *Appl. Math. Inform. Mech.* **8**(1), 104–125, 2003.

From Simulation to SHM: Reducing Numerical Errors for Reliable Neural-Network-Based Damage Detection

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KEYWORDS: *Damage Localisation, Convolutional Neural Network, SHM.*

Artificial neural networks (ANNs) are increasingly used in structural health monitoring (SHM) for damage detection and localization [1]. In our previous work, ANNs were successfully applied to identify damage in isotropic plates using data generated with the time-domain spectral finite element method (TD-SFEM). This approach forms the basis for the development of a digital twin framework, in which numerical simulations are used to generate training data for data-driven diagnostic models.

Accurate localization of smaller defects, as well as improvement of spatial resolution, requires the use of shorter wavelengths, which in turn necessitates higher excitation frequencies. However, increasing the frequency range introduces significant challenges in numerical modelling. In particular, discretization errors become more pronounced and may manifest as numerical anisotropy, including direction-dependent wave speeds and frequency band gaps. These effects distort the simulated wavefield and degrade the quality of the data used for training neural networks.

A straightforward way to extend the usable frequency range is to refine the mesh, increasing the number of finite elements. While this approach improves accuracy, it leads to a substantial increase in computational cost. This becomes a critical limitation in the context of ANN training, where large datasets are required and simulation time directly impacts the feasibility of the approach.

To address this issue, a class of spline-based finite elements is employed, which significantly reduces numerical anisotropy and eliminates numerical band gaps without a substantial increase in computational cost. As a result, the usable frequency range of the numerical model is extended, enabling one to generate higher-quality training data within practical computational limits.

The improved numerical data are subsequently used to train artificial neural networks for damage localization. The results demonstrate that the proposed approach allows for accurate identification of damage at higher frequencies, while maintaining computational efficiency. These findings highlight the importance of controlling numerical properties in simulation-based machine learning pipelines and demonstrate the potential of spline-based finite elements in supporting data-driven SHM applications.

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- [1] A. Sattarifar, T. Nestorović, Damage localization and characterization using one-dimensional convolutional neural network and a sparse network of transducers, *Eng. Appl. Artif. Intell.* **115**, 105273, 2022. <https://doi.org/10.1016/j.engappai.2022.105273>

Multi-field Mixed *hp*-FE Framework for Modeling Laser Pulse Heating Processes in Irreversible Thermodynamics

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KEYWORDS: *Mixed hp -FE Framework, Ballistic-Conductive Model, Maxwell–Cattaneo–Vernotte Model, Guyer–Krumhansl Model, Laser-Pulse Heating Processes.*

In this presentation, new multi-field variational formulations are introduced for solving the following thermodynamic models [1]: (i) the ballistic-conductive system, (ii) the Guyer–Krumhansl heat conduction model, and (iii) the Maxwell–Cattaneo–Vernotte model, which are representative models of extended irreversible thermodynamics. In these formulations, the temperature, heat flux, and the current density of heat flux are treated as independent field variables [2]. Based on this variational framework, a family of mixed *hp*-version finite element methods (FEM) is developed, which is capable of reliably and efficiently modeling temperature responses [1].

The performance of the proposed *hp*-FE framework is demonstrated through two benchmark heat pulse experiments: (1) a sinusoidal laser pulse heating process and (2) a rectangular (step-like) laser pulse train. Numerical results confirm that uniformly stable (robust) and oscillation-free temperature response functions can be obtained not only for the ballistic-conductive system and the Maxwell–Cattaneo–Vernotte model, but also for both under-diffusive and over-diffusive parameter regimes of the Guyer–Krumhansl model.

It is shown that the *hp*-FE solutions successfully reproduce the expected characteristics in all cases, in contrast to COMSOL Multiphysics simulations (see [3]). This is particularly significant, as low-order, mesh-refinement-based FE approaches do not perform satisfactorily in all scenarios.

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- [1] B. Tóth, A unified mixed *hp*-finite element framework for modeling laser pulse heating processes in the refined thermodynamics, *Int J Heat Mass Transfer*, **238**, paper ID 124663, 2025. <https://doi.org/10.1016/j.ijheatmasstransfer.2024.126456>
- [2] R. Kovács and P. Ván, Generalized heat conduction in heat pulse experiments, *Int J Heat Mass Transfer*, **83**, 613–620, 2015. <https://doi.org/10.1016/j.ijheatmasstransfer.2014.12.045>
- [3] A. Rieth, R. Kovács and T. Fülöp, Implicit numerical schemes for generalized heat conduction equations, *Int J Heat Mass Transfer*, **126**, 1177–1182, 2018. <https://doi.org/10.1016/j.ijheatmasstransfer.2018.06.067>

Numerical Verification of Euler's Observation that Loading by Conservative Body Forces is Equivalent to the Pressure Reaction for the Incompressible Elasticity

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KEYWORDS: *Incompressible Elasticity, Conservative Body Force, Finite Element.*

We verify the hypothesis attributed to L. Euler [1] that loading by conservative body forces in finite incompressible elasticity is manifested only by a change of the pressure reaction without affecting the deformation of the body. The modification of the pressure reaction is by the negative potential provided that also the Neumann boundary condition is modified by the corresponding negative potential.

We experiment with the so-called Eriksen's class of controllable deformation [2] in isotropic incompressible elasticity. These are the problems for which exclusively stress loading on the boundary is prescribed and whose analytical solutions are found. The numerical solutions corresponding to the additional conservative body forces are obtained using the Simo, Taylor and Pister [3] finite element method for nearly incompressible elasticity with hexahedral elements. The technique is based on a mixed formulation using the displacements and the pressure. Such mixed formulation prevents the solutions from instabilities, oscillations and locking usually appearing when one approaches to incompressible material.

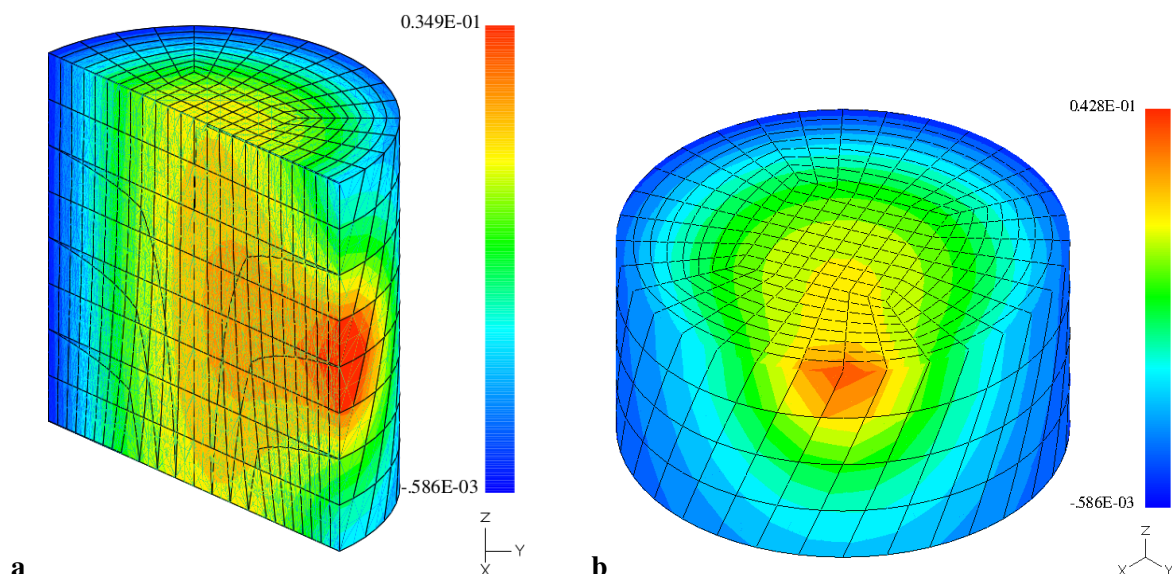


Figure 1: Pure torsion of a cylinder, $r = 1$, by angle of 45° . Gravitational potential $\bar{v} = -0.02/r$, $r = \|x - x_c\|$, $x_c = (1.4/\sqrt{2}, 1.4/\sqrt{2}, 1)$: a) pressure over vertical, and b) horizontal cross-section of the cylinder (deformed configuration)

- [1] C. Truesdell, R. Toupin, *The Classical Field Theories*, Springer, Berlin, Heidelberg, 1960, 226-858.
https://doi.org/10.1007/978-3-642-45943-6_2
- [2] J. L. Eriksen, *Zeitschrift fur Angewandte Mathematik und Physik (ZAMP)* **5**(6), 466–489, 1954.
<https://doi.org/10.1007/BF01601214>
- [3] J. C. Simo, R. L. Taylor, K. S. Pister *Comput. Methods Appl. Mech. Engrg* **51**(1), 177-208, 1985.
<https://www.sciencedirect.com/science/article/abs/pii/0045782585900337>

Weak and Strong Form Multipoint Meshless Method for Elliptic Problems

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KEYWORDS: *Meshless Methods, Multipoint Method, MLPG, Weak Formulation, Strong Formulation, PINN*

While the Finite Element Method (FEM) remains the dominant approach for engineering problems, meshless methods offer attractive alternatives. A wide range of meshless methods differ from each other in the process of construction of local approximation. In general, they can be classified into methods based on strong formulation and methods based on weak formulations [1].

One of the basic meshless methods, the Meshless Finite Difference Method (MFDM), is typically described in strong collocation form [2]. However, recent developments extended this method, including its higher-order multipoint variant [3], to various weak formulations [4]: global variational (Galerkin, Petrov-Galerkin), energy functional minimization, and meshless global-local Petrov-Galerkin (MLPG), particularly the computationally efficient MLPG5 approach using Heaviside test functions.

The multipoint meshless FDM raises approximation order by introducing additional degrees of freedom at stencil nodes via moving weighted least squares (MWLS), enabling analysis of elliptic boundary value problems in both strong local and various weak global and global-local formulations without mesh densification. The method also shows potential for integration with physics-informed neural networks (PINNs) via MFDM discretizations in the PDE residual loss [5].

Numerical tests for 2D elliptic Poisson problems, plate bending, and prismatic bar twisting confirm that all weak formulations yield results comparable to strong form solutions while global-local MLPG5 form [6] significantly reduces computational effort through boundary-only integration.

- [1] J.-S. Chen, M. Hillman, S.-W. Chi, *J. Eng. Mech.* **143**(4), 04017001, 2017. [https://doi.org/10.1061/\(ASCE\)EM.1943-7889.0001222](https://doi.org/10.1061/(ASCE)EM.1943-7889.0001222)
- [2] T. Liszka, J. Orkisz, *Comput. Struct.* **11**, 83-95, 1980.
- [3] I. Jaworska, *Comput. Math. Appl.* **66**(3), 238–249, 2013. <https://doi.org/10.1016/j.camwa.2013.04.027>
- [4] I. Jaworska, *Comp. Sc.*, LNCS 10476, pp. 523–531, 2023. https://doi.org/10.1007/978-3-031-36027-5_41
- [5] M. Łoś et al., *Comput. Struct.* **316**, 107839, 2025. <https://doi.org/10.1016/j.compstruc.2025.107839>
- [6] S.N. Atluri, T. Zhu, *Comput. Mech.* **22**, 117-127, 1998. <https://doi.org/10.1007/s004660050346>

Session TS6

Contact and interface mechanics

Atomistic modelling of structure and mobility of twin boundaries in NiTi shape memory alloys

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KEYWORDS: *Twinning, Shape Memory Alloys, NiTi, Atomistic modelling*

Shape memory alloys (SMAs) possess unique properties that make them suitable for various applications, including energy-efficient actuators, biomedical devices for minimally invasive surgery, and aircraft morphing. Their distinct behaviour involves the recovery of large strains under stress or thermal cycles, and it is well-known that microstructural twinning governs this exotic mechanism. However, it is crucial to understand the structure and mobility of twin systems in martensite microstructures to determine why specific twinning systems arise more frequently than others [1].

In this study [2,3], we demonstrate with the prototypical NiTi SMA that twin interface mobility can strongly influence twin emergence. We employ an integrated methodology that combines crystallographic theory [4], state-of-the-art atomistic modelling, topological model [5], and validation using high-resolution transmission-electron micrographs [6]. Our atomistic model is based on a machine learning Atomic Cluster Expansion (ACE) interatomic potential trained on an extensive density functional theory (DFT) database, and tested on key benchmark properties of B2 and B19' phases in NiTi.

Our atomistic simulations reveal that twinning stress, rather than interfacial energy, determines the occurrence of twins. Moreover, our simulations address long-standing questions by explaining the atomistic structure and propagation mechanisms of twin interfaces at zero and finite temperatures, which established theories of martensite crystallography cannot explain. This mechanistic understanding of the role of interface mobility in twin formation can help predict variant selection and inform the design of SMAs with enhanced functional performance. Moreover, our predictions of twin interface energetics and kinetics can inform higher scale models of microstructure formation (e.g. phase-field).

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- [1] Nishida, M., Ohgi, H., et al. *Acta Metall. et Mater.* (1995) 43:1219–1227.
- [2] La Rosa, L., and Maresca, F. *Communications Mater.* (2024) 5(1):142.
- [3] Turcan, E., La Rosa, L., Fioravanti, D. and Maresca, F. (2026) *Acta Mater.* 303:121651
- [4] Ball, J.M. and James, R.D. *Arch. Ration. Mech. Anal.* (1987) 100:13–52.
- [5] Pond, R.C. and Hirth, J.P. *Acta Mater.* (2018) 151:229–242.
- [6] Nishida, M., Yamauchi, K., et al. *Acta Metall. et Mater.* (1995) 43:1229–1234.

A chemo-mechano-thermodynamical contact formulation for (de)bonding

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KEYWORDS: *Chemical bonding, contact mechanics, coupled problems, implant osseointegration, nonlinear finite element analysis.*

This work presents a general contact formulation for coupled chemical, mechanical and thermal contact. It is derived from the balance laws of mass, momentum and energy at the contact interface, thus exposing the general coupling between the different fields [1]. Chemical bonding and debonding is assumed to occur between bonding sites following a kinetic reaction equation. A quadratic contact potential is used to describe the free energy of contact, bonding and debonding. The proposed formulation corresponds to the known thermo-mechanical contact equations [2] extended to chemical contact, see Fig. 1.

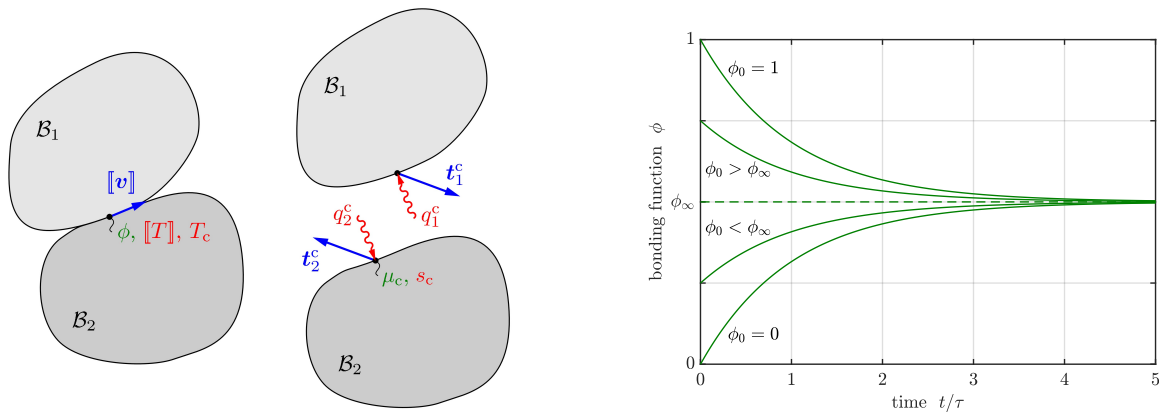


Figure 1: Thermo-chemo-mechanical contact [1]: Bodies in contact with their chemical, mechanical and thermal contact fields (left). Exemplary evolution of the contact bonding state for various initial conditions (right).

The formulation is discretized and implemented in the 3D nonlinear finite element framework of [3] using a fully monolithic coupling formulation. Implicit time integration is used of the chemical and thermal evolution equations. The formulation is illustrated by several applications. A particular focus is placed on implant osseointegration [4] and thermo-chemo-mechanical bonding.

- [1] R.A. Sauer, T.X. Duong and K.K. Mandadapu, A chemo-mechano-thermodynamical contact theory for adhesion, friction and (de)bonding reactions, *Math. Meth. Solids.*, 27(4):711-745, 2022.
- [2] T.A. Laursen, *Computational Contact and Impact Mechanics: Fundamentals of modeling interfacial phenomena in nonlinear finite element analysis*, Springer, Berlin, 2002.
- [3] R.A. Sauer, and L. De Lorenzis, An unbiased computational contact formulation for 3D friction, *Int. J. Numer. Meth. Engng.*, 101(4):251-280, 2015.
- [4] K. Immel, V.-H. Nguyen, G. Haiat and R.A. Sauer, Modeling the debonding process of osseointegrated implants due to coupled adhesion and friction, *Biomech. Model. Mechanobiol.*, 22:133-158, 2023.

Surface energetic elasticity problems for fractures and thin inclusions

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KEYWORDS: *Steigmann-Ogden surface energy, Gurtin-Murdoch surface energy, fracture, thin inclusions, integral equations.*

It is well-known that surface energy plays an increasingly important role in modeling of objects at nano-scales. In this talk, surface energy model proposed by Steigmann and Ogden will be applied to fracture problems and to problems with thin inclusions in two-dimensional setting. Introduction of surface energy leads to non-classical boundary conditions incorporating both stresses and derivatives of displacements. An importance of tip conditions, which is often overlooked in literature, will be explored. The mechanical problem will be reduced to systems of singular integro-differential equations which are further reduced to systems of weakly-singular equations. The existence and uniqueness of the solutions will be discussed. The effects of introduction of Surface mechanics on the solution fields will be investigated, including stress and strain singularities at the tips of inclusions and cracks, and size-dependency in the system. Both of those represent significant divergence of the studied theories from classic results. A numerical schemes of the solution of the relevant systems of integral and integro-differential equations will be suggested. The numerical results, parametric studies, and comparisons with known in the literatura results will be presented.

ACKNOWLEDGEMENT:

The author gratefully acknowledges the support from the Simons foundation under awards 713080 and SFI-MPS-TSM-00013162.

- [1] Zemlyanova. A straight mixed mode fracture with the Steigmann-Ogden boundary condition. *Quart. J. Mech. Appl. Math.*, 70(1):65–86, 2017.
- [2] Zemlyanova. Interaction of multiple straight fractures in the presence of the Steigmann-Ogden surface energy. *SIAM J. Appl. Math.*, 80(5):2098–2119, 2020.
- [3] Y. Zemlyanova. A problem for a material surface attached to the boundary of an elastic semi-plane. *Mathematics and Mechanics of Solids*, 29(2):303–326, 2024.
- [4] Y. Zemlyanova. A bimaterial plane with a nano-sized flexible line inclusion on the interface. *SIAM Journal on Applied Mathematics*, 85(2):477–498, 2025

Numerical studies on abrasion of decommissioned pipeline polymer coatings

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KEYWORDS: *Decommissioned pipelines; coatings; abrasion; finite element analysis.*

Polymers and polymer-based coatings are widely applied on pipelines exposed to abrasive environments, due to their low density, cost-effectiveness, mechanical reliability, and excellent corrosion resistance. Given the extensive use of polymer coatings in the oil and gas industry, especially as protection against the corrosion of subsea pipelines, an understanding of the long-term degradation of the polymer coatings is important for assessing the potential release of polymer waste into marine environment. Therefore, a practical model is required to evaluate abrasion due to interaction between polymer coating on pipelines and seabed sand particles. The primary objective of this study is to identify the dominant mechanisms and to develop a numerical framework capable of predicting the abrasion response of aged polymer coatings exposed to seabed sand particles.

In the present study a spherical indenter is employed to represent the sand particles. The analytical solution for a spherical contact follows Hertzian contact theory and distinguishes three deformation regimes—elastic, elastic–plastic, and fully plastic - based on the magnitude of the applied normal force. The proposed numerical model focuses on the elastic–plastic and plastic regimes by systematically varying the applied normal load.

Previous studies using the Finite Element Method (FEM) have demonstrated that the abrasion resistance and damage modes of polymer coatings are strongly correlated with their elastic–plastic properties and the associated contact conditions when a single hard spherical asperity slides across the surface [1], [2]. In the current study, finite element analysis is carried out to quantify the abrasion of polymer coating due to a hard spherical particle. The material nonlinearity is accounted for by using experimentally measured stress – strain response of the polymer. Consideration of multi-passes of the particle on the polymer surface enables the assessment of the evolution of the material loss due to increasing abrasion.

The results showed that the ratio of the shear or sliding force to the applied normal force is a linear function of the normalized normal force for a perfectly plastic polymer coating material, while the ratio is a quadratic function of normalized normal force for a strain hardening polymer coating material. An empirical model for the wear rate is developed which was found to be in good agreement with existing data from literature.

ACKNOWLEDGEMENT: This research is funded by Chevron through its Anchor Partnership with the UK National Decommissioning Centre (NDC).

- [1] S. E. Flores, M. G. Pontin, and F. W. Zok, “Scratching of elastic/plastic materials with hard spherical indenters,” *Journal of Applied Mechanics, Transactions ASME*, vol. 75, no. 6, pp. 0610211–0610217, Nov. 2008, doi: 10.1115/1.2966268.
- [2] M. M. Hossain, H. Jiang, and H. J. Sue, “Effect of constitutive behavior on scratch visibility resistance of polymers-A finite element method parametric study,” *Wear*, vol. 270, no. 11–12, pp. 751–759, May 2011, doi: 10.1016/j.wear.2011.01.022.

A Contact Problem for a Nonlinear Viscoelastic Rod with Subdifferential Boundary Condition

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KEYWORDS: *Viscoelastic Rod, Nonlinear Constitutive Law, Clarke Subdifferential, Weak Solution.*

We study the behavior of a nonlinear viscoelastic rod in contact with a deformable foundation along its length and with an obstacle at its end. The system is subjected to body forces, which drive the evolution of its mechanical response over time.

A key feature of the model is a boundary condition that describes the contact at the rod's end, where the internal stress depends on both displacement and velocity. This relation is formulated using a subdifferential inclusion and, in a particular case, reduces to the damped normal compliance condition introduced recently in [1].

The proposed model extends earlier approaches [2] in which the stress depended only on velocity, allowing for a more general and physically realistic description of contact effects.

From a mathematical perspective, we establish the existence of a weak solution to the problem. The analysis is based on a time discretization scheme for second-order differential inclusions with multivalued pseudomonotone operators.

ACKNOWLEDGEMENT: Research supported by the National Science Centre of Poland under Project No. 2021/41/B/ST1/01636.

- [1] M. Shillor, I. Pahuja, Damped Normal Compliance (DNC) and the restitution coefficient, *Mathematics and Mechanics of Solids*, **29**(8), 2024. <https://doi.org/10.1177/10812865241228230>
- [2] K. Bartosz, M. Sofonea, Modeling and analysis of a contact problem for a viscoelastic rod, *Zeitschrift für Angewandte Mathematik und Physik*, **67**(127), 2016. <https://doi.org/10.1007/s00033-016-0718-z>

The explicit nonsmooth newmark- β scheme for dynamic fragmentation simulations

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KEYWORDS: *Fragmentation, Satellite Debris, Contact mechanics, Non-smooth, Finite-elements.*

The increasing density of orbital debris poses a significant threat to the sustainability of our space environment. Collisions and breakups trigger an uncontrolled proliferation of fragments, heightening the risk of subsequent impacts; a cascade effect known as the Kessler syndrome [1]. To assess these risks, space agencies rely on breakup models, which in turn depend on empirical parameters. Physics-based models of dynamic fragmentation offer a path to significantly refine these models. Such simulations must capture multiple time scales—from crack initiation and propagation to secondary fragment interactions—making numerical robustness and computational efficiency a significant challenge. Prior work showed that combining explicit time integration with an extrinsic cohesive-zone model and penalty-based contact leads to severe instabilities [2]. While negligible over short durations, these instabilities worsen over time, introducing artificial fragmentation and energy errors that compromise the reliability of fragment statistics. To address these limitations, we propose an impulse-based contact treatment that accounts for the non-smooth nature of contact mechanics. This approach is embedded implicitly within an explicit time-integration framework, leveraging the nonsmooth Newmark- β scheme [3]. Benchmarking against dynamic fragmentation scenarios demonstrates that this method restores energy conservation and enhances long-term robustness. Despite an overhead of the implicit contact solver, the increased stability permits larger time steps, yielding computational efficiency comparable to, or exceeding, that of explicit penalty-based methods. This work establishes impulse-based contact as a reliable and efficient alternative for long-term fragmentation modeling.

ACKNOWLEDGEMENT: This research was funded by the Swiss National Science Foundation (SNSF) [Grant N° 212935].

- [1] D. J. Kessler and B. G. Cour-Palais, “Collision frequency of artificial satellites: The creation of a debris belt,” *Journal of Geophysical Research: Space Physics*, vol. 83, no. A6, pp. 2637–2646, 1978.
- [2] T. Ghesquière-Diéricks, J.-F. Molinari, and G. Anciaux, “Stability of extrinsic cohesive-zone model with penalty-based contact in explicit dynamic fragmentation simulations,” *Mechanics of Materials*, vol. 215, p. 105581, 2026.
- [3] Q.-z. Chen, V. Acary, G. Virlez, and O. Brûls, “A nonsmooth generalized- α scheme for flexible multibody systems with unilateral constraints,” *International Journal for Numerical Methods in Engineering*, vol. 96, no. 8, pp. 487–511, 2013.

Instabilities accelerate cyclic degradation: a macroscopic model of functional fatigue in shape memory alloys accounting for structure–material interplay

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KEYWORDS: *Shape memory alloys, Superelasticity, Functional fatigue, Propagating instabilities.*

Instabilities play a crucial role in stress-induced martensitic transformation in superelastic shape memory alloys (SMAs). Under tension-dominated loading, instabilities emerge as localized martensite bands, which, upon further loading, evolve into patterned interfaces (so-called macroscopic transformation fronts) separating austenite and martensite regions. The associated global mechanical response exhibits a stress drop followed by a stress plateau. The global stress that accompanies martensitic transformation is typically well below the plastic yield stress of the material. Nevertheless, as a results of cyclic forward–reverse transformation, the material accumulates irrecoverable strain and exhibits degradation of functional properties, notably reduction in the transformation stress and hysteresis loop area. This phenomenon is called functional fatigue and is generally attributed to the transformation-induced plasticity (TRIP). TRIP is inherently a multi-scale mechanism, operating across both the micro-scale and macro-scale levels [1]. Specifically, when phase transformation takes place within a grain, high strain incompatibilities and large local stresses are created near the austenite–twinned martensite interfaces, which promote dislocation slip. Upon cyclic transformation, slip accumulates and impedes the motion of phase interfaces, and thus gives rise to stabilized martensite that can no longer transform back to austenite. By a similar reasoning, transformation instabilities at the macro-scale level are expected to influence significantly the fatigue response of the material. Despite the longstanding recognition of this crucial aspect, its direct validation was provided only a few years ago in the experiments conducted by Zheng et al [2]. It was demonstrated that in view of the repetitive nucleation and propagation of the localized transformation, a rapid degradation of superelasticity occurs that accelerates the fatigue crack initiation and failure.

While existing models of functional fatigue are able to reproduce general degradation trends, they do not distinguish between homogeneous and localized transformation modes. To address this limitation, a novel macroscopic model of functional fatigue is developed in this work that integrates the effects of localized transformation into the fatigue constitutive description. The model adopts a gradient-enhanced formulation, in which the gradient of the martensite volume fraction is incorporated to represent the interfacial energy associated with the transformation front. The evolution law of fatigue-related variables is then enriched with the gradient effects so that the accelerating impact of localized transformation on the fatigue response is accounted for.

The resulting finite-element model is employed to investigate the impact of specimen thickness on the fatigue behavior of a straight NiTi specimen subjected to uniaxial tension with subloop deformation path. Experiments have shown that a thicker NiTi specimen develops a more diffuse transformation front, in contrast to a thin specimen with a sharp and more strongly branched front. Importantly, the latter exhibits a shorter fatigue life [3]. The developed model is capable of capturing morphology-dependent localization effects and their implications for the functional fatigue response.

- [1] Y. Zhang, Z. Moumni, Y. You, W. Zhang, J. Zhu, G. Anlas, Multiscale TRIP-based investigation of low-cycle fatigue of polycrystalline NiTi shape memory alloys, *Int. J. Plast.* **115**, 307–329, 2019. <https://doi.org/10.1016/j.ijplas.2018.12.003>
- [2] L. Zheng, Y. He, Z. Moumni, Effects of Lüders-like bands on NiTi fatigue behaviors, *Int. J. Solids Struct.* **83**, 28–44, 2016. <https://doi.org/10.1016/j.ijsolstr.2015.12.021>
- [3] S. Zhang, Y. He, Fatigue resistance of branching phase-transformation fronts in pseudoelastic NiTi polycrystalline strip, *Int. J. Solids Struct.* **135**, 233–244, 2018. <https://doi.org/10.1016/j.ijsolstr.2017.11.023>

Damage evolution in thin adhesive layer with tension–compression asymmetry: predictive asymptotic models

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KEYWORDS: *Asymptotic methods; interfaces; unilateral effects*

In structural engineering, accurate modeling of material damage is crucial, particularly the tension–compression asymmetry observed in quasi-brittle materials and adhesive joints. While cohesive interface models are commonly employed in the analysis of bonded structures, the parameters of these models frequently lack a direct correlation with the physical properties of the adhesive layer. To address this issue and capture the tension–compression asymmetry, this study uses asymptotic analysis to derive two new interface damage models (termed F1d and F2d) from a thin damaging interphase [1]. The proposed models are formulated within a thermodynamically consistent framework [2]. The F1d model uses a single damage variable with an asymmetric evolution law, whereas the more advanced F2d model uses separate variables for tensile and compressive damage, enabling independent evolution kinetics [3]. To bridge the gap between scales and link macroscopic damage to micro-defect evolution, the new models are coupled with two micromechanical schemes: the non-interacting Kachanov–Sevostianov model and the Mori–Tanaka–Benveniste model, the latter of which accounts for defect interactions. The theoretical formulations of the models are presented, and their predictive capabilities are demonstrated through numerical simulations of a bonded joint under axial loading.

[1] M. Serpilli, R. Rizzoni, F. Lebon, *Int. J. Eng. Sci.* **217**, 104384, 2025.

[2] M. Frémond, *Non-smooth thermomechanics*, Berlin Heidelberg: Springer-Verlag, 2002.

[3] M. Frémond, B. Nedjar, *Nucl. Eng. Des.* **156**, 323–335, 1995.

A Sharp-Interface Approach for Diffusion-Controlled Phase Transformations with Application to Cu_6Sn_5 Growth

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KEYWORDS: Diffusive phase transformations, Grain boundary diffusion and sliding, Intermetallic.

The formation and growth of intermetallic compounds (IMCs) are common in soldering and electroplating applications. In many cases, IMC growth is diffusion-controlled. At the atomistic scale, composition typically varies rapidly but continuously across phases. However, at the *mesoscale*, interfaces can be effectively treated as discontinuous, motivating the use of a sharp-interface formulation, which forms the basis of the present work.

We present a model that consistently couples mechanical deformation with atomic diffusion. The thermodynamic formulation treats the bulk material, grain boundaries, and phase interfaces within a unified framework, following [1]. The theoretical development follows a consistent structure in which general thermodynamic principles are clearly separated from constitutive assumptions. In the bulk, the framework allows for elasto-plastic deformation. At grain boundaries, the framework provides a thermodynamically consistent description of stress-driven grain boundary sliding and diffusion. Grain boundary diffusion and sliding are implemented through a three-field variational formulation, while phase interfaces are evolved using a level-set method known as the Voronoi implicit interface method.

A binary Cu–Sn system is considered, in which a Sn layer is deposited on a Cu substrate, leading to the formation of the IMC Cu_6Sn_5 at the interface. The evolution of biaxial stress in the Sn layer is shown in Figure 1 for both columnar and equiaxed microstructures. The results indicate that grain boundary diffusion significantly enhances stress relaxation in the equiaxed microstructure, while its effect is negligible in the columnar case. These findings suggest that grain boundary diffusion is a plausible mechanism for explaining the increased stress relaxation observed experimentally in equiaxed microstructures [2].

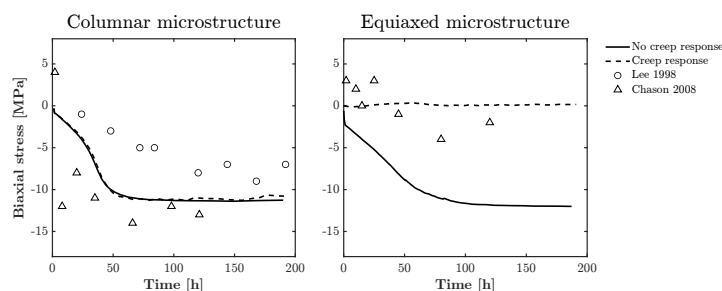


Figure 1. Biaxial stress in the Sn film for a columnar (left) and an equiaxed (right) microstructure.

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- [1] Eliot Fried and Morton E Gurtin. Coherent solid-state phase transitions with atomic diffusion: a thermo-mechanical treatment. *Journal of statistical physics*, 95(5):1361–1427, 1999.
- [2] E Chason, N Jadhav, WL Chan, L Reinbold, and KS Kumar. Whisker formation in Sn and Pb–Sn coatings: Role of intermetallic growth, stress evolution, and plastic deformation processes. *Applied Physics Letters*, 92(17), 2008.

Enforcing inequality constraints in phase-field method using Uzawa algorithm

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KEYWORDS: *Microstructure evolution, Constrained Optimization, Augmented Lagrangian Method, Uzawa Algorithm*

Multiphase-field models are essential for investigating materials systems where secondary precipitates emerge within a primary matrix. A prominent example is the titanium-molybdenum system, where the parent β phase and distinct ω phase variants coexist. These variants differ based on the crystallographic orientation with respect to the β phase [1]. In this study, a phase field framework [2] is applied to model the $\beta \rightarrow \omega$ transformation. Each phase is defined by an order parameter that is bounded between zero and one and satisfies a sum-to-unity constraint. The microstructural evolution is driven by the minimization of a global rate-potential [3], where interfacial contributions are modeled via a double-obstacle potential [2]. In this system, the energy associated with ω – ω interfaces is significantly higher than that of the ω – β interfaces [4]. So, the potential must be penalized to favor the formation of the β phase between ω variants. Enforcing these sharp energy gradients via the standard penalty method requires excessively high penalty parameters, which drastically increases the condition number of the system matrix. This induced ill-conditioning prevents the efficient application of iterative linear solvers that are needed in the case of large-scale simulations, particularly in 3D.

To overcome these limitations, an augmented Lagrangian framework is employed to transform the constrained minimization into a well-conditioned saddle-point system. This system is solved using the Uzawa algorithm, which iteratively computes the primal variables while holding the dual variables (Lagrange multipliers) constant, followed by an iterative update of the dual variables to approach the saddle-point solution. The results demonstrate that this reformulated optimization approach provides a numerically efficient and robust method for simulating complex transformations in metallic alloys, bypassing the convergence issues typical of high-penalty regimes.

- [1] S. Banerjee and P. Mukhopadhyay. *Phase transformations: examples from titanium and zirconium alloys*, volume 12. Elsevier, 2010.
- [2] I. Steinbach. Phase-field models in materials science. *Modelling and simulation in materials science and engineering*, 17(7):073001, 2009.
- [3] C. Miehe. A multi-field incremental variational framework for gradient-extended standard dissipative solids. *Journal of the Mechanics and Physics of Solids*, 59(4):898–923, 2011.
- [4] J. Kozlík, K. Tůma, O. Souček, J. Dobrzański, and S. Stupkiewicz. Multiwell phase-field model for arbitrarily strong total-spreading case. *International Journal of Engineering Science*, 221:104474, 2026.

Numerical modelling of contact-driven bearing fixation in staking-type joints for electric motor housings

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KEYWORDS: *Contact mechanics, finite element method, staking joints, bearing fixation*

This work presents the first stage of a study focused on the numerical modelling of bearing fixation mechanisms in electric motor housings applied in steer-by-wire systems using staking-type joints. This stage is dedicated to the development of a computational approach enabling the analysis of contact interactions and load transfer mechanisms governing the mechanical performance of such connections. The final objective of the study is to develop a comprehensive methodology for the design and optimisation of these joint systems.

A three-dimensional finite element model was developed in ANSYS Mechanical using a cyclic symmetry approach to represent a segment of the staking-type joint [1]. The model includes an elastic bearing and a deformable housing region, where fixation is achieved through geometric interference, with material behavior of the housing defined in the elastic–plastic regime. Contact interactions were defined using a frictionless formulation to ensure numerical stability. The loading scenario consists of an axial displacement applied to the bearing (see Fig. 1), simulating the extraction process and enabling determination of the force–displacement response. The analysis focuses on contact pressure, equivalent stress distribution, and reaction force evolution, while a parametric study is prepared to assess the influence of selected geometric parameters.

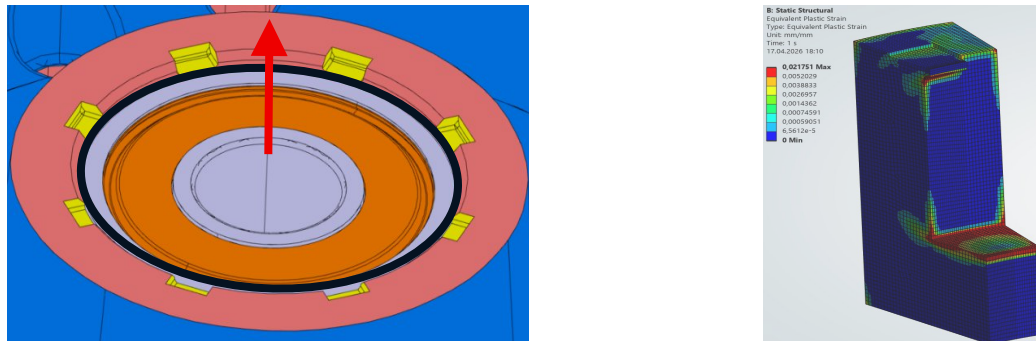


Figure 1. Left: geometry and loading scheme of the staking-type bearing fixation system (yellow - staking features; salmon red - motor housing; gray – bearing outer race; navy - bearing to housing contact zone; red – bearing push off force applied to bearing during the simulation); right: plastic strain simulation result.

The obtained results show the evolution of the reaction force with imposed displacement, allowing identification of the initial slip threshold and the maximum resistance force of the joint. The results indicate a strong dependence of the load–displacement response on staking geometry, where changes in design significantly affect stress concentration and joint stiffness. The numerical analysis reveals the occurrence of plastic deformation in the staking region, with a maximum equivalent plastic strain of 0.022, indicating localized material yielding governing the mechanical response of the joint. The maximum displacement obtained in the simulation reaches approximately 0.4mm, reflecting the progressive deformation of the joint under axial loading. Further work will include correlation of numerical results with experimental tests conducted on physical samples of the joint, aimed at refining the contact-based formulation.

ACKNOWLEDGEMENT:

- [1] O.C. Zienkiewicz and R.L. Taylor, J.Z. Zhu, *The Finite Element Method: Its Basis and Fundamentals*, Butterworth-Heinemann, 7th ed., 2013. <https://doi.org/10.1016/C2009-0-24909-9>

Three-dimensional multiwell phase-field model for athermal ω in Ti–Mo with a realistic chemical background

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KEYWORDS: Phase-field model, Ti–Mo alloys, $\beta \rightarrow \omega$ transformation, Total spreading, Synchrotron X-ray diffraction

Athermal $\beta \rightarrow \omega$ transformation in Ti–Mo alloys produces a multivariant microstructure with four ω variants. We build on our recent multiwell phase-field model for total spreading [1], in which a double-ditch term in the interfacial energy suppresses direct contact between different ω variants, keeping them separated by thin layers of the parent β phase. The four ω variants are described by order parameters, while the β phase follows from the sum-to-unity constraint. Here, we extend this framework by including fully anisotropic elasticity with phase-dependent stiffness tensors, a chemical driving force computed from the local molybdenum concentration and temperature through the Gibbs free energies of the β and ω phases [2], and a Langevin noise term representing thermal fluctuations and enabling nucleation from an initially β state. The molybdenum field is obtained by atomistic preprocessing with realistic short-range order and projected onto the computational grid.

We apply the model to cooling of a Ti–15Mo sample studied by in-situ synchrotron X-ray diffraction. The experiment resolves the parent β phase, four ω variants associated with the four $\langle 111 \rangle_\beta$ directions, and a transition phase related to incomplete $\beta \rightarrow \omega$ shuffle. Three-dimensional large-scale simulations in a periodic cube of side 42 nm with a realistic molybdenum background reproduce preferential nucleation of ω in chemically favorable regions, subsequent growth of the four variants, and their separation by the β phase, see Figure 1. The simulations show good agreement with the experimentally observed evolution during cooling.

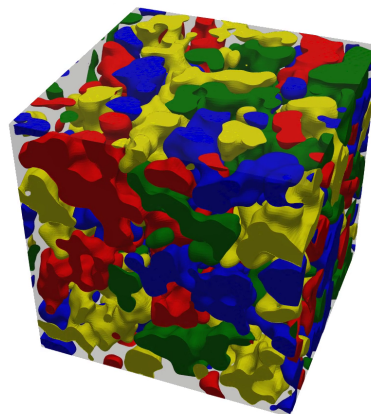


Figure 1: Snapshot of the simulated $\beta \rightarrow \omega$ transformation in Ti–15Mo during cooling at 200 K. The four colors denote the ω variants, which remain separated by the parent β phase (transparent).

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- [1] J. Kozlík, K. Tůma, O. Souček, J. Dobrzański, S. Stupkiewicz, *Multiwell phase-field model for arbitrarily strong total-spreading case*, International Journal of Engineering Science **221**, 104474, 2026.
- [2] J.Y. Yan, G.B. Olson, *Computational thermodynamics and kinetics of displacive transformations in titanium-based alloys*, Journal of Alloys and Compounds **673**, 441–455, 2016.

Modeling hierarchical branching near austenite–martensite interfaces: a phase-field study

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KEYWORDS: *Phase-field method, Shape memory alloys, Branched microstructures, Twinning .*

In most shape memory alloys (SMAs), a direct interface between the austenite phase and a single variant of martensite is typically not observed. Instead, compatibility is generally considered in an averaged sense through laminates composed of two variants of martensite, commonly referred to as twinned martensite. Within the framework of crystallographic theory of martensite, these laminate structures are postulated to be macroscopically stress-free. However, local incompatibilities still develop at the austenite–twinned martensite (A–MM) interface, which gives rise to microstructural morphologies within the transformation zone. Experimental studies indicate that a branched microstructure or a reduction in twin spacing occurs in the vicinity of the A–MM interface. This refinement is occurred to minimize elastic strain energy near this interface, even though it leads to an accompanying increase in twin boundary energy.

Early mathematical modeling of branching was introduced by Kohn and Müller [2], in which a scaling law for branching generations was proposed. Subsequently, Seiner et al. [3], based on the concept of a discrete branching framework and estimates of the elastic strain energy, twin boundary energy, and elastic micro-strain energy near the A–MM interface, calculated the number of branching generations in SMAs. More recently, Stupkiewicz et al. [4] proposed a one-dimensional model for twin branching based on the principle of energy minimization, in which the twin spacing varies continuously.

Accurate representation of branched microstructures in SMAs via the phase-field approach necessitates the use of highly refined meshes in order to resolve successive branching generations in the vicinity of the A–MM interface. This requirement significantly increases computational expense, thereby limiting the feasibility of capturing higher-order branching generations. Accordingly, an alternative modeling strategy is required.

The present work aims to establish a methodology for simulating branched microstructures in SMAs within a phase-field framework. To alleviate computational demands while preserving the morphological features of branching, the austenite phase is approximated by linear springs that mimic the elastic strain energy of the austenitic bulk material. By adjusting the stiffness of these springs, different branching levels can be represented, corresponding to various stages of microstructural refinement. The proposed approach is validated through comparison with previously reported results in the literature [3,4].

References

- [1] C. Zhang, G. Qin, S. Zhang, X. Chen, Y. He, Hysteresis effect on austenite-martensite interface in Ni-Mn-Ga single crystal, *Scripta Materialia* 222 (2023) 115029.
- [2] R.V. Kohn, and S. Müller, Branching of twins near an austenite-twinned-martensite interface, *Philos. Mag. A* 66 (1992) 697–715.
- [3] H. Seiner, P. Plucinsky, V. Dabade, B. Benesova, R. D. James, Branching of twins in shape memory alloys revisited, *J. Mech. Phys. Solids* 141 (2020) 103961.
- [4] S. Stupkiewicz, S. Amini, M. Rezaee-Hajidehi. Twin branching in shape memory alloys: A 1d model with energy dissipation effects. *Eur. J. Mech. A/Solids*, 113 (2025) 105671.

A Selection of Benchmarks in Third Medium Contact

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KEYWORDS: *Frictionless contact, Finite deformations, Third medium, Benchmarks*

A very simple scheme that avoids the complicated treatment of contact inequality constraints is provided by third medium contact, which was first introduced in [1] using anisotropic modelling near the contact area. Since then, the methodology has been improved and mainly applied in areas such as optimisation, soft robotics, and the development of metamaterials (see Fig. 1). Recently, however, the third medium approach has been (re)discovered for its potential to include contact in topology optimisation, where boundaries are a priori unknown. In this class of problem, voids are part of the modelling and make the contact problem differentiable. This has led to very recent rapid developments of the approach [2], [3], and the present paper contributes to this.

The third medium contact formulation is characterised by its simplicity of implementation, resulting in an abundance of proposed formulations in recent years that mainly differ in the regularisation term. The regularisation term is needed to control severely deformed elements that appear in finite strain contact problems. Despite the overall success of the formulation, several serious deficiencies have been recognised, including: the need for higher order elements in most formulations, lack of scale invariance, parameter dependency, ill-conditioning of the resulting system of linear equations, high spurious stresses in the case of separation, significant error in the deformation field of contact bodies just before first contact is made, inability to release contact when contact is lost due to sliding among the bodies, and the description of frictional contact is also not straightforward. In this contribution, we provide a series of benchmark problems in the field of third medium contact, where the above-mentioned issues will be discussed and compared for different recently proposed formulations.

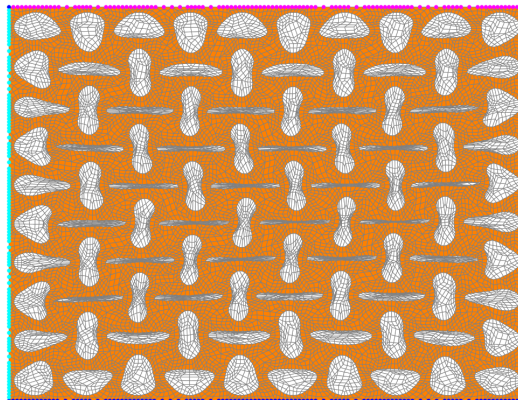


Figure 1. Third medium contact based simulation of evolving micro-structure.

- [1] Wriggers, P., Schröder, J. and Schwarz, A., “A finite element method for contact using a third medium”, *Comput. Mech.*, **52**, 837–847, (2013).
- [2] Bluhm, G.L., Sigmund, O. and Poulis, K., “Internal contact modeling for finite strain topology optimization”, *Comput. Mech.*, **67**, 1099–1114, (2021).
- [3] Wriggers, P., Korelc, J. and Junker, Ph., “A third medium approach for contact using first and second order finite elements,” *Comput. Methods Appl. Mech. Engrg.*, **436**, (2025) 117740.

On the Moving Interface Problem

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KEYWORDS: *Inclusion, Damage, Reinforcing and Frictional Slip Interfaces, Incremental Analysis.*

Numerous problems in material science and technology are related to varying interfaces. Let us mention such problems as crystalline grain growth or dissolution, austenite-martensite phase transformation, dislocation motion on slip plane, or frictional slip on contact surface. In the study of design improvement the interface shape is varied to obtain an improved or optimal design. In metal forming processes the interfaces between tool and work piece are modified to increase the product quality and reduce the work of acting loads.

The interface can be regarded as a surface on which static and kinematic fields suffer discontinuities. Several major types of interfaces can be considered. First, most popular is a coherent interface S^i specifying varying shape inclusion inducing stiffness increase, or growing damage zone with its interface boundary S^d to a limit state and ultimate failure. The discrete set of stiffeners in the form of thin shell or beam elements represent reinforcing interfaces S^r characterized by traction discontinuity. The softening response is generated by slip interfaces S^{sl} characterized by displacement discontinuity. Both elastic and dissipative slips then occur, such as friction, or dislocation slips.

On the interface S^i both displacements and surface tractions are continuous, thus $[u] = 0$, and $[T] = [\sigma n] = 0$, where u , ε , σ denote displacement, strain and stress fields, $[\]$ denotes the discontinuity of enclosed field symbol, thus $[u] = u_2 - u_1$. The displacement and traction gradients then are: $[u_{i,j}] = a_i n_j$ and $[T_{i,j}] = t_i n_j$.

The reinforcing interface S^r is represented by a thin shell inclusion of different stiffness from the matrix material or a thin layer of concentrated eigenstrains. This case can also correspond to a grain boundary or to an austenite-martensite interface. The traction discontinuity is related to interface generalized forces N through local equilibrium equations, thus: $[u] = 0$, and $[T] = [\sigma n] = L(N, q)$, where L is a differential operator and q characterizes geometric interface parameters.

On the softening or slip interface S^{sl} : the traction vector is continuous, but the displacement vector suffers discontinuity, so that: $[T] = 0$, $[u] = u^s = B T$, where B is the symmetric compliance matrix. The interface can be conceived as a thin surface layer undergoing localized shear strain, such as that growing in a delaminated inclusion boundary zone. Usually, the friction slip accompanies elastic deformation, then friction slip rules should be introduced.

The evolution of interfaces can now be specified by introducing a transformation velocity field $\dot{\phi}(x, t)$, such that each material element undergoes the shape transformation $x = x_0 + \dot{\phi} dt$ with no stress introduced. The rate (or incremental) formulation is presented for 4 types of interfaces. The limit state conditions for moving damage interfaces and post critical states are examined. A hysteretic response on the frictional interface in reciprocal slip-sliding regime is discussed, presenting dissipated and stored energy balance.

Thermodynamically Consistent Modeling of an Electro-chemo-thermo-mechanical System with Imperfect Interfaces

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KEYWORDS: *Electro-chemo-thermo-mechanical interactions, Imperfect energetic interface, Thermodynamic consistency.*

Electro-chemo-thermo-mechanical couplings, wherein electro-chemo-thermal processes interact with mechanical deformation, govern the behavior of a wide class of multi-functional materials and devices. Typical examples are batteries and shape-morphing devices that comprise electrodes separated by (liquid or solid) electrolyte. In these systems, ionic transport, electrochemical reactions, and electric fields are intrinsically coupled with deformation, both in the bulk material and, not the least, at interfaces.

To retain maximal generality at the outset, we consider the interface as an "energetic" surface that is equipped with its own balance and constitutive equations. It is thereby tacitly assumed that the interface is "imperfect" in the sense that kinematic as well as flux variables are discontinuous across the interface. We develop a generic thermodynamically consistent framework, while restricting to small strain kinematics, that provides constraints on constitutive relations for the bulk material, as well as for the interface. A particular challenge is offered by extending Ampere's and Faraday's laws, as well as establishing the proper definition of the Poynting vector (representing the electro-magnetic power), for interfaces. The work represents an extension of previous efforts pertinent to mechanics, Javili et al. [1, 2]. As an illustration of the general framework, we consider the specific system (under isothermal conditions) of a half-cell, wafering an SEI-layer, in a battery or in a shape-morphing device.

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- [1] A. Javili, F. Larsson, K. Runesson, P. Steinmann, *Comput. Meth. Appl. Mech. and Engng.*, **440**, 2025. 117925.
- [2] A. Javili, F. Larsson, K. Runesson, P. Steinmann, *Comput. Meth. Appl. Mech. and Engng.*, **451**, 2026. 118694.

Numerical modelling of rolled plug installation inside steam generator tube

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KEYWORDS: *Steam generator tube, Rolled plug, Numerical modelling.*

Nuclear power plants represent safe and reliable source of electrical energy with low carbon emissions. Steam generator tubes represent critical component in nuclear power plant as they form boundary between primary circuit with radioactive water and secondary circuit with clean water. Rolled plugs are used for defected steam generator tubes plugging by forming leak tight seal with the tube to prevent leakage of radioactive water from primary circuit into the environment. Proper installation and formation of leak tight seal between rolled plug and tube is of pivotal role.

Installation of rolled plug is performed by roll expansion process. Roll expansion uses rollers which are rotating and radially expanding rolled plug shell to form a leak tight seal with defected steam generator tube. Numerical modelling of roll expansion process is essential to accurately determine the impact roll expansion process has on the formation of leak tight seal and also to determine stress distribution and impact process has on the rolled plug structural integrity. Impact of the contact area between rolled plug and tube also causes stress distribution inside the tube and tube sheet [1]. Additionally, by implementation of phase field method to determine damage levels in rolled plug provides additional layer of information rolled plug installation process has on the rolled plug structural integrity, especially in area where significant radial expansion occurs.

Numerical modelling of roll expansion process allows to determine proper roll expansion parameters [2]. Determined roll expansion parameters are used for numerical modelling of rolled plug installation with aim to form a proper leak tight seal with the tube and prevent radioactive water leakage but also to have a minimal impact on the tube and tube sheet structural integrity.

This paper presents numerical modelling of roll expansion process which includes non-linear analysis, contact analysis and simulation of complex roller kinematics and results analysis of overall impact of the roll expansion process.

ACKNOWLEDGEMENT: INETEC is fully funding the R&D of presented product.

- [1] A. S. Al-Aboodi, „Kinematic Simulation of Three Rollers in Circular Motion Using 2D Planar FE Modeling,” *International Journal of Engineering and Advanced Technology (IJEAT)*, Vol.3, April 2014
- [2] J. Messier, V. Cano, S. Geniaut, F. Hasnaoui, N. Sellali „Simulation of roll expansion of Steam generator tubes,” *20th International Conference on Structural Mechanics in Reactor Technology*, Finland, August 2009

3D Isogeometric Simulation of Mechanized Tunnelling: Application for Excavation Analysis in Partially Saturated Ground

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KEYWORDS: *CAD-based Modelling, Processes-oriented Analysis, Mechanized Tunnelling, NURBS, BIM.*

Numerical simulations in mechanized tunnelling is subject of long-term research due to the highly complex interactions between the various components involved in the construction process, namely the ground, the tunnel lining, the grouting medium and the tunnel boring machine (TBM). Solutions based on standard FEM- and Cut-FEM techniques have already been developed to predict the excavation-induced response [1], but are lacking in terms of computational costs and numerical robustness. Thus, to address the challenge of performing efficient and accurate large-scale three-dimensional analysis, we developed a fully IGA-based simulation framework, able to capture the strongly non-linear and coupled-field behavior arising during the excavation process. The computational model inherits multiphase formulations for fully and partially saturated soils, as well as the contact between the TBM and the ground. To account for the process-oriented analysis, the pressure boundary conditions are also included.

By employing trivariate Non-Uniform Rational B-Spline (NURBS) shape functions together with combining Isogeometric Analysis (IGA) with Bézier decomposition, circular tunnel profiles can be precisely described in the numerical simulation, directly. This eliminates the need for conventional mesh generation and, thus, the corresponding geometric error often seen in FEM, allowing the presented framework to be integrated within an automated BIM-FEM design-to-analysis workflow in the future [3]. Furthermore, the smoothness and continuity of NURBS-based surface representations improves the robustness and accuracy of the contact algorithm. The computational model comprises only several patches and connecting interfaces, therefore constructing it is done fast and easily during preprocessing stage. On top of that, the higher-order discretization capabilities, enabled by hpk-refinement, improves computational efficiency of the simulation [4]. The results show that the convergence rate is faster than with traditional finite element analysis (FEM) using Lagrange shape functions.

ACKNOWLEDGEMENT: Financial support is provided by the Vietnam National Foundation for Science and Technology Development (NAFOSTED) (Project number DFG.105-2022.03) and the German Science Foundation (DFG) (Project number 518862444).

- [1] T. Kasper, G. Meschke, A 3D finite element simulation model for TBM tunnelling in soft ground, *International Journal for Numerical and Analytical Methods in Geomechanics*, 28th ed., 1441-1460, 2004. <https://doi.org/10.1002/nag.395>
- [2] H.-G. Bui, D. Schillinger, Y. Zendaki, G. Meschke, A CutFEM based framework for numerical simulations of machine driven tunnels with arbitrary alignments, *Computers and Geotechnics*, 144th ed., 104637, 2022. <https://doi.org/10.1016/j.compgeo.2022.104637>
- [3] H.-G. Bui, J. Ninić, C. Koch, K. Hackl, G. Meschke, Integrated BIM-based modeling and simulation of segmental tunnel lining by means of isogeometric analysis, *Finite Elements in Analysis and Design*, 229th ed., 104070, 2024. <https://doi.org/10.1016/j.finel.2023.104070>
- [4] T. Hughes, J. Cottrell, Y. Bazilevs, Isogeometric analysis: CAD, finite elements, NURBS, exact geometry and mesh refinement, *Computer Methods in Applied Mechanics Engineering*, 194th ed., 4135–4195, 2005. <https://doi.org/10.1016/j.cma.2004.10.008>

Session TS7

Experimental mechanics

Real-time in-situ X-ray imaging of dynamic shear fracture and spallation in porous metals

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KEYWORDS: *Planar plate impact, Spall fracture, Split Hopkinson pressure bar, Shear fracture, X-ray phase-contrast imaging, X-ray tomography, Porous microstructure, Additively manufactured metals*

Recent advances in high-energy X-ray imaging enable real-time, in-situ observation of dynamic deformation and fracture processes in metals subjected to extreme loading. This lecture presents results from impact experiments conducted at the ID19 beamline of the European Synchrotron Radiation Facility, where ultra-high-speed detectors resolve damage evolution over nanosecond to microsecond time scales. The study focuses on additively manufactured Ti6Al4V and AlSi10Mg specimens with controlled porosity, exhibiting void volume fractions from 0.04 % to 0.77 % and broad pore size distributions spanning a few micrometers to more than 180 μm . Dynamic shear fracture is investigated through impact loading of shear-compression specimens in Split Hopkinson Pressure Bar experiments, while spallation is examined through planar plate impact tests performed with a single-stage helium-driven gas gun. These two complementary loading configurations allow the influence of porosity on shear- and tension-dominated failure regimes to be explored within a consistent experimental framework and a wide range of loading rates. Time-resolved radiographic measurements provide direct insight into porosity evolution during dynamic deformation and the formation of shear bands and spall planes. These in-situ observations are complemented by extensive post-mortem X-ray computed tomography, enabling the contribution of individual voids to shear fracture and spallation to be identified. Together, the measurements clarify the interplay between pore collapse, void growth, strain localization, and crack initiation, and distinguish damage mechanisms governed by pre-existing pores from those associated with sub-resolution or dynamically nucleated defects. The lecture concludes with a brief outlook on current limitations and future directions, including three-dimensional time-resolved tomography, higher repetition rates, and tighter integration with physics-based modeling approaches.

ACKNOWLEDGEMENT

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Orientation-Dependent Yield Surface Evolution and Anisotropic Plasticity in LPBF-Manufactured SS316L

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KEYWORDS: Additive manufacturing, Laser powder bed fusion (LPBF), Yield surface, Multiaxial loading.

The rapid adoption of laser powder bed fusion (LPBF) for stainless steel 316L (SS316L) components necessitates a deeper understanding of anisotropic plasticity under complex loading conditions [1]. This study presents a comprehensive experimental investigation of the initial and evolving yield surfaces of LPBF-fabricated SS316L, explicitly addressing the influence of printing orientation and plastic pre-deformation. Tubular specimens were manufactured in three orientations (XY, ZX45 and Z) and subjected to multiaxial loading using a single-specimen probing methodology, enabling efficient and precise yield surface characterization in axial–shear stress space.

Yield surfaces were determined using Szczepiński anisotropic yield criterion at initial state and subsequently tracked after controlled tensile plastic pre-strain equal to 0.35%, 0.5% and 0.8%. The results reveal pronounced anisotropy in LPBF specimens, strongly governed by build orientation. The Z-oriented samples exhibit reduced yield strength and enhanced softening in yield loci, while XY and ZX45 orientations demonstrate comparatively higher yield strength under selected loading paths. Additionally, specimens exhibit orientation-dependent yield surface translation and rotation, indicating complex interactions between strain-induced hardening/softening mechanisms and inherent microstructural anisotropy [2].

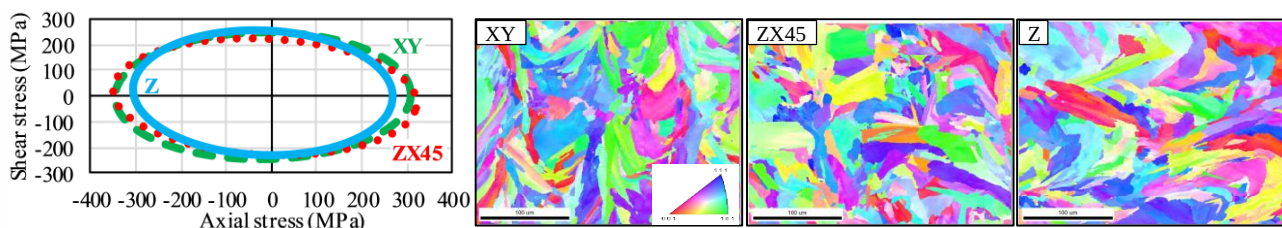


Figure 1. Initial yield surfaces at 10µε offset definition of yield and IPF maps of three printing orientations.

Microstructural analysis using electron backscatter diffraction (EBSD) establishes a strong correlation between grain morphology and mechanical anisotropy. Columnar grains aligned along the build direction in Z-oriented samples promote directional deformation and strain localization, whereas more equiaxed structures in XY and ZX orientations contribute to improved mechanical uniformity. Despite weak crystallographic texture, melt pool geometry and interlayer boundaries emerge as primary drivers of anisotropic plastic response.

ACKNOWLEDGEMENT: This work was funded by the National Science Centre, Poland through the grant no. 2023/51/B/ST8/01751.

- [1] V.P. Dubey, D. Przygucka, M. Pawlik, Z.L. Kowalewski, P. Wood and M. Kopec, *Materials Today Communications* **50**, 114531, 2026. <https://doi.org/10.1016/j.mtcomm.2025.114531>
- [2] V.P. Dubey, M. Kopec, D. Przygucka, M. Pawlik, P. Wood and Z.L. Kowalewski, *Int. J. Adv. Manuf. Technol.* **140**, 313–334, 2025. <https://doi.org/10.1007/s00170-025-16296-y>

Rapid crack propagation in disordered brittle solids

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KEYWORDS: *Dynamic Fracture mechanics, Brittle solids, Energy release rate (ERR), Crack growth*

Understanding dynamic fracture in brittle solids is a fundamental aspect of materials science, with implications for engineering, geophysics, and advanced manufacturing. Linear Elastic Fracture Mechanics (LEFM) provides the relevant framework to evaluate quantitatively the mechanical energy flux released to the tip of a growing crack and subsequently to predict fracture speed [1]. Still, observations revealed different instabilities occurring at high speed, which render the problem more complex. In particular, it has been observed in amorphous polymers [2, 3] that crack growth can suddenly switch from a slow-speed regime ($< \text{cm/s}$) to a fast-speed regime ($> 100 \text{m/s}$), which cannot be explained within conventional LEFM [4].

The present research intends to shed light on this instability by experimentally studying the mode-I fracture and crack velocity that develop during the dynamic failure of brittle solids, such as polymethylmethacrylate (PMMA, classically considered the archetype of brittle amorphous materials) and artificial rocks (heterogeneous materials made of sintered glass beads). Crack speed is measured by potential drop methods, and meso-scale dissipation and damage processes are inferred from morphological analysis of fracture surfaces. The transition between the slow and fast fracture regimes will be characterized, and the role played by damage processes occurring at the fracture process zone scale will be discussed.

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- [1] Freund LB, Freud L. Dynamic fracture mechanics. Cambridge university press; 1998.
- [2] Ravi-Chandar K, Balzano M. On the mechanics and mechanisms of crack growth in polymeric materials. *Engineering fracture mechanics*. 1988;30(5):713-27.
- [3] Vincent-Dospital T, Toussaint R, Santucci S, Vanel L, Bonamy D, Hattali L, et al. How heat controls fracture: the thermodynamics of creeping and avalanching cracks. *Soft Matter*. 2020;16(41):9590-602.
- [4] Heinzmann R, Seghir R, Alam SY, Réthoré J. Experimental investigation of the alternate recurrence of quasi-static and dynamic crack propagation in PMMA: R. Heinzmann et al. *International Journal of Fracture*. 2023;242(2):227-45.

Elastic Wave-Based Identification of Applied Load in a Steel IPE Beam

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KEYWORDS: *elastic waves, piezoelectric transducers, structural health monitoring, steel structures, load identification*

The progressive ageing of infrastructure and increasing safety requirements for engineering structures have driven the rapid development of structural health monitoring (SHM) and non-destructive evaluation techniques. In recent years, particular attention has been devoted to methods based on the propagation of elastic waves generated, among others, by piezoelectric transducers (PZT). These approaches enable the detection of changes in material properties, stress states, and local damage, thereby supporting real-time monitoring of structural condition [1-3]. As shown in [4], the changes in the strain field result in changes in elastic wave propagation. Acknowledging the truth of this phenomenon, inverse problem solving is trying. Namely, the load level identification. The presented study aims to investigate the possibility of actual applied load identification, based on the elastic wave propagation, generated and registered using the PZT transducers in a steel structural element with dimensions and shape identical to those of civil engineering structures. The experimental study is conducted using a laboratory test setup in which the steel element (a node combined with HEB 160 column-fixed on the top and bottom in a measuring stand, and IPE 300 cantilever beam welded to the column and loaded near the free end) is subjected to cyclic static loading, resulting in a gradual increase in displacement at the free end of the cantilever. The measurement system consists of four piezoelectric PZT transducers installed on the upper and lower flanges of the cantilevered part of the element, and two electrical resistance strain gauges used to measure local strains in the structure. The 3.5 sine signal at 38,571 Hz (resulting in an operational frequency of 135 kHz) was used to excite the wave. Measurements are performed at successive loading stages, allowing analysis of changes in wave-propagation parameters as a function of load level. Simultaneously, the magnitude of force, hydraulic piston displacement, and strain at selected points of the structure are continuously recorded. Recorded signals are filtered, carefully analysed to select the crucial parameters, and divided into learning and testing pattern sets. Due to the load level identification the artificial intelligence tools are applied. The results show the potential application of wave-based methods for structural health monitoring of steel structures with complex geometry.

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- [1] V. Giurgiutiu, *Structural Health Monitoring with Piezoelectric Wafer Active Sensors*, Academic Press, 2nd ed., 2014, <https://doi.org/10.1016/C2013-0-00155-7>
- [2] L. Yu, Y. Shen, V. Giurgiutiu, *Piezoelectric Transducer-Based Structural Health Monitoring*, *Sensors*, 24, 3438, 2024, <https://doi.org/10.3390/s24113438>
- [3] P. Jiao, K.-J.I Egbe, Y. Xie, A. Matin Nazar, A.H. Alavi, *Piezoelectric Sensing Techniques in Structural Health Monitoring: A State-of-the-Art Review*, *Sensors*, 20, 3730, 2020 <https://doi.org/10.3390/s20133730>
- [4] D. Ziaja, M. Jurek, B. Miller, *An influence of strain field on guided wave propagation in steel cantilever beam under bending*, *Journal of Civil Structural Health Monitoring*, 15, 4041–4060 2025, <https://doi.org/10.1007/s13349-025-01028-3>

Strength Evaluation of Cellulose Nanofiber Materials by Sequential Digital Image Correlation

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KEYWORDS: *Cellulose Nanofiber, Digital Image Correlation, Deployable Structure, Tensile Strength.*

Development of lunar habitation modules is actively underway for future lunar exploration [1]. In the early stages of construction, building materials must be transported from Earth; therefore, lightweight materials and deployable structures are of particular interest. In this study, cellulose nanofiber (CNF) materials were investigated as candidate structural materials due to their low density, high strength [2], and water-induced flexibility, which enables folding and deployment. However, lunar environments are characterized by intense ultraviolet (UV) radiation and extreme temperature fluctuations, which may significantly degrade material performance. In particular, the influence of UV irradiation on the mechanical properties and durability of CNF has not yet been sufficiently clarified. Therefore, this study first aims to evaluate the effects of UV exposure on the mechanical properties and failure behavior of CNF materials under simulated lunar conditions. In addition, since CNF materials are expected to be used in deployable structures, they are subjected to repeated folding and unfolding processes. Such mechanical loading may also affect their structural integrity. Therefore, the influence of folding conditions, including folding angle, on the mechanical properties of CNF is also investigated. To evaluate these effects, tensile tests were conducted, and deformation behavior was analyzed using sequential digital image correlation (DIC). Video images captured during the tests were divided into consecutive frames, and DIC analysis was applied to quantify time-resolved deformation and strain fields. This approach enabled visualization of localized deformation and the progression of damage leading to failure. CNF specimens were first exposed to UV irradiation, and their mechanical properties, including tensile strength and elastic modulus, were evaluated before and after exposure. Subsequently, the relationship between folding angle and strength was examined. Furthermore, microstructural observations of surfaces and cross-sections were conducted using scanning electron microscopy (SEM) to characterize internal damage. The results revealed the effects of UV irradiation and folding conditions on the mechanical properties of CNF. In addition, sequential DIC analysis provided detailed insights into strain localization and failure processes. These findings contribute to evaluating the applicability of CNF materials for deployable structures in lunar environments.

ACKNOWLEDGEMENT: This research was supported by Special Research Project Grant (B) by Institute of Science and Technology, Meiji University.

- [1] International Space Exploration Coordination Group (ISECG), *Global Exploration Roadmap 2024*, ISECG, 2024.
- [2] T. Saito, R. Kuramae, J. Wohler, L.A. Berglund and A. Isogai, *An ultrastrong nanofibrillar biomaterial: The strength of single cellulose nanofibrils revealed via sonication-induced fragmentation*, *Biomacromolecules* 14, 248–253, 2013. <https://doi.org/10.1021/bm301674e>

Dynamic Stress Measurement Behind Shock-Loaded Collapsible Materials

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KEYWORDS: Collapsible Material, Shock Wave, Sensor, Foam, Balsa Wood.

Collapsible materials like closed-cell aluminum foams, being lightweight and effective energy-absorbers, are desirable options in the manufacture of blast shields. In order to minimize the damage, the collapsibility of such materials is utilized to arrest shrapnel, solid debris and fragments flying out of a blast. But these materials are not effective mitigators of a blast wave emerging out of a detonation, for the reason of stress amplification at the distal end [1], damaging the objects covered by the collapsible shields. Due to the impulsive collapse involved in the phenomenon, the direct sensors used for measuring the distal-end stress are often worn-out and damaged during the process requiring multiple replacements affecting the accuracy, repeatability and reliability of the measurement [2]. Hence an accurate, robust and a high-fidelity stress measurement technique is required for the analysis of shock mediation by the collapsible materials used in blast shields.

In this backdrop, we developed a transducing-type measurement technique to capture the dynamic stress-time

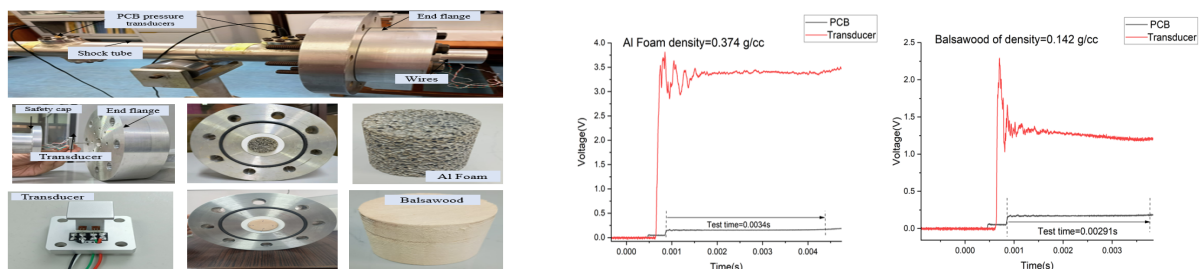


Figure 1. Experimental setup and signal output of the stress transducer.

history at the distal-end of collapsible materials exposed to shock waves. The technique involves a T-beam transducer instrumented with high-frequency strain gauges, in which the head of the T-beam is exposed to the collapse of the functional material, while the sensing junction is located near the bottom of the beam, away from the spot of impact, thus preventing the sensor impairment. The strain gauges are rigged in a modified, full Wheatstone bridge configuration, embedded in a strain meter. Calibration of the sensor was carried out using known inputs from an impulse hammer of PCB Piezotronics make, yielding a sensitivity of $0.556 \mu\epsilon/N$. Post calibration, the sensor was tested in a shock tube for a dynamic response under shock loading, without and with two collapsible materials, viz. closed cell of aluminum foam ($\rho = 0.374 \text{ g/cc}$) and balsa wood ($\rho = 0.142 \text{ g/cc}$), which have a potential utility as blast shield materials. The output of the sensor was collected on a PC-based data acquisition system, through a signal conditioner. The sensor output indicated an amplification of 4.8 times the applied shock load at the proximal end of the aluminum foam, which is consistent with the information reported in literature [1, 2]. At the distal end of balsa wood, the amplification factor was 2.95 times the applied load/pressure at the proximal end. Finite element analysis was performed on the transducer, using ANSYS, to validate its dynamic response numerically, the results of which show a good agreement with the experimental data. The sensor developed is compact, durable, cost-effective and moreover, can be designed to suit the harsh test environments of blast loading.

- [1] O.E. Petel, S. Ouellet, A.J. Higgins, D.L. Frost, *Shock Waves*. **23**(1), 55-67, 2013. <https://doi.org/10.1007/s00193-012-0414-7>
- [2] M. Thorat, V. Menezes, A. Gokhale, C. Dey, *Journal of Performance of Constructed Facilities*. **35**(6), 06021005, 2021. [https://doi.org/10.1061/\(ASCE\)CF.1943-5509.0001673](https://doi.org/10.1061/(ASCE)CF.1943-5509.0001673)

Experimental Insights into a New Generation Irradiation Resistance Fe-30Mn-5Al-1C-3Mo based alloys

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KEYWORDS : *Ni-free austenitic steels, radiation resistance, nanoindentation, microstructure*

Advanced nuclear reactor concepts require novel alloy designs to circumvent irradiation-induced degradation in existing materials. Although Fe-Ni-Cr-based austenitic steels (ρ : 7.85 g·cc⁻¹) are widely adopted for various reactor core structural applications, they are susceptible to radiation-induced phase instabilities, such as void swelling, embrittlement, and irradiation-assisted stress-corrosion cracking. The present investigation explores a Ni-free alloy design in the form of a lightweight austenitic steel (Fe-30Mn-5Al-1C-3Mo, wt.%) with reduced density (~ 7 g·cc⁻¹), exhibiting deformation characteristics comparable to those of 316 LN at high temperatures. The defect evolution has been characterised using EBSD, ECCI, and TEM, revealing limited grain growth, the absence of the RIS effect, and network dislocations. The room-temperature and elevated-temperature mechanical properties of bulk material is evaluated using hardness (nanoindentation), uniaxial tensile, and creep tests at 650°C. The underlying mechanisms are established in post-deformed substructures using correlative microscopy and compared with SS 316 LN under similar conditions. The alloy has been subjected to 10 MeV Fe²⁺ ion irradiation at 300°C and doses up to ~ 8 dpa, mimicking the end of the material's lifetime under operating conditions, as shown by SDTrimSP simulations at a fluence of 5×10^{15} ions·cm⁻². The calculations incorporate temperature-dependent corrections, including thermally activated diffusion and dynamic target evolution, enabling a more realistic representation of high-temperature irradiation conditions. The key results of the investigation will be discussed in detail.

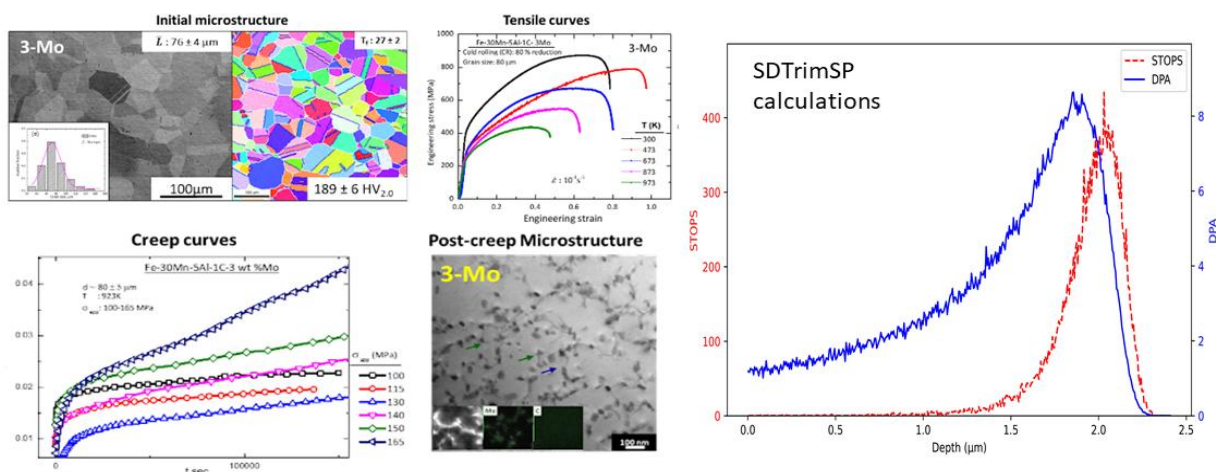


Figure 1. Initial microstructure with tensile and creep curves, and crept microstructure.

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- [1] Kotla Sairam, M.P. Phaniraj, and Korla Rajesh, Scr. Mater. 230, 2023.
- [2] Kotla Sairam, M. Phaniraj, and Korla Rajesh, Metall Mater Trans A 56, 1799–1816 (2025).

Assessment of the technical condition of high-strength steel structures using the Barkhausen noise method

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KEYWORDS: *Barkhausen noise, high-strength steel, exploitation time, plastic deformation, damage*

In this work, the magnetic Barkhausen noise method will be presented as a tool for assessing the service life of structural components. The presented article extends the author's previous research on the application of Barkhausen noise in the diagnostics of structural material degradation [1, 2], as well as in the assessment of microstructural quality and mechanical properties of manufactured components [3].

The blades working under identical operation parameters were cut from four steam turbines that were taken out of service after various periods of exploitation. The operating times of the blades were 26 400 h, 39 800 h, 36 100 h, and 60 800 h. Barkhausen noise measurements were performed on the trailing edge and the leading edge of the blades before and after removing the oxide layer. The results of such tests are presented in Fig. 1.

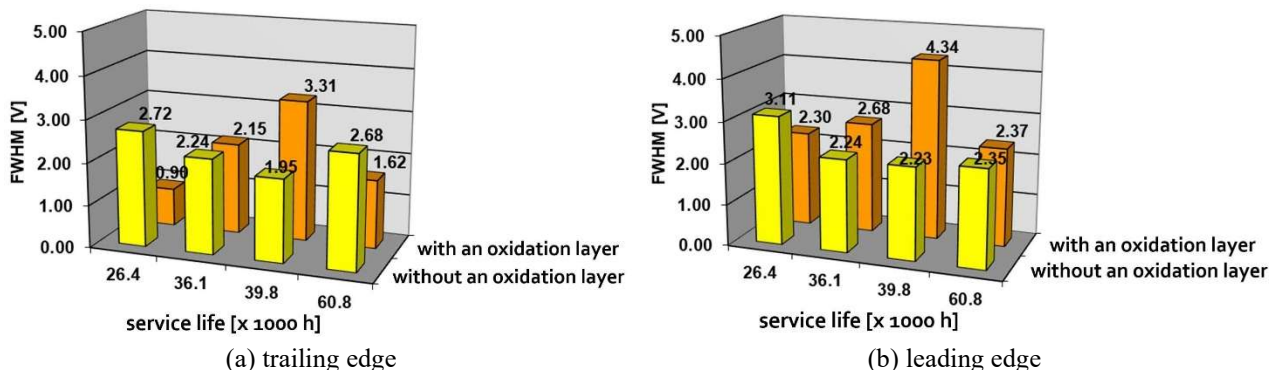


Figure 1. Full width at half maximum (FWHM) of the effective Barkhausen noise voltage envelope in relation to the service life of the turbine blade

The FWHM parameter clearly changed for both the trailing and leading edges of the blades as their service time increased. These relationships were observed for specimens with the oxide layer and without it.

ACKNOWLEDGEMENT: This work was partly financed by the Military University of Technology under research project UGB No. 531-000048-W200-22.

- [1] K. Makowska, T. Szymczak, Z.L. Kowalewski, *Acta Mech. Autom.* 18(1), 40–47, 2024. <https://doi.org/10.2478/ama-2024-0005>
- [2] K. Makowska, T. Szymczak, Z.L. Kowalewski, *J. Theor. Appl. Mech.* 63(3), 657–672, 2025. <https://doi.org/10.15632/jtam-pl/205163>
- [3] K. Makowska, Z.L. Kowalewski, *J. Theor. Appl. Mech.* 62, 2024. <https://doi.org/10.15632/jtam-pl/191444>

Predicting Fatigue Life Using Energy-Based Damage Measures

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KEYWORDS: *Low-Cycle Fatigue, Unified Mechanics Theory, Energy-Based Approach*

This study evaluates energy-based fatigue damage measures - specifically the energy accumulation graph and the unified mechanics theory (UMT) thermodynamic approach - for predicting low-cycle fatigue life in steels exhibiting cyclic softening. The energy accumulation graph characterizes fatigue behavior by relating cumulative plastic strain energy to the number of cycles to failure in a double-logarithmic scale, obtained by summing the plastic strain energy dissipated in successive hysteresis loops (Fig. 1). This representation extends the classical Palmgren-Miner concept by using experimentally measured cumulative energy rather than assuming a constant per-cycle damage fraction. Lines parallel to the main curve denote equal damage levels and enable fatigue-life prediction under variable loading by comparing accumulated energy with the critical failure threshold. As an energy-based metric, it provides a more physically grounded description of degradation than stress- or strain-based methods and captures microstructure-dependent effects, including anisotropy.

The UMT approach further enhances fatigue prediction by integrating energy, entropy, and thermodynamic state variables, offering a more robust description of degradation than empirical models and improving differentiation between sample orientations. Experimental verification demonstrates that these energy-based methodologies improve the accuracy of fatigue-life calculations, particularly for anisotropic materials or components produced using advanced manufacturing, by enabling service load histories to be transformed into incremental plastic energy contributions and summed to a critical failure value.

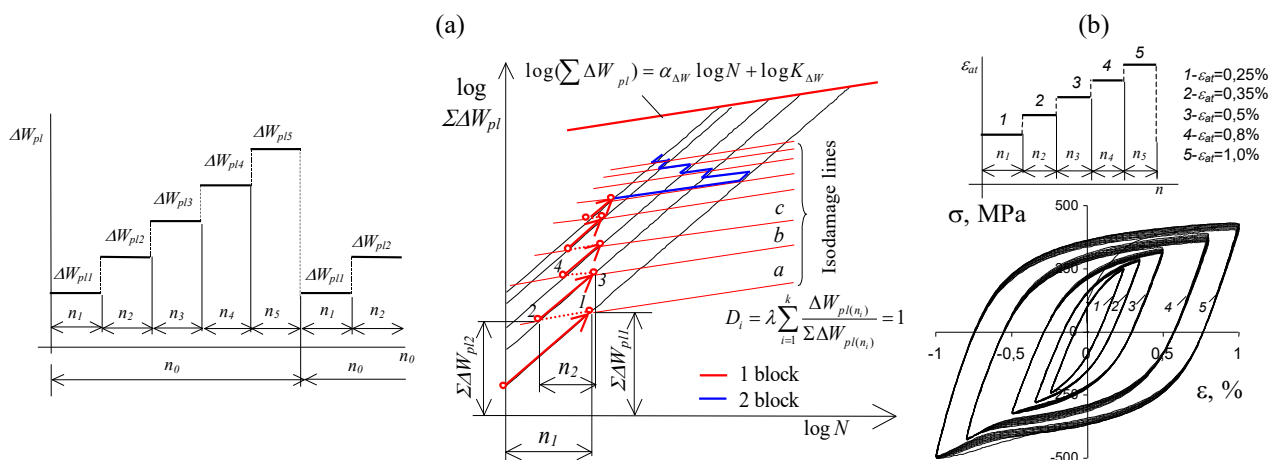


Figure 1. (a) Summing up damage using a cumulative chart; (b) Hysteresis loops in a single load block (last block before sample fracture) [1].

- [1] A. Mroziński, M. Piotrowski, W. Egner, H. Egner, *Materials* **19**(2), 352, 2026.
<https://doi.org/10.3390/ma19020352>

Viscoelastic Behavior Across the Glass Transition Temperature using Vibrational Testing

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KEYWORDS: *Bio Composite Material, Glass Transition Temperature, Viscoelasticity, Vibration.*

The behavior of bio-based composite materials reinforced with flax fibers as a function of temperature beyond T_g has been very little studied. In this study, our aim is to make a significant theoretical and experimental contribution to this issue. The viscoelastic behavior of the material is described by a complex modulus dependent on the frequency of loading and on temperature.

An original experimental setup was designed to determine the stiffness modulus and the loss factor as a function of temperature, including beyond the glass transition temperature, a range that few standard devices manage to cover reliably. The setup combines regulated heating elements, a specimen excitation system in a clamped-free configuration, a vibration response sensor, a data acquisition chain, as well as thermal monitoring through thermocouples and infrared thermometry. We tested the two classical methods for determining the loss factor: the first method using the -3 dB bandwidth and the time decay method. For our materials, whose typical damping values are on the order of 1.2%, the -3dB method requires very fine sampling to achieve a good resonance peak resolution. For this reason, the time decay method was chosen. The storage modulus is derived from the resonance frequency using the classical modal relationship. This frequency is itself obtained by two complementary methods: extraction of the peak from the frequency response function, and fitting of the time signal with a damped sinusoidal response.

The tests confirm the expected trend: a marked drop in the storage modulus at the passage through T_g , accompanied by a peak in the loss factor. These observations qualitatively validate the implemented setup and will help to support the complex modulus approach adopted in the theoretical study.

Mechanical Properties of Thermally Sprayed Ceramic-Metallic Materials

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KEYWORDS: *Thermally sprayed composites, Ceramic-metallic materials, Mechanical properties*

Current knowledge of thermally sprayed cermets is mostly limited to surface-level properties, and existing studies focus on these materials as thin coatings, where the physical volume is negligible[1]. Therefore, this talk investigates the mechanical properties of these, but fabricates them thick enough to be considered bulk material. This study specifically focuses on evaluating and analyzing the stress-strain behavior of those materials as well as strain-rate dependence. The methodology employs a dual-testing approach to assess the mechanical properties of the cermet using distinct procedures. A hydraulic testing machine was used to perform quasi-static compression tests to determine the material's properties under low-strain-rate loading. Additionally, dynamic compression experiments were conducted using a Split-Hopkinson Pressure Bar (SHPB), a well-established method for testing materials under high-strain-rate conditions[2]. Cylindrical specimens with a diameter of 6 mm and a height of 3 mm were used for experimental testing. The results show a strong strain-rate sensitivity, with the flow stress of the ceramic-metallic composite increasing significantly under dynamic loading compared to quasi-static conditions. In this paper, the results presented provide a novel qualitative and quantitative analysis of the mechanical properties of these materials in bulk form, providing important data on their response under both static and dynamic testing conditions, which is crucial for applications.

ACKNOWLEDGMENT

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[1] Wypych A., Jankowiak T., Sumelka W., Mechanical and Microstructural Properties of Thermally Sprayed Metallic Materials in Compression Tests over a Vast Range of Strain Rates, Materials, 2023. <https://doi.org/10.3390/ma16247566>

[2] Chen W., Song B., Split Hopkinson (Kolsky) Bar: Design, Testing and Applications, Springer, 2011.

Structured light vs Digital Image Correlation for shape measurements

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KEYWORDS: *Digital Image Correlation, Structured Light, Shape Measurement, Subset Size.*

The structured light (SL) method is currently one of the most widely used techniques for accurate shape measurement in industry, medicine, and cultural heritage applications [1]. However, when displacement and strain measurements are also required, for example in structural integrity monitoring, 3D digital image correlation (3D DIC) is often preferred. In 3D DIC, all relevant quantities – namely 3D shape as well as displacement and strain fields – can be obtained using a relatively simple measurement setup consisting of only two cameras [2].

It should be noted, however, that successful application of 3D DIC requires the presence of a sufficiently random surface texture (either natural or artificially applied), and the subset selection strongly depends on the quality of this texture. Therefore, the aim of this work is to provide practical guidance on whether, and under what conditions, the accuracy of shape reconstruction using 3D DIC can be comparable to that achieved by the structured light method, which is here treated as a reference (SL measurements done with Smarttech3D MICRON3D scanner). In particular, we investigate how the choice of subset size affects the reconstruction accuracy.

To evaluate the influence of 3D DIC parameters on the recovery of both global and local geometric features, we analyse several objects with different spatial frequency content, including a technical sample (wire arc additive manufacturing (WAAM) specimen), a cup (both with artificial texture), and an oil painting (with natural texture). Example results illustrating the influence of subset size on the shape measurement of the WAAM specimen are presented in Fig. 1.

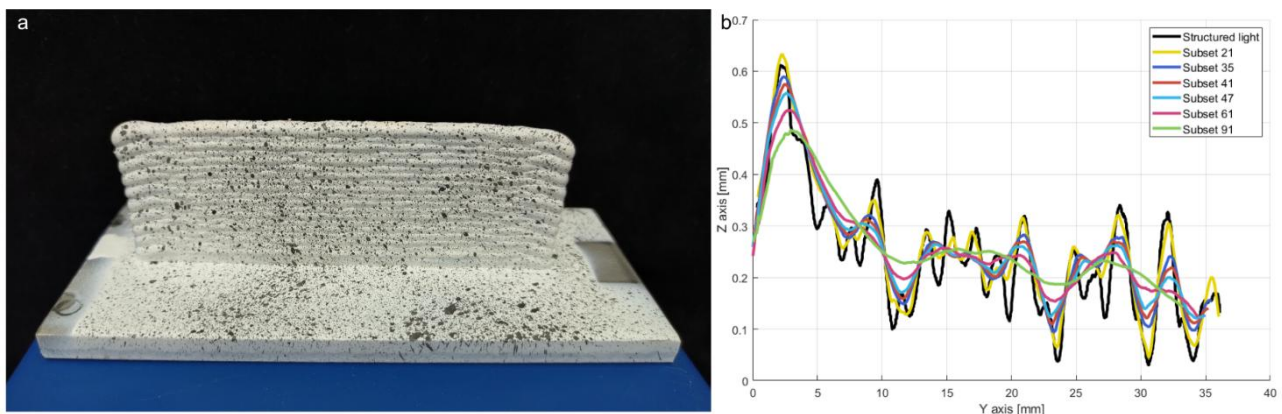


Figure 1. a) WAAM specimen used for shape measurements, b) cross-section of WAAM specimen with SL compared to different subsets of DIC.

ACKNOWLEDGEMENT: This work was partly supported by 23IND08 DI-Vision grant by European Partnership on Metrology.

[1] J. Xu, S. Zhang, Status, challenges, and future perspectives of fringe projection profilometry. *Opt. Lasers Eng.* 2020, 135, 106193.

[2] M. Sutton, J. Orteu, H. Schreier, *Image Correlation for Shape, Motion and Deformation Measurements. Basic Concepts, Theory and Applications*, 2009. 10.1007/978-0-387-78747-3.

DIC-enhanced experimental platform with a multi-detector array for tensile test at cryogenic temperatures

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KEYWORDS: *cryogenic tensile testing; Digital Image Correlation (DIC); multi-detector experimental platform; acoustic emission (AE); plastic flow instability*

Material testing at cryogenic temperatures is essential for the development and validation of materials for energy, aerospace, and superconducting applications. Accurate characterization under such conditions requires experimental systems capable of stable operation at very low temperatures and synchronized acquisition of multiple physical signals.

This work presents a DIC-enhanced experimental platform with a multi-detector array designed for uniaxial tensile testing at cryogenic temperatures. The system enables tests at 4 K, 77 K, 300 K and integrates force and displacement measurements with full-field strain analysis using Digital Image Correlation (DIC). The experimental setup is equipped with a cryostat featuring an optical access window, allowing in-situ DIC measurements under cryogenic conditions. In addition, the platform incorporates acoustic emission (AE) monitoring and temperature sensing, with all signals fully synchronized in time.

The developed system enables quantitative characterization of deformation processes, including strain localization, plastic instability, and the evolution of deformation mechanisms at cryogenic temperatures [1, 2]. The combination of full-field measurements and multi-sensor data provides a detailed insight into the material response beyond conventional stress-strain analysis.

The proposed platform offers a versatile and reliable tool for advanced material characterization and supports the investigation of coupled thermomechanical phenomena in cryogenic environments.

ACKNOWLEDGEMENT: This work has been supported by the National Science Centre through Grant No UMO-2023/51/D/ST8/02370.

- [1] Nalepka, K., Tabin, J., Kawałko, J., Brodecki, A., Bała, P., Kowalewski, Z., 2024. Plastic Flow Instability in Austenitic Stainless Steels at Room Temperature: Macroscopic Tests and Microstructural Analysis. *International Journal of Plasticity*, 104159.
- [2] Tabin, J., Kawałko, J., Schob, D., Roszak, R., Brodecki, A., Bała, P., Maasch, P., Kowalewski, Z., Ziegenhorn, M., 2025. Deformation-induced martensitic transformation in Fused Filament Fabrication austenitic stainless steels during tension at wide range of temperatures (77 K, RT). *Materials Science and Engineering: A*, 149552.

Monitoring the Progressive Degradation of Steel in Energy Facilities as a Result of Fatigue

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KEYWORDS: *Fatigue, Damage, Optical methods, Indicators of damage development.*

The safe service life for most power units used in domestic power plants has already been significantly exceeded, and therefore ongoing actions are being taken to monitor the condition of structural elements still in operation. Heat-resistant steels used in heating devices and steam transport during the commissioning period of the mentioned energy facilities were characterized by significantly lower strength than materials used today. During repairs and the construction of new structures, increasingly modern heat-resistant materials are being used, such as steels with increased chromium or nickel content. Despite the use of advanced materials, there is still a lack of sufficient research aimed at predicting their behaviour in the period preceding failure. Therefore, the presented work proposes a new methodology that allows assessing the effectiveness of non-destructive testing in the form of optical measurement systems in monitoring the development of damage in power engineering steel subjected to cyclic loading. The tests were carried out on power engineering steel 10CrMo9-10 (10H2M) used in pipelines and steam distribution systems in the supercritical state. Experiments were conducted on the material in the as-received state and after its long-term service for 280 000 hours at an elevated temperature of 540°C and an internal pressure of 2.9 MPa. A series of strength and microstructural studies were conducted, including tensile tests as well as high- and low-cycle fatigue tests within a stress amplitude range from 250 MPa to 450 MPa, in order to characterize the damage mechanisms depending on the degree of material exploitation. A development of damage during fatigue tests was monitored using Digital Image Correlation. In addition, to characterize the dynamics of material damage development, laboratory-measurable indicators of material damage were used in the form of: (a) fatigue damage strain indicator ϕ , reflecting the mechanisms of the degradation process, Fig.1; (b) defined fatigue damage parameter D; [1].

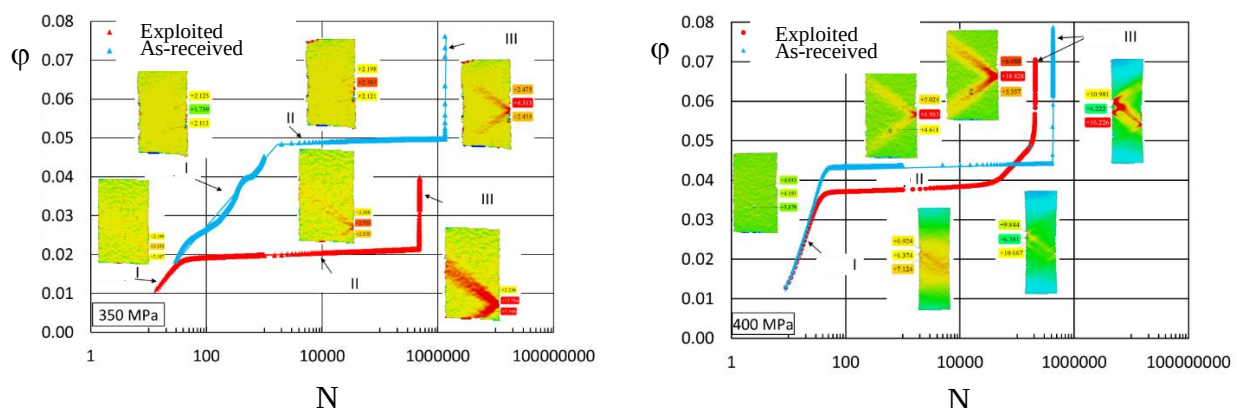


Figure 1. Variation of the fatigue damage strain indicator ϕ as a function of the number of cycles for the as-received and exploited steel; tests were carried out for stress range 350 MPa and 400 MPa.

ACKNOWLEDGEMENT: This work was funded partly by the National Science Centre in Poland through the grant no. 2023/51/B/ST8/01751.

- [1] A. Brodecki, M. Kopeć, Z.L. Kowalewski, *Int. J. Pres. Ves. & Pip.*, **202**, No.104889, pp.1-9, 2023, <https://doi.org/10.1016/j.ijpvp.2023.104889>

Self-Sensing Behavior of Laser-Processed sCFRP Based on Electrical Resistance Change

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KEYWORDS: *sCFRP, Laser-processing, Electrical resistance, Strain sensor, Self-sensing.*

This study proposes a self-sensing approach for laser-processed short carbon fiber reinforced plastic (sCFRP) based on electrical resistance change. In recent years, lightweight and highly formable sCFRP has been increasingly used in automotive components and complex-shaped parts. However, internal microdamage is difficult to detect from the surface, which may reduce structural safety. Therefore, the development of a self-sensing technique that enables the material itself to detect damage and strain without external sensors is required. In this study, local electrical conductivity is introduced into originally insulating sCFRP by laser processing [1]. The objective is to investigate the possibility of using the material itself as a strain sensor by utilizing changes in electrical resistance associated with mechanical strain.

The effects of processing conditions on the electrical properties are investigated by characterizing the processed surfaces. Scanning electron microscopy (SEM) observations show that carbon fiber accumulation in the laser-processed region strongly influences conductive path formation. In regions with greater fiber accumulation, increased fiber-to-fiber contact forms a continuous conductive network, resulting in electrical conductivity. Surface roughness measurements using a laser microscope further show that the smoothest processing condition gives the lowest initial resistance. On smoother surfaces, electric current flows more directly, whereas on rougher surfaces, the current path becomes more tortuous, leading to higher resistance. These results indicate that both carbon fiber accumulation and surface morphology affect the electrical properties.

The relationship between electrical resistance and strain is examined under tensile loading. Laser processing is performed at different scanning speeds to compare the conductive paths formed under each condition. Strain is measured using a strain gauge, and electrical resistance is simultaneously recorded using a radio-frequency identification (RFID) tag, enabling correlation between mechanical deformation and electrical response. At low laser scanning speeds, longer irradiation promotes carbon fiber accumulation, resulting in low initial resistance and a small resistance change rate. The resistance changes linearly with strain and shows stable, reproducible behavior. In contrast, at high laser scanning speeds, insufficient laser energy hinders conductive path formation. As a result, the initial resistance is high, and even small strain causes large changes in fiber-to-fiber distance, leading to a high resistance change rate. The response is nonlinear, variable, and unstable. Cyclic tensile tests further show that electrical resistance increases during loading and decreases during unloading. These results demonstrate the potential of laser-processed sCFRP as a self-sensing material.

REFERENCES

- [1] M. Enomoto and A. Todoroki, Electrical resistance welding of 3D-printed short carbon fiber/PA-6 using laser surface treatment, 70(6), 30-35, 2024.

Dynamic Compression Characterization of Multilayered Composite Materials Using SHPB

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KEYWORDS: SHPB, High-Speed Deformation, Energy Dissipation, Composite Materials, Polymer Materials.

Engineered wood products and bio-based layered materials are widely used due to their favorable strength-to-weight ratio, energy absorption capabilities, and potential for sustainable material design. In many engineering applications, including impact loading, crash scenarios, and high-rate material processing, these materials are subjected to dynamic loading conditions. However, material models are often based on quasistatic data, which do not adequately capture their behaviour at high strain rates. This limitation is particularly critical for anisotropic multilayered composites, where strain-rate sensitivity, interlayer interactions, and wave propagation effects influence both the mechanical response and the governing failure mechanisms. Reliable experimental methods are therefore required to improve understanding and support predictive modelling.

The Split Hopkinson Pressure Bar (SHPB) technique is a well-established method for investigating material behaviour at strain rates ranging from approximately 10^2 to 10^4 s⁻¹ [1]. The method is based on one-dimensional elastic wave propagation in bars, where incident, reflected, and transmitted strain signals are used to determine stress-strain response, strain rate, and energy absorption of the tested specimen (see Fig. 1).

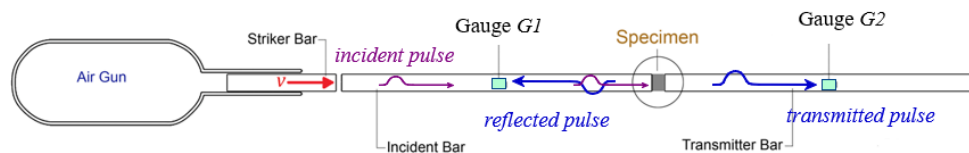


Figure 1. Principal sketch of split Hopkinson pressure bar apparatus.

In this study, compression experiments were performed on selected multilayered composite materials, including carbon-epoxy laminates and Norway spruce. A wide range of strain rates was covered by combining quasi-static testing using an MTS system with high strain-rate experiments using SHPB. Mechanical response parameters, including stress, strain, boundary forces, stiffness, and energy dissipation, were evaluated. The influence of strain rate and material orientation was examined, and differences in deformation and energy absorption between polymer-based and bio-based layered materials were observed.

The results highlight the importance of strain-rate effects in composites under compression and the need for further experimental work to support reliable modelling and engineering design.

ACKNOWLEDGEMENT: The work was done within the research profile Neopulp financed by the Knowledge Foundation.

- [1] Kolsky, H. An investigation of the mechanical properties of materials at very high rates of loading. Proc. of the Physical Society B, 62, 676–700, 1949. <http://dx.doi.org/10.1088/0370-1301/62/11/302>

On the Origin of Discontinuous Plastic Flow in Austenitic Steels: An Acoustic Emission Study

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KEYWORDS: *acoustic emission, cryogenic tensile test, austenitic steel, experimental mechanics, waterfall plot analysis*

Austenitic steels subjected to cryogenic tensile loading may exhibit discontinuous plastic flow (DPF) below temperature T_0 , [2] visible as serrations in stress-strain response [1,2]. Acoustic emission (AE) provides a complementary in-situ tool for tracking intermittent plastic activity associated with this instability [3]. In this study, cryogenic tensile tests of 304, 316L and N50 austenitic steels were performed with simultaneous monitoring of stress response and AE activity investigated on site shown on Fig. 1.

Particular attention was paid to individual serration events and to short time intervals containing one or two serrations, analyzed together with the corresponding stress response. Full-record AE representations were complemented by selected interval-based time-frequency plots in order to resolve local changes in signal organization associated with isolated discontinuities of plastic flow [3]. The results indicate that AE signal evolution correlates with the stress response and enables identification of successive stages of DPF [4] and give an ability to predict its occurrence.

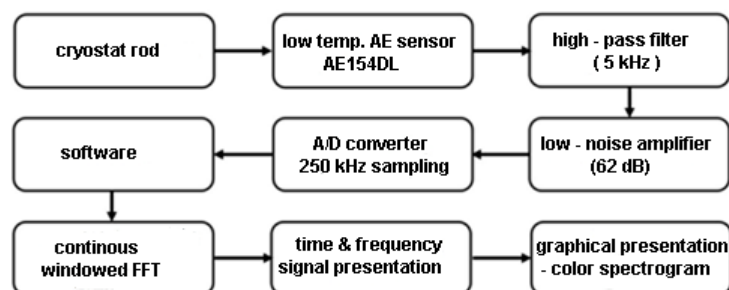


Figure 1. Acoustic emission (AE) signal acquisition and processing workflow used in cryogenic tensile tests.

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- [1] L. Xie, H. Zhang, J. Xin, F. Shen, Z. Geng, M. Jiang, Z. Huang, B. Li, W. Wang, C. Huang, L. Li, Commun. Mater. 6, 159, 2025. <https://doi.org/10.1038/s43246-025-00882-4>
- [2] B. Skoczeń, J. Bielski, S. Sgobba, D. Marcinek, Int. J. Plast. 26, 1659–1679, 2010. <https://doi.org/10.1016/j.ijplas.2010.02.003>
- [3] A. Vinogradov, Metals 15(1), 46, 2025. <https://doi.org/10.3390/met15010046>

The Influence of Build Parameters on the Collapse Behaviour of a Highly Porous, Random, Open-Cell Lattice 3D Printed from IN718 Alloy

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KEYWORDS: *Open-Cell Lattice, Selective Laser Melting (SLM), IN718 Alloy, Dynamic Impact Testing*

Modern additive manufacturing (AM) strategies increasingly focus on optimizing process parameters in order to balance production efficiency with the mechanical performance of complex geometries. In this context, particular attention is given to structures with an extremely high volumetric porosity of 96% and ligament diameters ranging from 0.4 to 1.2 mm, whose collapse behaviour is especially sensitive to microstructural defects and phase distribution. This study investigates the influence of Selective Laser Melting (SLM/PBF-LM) build parameters on the mechanical response of High-Porosity Random Open-Cell Lattices (HPROCL) fabricated from Inconel 718 (IN718) alloy using a Renishaw AM 250 system [1].

Two distinct sets of build parameters, designated as Set A and Set B, were evaluated to assess the effect of processing conditions on the collapse behaviour of the lattice while reducing build time and microporosity. For the standard configuration (Set A), a laser power of 200 W was employed, with energy densities ranging from 2.2 to 5.5 J/mm² for volume scanning and from 0.6 to 3.1 J/mm² for surface layers. In contrast, the modified configuration (Set B) utilized a lower laser power of 175 W, with energy densities of 1.9 to 4.9 J/mm² for the volume and 4.5 to 6.4 J/mm² for the surface. The resulting structures were then subjected to quasi-static (MTS) and dynamic (DIHPB [2]) compression at loading velocities of 2.5×10^{-5} m/s and 10 m/s, respectively. Dynamic impacts reached nominal strains above 0.5, with collapse mechanisms and failure modes captured via synchronized DIC and high-speed imaging (HSC).

The results confirm that appropriate adjustment of SLM/PBF-LM build parameters can enhance both manufacturing efficiency and the collapse resistance of highly porous IN718 lattice structures.

ACKNOWLEDGEMENT: The support of the National Agency for Academic Exchange (NAWA, PPI/APM/2018/1/00045/U/001), Poland, is gratefully acknowledged.

- [1] P. Wood, T. Libura, Z.L. Kowalewski, G. Williams, A. Serjouei, *Materials* **12**(24), 4203, 2019.
<https://doi.org/10.3390/ma12244203>
- [2] P. Płatek, J. Sienkiewicz, J. Janiszewski, F. Jiang, *Materials* **13**(9), 2204, 2020.
<https://doi.org/10.3390/ma13092204>

Thermographic Measurements of Selected Materials During Uniaxial Tensile Testing

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KEYWORDS: *Thermographic Measurements, Experimental Mechanics, Tensile Test, Ballistic Materials.*

Modern materials require reliable characterization of failure parameters for numerical modelling, particularly in ballistic applications. This includes proper description of failure initiation and propagation mechanisms, as well as the associated thermo-mechanical effects. The aim of this study was to investigate temperature evolution on the surface of selected materials during uniaxial tensile testing using infrared thermography. The investigated materials included structural steel as well as high-performance ballistic fibres such as aramid fibres and ultra-high molecular weight polyethylene (UHMWPE). Two measurement approaches were analysed: (i) specimens with natural surface condition and (ii) specimens coated with black paint to increase and standardize surface emissivity. Temperature fields were evaluated in terms of average temperature within the selected region of gage length as well as maximum local temperature. The UHMWPE fibre specimen mounted in the testing machine together with the thermographic images obtained during tensile testing are presented in Figure 1.

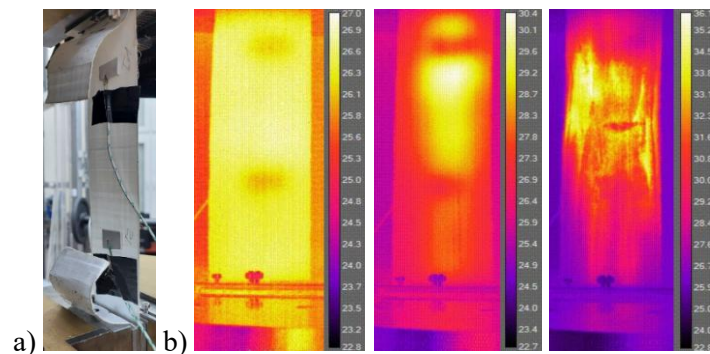


Figure 1. Example UHMWPE specimen mounted in a universal testing machine during uniaxial tensile testing (a), and representative failure progression recorded by infrared (IR) thermography during tensile loading (b).

The thermographic signal is fundamentally related to thermal radiation governed by the Stefan–Boltzmann law, where the emitted radiation E is proportional to the fourth power of the absolute temperature T [1]:

$$E = \varepsilon \sigma T^4. \quad (1)$$

In practical infrared thermography, the recorded signal includes emitted and reflected radiation contributions, while atmospheric effects are typically negligible under laboratory conditions [2]. Therefore, emissivity coefficients ε were experimentally determined for all investigated materials. The observed temperature distributions reflected the local damage development and failure progression occurring during tensile loading.

ACKNOWLEDGEMENT: This work was financed/co-financed by Military University of Technology under research project UGB 531-000103-W100-22.

- [1] Maldague, X.P.V., Theory and Practice of Infrared Technology for Nondestructive Testing, Wiley, 2001.
- [2] Vollmer, M., Möllmann, K.-P., Infrared Thermal Imaging – Fundamentals, Research and Applications, Wiley, Second Edition, 2018.

Experimental Identification of the Yield Surface for Inconel Alloys Manufactured by Using Laser Engineered Net Shaping

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KEYWORDS: *Inconel, Yield surface, Additive manufacturing, Laser Engineered Net Shaping*

In this study, tubular specimens of Inconel 625 and Inconel 718 were additively manufactured using the Laser Engineered Net Shaping (LENS) technique (Fig.1a). Their initial yield surfaces were experimentally determined under biaxial stress loading at 0.005% and 0.01% plastic offset strain (Fig.1b). Uniaxial tensile tests showed yield strengths of 509 MPa and 461 MPa, with Young's moduli of 180 GPa and 171 GPa for Inconel 625 and Inconel 718, respectively. Yield surfaces, fitted using the Szczepiński anisotropic criterion, revealed elliptical shapes with axis ratios below 1.73, confirming moderate anisotropy. Inconel 625 exhibited nearly symmetric yield strengths in tension and compression, with a higher tensile-direction elongation of the surface, whereas Inconel 718 showed stronger directional dependence, reflecting a higher degree of mechanical anisotropy [1].

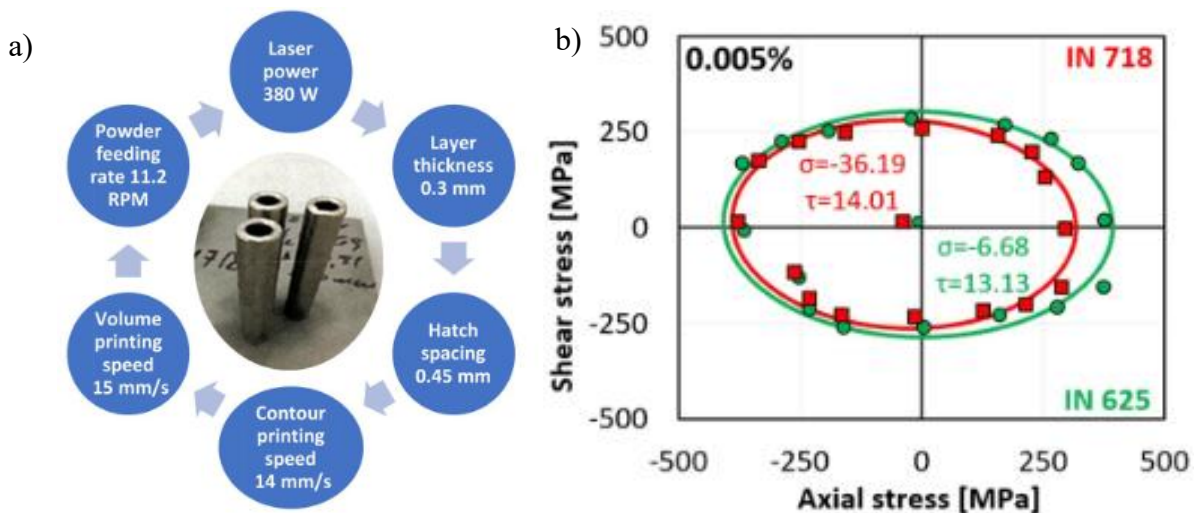


Figure 1. LENS process parameters with overview of the built plate with manufactured specimens (a); comparison of the yield surfaces of Inconel 625 and Inconel 718 for 0.005% plastic offset strain (b).

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- [1] H. Przygucki, V.P. Dubey, T. Durejko, D. Przygucka, Z. L. Kowalewski, S. Jóźwiak, M. Kopec, *Experimental identification of the yield surface for inconel alloys manufactured by using laser engineered net shaping*. Int J Adv Manuf Technol (2026). <https://doi.org/10.1007/s00170-026-17839-7>

Development of Highly Oriented CNF Long Filaments by Air Drying

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KEYWORDS: Cellulose Nanofiber, Orientation, Tensile Strength, Filament.

Cellulose nanofibers (CNF) are attracting attention as a sustainable natural resource for reducing environmental burden. CNF is a lightweight, high-strength renewable resource, and further increases in strength are expected by enhancing the orientation of the fibers.

In previous studies, it was confirmed that producing CNF in a filamentary form result in high orientation and improved mechanical properties[1]. There is a need for longer CNF filaments that offer high performance at a lower cost. In this study, we aim to develop a simple, low-cost method for producing filaments composed solely of CNF, with the goal of achieving high orientation and long lengths through air drying.

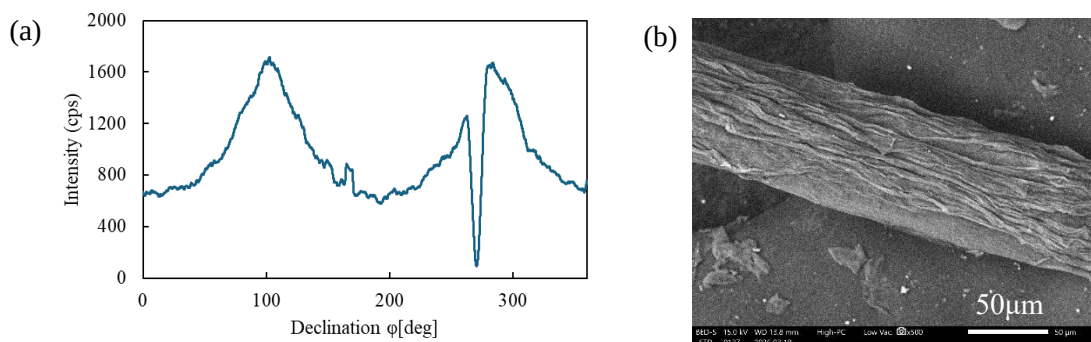


Figure 1. (a) the relationship between the X-ray diffraction angle and intensity (b) SEM image

Test specimens were produced by filling a syringe with Sugino Machine Co., Ltd.'s 2 wt% CNF water dispersion (Ima-10002), manually extruding the material, and air-drying. A 1 ml syringe was used, fitted with a 38 mm long needle having an inner diameter of 0.25 mm and a flat-tipped design. It was possible to produce a filament up to approximately 150 mm in length with a diameter of 100 μm or less.

Fig. 1(a) shows the relationship between the diffraction angle and intensity in X-ray diffraction. It confirms the fiber of orientation. Fig. 1(b) shows a SEM image of the produced CNF filament. It clearly demonstrates the high orientation of the CNF.

In addition, tensile strength is evaluated. Further improvements in performance are being considered.

- [1] Guantong Wang et al, "Enhanced High Thermal Conductivity Cellulose Filaments via Hydrodynamic Focusing", NANO Letters, Vol. 22. No.21, pp. 8406-8412, 2022.

Evaluation of Mode I and Mode II Fracture Toughness on Ramie, Basalt and Hybridised Reinforced Polymer Composites.

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KEYWORDS: *Sustainable Materials, Ramie Composite, Basalt Composite, Fracture Toughness, Mode I fracture, Mode II fracture, Hybridisation,*

Conventional composites made of synthetic fibres are widely used in various applications, ranging from the wind-energy sector to the automotive and aerospace industries. Most of them are non-biodegradable and non-recyclable, and are ultimately disposed of in landfills after their service life. Therefore, it is imperative to develop environmentally friendly composite materials. Plant and mineral-based fibers have shown promising results as alternatives to non-biodegradable fibers for semi-load-bearing structural elements. This research investigates the fracture toughness behavior of Ramie, Basalt, and Hybrid combination in Ramie/Basalt laminates under Mode I and Mode II loadings. The specimens were fabricated by hand layup method followed by vacuum bagging using unidirectional Ramie and Basalt fibers and an aircraft-grade epoxy resin system (Araldite LY5052 / Aradur 5052 CH). A major focus of the study is on understanding how hybridization affects the fracture toughness relative to the reference samples. The experiments were performed using Double Cantilever Beam (DCB) and End-Notched Flexural (ENF) tests in accordance with ASTM standards. The findings give insights into the synergistic toughening mechanism, which ultimately helps us to design a reliable and sustainable hybrid composite structure at a commercial level.

Session TS8

Geomechanics and granular materials

Multiphysics Analysis of Salt-Induced Degradation in Porous Materials

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KEYWORDS: *Salt crystallization, Capillary uptake, Localized damage, Structural masonry.*

Salt crystallization is a primary factor contributing to the deterioration of porous building materials, including masonry, concrete, and natural stone. Salt damage occurs when a porous medium contains both soluble salts and moisture. Dissolved ions, such as chlorides, nitrates, and sulfates, are transported by liquid water through the interconnected pore network via capillary flow. Moisture ingress can result from hygroscopic absorption, rainwater infiltration, condensation, or capillary rise from the ground, the latter being particularly common and difficult to mitigate. Under conditions that promote evaporation or temperature fluctuations, supersaturation may develop, leading to the nucleation and growth of salt crystals within the pore structure.

Salt crystallization can induce surface exfoliation or the development of microcracks due to crystallization pressure. The latter process, referred to as subflorescence, is particularly damaging, as crystal growth within pores generates expansive forces that lead to the initiation and propagation of internal damage within the material.

This paper focuses on the mechanical analysis of the effects of salt crystallization in porous materials, with primary emphasis on structural masonry components. In the first part of the study, inelastic constitutive relations governing deformation in the presence of salt crystallization are presented. Instead of explicitly modeling crystallization pressures, which are difficult to quantify due to complex pore geometry, the approach extends classical rate-independent plasticity by introducing an additional internal variable, viz. the pore volume fraction occupied by crystallized salt, defined as an explicit function of time. Subsequently, a coupled hydro–chemo–thermal framework for modeling salt crystallization in porous masonry materials is outlined. The formulation integrates moisture transport, dissolved salt advection–diffusion, temperature-dependent solubility, and kinetic crystallization laws within a finite element framework. The evolution of porosity and permeability induced by salt precipitation is explicitly incorporated, enabling reliable prediction of transport–crystallization interactions under transient environmental conditions.

Two independent benchmark problems are analyzed first to validate the transport formulation. These involve (i) a cooling–warming simulation focused on the evolution of dissolved salt concentration and crystallization dynamics under cyclic thermal loading, and (ii) the simulation of a drying process that captures evaporation-driven supersaturation and surface-dominated precipitation. The mechanical effects of crystallization are examined by analyzing a masonry specimen subjected to tension parallel to the bed joints. The spatial distribution of precipitated salt obtained from the transport analysis is incorporated into the mechanical model, and the localized fracture mechanism is analyzed by employing a constitutive law with embedded discontinuity. The crystallization effects are introduced through degradation of strength parameters at the brick–mortar interfaces. In addition, another heuristic example is provided, in which a masonry triplet is subjected to a sustained lateral load under a prescribed temporal history of salt deposition. This loading scenario leads to a spontaneous loss of stability of the specimen.

Modelling of concrete behaviour using a novel DEM-based thermal-hydro-mechanical model

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KEYWORDS: Concrete, DEM-CFD, Heat transfer, Strain rate, Fragmentation

The numerical investigations focus on two-dimensional simulations of the behavior of concrete under uniaxial compression and tension in both quasi-static and dynamic conditions. The influences of fluid migration, aggregate fragmentation, strain rate, and thermal conditions were examined. Concrete was characterized as a four-phase material, consisting of aggregate, mortar, interfacial transition zones (ITZs), and pores, derived from a micro-CT image. A comprehensive coupled DEM/CFD methodology, grounded in a pore-scale thermal-hydro-mechanical model [1], was employed for simulations. The method's concept established a network of channels among 3D discrete elements inside a continuous region to facilitate fluid flow. It was proposed that partly saturated material with low porosity exhibited a two-phase laminar fluid flow consisting of air and water. The fluid in the channels was both immiscible and incompressible across all flow regimes. In contrast to the channels, the fluid was compressible within the pores and fractures (grid elements). The locations and volumes of pores and fractures were ascertained to precisely monitor the liquid/gas content. Heat transport was regulated by fluid dynamics (diffusion and advection), particle interactions (conduction), and phase transitions. In multi-phase fluid flow, temperature was uniform, although enthalpy was exchanged. The heat transmission model was simplified in a manner analogous to the fluid flow model. Consequently, a homogenous heat transfer model was presumed in multiphase flow, disregarding mass transfer between phases. The multi-phase fluid was converted into a single-phase fluid. The effective fluid characteristics and velocity were determined using volume averaging over the phases. The numerical solution used the identical coarse mesh of both domains utilized to establish the fluid flow network for solving the governing equations. The model [1] was augmented by incorporating phase transitions at elevated temperatures. An technique known as clump breakage [2] was utilized to simulate intra-granular fragmentation of aggregate, employing clumps made of small spheres to represent particles of varying dimensions and shapes. Various aggregate strengths were expected.

Numerical computations were conducted with YADE, an open-source discrete element method (DEM) tool, employing the soft-particle methodology. Focus was directed towards the strength, brittleness, fracture mechanisms, free water pressures and velocities, and temperatures in concrete during simulations of uniaxial compression and tension at varying strain rates. The effects of fluid viscosity and fluid saturation were also examined. The numerical results were juxtaposed with the relevant experiments [3].

REFERENCES

- [1] M. Krzaczek, J. Tejchman, M. Nitka, A novel DEM-based pore-scale thermal-hydro-mechanical model for fractured non-saturated porous materials, *Acta Geotechnica*, **18**, 2487–2512, 2023.
- [2] M. Krzaczek, J. Tejchman, M. Nitka, Impact of strain rate, free water, and aggregate fragmentation on the dynamic behavior of concrete in compression regime using a unique coupled DEM/CFD technique, *Granular Matter*, **27**(79), 1-20, 2025.
- [3] O. Arioz, Effects of elevated temperatures on properties of concrete, *Fire Safety Journal*, **42**, 516-522, 2007.

A New Loading Fixture for Direct Rock Fracture Toughness Determination Using pCT and Short Rod Specimens

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KEYWORDS : *fracture toughness, pCT, short rod, direct shear apparatus, experimental methods*

Determination of Mode I fracture toughness in brittle geomaterials typically requires complex and specialized loading systems, limiting the practical use of established methods such as the pseudo-Compact Tension (pCT) and ISRM Short Rod (SR) tests [1,2]. This study presents a simplified and cost-effective approach that enables both methods to be performed using a conventional direct shear apparatus. A novel shear-to-tensile (ST) loading fixture is developed to generate controlled tensile loading within the shear box. The fixture consists of CNC-cut structural steel plates and can be easily installed without additional equipment. This setup allows the execution of pCT, proposed here as a direct fracture mechanics test, and SR testing within a single, accessible system. Finite element simulations in Abaqus were conducted to design and optimize the fixture prior to manufacturing, ensuring adequate stiffness and load transfer. The numerical model and representative pCT results are shown in Fig. 1. The method supports both dry and submerged testing conditions and enables stable crack propagation with post-peak response capture. Experimental validation on gypsum specimens shows that the obtained fracture toughness values are consistent with standard methods, including Semi-Circular Bend (SCB) and Cracked Straight Through Brazilian Disc (CSTBD) tests. For SR, an average K_{IC} of approximately $0.287 \text{ MPa}\sqrt{\text{m}}$ was obtained, compared to approximately $0.288 \text{ MPa}\sqrt{\text{m}}$ from SCB, demonstrating good agreement. The proposed approach significantly reduces experimental complexity, cost, and setup time, while eliminating the need for external displacement measurement devices such as LVDTs. It provides a practical and efficient alternative for fracture toughness testing, with potential for broader application to stronger rock materials.

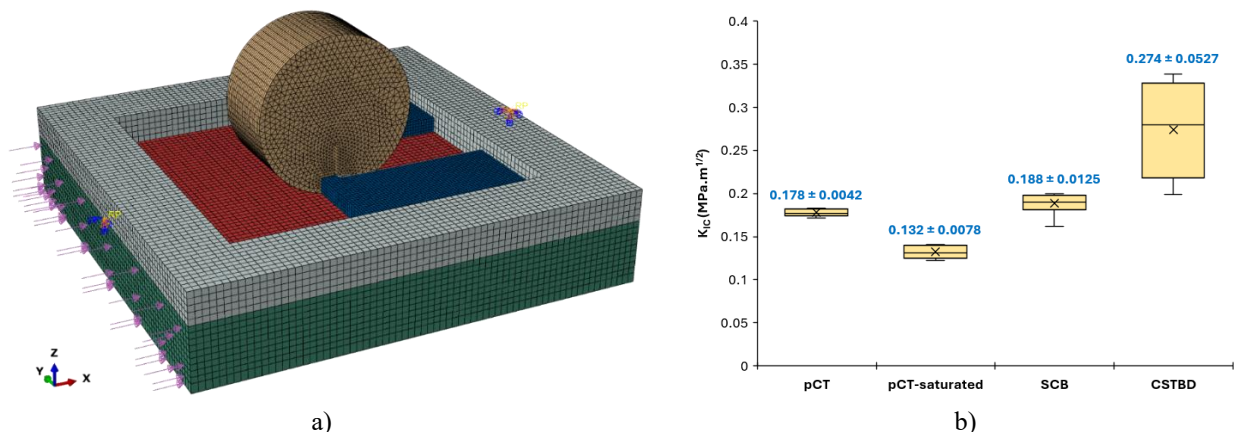


Figure 1. (a) FEM model of the ST tool for pCT. (b) Comparison of K_{IC} results from pCT, SCB, and CSTBD tests.

- [1] Muñoz-Ibáñez, A., Delgado-Martín, J., Costas, M., & Juncosa-Rivera, R. (2020). Pure Mode I fracture toughness determination in rocks using a pseudo-compact tension (pCT) test approach. *Rock Mechanics and Rock Engineering*, 53, 3267–3285. <https://doi.org/10.1007/s00603-020-02102-6>
- [2] Ouchterlony, F. (1988). ISRM commission on testing methods: Suggested methods for determining the fracture toughness of rock. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, 25(2), 71–96.

Investigation of Frictional Behavior on Corrugated Silo Walls During Confined Granular Flow

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KEYWORDS: *Sand, Silo, Granular Flow, Discrete Element Method.*

Bulk solid-structure interfaces commonly occur in the field of silo constructions. The study investigates the interface between granular material and silo walls during confined flow, with particular emphasis on frictional behavior and wall geometry. The interface behavior is characterized by the formation of shear zones in the material region adjacent to the construction surface which play a critical role in governing flow kinematics and stress transmission in silo structures [1]. For this purpose, a series of experimental and numerical tests of granular flow in a model-scale silo have been carried out.

Laboratory experiments and numerical simulations were conducted using a rectangular silo. In the experimental part, Digital Image Correlation (DIC) was applied to quantify displacement and strain fields, enabling identification of shear localization zones near the wall. Tests were performed for different wall geometries (shallow and wavy), using sand as bulk material. In addition, during the experimental study, forces acting on corrugated walls and on the silo bottom were measured. The results demonstrate that wall geometry-especially corrugation depth-strongly influences flow patterns and the development of shear zones at the interface.

Complementary numerical analyses were carried out using the Discrete Element Method (DEM) [2]. In the study, the granular material was modelled as hundreds of thousands spheres with rolling resistance. The simulations reproduced the experimental setup and provided insight into both macroscopic flow behavior and grain-scale mechanisms, including particle rotations, force chains, and void distribution. The numerical results showed good agreement with experiments and confirmed that wall profile significantly affects flow force distribution. During the flow, the forces between the grains and the walls of the silo were measured along the entire height of the silo wall. It has been shown that the increase of the, e.g. corrugation depth induced the increase of the pressures exerted on these walls.

Overall, the study demonstrates that wall geometry has a substantial impact on interface behavior and pressures exerted on silo walls. These findings contribute to a more accurate assessment of loads in corrugated silo structures.

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- [1] Wójcik, M., Sondej, M., Rejowski, K., & Tejchman, J. (2017, April). Full-scale experiments on wheat flow in steel silo composed of corrugated walls and columns. *Powder Technology*, 311, 537–555. <https://doi.org/10.1016/j.powtec.2017.01.066>.
- [2] Cundall, P. A., & Strack, O. D. L. (1979). A discrete numerical model for granular assemblies. *Géotechnique*, 29(1), 47–65. <https://doi.org/10.1680/geot.1979.29.1.47>

Prediction of elastic properties of cement paste using computational homogenization: a comparison of different microstructural models

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KEYWORDS: *Computational Homogenization, Micro-CT, Micromechanics, Multiscale Modelling, Representative Volume Element, Numerical Methods.*

The microstructure of cement paste, formed during hydration, is typically composed of hydration products, unreacted clinker particles, and pores. Microstructure-informed micromechanical models establish a link between the microstructure and the effective mechanical properties [1]. This study addresses the computational homogenization of cement paste, accounting for different types and sizes of representative volume elements (RVEs). Two microstructure models are considered: one based on simulations of the hydration process, and the other derived from experimental microtomographic data [2]. The hydration process is simulated using the Virtual Cement and Concrete Testing Laboratory (VCCTL) software [3]. To enable a direct comparison between the considered microstructure models, a simplified three-phase virtual microstructure is also developed [4]. A multilevel Mori–Tanaka analytical scheme is employed to perform preliminary homogenization of anhydrous cement grains and hydration products. Subsequently, the homogenization is carried out using a Fast Fourier Transform (FFT)-based method. In addition, local stress distributions at the microstructural level are analyzed for both microstructure models. For sufficiently large RVEs, good agreement is observed between the simulation-based and experimentally based microstructure models. During the conference, the influence of RVE size on effective properties, along with the differences between model outcomes, will be discussed.

ACKNOWLEDGEMENT: The research is supported by a grant implemented within the framework of the Excellence Initiative—Research University program, Silesian University of Technology (10/040/SDU/10-07-02) and partially by the Institute of Fundamental Technological Research of Polish Academy of Sciences.

- [1] H. Zhang, Y. Xu, Y. Gan, Z. Chang, E. Schlangen, B. Šavija, *Constr Build Mater*, 251:118983, 2020.
<https://doi.org/10.1016/j.conbuildmat.2020.118983>
- [2] M. Hlobil, I. Kumpová, A. Hlobilová, *Cem Concr Compos*, 134:104798, 2022.
<https://doi.org/10.1016/j.cemconcomp.2022.104798>
- [3] I. Pokorska, M. Poński, T. Burczyński, *Comput Assist Methods Eng Sci*, 31:507–18, 2024.
<https://doi.org/10.24423/comes.2024.1770>
- [4] W. Ogierman, I. Pokorska, T. Burczyński, *Int. J. Numer. Methods Eng.* 126, 1–22 2025.
<https://doi.org/10.1002/nme.70200>

Application of FEM for the assessment of the load-bearing capacity of reinforced concrete and prestressed structures at risk of corrosion

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KEYWORDS: *FEM, corrosion, elastic-plastic, diffusion, degradation.*

The problem of reinforcement degradation is a key issue in assessing the durability of reinforced and prestressed concrete structures. The term corrosion here refers to the combined effects of various mechanisms, including electrochemical and stress corrosion, as well as, in some cases, the influence of aggressive substances that contribute to the degradation of both steel and concrete (e.g., ammonium ions). An example illustrating the importance and complexity of corrosion-induced damage is the collapse of the prestressed Carola Bridge in Dresden in 2024 [1].

This paper concerns the generalization and application of a thermomechanical model formulated in [2] to an elastic–plastic medium with diffusion (a non-electrically neutral model). The study focuses on applying the model to various material descriptions of steel (e.g., J2 and Chaboche models with different hardening rules), concrete (e.g., Menétrey–Willam and microplane models), degradation of the contact zone, and different types of reinforcement corrosion (e.g., stress corrosion and the effects of ammonium ions). The calculations were performed using ANSYS software and the APDL scripting language.

- [1] M. Fiedler, G. Schacht, R. Ritter, S. Marx, S. Scheerer, L. Clages, G. Ebell, D. Czeschka, C. Voigt, The Collapse of the Carola Bridge – Forensic Engineering and Palliative Monitoring, in.: 13th International Conference on Structural Health Monitoring of Intelligent Infrastructure; SHMII-13, Verlag der Technischen Universität Graz, 762-767, 2025. [https:// doi.org/10.3217/978-3-99161-057-1-118B](https://doi.org/10.3217/978-3-99161-057-1-118B)
- [2] T. Krykowski, Application of the theory of diffusion-elastic-plastic medium to evaluate the load-bearing capacity of structural elements subject to corrosion, no. 4, 2026 (accepted to print).

Incorporation of cross-anisotropic small strain stiffness into the Hardening Soil model

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KEYWORDS: *Cross-anisotropy, Soil small strain stiffness, Hardening Soil model, FE modelling.*

The Hardening Soil (HS) model [5] is widely used as a standard simulation tool in advanced geotechnical analyses. It is implemented in many commercial finite element codes, and its parameters are typically derived from standard laboratory or field tests, or from empirical correlations. The model incorporates well-established concepts in soil mechanics, including barotropy, dilatancy, shear strength, and nonlinear pre-failure stiffness. In its basic form, the elastic component of the HS model is isotropic and hypoelastic. In a recent refinement of the HS model, a small-strain stiffness extension, referred to as HS-Brick, was introduced [3]. This extension accounts for the degradation of small-strain stiffness. It captures the initially high stiffness of soil before shear strains are mobilized, enabling more realistic predictions of deformation in engineering practice. It preserves the same general assumptions and material parameters as the widely used HSS model [1], but without the significant issue of stiffness overshooting observed in the HSS model. Both the original HS model and its small-strain extensions remain entirely isotropic. While accounting for the nonlinearity of small-strain stiffness represents a significant improvement, numerous studies have shown that incorporating anisotropy of small-strain stiffness leads to much more accurate deformation predictions when compared with geotechnical measurements. Despite its importance, anisotropic pre-failure stiffness is rarely implemented in commercial constitutive models due to the increased complexity of their formulation and calibration. Its practical application is also limited by the scarcity of reliable parameters describing anisotropy. However, recent advances in field and laboratory testing have enabled more precise investigations of anisotropic soil behavior. In most cases, cross-anisotropy is assumed to describe the directional dependence of soil mechanical properties. In elastoplastic modelling, cross-anisotropy can be introduced in both pre-failure stiffness and ultimate shear strength (e.g., via strength criteria or yield surfaces). The Anisotropic HS-Brick model (AHS-Brick), proposed and validated in this presentation, is the first extension of the HS-Brick model to incorporate inherent cross-anisotropy, limited to the pre-failure range [2]. Cross-anisotropy is introduced through a specialised scaling of the isotropic hypoelastic stiffness matrix [4]. The model is primarily intended for simulating the pre-failure mechanical behaviour of cross-anisotropic, stiff, fine-grained soils. Details of the finite element implementation are provided, along with selected element-level tests. Finally, the model performance is evaluated using an exemplary boundary value problem involving tunnelling-induced deformations. The results are analysed and discussed.

- [1] T. Benz. *Small-strain stiffness of soils and its numerical consequences*. PhD thesis, University of Stuttgart, 2007.
- [2] M. Cudny, K. Lisewska, and A. Truty. Incorporation of cross-anisotropic small strain stiffness into the hardening soil model. *accepted to Acta Geotechnica*, 2026.
- [3] M. Cudny and A. Truty. Refinement of the Hardening Soil model within the small strain range. *Acta Geotechnica*, 15(8):2031–2051, 2020.
- [4] A. Niemunis and K. Staszewska. Pure cross-anisotropy for geotechnical elastic potentials. *Acta Geotechnica*, 17:1699–1717, 2022.
- [5] T. Schanz, P. A. Vermeer, and P. G. Bonnier. The Hardening Soil model: Formulation and verification. In *Beyond 2000 in Computational Geotechnics - 10 Years of Plaxis*, pages 1–16. Balkema: Rotterdam, 1999.

Session TS9

**Mechanics of advanced materials
and smart structures**

Investigation on Improving the Performance of Mechanical Metamaterials Expanded by Sound Waves

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KEYWORDS: *Mechanical Metamaterial, Actuator, Regular Structure, Sound Waves, Smart Material.*

This study proposes a hexagonal unit cell with an asymmetric membrane that undergoes expansion deformation under acoustic excitation. The proposed design aims to realize a two-dimensional periodic structure driven by contactless and wireless acoustic energy transfer, eliminating the need for conventional wiring or onboard power supplies. First, finite element analysis was conducted to investigate the deformation behavior of the proposed structure under sound-wave excitation. Based on the analytical model, test specimens were fabricated using a 3D printer, and experiments were performed to validate the deformation characteristics. In the experiments, the membrane was excited by acoustic waves incident normal to its surface. Under acoustic excitation at the resonant frequency of 50 Hz, the membrane exhibited stable expansion deformation, and the expansion behavior was maintained even when multiple unit cells were connected vertically and horizontally to form a two-dimensional periodic structure. Quantitative evaluation showed that the static expansion displacement increased from 5 μm in a single unit cell to 10 μm after interconnecting the unit cells into a periodic structure. Moreover, the equilibrium position shifted by 20 μm toward the expansion direction, suggesting that structural periodicity promotes both static and dynamic expansion responses under acoustic excitation. The proposed expansion behavior under acoustic excitation was confirmed through both numerical analysis and experimental validation.

In addition, theoretical investigations were conducted to clarify the conditions required to sustain the expanded state by examining the curvature and bending moments induced by membrane resonance. These findings demonstrate the potential of acoustically driven mechanical metamaterials ^[1] for lightweight, adaptive, and wirelessly actuated structures.

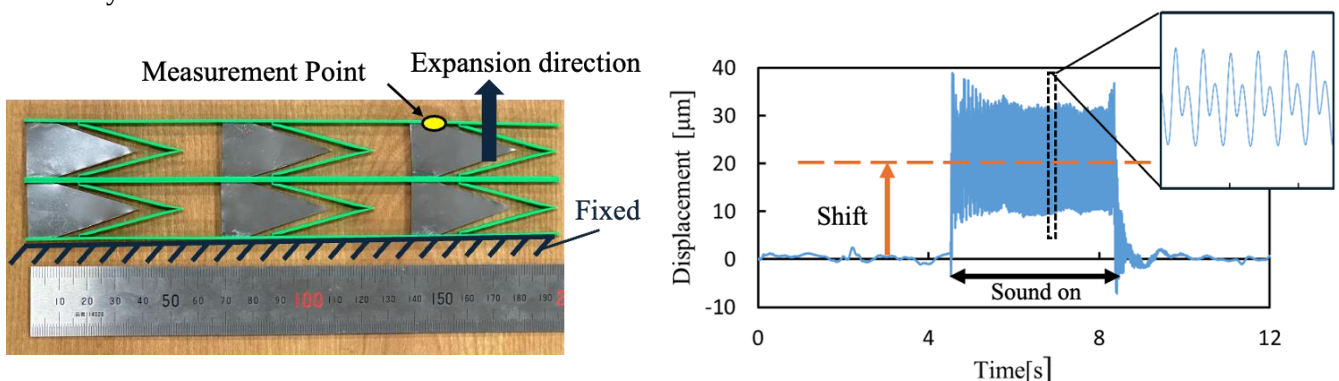


Figure 1. Test specimens and experimental results

- [1] Pengcheng Jiao, Jochen Mueller, Jordan R. Raney, Xiaoyu (Rayne) Zheng, Amir H. Alavi, Mechanical metamaterials and beyond, *Nature Communications* (2023)14:6004

Characterization of the mechanical response of 3D-printed metamaterials under static tensile, compressive and bending loads

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KEYWORDS: *Mechanical Metamaterials, Additive Manufacturing, Static Behaviour, Digital Image Correlation, Finite Element Method.*

This study examines the mechanical response of additively manufactured metamaterial specimens under tensile, compressive and bending loads. The analysis focuses on how cell orientation and internal topology affect the macroscopic performance of the structures. Two principal geometric concepts of regular lattices were considered (see Fig. 1): auxetic, composed of re-entrant concave cells and conventional, with convex unit geometries. Both variants were analysed in horizontal and vertical orientations of the unit cells.

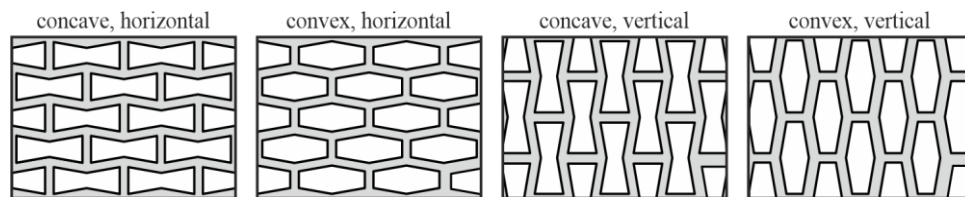


Figure 1. Metamaterial geometry concepts considered in the study.

Comprehensive experimental static tests were carried out using a universal testing machine integrated with a digital image correlation (DIC) system, enabling full-field deformation measurements. Based on the obtained results, a thorough quantitative and qualitative comparison of structural performance was carried out. From the tensile and compression data, effective elastic constants such as the Young's modulus and Poisson's ratio were derived, confirming that internal geometry plays a decisive role in tuning metamaterial stiffness. Bending tests further demonstrated that auxetic configurations are particularly sensitive to nonuniform stress distribution. Local damage effects caused by 3D printing imperfections were also observed. To complement the experimental work, numerical simulations of the laboratory tests were performed using the finite element method. The results exhibited good agreement with experimental data, confirming the reliability of the models. The combined experimental and numerical findings highlight the governing influence of geometrical design on the mechanical behaviour of additively manufactured metamaterials and validate the applied methodology as a reliable tool for predicting their load-bearing performance.

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Modeling metamaterials by second-order rate-type constitutive relations between only the macroscopic stress and strain

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KEYWORDS: *metamaterials, mathematical modelling, constitutive relations, nonlinear elasticity*

Metamaterials are materials with specifically designed microstructure which grants them unusual properties not typically seen in nature such especially regarding wave propagation. Macroscopic behavior of such materials is typically described by homogenous linear elastic material with the effective density and stiffness depending on the frequency. The resulting effective density / stiffness can be even negative for certain frequencies. Such interpretation contradicts the principles of Newtonian mechanics that the mass is constant. A few different ways have been proposed to address this issue. These alternative models utilize concepts of "micro-level deformation", "micromorphic continua" or "enriched continua". While details may vary, the key idea is the same – introduce an additional kinematic variable.

We present yet another approach that addresses the issue, and which results in effective rate-type constitutive relations. The relations are formulated as second-order in time rate-type Eulerian constitutive relations between only the Cauchy stress tensor, the Hencky strain tensor and objective time derivatives thereof without the need to introduce additional kinematic variables. Furthermore, the proposed approach works even in finite deformations setting, and the resulting constitutive relations are thermodynamically consistent. The linearisation of the constitutive relations leads to the same Fourier representation as the model utilizing frequency dependent quantities, but with constant material parameters.

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- [1] D. Cichra, V. Průša, K.R. Rajagopal, C. Rodriguez and M. Vejvoda: *The conclusion that metamaterials could have negative mass is a consequence of improper constitutive characterization*, Mathematics and Mechanics of Solids, **30**(12), 2762–2779, 2025. <https://doi.org/10.1177/10812865241308823>
- [2] V. Průša, C. Rodriguez, L. Trnka and M. Vejvoda: *Modeling metamaterials by second-order rate-type constitutive relations between only the macroscopic stress and strain*, European Journal of Mechanics - A/Solids, 116, 2026, <https://doi.org/10.1016/j.euromechsol.2025.105879>

Sierpinski–Knopp Fractal Based Architected Composite for Improved Competing Mechanical properties

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KEYWORDS: Architected Composite, SK Fractal, Design of Composite, Stiffness, Damping.

Architected composites are materials in which the mechanical performance is governed by the deliberate design of internal geometry and spatial arrangement of constituent phases. The designed materials allow tailorability in mechanical properties as well as combine otherwise competing mechanical properties. Stiffness and damping are competing mechanical properties in engineering materials. In this work, a planar design, based on Sierpinski–Knopp (SK) curve, for architected composite is presented for simultaneous stiffness, toughness and damping. SK space filling curve is a fractal curve generated by recursive sub-structuring based on right, isosceles triangle. To achieve planar isotropy, SK curve is implemented over equilateral triangles maintaining hexagonal symmetry (Fig. 1). Owing to interlocking nature and ease of fabrication (3D printing) 6th iteration of SK curve is used. The constituents are considered to be stiffer polylactic acid (PLA) and a compliant polyurethane (PU). The dimensions of the geometry are chosen considering fabrication by 3D printing and experimental characterization. Finite element simulations are performed to evaluate the effective elastic modulus and damping characteristics. The stiff PLA has elastic modulus of 1210 MPa and zero damping capacity, whereas PU has high damping of 0.6 and low stiffness. The results demonstrate nearly isotropic elastic behaviour with an effective modulus of 124 MPa. Furthermore, a significant increase in stiffness (up to 190 MPa) can be obtained with reduced compliant layer thickness. Simultaneous stiffness-damping is found to be enhanced in the proposed architected composite. These findings highlight the potential of fractal-inspired architected composites for applications requiring simultaneous mechanical robustness and vibration damping. This paper will present the salient results of a numerical and experimental study through mechanical testing, deformation analysis using Digital Image Correlation (DIC) to assess the performance of the proposed design.

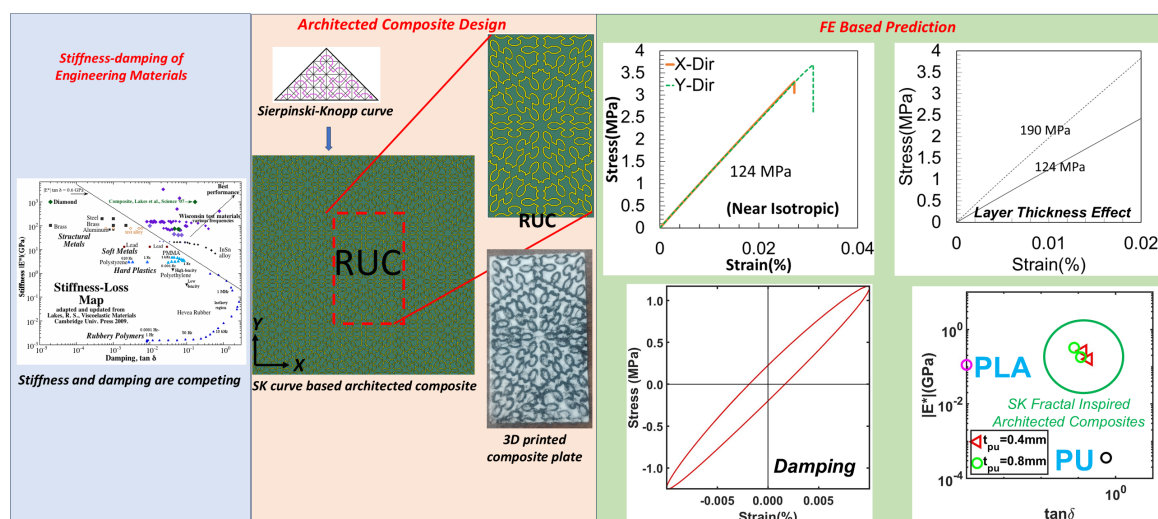


Figure 1. Architected composite using Sierpinski–Knopp fractal for simultaneous stiffness-damping performance.

Finite-strain constitutive model for shape memory alloys formulated in the logarithmic strain space

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KEYWORDS: *Constitutive Model, Shape Memory Alloys, Finite Strains, Vectorization.*

The unique mechanical properties of shape memory alloys (SMAs) have found applications in numerous engineering devices across different industries. Many of these applications inherently undergo large rotations and/or moderate or finite strains. Consequently, computational analysis of their mechanical response must be extended beyond the small-strain regime.

This contribution presents a finite-strain version of an established three-dimensional constitutive model for polycrystalline SMAs [1]. The original small-strain model, developed within the Generalized Standard Materials framework, was augmented to be more versatile in capturing the transformation kinetics. Then it was extended to the finite strains regime using the approach introduced in [2]: instead of modifying the constitutive core, the extended model was constructed via reinterpreting the inputs of the original small-strain model within the Lagrangian logarithmic (Hencky) strain space and via employing geometric pre- and post-processing to map between the objects in logarithmic strain space (e.g. Hencky strain, logarithmic stress) and those in the Lagrangian reference (e.g. right Cauchy–Green deformation tensor, nominal stress).

The main implementation challenge lies in algorithmizing the pre- and post-processing phases, with tensor spectral decomposition as the primary computational bottleneck. This was addressed by leveraging the vectorization capabilities of MATLAB software and the techniques introduced in [3]. The model was then implemented in finite element software to solve evolutionary boundary value problems. Material parameters were fitted to experimental data for two SMAs, and computational simulations of SMA components were conducted to demonstrate the model's performance and validate the implementation. The applied approach is highly flexible for incorporating also other phenomena, e.g., irreversibility associated with plasticity, into the model.

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- [1] A. Moskovka, M. Horák, J. Valdman, M. Knappek, M. Janeček, P. Sedlák, M. Frost, *Shap. Mem. Superelasticity* **11**, 726–737, 2025. <https://doi.org/10.1007/s40830-025-00562-9>
- [2] C. Miehe, N. Appel, M. Lambrecht, *Comput. Methods Appl. Mech. Engrg.* **191**, 5383–5425, 2002. [https://doi.org/10.1016/S0045-7825\(02\)00438-3](https://doi.org/10.1016/S0045-7825(02)00438-3)
- [3] A. Moskovka, T. Rahman, J. Valdman, J.E. Vatne, *Appl. Math. and Comput.* **513**, 129778, 2026. <https://doi.org/10.1016/j.amc.2025.129778>

Overcoming the Strength–Ductility Trade-Off in LPBF Duplex Stainless Steel via Heterogeneous Phase Structuring

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KEYWORDS: *Laser powder bed fusion (LPBF), Solution annealing, Tensile strength.*

The annealing process plays an important role in unlocking the full potential of 3D printed duplex stainless steels (DSS). While Laser Powder Bed Fusion (LPBF) enables the production of complex geometries, the process introduces a fundamental material challenge: the rapid cooling and solidification rates inherent to LPBF typically result in ferrite supersaturation [1]. This creates an "as-built" microstructure that is extremely hard and strong, often exhibiting yield strengths exceeding 1000 MPa but is compromised by significant brittleness and a deviation from the ideal 50:50 austenite-ferrite balance.

To address this, post-processing solution annealing (typically performed above 1000°C) is standard practice. This treatment successfully promotes the transformation of metastable ferrite into softer austenite and restores the protective passive film essential for corrosion resistance [2]. However, this restoration comes at a steep mechanical cost. As the material recovers and recrystallizes to relieve residual stress, the tensile strength drops often falling to 500–600 MPa in exchange for improved ductility. Consequently, current processing methods force a binary choice: the high strength of the as-printed state or the high ductility of the annealed state.

This study proposes a novel approach to bridge this trade-off by engineering a heterogeneous structured DSS. By optimizing 3D printing parameters to generate alternating layers of ferrite and austenite, we aim to retain structural strength while introducing necessary ductility without relying solely on strength-depleting annealing cycles.

To validate this methodology, a multi-faceted characterization strategy was employed. First, Scanning Electron Microscopy (SEM) was utilized to visualize the layer morphology and assess the structural integrity of the printed lattice. Following this, Electron Backscatter Diffraction (EBSD) was used to quantify the phase distribution, specifically verifying if the optimized scan strategy successfully increased the austenite volume fraction to the desired levels. Finally, the mechanical efficacy of this heterogeneous structure was tested through uniaxial tensile testing. Tensile testing increased due to the grain size difference between the alternating layers. Ferrite layer showed a coarse grain size distribution while the austenite layer showed a fine grain size distribution resulting in a more ductile DSS. The initial research demonstrated a processing route that achieves a superior balance of strength and ductility than traditional post-processing methods allow.

- [1] S. Papula *et al.*, "Selective Laser Melting of Duplex Stainless Steel 2205: Effect of Post-Processing Heat Treatment on Microstructure, Mechanical Properties, and Corrosion Resistance," *Materials*, vol. 12, no. 15, Aug. 2019, doi: <https://www.doi.org/10.3390/ma12152468>.
- [2] C. Herrera, D. Ponge, and D. Raabe, "Recrystallization during Annealing of a Cold Rolled Lean Duplex Stainless Steel," *Mater. Sci. Forum*, vol. 715–716, pp. 550–550, Apr. 2012, doi: <https://www.doi.org/10.4028/www.scientific.net/MSF.715-716.550>.

Design of Actuation Performance of a Rubber Metal bimaterial

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KEYWORDS: *Smart materials, Rubber, Bimaterial, Actuator, Large deformation*

Actuators using smart materials offer significant advantages in weight reduction and installation flexibility. This study focuses on the design and mechanical evaluation of a light-driven actuator composed of a rubber-layer and metal layer. While its driving principle is similar to a conventional bimetal^[1], this composite utilizes the negative linear expansion coefficient of pre-stretched rubber^[2]. This characteristic allows for significantly larger deformation compared to standard metallic bimetals, which is a key advantage for compact robotic applications.

However, the substantial difference in expansion rates between the rubber and metal layers leads to a large deformation condition, making the precise prediction of the force and the deformation highly complex. To address this, loading tests using a horizontal cantilever beam configuration was conducted. The experimental setup is shown in Fig. 1, illustrating the beam's response under thermal loading with external weights. To establish a reliable design framework, a theoretical formulation considering large-scale deflection was considered and compared with Non-linear Finite Element Analysis (FEA). By analyzing the correlation between experimental data and numerical results, we clarified the mechanical behavior of the composite. These findings provide the parameters for the optimal design of this material as a functional, large deformation actuator in practical environments.

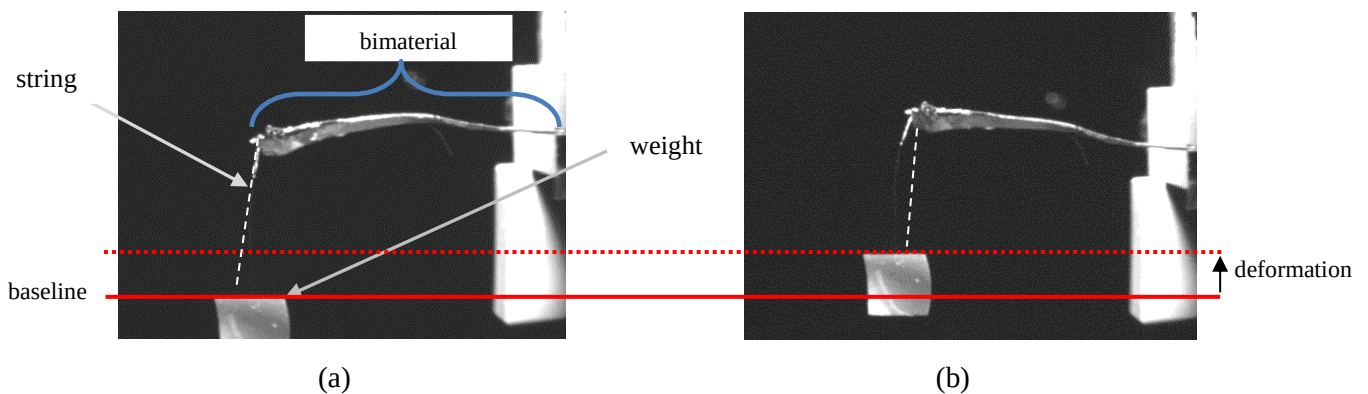


Figure 1. Experimental setup for thermal deformation of a horizontal beam with weight.

(a) before heating, (b) after heating

[1] S. Timoshenko(1925) Analysis of bimetal thermostats. J.Opt.Soc. Am,11(3), 233-255.

[2]. K. H. Meyer, C. Ferri (1935) Hely. Chim. Ada, 18, 570

Contraction Performance of a Structure Contracted by Sound Waves for Mechanical Metamaterials

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KEYWORDS: *Mechanical Metamaterials, Sound Waves, Actuator, Additive Manufacturing.*

Recently, the artificial materials, so-called metamaterials[1] have attracted attention due to their special properties. According to the progress of 3-D printing technologies, mechanical metamaterials[2] have also been studied. In the mechanical metamaterials, various artificial material properties can be designed by the structure of the unit cell of the regular structures.

In this study, the actuation performance of a mechanical metamaterial that responds to sound waves was investigated. A schematic figure of the unit cell of the metamaterial is shown in Figure 1, right. Hexagonal frames are connected, and a membrane is attached to the upper frame. The bottom of the lower frame is fixed, and sound waves having the resonant frequency are applied to the membrane surface. The unit cell can keep the contraction deformation during the sound wave application. The deformation performance of the unit cell was investigated theoretically and experimentally, as shown in Figure 1, middle, and an equation below. The shape of the membrane and the frame were improved by the results of the theoretical investigation.

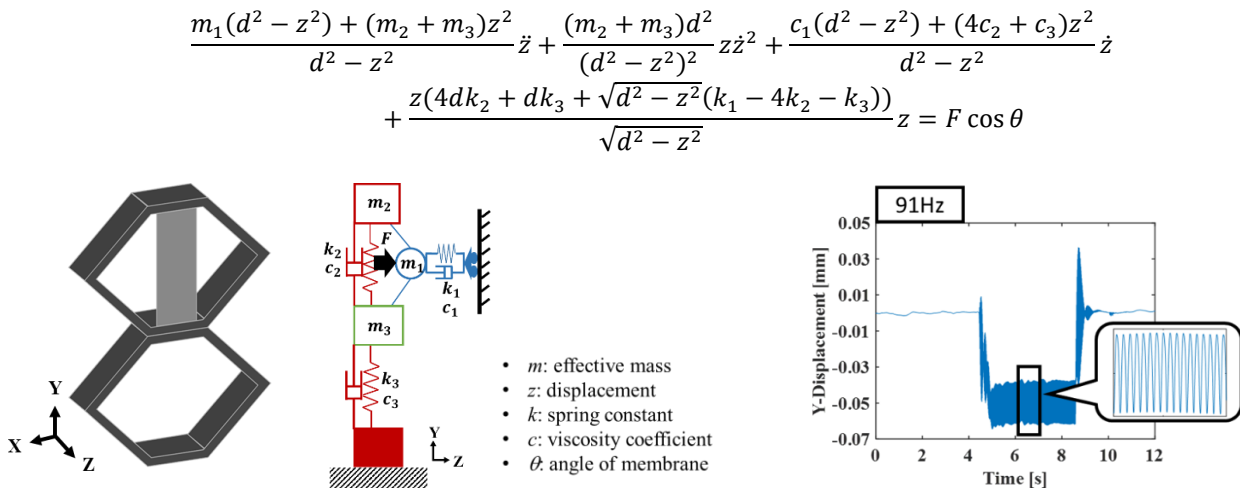


Figure 1. Schematic figure of the unit cell, left, the mechanical model for the theory, middle and the displacement profile obtained by an experiment, right.

The y-displacement profile at the top of the unit cell from an experiment is shown in Figure 1, right. The sound waves having a resonant frequency were applied for about 4 seconds from 4 to 8 seconds. The unit cell then kept the contraction displacement. It is expected that the mechanical metamaterial using the developed unit cell will be realized in the future.

- [1] Ying Wu, Yun Lai, Zhao-Qing Zhang, Elastic metamaterials with simultaneously negative effective shear modulus and mass density, Phys. Rev. Lett. 107, 105506, 2011
- [2] T. A. M. Hewage, K. L. Alderson, A. Alderson, and F. Scarpa, Double-negative mechanical metamaterials displaying simultaneous negative stiffness and negative Poisson's ratio properties, Adv. Mater. 28, pp. 10323–10332 (2016)

Spectral electromagnetic couple-stress modelling of stiff fibre-reinforced composites

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KEYWORDS: *Fibre-reinforced solids, Electromagnetic fields, Bending stiffness, Spectral invariants and formulation, Couple-stress Equations.*

This study presents a nonlinear modelling framework based on spectral invariants to describe the electromagnetic behaviour of fibre-reinforced composites, with explicit consideration of fibre bending stiffness. Using Cosserat continuum theory, we derive general constitutive relations for both stress and couple stress that account for the coupling between mechanical and electromagnetic effects. The formulation also provides a physically meaningful decomposition of the couple stress tensor. For materials where fibre bending is dominant, the model is further refined by limiting its dependence on fibre direction gradients to directional derivatives along the fibre axis. Prototype expressions for the internal energy are introduced for both the general and specialized formulations. The effectiveness of the specialized model is demonstrated through boundary value problems (BVPs) involving the pure bending of a slab and the extension and inflation of a solid cylinder, where they are important for validating our model from the experimental and numerical point of view. The BVP results indicate that the electromagnetic fields significantly affect the stress-strain behavior and our couple-stress formulation helps us to analyze the effect of bending stiffness in these BVPs. Overall, the proposed framework establishes a foundation for the analysis and design of advanced smart materials in which electromagnetic interactions and fibre microstructure are strongly coupled.

- [1] MHBM Shariff, On the electromagnetic Cosserat spectral modelling of fibre-reinforced composites with fibre bending stiffness, *International Journal of Engineering Science*. **217**, 104360, 2025. <https://doi.org/10.1016/j.ijengsci.2025.104360>

Mechanical performance of a WB₂-Al and WB₂-Ag composite coatings deposited by HiPIMS magnetron sputtering

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KEYWORDS: *protective coatings, mechanical properties, residual stress measurement methods, wear resistance, magnetron sputtering*

High-power pulsed magnetron sputtering is an effective engineering technique for improving the oxidation and wear resistance of metallic materials through the deposition of thin films [1].

In this work, WB₂-Al and WB₂-Ag composite coatings were fabricated by magnetron sputtering to mitigate the degradation of stainless steel under wear conditions while simultaneously increasing their thermal conductivity. The phase composition, microstructure, hardness, residual stress, and fracture toughness were measured. In the case of residual stress two methods were compared. The results of residual stress measurement with Laser Spallation Technique LST was compared with more common method using the modified Stoney equation. Additionally, wear resistance was systematically measured for various metal addition rates. At low metal addition amounts (1-8 at.%), the coatings deposited at 400°C were crystalline (polymorph P6mmm α -WB₂) and characterized by hardness exceeding 30 GPa. Further increasing the metal content resulted in the appearance of a second phase. The release of second phase could be detected, and the microstructure of the ceramic matrix changed to an amorphous one. The hardness and residual stress of the layer decreased, but wear resistance and measured by cantilever bending fracture toughness increased. For example, at room temperature, the wear rate of WB₂ coatings with an 8 %at. Ag coating is $6.563 \times 10^{-6} \text{ mm}^3/(\text{N m})$, approximately two orders of magnitude lower than the $8.175 \times 10^{-4} \text{ mm}^3/(\text{N m})$ of the substrate.

The metal addition and the oxide scale formed on the surface act as a lubricant. The introducing of a conductive metal to the ceramic matrix further increases the thermal conductivity of the deposited coatings. This work demonstrates that magnetron-sputtered WB₂-Al and WB₂-Ag composite coatings can improve the fracture toughness and simultaneously the wear resistance of steel materials. Hard and efficiently heat-conducting composite coatings made of W-B materials with Al or Ag filler may be good candidates for anti-radiation-related applications.

ACKNOWLEDGEMENT: This work was supported by the National Science Centre (NCN – Poland) Research Project: 2022/47/B/ST8/01296.

- [1] J. Rzempełuch, T. Stasiak, M. Maździarz, J. Jasiński, U. Woy, R. Psiuk, M. Kowal, A. Kosińska, M. Wilczopolska, K. Mulewska, M. Barlak, K. Ciporska, Ł. Kurpaska, J. Jagielski, T. Mościcki, J. Nucl. Mater. 616, No.156091, 2025 <https://doi.org/10.1016/j.jnucmat.2025.156091>

Tensile deformation of stainless steel and shape memory alloys inspected by acoustic emission and full-field techniques - a focus on old and new results

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KEYWORDS: *Stainless Steel, Shape Memory Alloys, Acoustic Emission, Digital Image Correlation, Infrared Thermography.*

This paper presents how the acoustic emission (AE) method allows for the study of phase transformations in austenitic steel and shape memory alloys (SMA), in relation to the results obtained from other experimental methods. We will demonstrate how the AE research methodology has evolved over the past 30 years and how other methods have emerged or evolved at that time for comprehensive diagnostics of newly developed materials with properties of interest for the applications. We will present results for four different materials subjected to tensile loading under various conditions. Interestingly, we will begin and end with results obtained for austenitic steel: formerly 1H18N9T - a steel used in the food industry, including milk churns, and more recently, 316L, 304, and N50 stainless steels – the steels operating under cryogenic conditions and used for nuclear reactor components, tested at 4 K. We will compare the results obtained for two types of titanium-based SMAs - a commercial TiNi, manufactured by Furukawa, and Ti-26 Nb with addition of O or N, elaborated in laboratory of the *University of Tsukuba*, Japan. We will also discuss the field research methods used: infrared (IRT) measurements and digital image correlation (DIC).

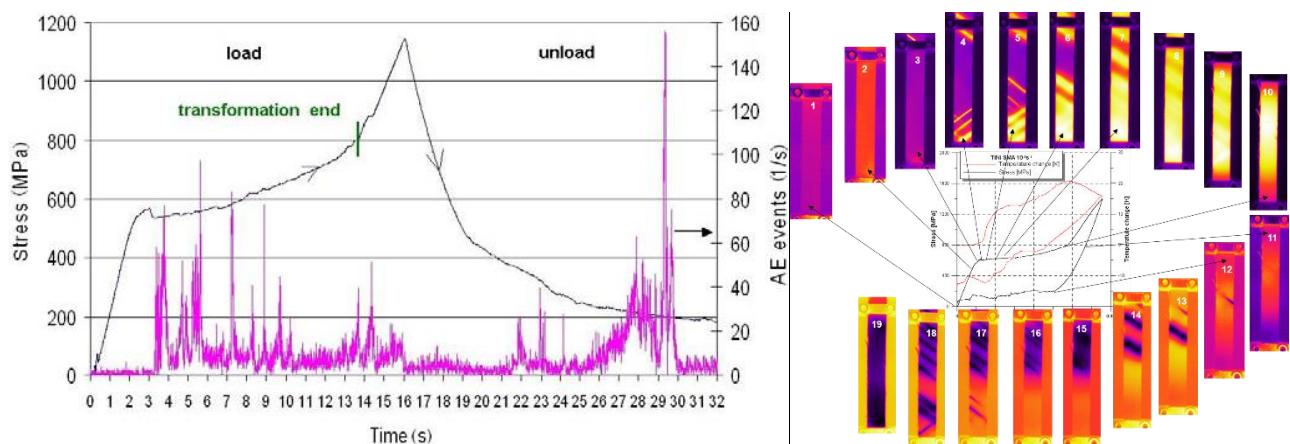


Fig. 1. TiNi SMA results obtained during loading- unloading tension at strain rate 10^{-3} s^{-1} . Left - Stress and AE counts rates vs. time. Right - the related stress and temperature changes vs. strain. Thermograms show in infrared a nucleation and evolution of macroscopic transformation bands, related to martensite forward (1–10) and reverse (11–19) transformation.

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- [1] E.A. Pieczyska, H. Tobushi, K. Takeda, D. Stróż, Z. Ranachowski, K. Kulasiński, Jr S. Kúdela, J. Luckner, *Martensite transformation bands studied in TiNi shape memory alloy by infrared and acoustic emission techniques*, **Kovove Mater.** **50**, 2012.
- [2] K. Golasiński, A. Brodecki, Z. Ranachowski, W. Tasaki, E. Pieczyska, H.Y. Kim, **Arch. Civ. Mech. Eng.** **26** (10), 2026. <https://doi.org/10.1007/s43452-025-01387-0>
- [3] Tabin J., Nejman H., Szyszko A., Ranachowski Z., Kawałko J., *Acoustic Emission-Based Identification of Discontinuous Plastic Flow in Austenitic Stainless Steels*, **Metall. Mater. Trans. A.**, ISSN:1073-5623, <https://doi.org/10.1007/s11661-026-08252-6>, Vol.48, No.1, pp.1-6, 2026

Session TS10

**Micromechanics of heterogeneous
and multi-component materials**

Supershear mode I and mode II fracturing in dry and saturated porous media

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Classical fracture mechanics predicts an upper bound on crack propagation speed, typically the Rayleigh wave speed for mode I fractures and the shear wave speed for mode II ruptures. Beyond these limits, tensile and shear fracture are traditionally considered energetically forbidden. However, experimental observations, field evidence from large earthquakes, and recent numerical studies increasingly demonstrate the existence of sub-, inter-, and supershear rupture regimes. In this study, we investigate the dynamic propagation of mode I and mode II fractures in dry and fluid-saturated media using multiple numerical frameworks, including the Extended FEM (XFEM), peridynamics (PD), and hybrid FEM/PD formulations.

For mode I fracture, simulations reveal a systematic transition in fracture behavior with increasing mechanical or hydraulic loading. Crack propagation evolves from smooth steady growth to stepwise regime, and ultimately to previously undocumented forerunning characterized by the nucleation of cracks ahead of the main tip. This progression is observed in both dry and saturated porous media, under mechanical loading and fluid injection. Notably, forerunning is shown to occur not only at supershear speeds but also under subsonic crack advance, as demonstrated in a beam on an elastic foundation subjected to sinusoidal loading. In saturated media, increased injection rates strongly promote the transition to stepwise and forerunning behavior, enabling crack speeds that exceed both shear and dilatational wave velocities.

For mode II fracture, we employ a newly developed 2-D hybrid FEM/PD model to study the transition from sub-Rayleigh to supershear rupture in dry and fluid-saturated media. The model reproduces laboratory observations of direct and indirect (mother-daughter crack or Burridge-Andrews) transitions and captures the formation of shear Mach cones. In fluid-saturated media, poroelastic coupling near the rupture front favors direct transitions to supershear fracturing, even in the absence of daughter cracks.

The consistency of these results across distinct numerical methods and constitutive descriptions supports the robustness of supersonic fracture and rupture in both tensile and shear modes. The findings have direct implications for earthquake dynamics, fluid-rich fault zones, and geophysical processes involving rapid fracture acceleration (slab tearing, volcanic systems).

Anisotropic elastic properties of smoothed interphase in heterogeneous materials

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KEYWORDS: *FFT solvers, mechanical field fluctuations, interphase properties, composites, polycrystals*

This work addresses the description of the spatial distribution of mechanical fields for elastic heterogeneous materials by using the fast Fourier transform (FFT) numerical method [1]. It relies on the resolution of the elastostatic boundary value problem with the Green functions method. By using a classical approach in micromechanics, the original elastic heterogeneous media is replaced by an homogeneous elastic media with a heterogeneous polarization field to be determined. This leads to a Lippmann-Schwinger equation which can be efficiently solved by a FFT-based iterative scheme on a regular grid. This approach has been the subject of numerous developments and is now widely used in micromechanics [2]. However, this reformulation of the local problem, based on Fourier series, can lead to spurious oscillations on local fields. This phenomenon emerges when (i) the polarization field has some discontinuities and (ii) pseudo-spectral differentiation is used [3]. To tackle this problem, modified Green operators and interface spreading approaches have been proposed. The latter consist in the introduction of an interphase, whose properties have to be defined, between domains with different elastic properties. This approach can be performed locally using composite voxel techniques [4], or globally using smoothing techniques [3]. By reducing material discontinuities, it improves consistency with the Fourier-series representation of the local fields.

Building on the previous work of Morin *et al.* [3], the present contribution aims at presenting two improvements: first, to provide a smoothing of elastic properties which is invariant when applied to stiffness or compliances, and second, to consider general anisotropic elastic properties. To do so, use is made of the logarithm of elasticity tensors following ideas of Moakher and Norris [5] to define an invariant distance between tensors. Numerical experiments are performed on elasticity problems involving isotropic and anisotropic phases, for composites and polycrystals. A significant reduction of spurious oscillations is observed on the local fields.

- [1] H. Moulinec, P. Suquet, *Comput. Methods Appl. Mech. Engrg* **157**, 69-94, 1998.
[https://doi.org/10.1016/S0045-7825\(97\)00218-1](https://doi.org/10.1016/S0045-7825(97)00218-1)
- [2] M. Schneider, *Acta Mech.* **232**, 2051–2100, 2021.
<https://doi.org/10.1007/s00707-021-02962-1>
- [3] L. Morin, R. Brenner, K. Derrien, K. Dohrmi, *Comput. Methods Appl. Mech. Engrg* **373**, 113549, 2021.
<https://doi.org/10.1016/j.cma.2020.113549>
- [4] L. Gélébart, F. Ouaki, *J. Comput. Phys.* **294**, 90-95, 2015.
<https://doi.org/10.1016/j.jcp.2015.03.048>
- [5] M. Moakher, A. Norris, *J. Elast.* **85**, 215-263, 2006.
<https://doi.org/10.1007/s10659-006-9082-0>

Data-driven mean-field homogenization for the analysis of composites with a wide range of microstructural features

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KEYWORDS: *Micromechanics, Effective properties, Mori-Tanaka method, Discontinuous reinforcement*

Discontinuously reinforced composites, comprising particles or short fibres, represent an important class of engineering materials. Their effective properties are governed by both the intrinsic properties of the constituent phases and key microstructural characteristics, including reinforcement shape, spatial orientation, and distribution. Numerical homogenization methods (full-field approaches) enable the prediction of these effective properties by analysing representative volume elements (RVEs) that capture the composite's heterogeneous microstructure. Among full-field approaches, the most widely used methods rely on the finite element method (FEM) or the fast Fourier transform (FFT) to resolve stress and strain fields. In general, full-field models provide high accuracy and broad modelling capabilities. Nonetheless, in practical applications, numerical homogenization can be highly time-consuming, which limits its applicability. A computationally efficient alternative is offered by mean-field models, such as the Mori–Tanaka method, which generally provide good predictive capability but have certain limitations. In its basic form, the modelling capabilities are limited, among other factors, to the ellipsoidal shape of inclusions, and the accuracy of the results decreases with increasing volume fraction of the reinforcing phase.

To overcome these limitations, a data-driven mean-field homogenization framework is developed by combining the physics-based foundations of the Mori–Tanaka method with data obtained from the full-field simulations [1, 2]. Following the concept presented in [2], the original strain concentration tensor is modified by fitting it to RVE-based data as a function of the volume fraction of inhomogeneities. Results reported in [2], associated with the case of composites reinforced with spherical particles, demonstrate very good agreement with full-field predictions across a wide range of stiffness contrasts and volume fractions. This study aims to extend the model to account for different shapes of the reinforcing phase, including those not captured by analytical solutions. In this case, both the strain concentration tensor and Eshelby's tensor are modified using data-driven corrections. The coefficients associated with the modified tensors are computed using a genetic algorithm. The proposed approach is expected to provide predictions comparable to those of full-field homogenization, while retaining the computational efficiency of mean-field models. During the conference, details of the database generation, the proposed numerical procedures, the obtained results, and future research directions will be presented.

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- [1] W. Ogierman, A data-driven model based on the numerical solution of the equivalent inclusion problem for the analysis of nonlinear short-fibre composites, *Compos. Sci. Technol.* 250, 110516, 2024. <https://doi.org/10.1016/j.compscitech.2024.110516>
- [2] W. Ogierman, Data-Driven Mean-Field Homogenization : Enhancing the accuracy of the Mori-Tanaka method, *Compos. Struct.* 358, 118985, 2025. <https://doi.org/10.1016/j.compstruct.2025.118985>

Gradient of mechanical properties in polymer nanocomposites: From atomistic scale to the strain gradient effective continuum

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Keywords: *Polymer nanocomposite, Molecular dynamic simulations, Strain gradient interphase, Hyperstress and strain gradient, Unfolding method for homogenization, Strain gradient constitutive law*

Glassy polymer nanocomposites (PNCs) exhibit heterogeneous mechanical properties due to the presence of a distinct polymer/nanoparticle (NP) interfacial region, whose rigidity strongly influences the overall mechanical response. Classical continuum theories typically model the interphase behavior as dependent only on deformation, neglecting the strong internal deformation gradients that call for enriched continuum descriptions of PNCs. In this work, we formulate a higher-gradient elasticity constitutive law for the polymer/NP interphase via a systematic micro–meso–macro coupling informed by atomistic molecular dynamics (MD) simulations. We show that an accurate description of the polymer/NP interphase requires modeling it as a strain-gradient material, while the bulk polymer can still be treated as a Cauchy material due to significantly weaker strain-gradient effects. The interphase thickness is determined from equilibrium density profiles obtained from MD simulations. By upscaling the molecular response within the interphase, an effective strain-gradient continuum model is derived, in which stress, strain, hyperstress, and conjugate strain gradients are computed at the atomic scale. A further homogenization step, based on the unfolding method, enables identification of the strain-gradient elastic moduli, leading to a second-gradient linear elastic constitutive law for the interphase.

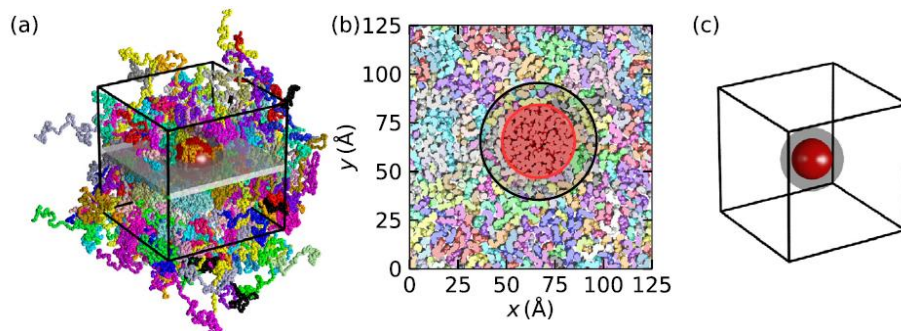


Figure 1. (a) Snapshot of the atomistic PNC model. The interphase is presented by the region between the semitransparent grey sphere and the NP. A slice of thickness 6 Å passing through the center of NP is also shown. (b) Top view of the distribution of atoms through the slice shown in (a). (c) Schematic of the equivalent continuum model employed for the strain gradient homogenized model, showing the internal structure of the NP (red) and interphase (grey). The material within the rest of the box is filled with polymer (PB) matrix.

- [1] H. Reda, A. Chazirakis, N. Savva, J.-F. Ganghoffer, V. Harmandaris, 2022. Int. J. Solids Struct., 256, 111977. <https://doi.org/10.1016/j.ijsolstr.2022.111977>
- [2] Ganghoffer, J.-F., Maurice, G., Rahali, Y., 2019. Math. Mech. Solids 24 (5), 1475–1502. <http://dx.doi.org/10.1177/1081286518798873>.

In-situ synchrotron diffraction and self-consistent modelling used to determine plastic incompatibility stresses in textured AZ31 magnesium alloy

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KEYWORDS: *Synchrotron diffraction, Crystallographic slip, Twinning, Critical resolved shear stress, Elastoplastic self-consistent model, Magnesium alloy.*

A comprehensive study on the evolution of internal stresses in an extruded AZ31 magnesium alloy was conducted using energy-dispersive synchrotron X-ray diffraction (ED-XRD). The research evaluates both macroscopic (first-order) and intergranular (second-order) stresses that arise during uniaxial tensile deformation of a strongly fibre textured hexagonal close packed (hcp) material. Lattice strains were recorded for 16 sample orientations using nine crystallographic reflections [1].

An advanced q-parameter approach [2] was applied to separate the elastic lattice strain components related to the externally applied macroscopic load from those generated by grain-scale plastic incompatibilities caused by heterogeneous deformation. The findings demonstrate strong plastic anisotropy, premature yielding of favourably oriented grains, and significant development of intergranular stresses due to heterogeneous slip activity and twinning. Slip systems were classified into groups based on their similar roles in plastic deformation and grain-level stress evolution, which reduced the number of parameters necessary to describe the deformation mechanisms. In addition, combining Schmid factor analysis with stress distribution functions made it possible to identify the slip and twinning systems mainly responsible for the formation of second-order stresses associated with plastic incompatibility.

It was found, that under tensile loading, basal slip governs the evolution of plastic incompatibility stresses throughout deformation, initiating stress heterogeneity prior to macroscopic yielding [3]. With increasing strain, activation of non-basal $\langle a \rangle$ slip and twinning redistributes load toward harder grains associated with stable texture maxima. Under compressive loading, the twinning process initially reduces grain stresses, producing a plateau in the macroscopic stress-strain response. At later stages, plastic incompatibility stresses, governed by non-basal slip and the evolving twin orientations, cause the twins to become harder due to reorientation and progressively carry increasing load, resulting in material strain hardening.

ACKNOWLEDGEMENT: This work was founded by a grant from the National Science Centre, Poland (NCN), No. UMO-2023/49/B/ST11/00774.

[1] G. Garcés, E. Oñorbe, P. Pérez, I.A. Denks, P. Adeva, Mater. Sci. Eng.: A 523 (2009) 21–26

[2] A. Baczmański, P. Lipinski, A. Tidu, K. Wierzbowski, B. Pathiraj, J. Appl. Crystal. 41 (2008) 854–867.

[3] A. Baczmański, M. Wroński, P. Kot, S. Wroński, A. Łabaza, K. Wierzbowski, A. Ludwik, M. Marciszko-Wiackowska, Mater. Des. 202 (2021) 109543.

Role of deformation twinning and plastic anisotropy on void growth in HCP Mg polycrystals: A crystal plasticity finite element study

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KEYWORDS: *Crystal plasticity, Finite element method, RVE, twinning, void growth, damage*

Ductile damage in HCP metals is governed by a complex interaction between plastic anisotropy, deformation twinning, and the void evolution. Despite this complexity, studies that investigate damage mechanisms in porous HCP polycrystals remain scarce. Most existing investigations based on the crystal plasticity finite element method (CPFEM) have focused on single-crystal unit cell models. For instance, void growth under plane strain conditions using cylindrical voids in 2D [1], and spherical void growth in 3D unit cells [2], both in the context of HCP Mg single crystals. Although these unit cell studies provide valuable insights into the fundamental mechanisms governing void evolution in HCP crystals, they do not capture key microstructural features of polycrystalline materials. In particular, they neglect grain-to-grain interactions, crystallographic heterogeneity, and the competition between differently oriented grains that strongly influence damage development in real polycrystals. To address this gap, the present study conducts a full-field CPFEM analysis on a RVE of porous HCP Mg polycrystal, constructed by periodically translating a cubic unit cell containing a centrally positioned spherical void along all three orthogonal directions, yielding an aggregate of multiple grains. Crystallographic orientations are independently assigned to each grain using a single realization of randomly sampled Bunge Euler angles, introducing grain-to-grain orientation variability while maintaining the overall statistical homogeneity of the polycrystalline aggregate. To ensure mechanical consistency with the periodic microstructural construction, periodic boundary conditions are imposed on all external faces of the RVE.

The constitutive framework employed in this study is a rate-dependent crystal plasticity model formulated within a Lagrangian framework, incorporating both slip and deformation twinning. Twinning-induced lattice reorientation is treated using the Probabilistic Twin Volume Consistent (PTVC) scheme [3], which ensures consistency between the evolution of the twin volume fraction and the probability of grain reorientation. The hardening formulation accounts for the interactions among deformation systems, including slip-slip, slip-twin, and twin-twin interactions, thereby capturing the anisotropic hardening behavior characteristic of HCP crystals. Within this framework, the present study systematically investigates the influence of the initial basal slip resistance, neighboring grain orientations, and stress triaxiality on void evolution in an elasto-viscoplastic porous HCP Mg polycrystal. Both local and macroscopic responses are analyzed in detail, with particular emphasis on the underlying microstructure evolution, including twinning-induced lattice reorientation and the spatial distribution of accumulated slip/twin. This analysis elucidate the roles of slip and twinning mechanisms in governing the path to ultimate failure in HCP polycrystals.

ACKNOWLEDGEMENT: The research was partially supported by the project No. 2024/55/B/ST8/01333 of the National Science Centre, Poland

- [1] N. Subrahmanya Prasad, R. Narasimhan, & S. Suwas. *International Journal of Fracture*. 200:159–183 (2016).
- [2] B. Selvarajou, S. P. Joshi, and A. A. Benzerga. Void growth and coalescence in hexagonal close packed crystals. *Journal of the Mechanics and Physics of Solids*, 125:198–224, (2019).
- [3] K. Kowalczyk-Gajewska, Modelling of texture evolution in metals accounting for lattice reorientation due to twinning, *European Journal of Mechanics - A/Solids*, 29(1):28–41, (2010).

Anisotropy of Elasto-Plastic Composite Materials Induced by Spatial Distribution of Inhomogeneities

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KEYWORDS: *Mean-field modelling, Finite element method, Cluster model.*

Heterogeneous materials always have posed significant difficulties in regard to assessing their macroscopic properties. Decades of development of various procedures based on numerical homogenisation now allow for a high level of detail and flexibility in terms of replicating different microstructure morphology, but consume a lot of computing power and time. Thus, many attempts have been made to develop analytical models that could provide robust and computationally efficient tools for this purpose.

In this presentation, an analytical approach to finding the effective response of elastoplastic composites using the cluster model with a modified tangent linearisation scheme is discussed [1]. It is based on the idea of Molinari & El Mouden (1996) [2] to extend classical mean-field models by taking into account the interactions between inhomogeneities within the material volume. Elastoplastic regime is examined for two material scenarios: matrix reinforced with inclusions or weakened with voids. Two Bravais lattices of cubic symmetry (regular cubic and body-centred cubic) are considered. For each case, periodic unit cells are generated and subjected to external isochoric and hydrostatic strain conditions. The results show a significant impact of the spatial arrangement of inhomogeneities on the overall material anisotropy, which is not accounted for by classical micromechanical mean-field models. Applied modified tangent linearisation scheme allows for the initiation of plastic flow even under hydrostatic loading scenarios.

The results of the analytical model are verified by comparison with those of numerical homogenisation performed using the Finite Elements Method (FEM) with meshing requirements discussed. The results from the cluster model are qualitatively and quantitatively, consistent with FEM.

Additional procedure for a multi-criteria optimisation is proposed. It shows that the cluster model might be an effective tool for finding the optimal microstructure (i.e. the optimal spatial arrangement of inhomogeneities or their volume fraction) for a given application of the material, allowing for a broad filtering of possible scenarios on the initial stage of the design process.

ACKNOWLEDGEMENT: Presented results have been partially acquired within scope of a project co-funded by National Science Centre, no 2021/41/B/ST8/03345.

- [1] Bieniek K., Majewski M., Hołobut P., Kowalczyk-Gajewska K. (2024), Anisotropic effect of regular particle distribution in elastic–plastic composites: The modified tangent cluster model and numerical homogenization, *International Journal of Engineering Science*, Vol. 203, 104118. <https://doi.org/10.1016/j.ijengsci.2024.104118>
- [2] Molinari A., El Mouden M. (1996). The problem of elastic inclusions at finite concentration. *Int. J. Solids Structures*, 33, 3131–3150. [https://doi.org/10.1016/0020-7683\(95\)00275-8](https://doi.org/10.1016/0020-7683(95)00275-8)

Remarks on the Modeling of Deformation-Induced Crystallographic Textures

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KEYWORDS: *Texture, misorientation distribution, crystalline deformation models, Lagrangian and Eulerian approaches*

This work discusses several aspects of crystallographic texture prediction using deformation models. In general, two principal approaches to texture modelling and analysis can be distinguished, analogous to those employed in fluid flow descriptions.

In the Lagrangian approach, the evolution of the lattice orientation of each grain is tracked in orientation space, and the final texture is determined from the set of final lattice orientations of all grains. In contrast, in the Eulerian approach, the intensity of the texture function is evaluated at different points in orientation space using the rotation field of crystal orientations, in a manner analogous to the velocity field in fluid flow. In this case, the evolution of texture is described using the continuity equation.

The results of texture prediction and misorientation distribution obtained using the first method, namely the Lagrangian description combined with a crystalline deformation model, are presented and compared with experimental data. The textures of polycrystalline copper, brass, and low-carbon steel are analyzed. Furthermore, an approach based on local grain–neighbor interactions is compared with one based on average global interaction.

In addition, the prediction of copper-type texture and the stability conditions of the main components of the three examined texture types are analyzed using the Eulerian approach and the continuity equation.

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Modelling mechanical and radiation shielding properties of 316L-B₄C metal matrix composites

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KEYWORDS: *Metal-matrix composites, Finite element method, Monte Carlo, Crystal plasticity.*

Multi-functional materials are one of the key research areas driving technological progress. One example of a multi-functional material is the metal-matrix composite (MMC), where matrix phase consists of 316L stainless steel and reinforcement is made of B₄C. The material is still under development and it is hoped that it will possess excellent properties, such as excellent mechanical properties both at static and dynamic conditions, radiation shielding and resistance to corrosion.

During the presentation, two types of modelling results will be presented. First of all, finite element method simulations of mechanical response will be shown. To this aim, a two-phase material was modelled. The parameters of the (crystal) elasto-plastic model (cf. e. g. [1]) were calibrated by comparing model predictions to the experimental measurements. Similarly, the model of B₄C phase was established. Then, various computational microstructures of the MMC composite were generated in such a way to have the best representation of real microstructures observed under the microscope.

In addition, results of radiation shielding simulation will be presented. A series of simulations was performed for 316L steel samples containing various B₄C concentrations to determine the photon linear attenuation coefficients for standard ⁶⁰Co and ¹³⁷Cs gamma-ray sources, as well as the effective neutron attenuation coefficients for monoenergetic neutrons with energies ranging from thermal energies up to 20 MeV. In addition, the shielding performance was assessed in a realistic mixed neutron/gamma radiation field representative of the horizontal channel of the MARIA research reactor. The calculations were carried out using the MCNP and FLUKA Monte Carlo codes (cf. e. g. [2]) and the computational resources of the Świerk Computing Centre at the National Centre for Nuclear Research.

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- [1] K. Frydrych and. K. Kowalczyk-Gajewska, *Model. Simul. Mater. Sci. Eng.* **26**, 065015, 2018. <https://doi.org/10.1088/1361-651X/aad46d>
- [2] M. Maciak, S. Domański, P. Tulik, K. Tymińska and M. A. Gryziński, *Radiat. Prot. Dosim.*, **199** (15-16), 1883-1888, 2023. <https://doi.org/10.1093/rpd/ncac291>

Dynamic interaction of cracks and rigid-line inclusions

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KEYWORDS: *Crack, Rigid Line Inclusion, Dynamic Interaction, Impact Load, Boundary Element Method.*

The purpose of the research is to formulate the boundary element method (BEM), develop a computer code, and analyze dynamically loaded linear-elastic and isotropic plates containing cracks and rigid, thin, and straight inclusions. The inclusions, which are also called rigid-line inclusions or anticracks, can be used to model very stiff fibres, for example carbon nanotubes. There is assumed to be a perfect connection between inclusions and the deformable matrix and the coincidence of the crack surfaces in the unloaded state. The time-dependent problem is solved using the Laplace transform method. The boundary integral equations are used to determine the relationship between the boundary tractions and displacements. Additionally, equations of motion are applied for rigid inclusions. In order to analyze the problem using the BEM, the boundaries of the plate, cracks, and inclusions are divided into boundary elements. Boundary integral equations are used for the nodes on the external boundaries of the plate, cracks, and inclusions. Unknown quantities in the presented method are displacements and tractions along the boundaries. Solutions in the time domain are obtained using the numerical inverse Laplace transform. Stress concentrations occur at the tips of cracks and inclusions, and stress intensity factors are calculated using displacements of crack surfaces and tractions along inclusions.

The author used in the past separately the Laplace transform BEM for plates containing cracks [1] and inclusions [2]. This work is an extension of the previous works on static interaction of cracks and rigid-line inclusions [3-4] and a first attempt to analyze the dynamic interaction. Influences of the configuration, distances and length of cracks and inclusions on stress intensity factors and displacements will be shown.

The boundary element method is a very efficient method for modeling elastic bodies that contain cracks and rigid inclusions. The modeling of such materials is significantly simplified in comparison to domain methods, for example the finite element method, because nodes are situated only along the external boundaries, crack edges and inclusions. The numbers, positions, shapes, and dimensions of cracks and inclusions can be modified very simply. Stress intensity factors can be calculated with great accuracy.

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- [1] P. Fedeliński, M.H. Aliabadi, D.P. Rooke, The Laplace transform DBEM method for mixed-mode dynamic crack analysis, *Comput. Struct.* **59**(6), 1021-1031, 1996. [https://doi.org/10.1016/0045-7949\(95\)00347-9](https://doi.org/10.1016/0045-7949(95)00347-9)
- [2] P. Fedeliński, Analysis of carbon nanotube-reinforced composites subjected to impact loads by the BEM, *Acta Mech. Autom.* **19**(4), 585-596, 2025. <https://doi.org/10.2478/ama-2025-0066>
- [3] Dong C.Y., Lo S.H., Cheung Y.K., Interaction between cracks and rigid-line inclusions by an integral equation approach, *Comput. Mech.* **31**(3), 238-252, 2003. <https://doi.org/10.1007/s00466-003-0427-2>
- [4] P. Fedeliński, Computer modeling and analysis of microstructures with fibres and cracks, *J. Achiev. Mater. Manuf. Eng.* **54**(2), 242-249, 2012.

Homogenization of particulate composites: inclusion packing effects

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KEYWORDS: *Homogenization, Finite Elements, Cluster Model.*

Most of the analytical homogenization methods for particulate composites rely on the volume fraction of inclusions and their shape. Molinari and El Mouden [1] proposed a model taking into account the spatial distribution of inclusions, through the interactions between ellipsoidal elastic inclusions, in an elastic matrix. Kowalczyk-Gajewska et al. [2] extended the Cluster Model to elastic-viscoplastic composites, and showed that the spatial distribution of inclusions has a significant effect on the overall response of the material, especially at high volume fractions.

The present work aims at investigating how the spatial distribution of inclusions in a particulate composite affects the overall response of the material. For simple microstructures, such as periodic arrays of inclusions, the effective properties determined using analytical methods, such as Mori-Tanaka or the Cluster Model are compared to numerical results obtained using Finite Element simulations. By modeling different simple microstructures, the benefits and limits of the Cluster Model are highlighted, in comparison to Mori-Tanaka scheme. The response is anisotropic, depending on the position of the inclusions, in agreement with Finite Element results.

The range of validity of the Cluster Model is also discussed by increasing the volume fraction of inclusions. It is shown that the predictions of the Cluster Model remain reliable for higher volume fractions of inclusions than those from the Mori-Tanaka model. However, the Finite Element results show that when strains can no longer be considered as uniform in the inclusions, the Cluster Model fails to predict accurately the overall response of the material. This is due to the fact that it relies on the Berveiller et al. result [3] for two inclusions interacting in an infinite medium, according to which the field fluctuations within the inclusions are neglected. This underlines the need for a model to account as well for the interactions effects and for the non-uniformity of strains in the inclusions.

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- [1] A. Molinari, M. El Mouden: The problem of elastic inclusions at finite concentration. *IJSS* **33**(20-22), 3131–3150, 1996. [https://doi.org/10.1016/0020-7683\(95\)00275-8](https://doi.org/10.1016/0020-7683(95)00275-8)
- [2] K. Kowalczyk-Gajewska, M. Majewski, S. Mercier, A. Molinari: Mean field interaction model accounting for the spatial distribution of inclusions in elastic-viscoplastic composites. *IJSS*, **224**, 111040, 2021. <https://doi.org/10.1016/j.ijsolstr.2021.111040>
- [3] M. Berveiller, O. Fassi-Fehri, A. Hihi: The problem of two plastic and heterogeneous inclusions in an anisotropic medium. *Int. J. Engrg. Sci.* **25**, 691–709, 1987. [https://doi.org/10.1016/0020-7225\(87\)90058-9](https://doi.org/10.1016/0020-7225(87)90058-9)

Microscale Phase-Field Study of Crystal Growth and Particle Dynamics in Directionally Solidified Colloidal Suspensions

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KEYWORDS: *Directional solidification, colloidal suspensions, phase field modeling, porous microstructure, crystal growth.*

Solidification of colloidal suspensions during ice-templating (freeze-casting) generates porous and frequently anisotropic microstructures, as the advancing ice front rejects suspended particles and drives their accumulation ahead of the interface [1, 2]. This study focuses on a microscale description of this phenomenon, emphasizing the evolution of crystal growth and the dynamics of colloidal particles under directional solidification. The methodology relies on phase-field simulations conducted within representative volume elements using the PRISMS-PF framework.

The model enables detailed tracking of the morphology and kinetics of the solid–liquid interface, together with particle redistribution, segregation, and local packing in the region ahead of the growing crystals. Special attention is given to the influence of thermal conditions specifically the local cooling rate and temperature gradient on interface stability, crystal spacing, and the emergence of particle-enriched zones. The formulation is designed to capture key mechanisms identified in recent freeze-casting research, including particle-front interactions and growth-front instabilities that drive hierarchical pattern formation [2].

Overall, the proposed microscale model provides a mechanistic basis for understanding how local solidification conditions govern crystal growth and colloidal particle behavior, and it establishes a foundation for future quantitative analyses of microstructure development in freeze-cast materials.

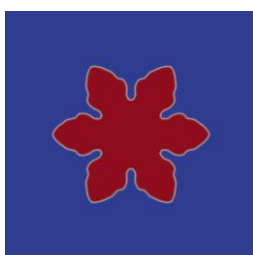


Figure 1. Example of anisotropic ice dendrite growth.

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[1] S. Deville, A. P. Tomsia, S. Meille, *Acc. Chem. Res.* **55**(11), 1492-1502 (2022).
<https://doi.org/10.1021/acs.accounts.2c00064>

[2] S. Tyagi, C. Monteux, S. Deville, *Sci. Rep.* **11**, 3513 (2021).
<https://doi.org/10.1038/s41598-021-82713-3>

Homogenized descriptions for elasto-(visco)plastic composites based on a linear viscoelastic comparison composite

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KEYWORDS: *Homogenization, Elasto-(visco)plasticity, Laplace–Carson Transform, Hardening.*

This work reports new homogenized descriptions for two-phase elastoplastic composites under complex loadings. The matrix response is characterized by archetypical elastoplastic relations with rate-dependent isotropic and kinematic hardening, while the inclusions are elastic. The macroscopic response is characterized by the effective free-energy density and dissipation potential in terms of the macroscopic deformation of the composite and the microscopic plastic deformation field within it. Two approximations are then performed in the context of an incremental variational principle governing plastic flow in accordance with these effective potentials [1]. The first approximation relies on a variational linearization which produces an alternative functional containing secant moduli of the nonlinear constitutive relations evaluated at the second moments of the pertinent mechanical fields within the matrix phase [2]; as such, it characterizes the viscous flow of a viscoelastic linear-comparison composite (VLCC) with the same microstructure as the elastoplastic composite. The second approximation consists in the estimation of this linear-comparison functional with effective potentials of the Hashin-Shtrikman type recently derived by means of the Correspondence Principle [3]. Crucially, these potentials depend on a finite number of effective internal variables characterizing the inelastic state of the composite. Unlike previous descriptions based on the intraphase uniformization of plastic deformations advocated in [1], this description is found to produce cyclic stress-strain curves with the expected shape, consistent with bounds, and free of spurious transients. The descriptions can be regarded as an extension of those proposed in [4] to composites with more complex rheologies allowing for plastic hardening.

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- [1] Lahellec, N. and Suquet, P. (2006). Effective behavior of linear viscoelastic composites: A time-integration approach. *International Journal of Solids and Structures* 44 (2007) 507–529.
- [2] Lahellec, N. and Suquet, P. (2012), *Effective response and field statistics in elasto-plastic and elasto-viscoplastic composites under radial and non-radial loadings*, *International Journal of Plasticity*, 42 (2013), 1–30.
- [3] Lahellec, N., Masson, R. and Suquet, P. (2024). Effective thermodynamic potentials and internal variables: Linear viscoelastic composites. *Journal of the Mechanics and Physics of Solids* 188 (2024) 105649.
- [4] Spadea, C. and Ponte Castañeda, P. (2026). Variational linear comparison estimates for elasto-viscoplastic composites with isotropic phases and microstructures. *Journal of the Mechanics and Physics of Solids* 211 (2026) 106546.

Mechanical homogenization at the level of the microvia in printed circuit boards containing embedded components

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KEYWORDS: *Homogenization - Microvias - Finite Element Method - Printed Circuit Board - Embedded Components.*

E-mobility has raised the need in power electronics for higher chip densification. One solution is to integrate active components into printed circuit boards (PCB). This technology increases the diversity of materials, particularly in interconnection areas. As a single failure in the board can lead to the total failure of electronic assemblies, these interconnection regions are studied in order to increase the service life of PCBs [1].

The proposed talk focuses on the finite element analysis of double-sided microvia technology for buried components. The first obstacle to overcome concerns the large number of microvias present on a chip. It is indeed impossible to model such a PCB, both because of the meshing time and the calculation time required. Therefore a method based on the homogenization of a unit cell including a microvia is proposed. Thus, the mechanical response of the equivalent homogeneous material is captured and next validated by experimental tensile tests containing a large number of RVEs. Once validated, reduced models of the interconnection layer are introduced, on the one hand with the equivalent homogeneous material and on the other hand with the completely discretized geometry. The average responses in terms of stress and strain tensors are found to be accurate, see [2] for stacked microvias. To address local failure mechanism, a coupled model is defined and is found to have predictive capabilities comparable to the full discretized model. Finally, the proposed method allows access to local fields so as to anticipate potential failure in the interconnection layer for embedded components in printed circuit boards, subject to thermal cycles.

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- [1] T. Huesgen, Printed Circuit Board Embedded Power Semiconductors: A Technology Review, Power Electronic Devices and Components (2022) 100017. doi:10.1016/j.pedc.2022.100017.
- [2] F. Dailland, G. Girard, M. Bouarroudj, M. Martiny and S. Mercier, "Microvia Homogenised Behaviour for the Mechanical Modelling of PCB with Embedded Components," 2025 26th International Conference on Thermal, Mechanical and Multi-Physics Simulation and Experiments in Microelectronics and Microsystems (EuroSimE), Utrecht, Netherlands, 2025, pp. 1-7, doi: 10.1109/EuroSimE65125.2025.11006591.

Mathematical and Numerical Modelling of Materials and Structures with Functionally Variable Properties

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KEYWORDS: *Functionally Graded Materials, Effective Properties, Composite Materials.*

Research on functionally graded materials (FGMs) is highly active, particularly in achieving desired property gradients for structural engineering applications. This field requires methods to: (1) determine effective FGM properties based on volume fractions and component configurations, and (2) optimize material profiles through strategic design of continuous variations in composition and microstructure to achieve location-specific optimal properties.

The aim of this research is to develop a methodology for designing the distribution of reinforcing particles in complex structural elements to achieve better performance parameters. The influence of the reinforcing particle distribution function on the distribution of fundamental mechanical quantities (stress, strain, displacement) in selected structural elements is analyzed using both analytical methods and finite element method (FEM). To estimate effective FGM properties, this research employs the energy equivalence hypothesis (Wiśniewska et al., 2019). Figure 1 presents exemplary results for a cantilever beam where the particle volume fraction $\xi(z)$ distribution is described by a polynomial function of the cross-section vertical coordinate, approximated in the FEM model by a stepwise change.

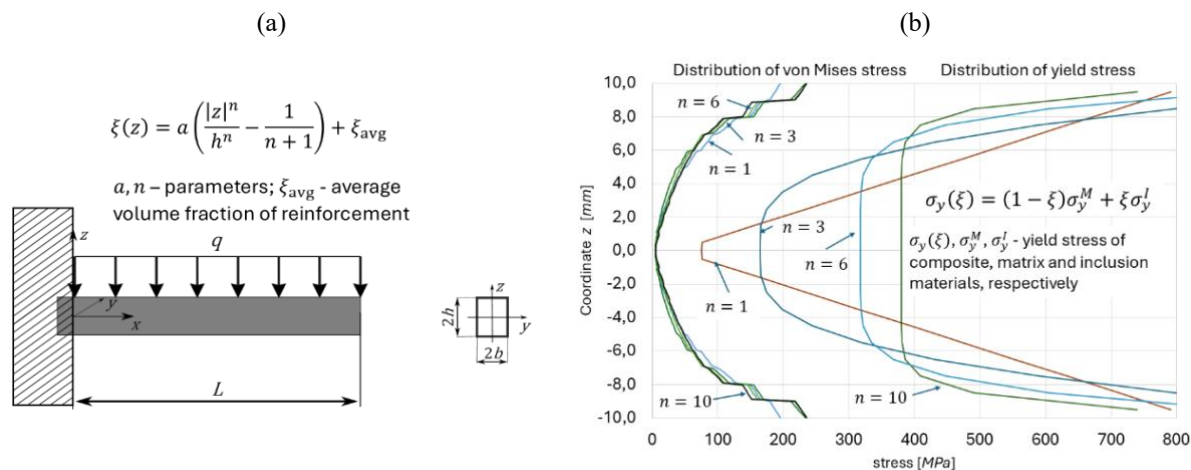


Figure 1. (a) Geometry and loading; (b) stress distribution in clamped cross-section.

The results obtained from the selected structural elements confirm that the applied method is capable of accurately determining the equivalent isotropic properties of composite materials required for the design of FGM structural elements.

- [1] A. Wiśniewska, S. Hernik, A. Liber Kneć, H. Egner, *Compos B Eng.* **166**, 213–220, 2019.
<https://doi.org/10.1016/j.compositesb.2018.11.094>

From inverse homogenization problems to closed-form models: simplified equivalent microstructure approach

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KEYWORDS: *micromechanics, effective properties, microstructure, electric permittivity.*

Predicting effective properties of random heterogeneous media remains an important challenge in micromechanics, particularly when phase property contrasts span wide ranges [1, 2]. Classical equivalent microstructure approach [3] provides a powerful framework for linking macroscopic response to simplified representations of complex media; however, it typically relies on solving an ill-posed inverse problem associated with significant computational cost.

In this work, we propose a generalized yet discrete formulation of the equivalent microstructure concept, with particular emphasis on its behavior across arbitrary phase contrasts. The proposed approach shifts the focus from detailed inverse reconstruction towards a reduced, forward modeling perspective, enabling a more direct characterization of the effective properties. At the same time, the key assumption of invariance with respect to the properties of the constituents is retained.

Building upon the Mori–Tanaka homogenization scheme [4], we introduce a minimal-parameter representation of the equivalent microstructure, in which combinations of a small number of discrete inclusion shape families are used to capture the effective response, thereby reducing the original continuous formulation to a low-dimensional, computationally efficient form. This formulation retains the key advantages of the original framework – namely its ability to represent a broad class of random media – while significantly reducing computational complexity and enabling partially closed-form expressions.

The approach is benchmarked in electric permittivity and thermal conductivity problems using several generated artificial and real microstructure representations. Performance of the proposed models is tested against the original model [3] and other semi-analytical approaches. The results demonstrate that the proposed formulation provides an accurate yet computationally efficient alternative for modeling effective properties across a wide range of phase property contrasts.

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- [1] I. Sevostianov, M. Kachanov: Is the concept of “average shape” legitimate, for a mixture of inclusions of diverse shapes? *Int. J. Solids Struct.* 49, 3242–3254, 2012.
<https://doi.org/10.1016/j.ijsolstr.2012.06.018>
- [2] I. Sevostianov, M. Kachanov: On the possibility to represent effective properties of a material with inhomogeneities in terms of concentration parameters. *Int. J. Solids Struct.* 52, 197–204, 2015.
<https://doi.org/10.1016/j.ijsolstr.2014.10.003>
- [3] D. Łydźba, A. Róžański, D. Stefaniuk: Equivalent microstructure problem: Mathematical formulation and numerical solution. *Int. J. Eng. Sci.* 123, 20–35, 2018.
<https://doi.org/10.1016/j.ijengsci.2017.11.007>
- [4] T. Mori, K. Tanaka: Average stress in matrix and average elastic energy of materials with misfitting inclusions. *Acta Metallurgica*. 21, 571–574, 1973. [https://doi.org/10.1016/0001-6160\(73\)90064-3](https://doi.org/10.1016/0001-6160(73)90064-3)

Macroscopic Yield Surfaces of Porous Solids with Anisotropic Matrix Behavior

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KEYWORDS: *Numerical limit analysis, Unit cell modelling, Porous plasticity, Anisotropic plasticity*

This study develops a theoretical and micromechanical framework to predict the macroscopic plastic response of porous materials with anisotropic matrix behavior. The formulation is built within the Gurson homogenization approach [1] and combines the Isotropic Plasticity Equivalent (IPE) concept of Karafillis and Boyce [2] with the procedure proposed by Benallal [3], enabling the development of macroscopic yield criteria for voided solids with general isotropic and anisotropic matrix constitutive laws. In the case of isotropic matrices, the framework accommodates general constitutive models, including Lode angle sensitivity. The approach naturally incorporates various material symmetries within the homogenization procedure, facilitating the derivation of anisotropic effective yield surfaces for porous solids.

For simplicity, the classical kinematically admissible velocity field proposed by Gurson is employed, although the methodology is general and allows for more refined trial velocity fields. Matrix anisotropy is represented via a traceless linear transformation within the IPE formulation. The macroscopic yield surface is obtained considering a spherical unit cell, yielding a parametric representation of the full six-dimensional effective yield surface. A numerical algorithm is developed to evaluate and visualize arbitrary sections of this surface, and illustrative results are provided for different matrix plastic behaviors, including Lode angle effects and distinct symmetry classes.

The analytical framework is validated against three-dimensional finite element simulations of hollow spherical unit cells with an isotropic or anisotropic matrix yield function, performed in Abaqus for a wide range of stress triaxialities, including both positive and negative values, and porosity levels. The proposed homogenization model shows very good agreement with the numerical predictions across all stress states, matrix responses, and porosity levels. The macroscopic yield locus is analyzed across the full range of triaxialities to illustrate its overall shape and anisotropy characteristics. In particular, at high positive and negative triaxialities, a comparative assessment of isotropic and anisotropic matrix behaviors is performed, highlighting the differences in the evolution and shape of the macroscopic yield surfaces.

[1] A.L. Gurson, J. Eng. Mater. Technol. 99(1), 2–15, 1977. <https://doi.org/10.1115/1.3443401>

[2] A.P. Karafillis, M.C. Boyce, J. Mech. Phys. Solids 41, 1859–1886, 1993. [https://doi.org/10.1016/0022-5096\(93\)90073-O](https://doi.org/10.1016/0022-5096(93)90073-O)

[3] A. Benallal, Int. J. Impact Eng. 108, 47–62, 2017. <https://doi.org/10.1016/j.ijimpeng.2017.05.004>

Influence of boundary conditions on the response of porous unit cells with random void arrangements

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KEYWORDS: *Heterogeneity, Random void distribution, Boundary conditions, Ductile failure*

The study investigates how the predicted mechanical response of porous ductile solids depends on the choice of boundary conditions and the spatial arrangement of voids in finite element unit-cell models. Two-dimensional plane-strain unit cells with randomly distributed spherical voids were analyzed using both periodic boundary conditions (PBC) and kinematically uniform boundary conditions (KUBC). Two void population sizes were considered (5 and 25 voids) for a fixed porosity, and several void samples were generated for each population size, each corresponding to a unique Statistical Volume Element (SVE). Each of the SVEs were subjected to several macroscopic stress states governed by various ratios between the in-plane macroscopic stress components. In addition to the role of boundary conditions for the numerical predictions of macroscopic behavior, the study evaluates whether spatial clustering descriptors can be used to predict the failure strain more effectively than porosity or average void spacing alone.

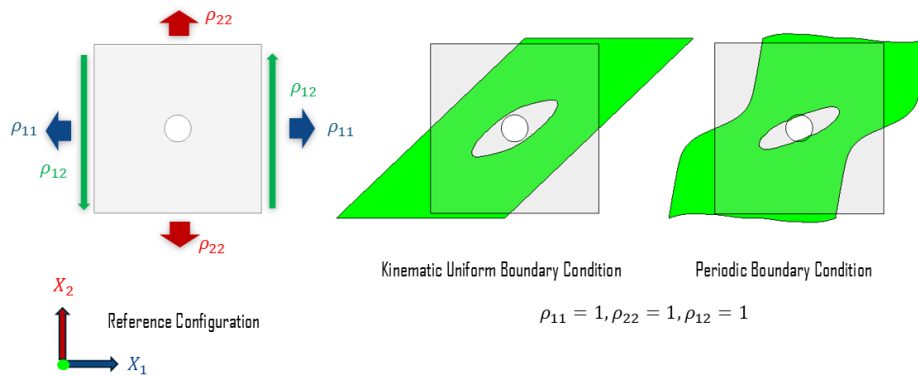


Figure 1: Illustration of boundary conditions.

The results show that the predicted failure strain depends strongly on the imposed stress state, the boundary conditions, and the spatial distribution of voids. A systematic difference is observed between the two boundary-condition choices, with KUBC consistently predicting higher stress levels and larger failure strains than PBC because the more restrictive kinematic constraints suppress deformation modes and delay localization. The difference between KUBC and PBC is largest for plane-strain tension and shear-dominated loading, while the responses become increasingly similar as the stress triaxiality increases. Increasing the number of voids from 5 to 25 reduces the scatter and narrows the gap between KUBC and PBC, but still the influence of boundary conditions remains significant for all loading cases considered. The study further demonstrates that descriptors accounting for spatial clustering are better predictors of failure strain than porosity or average spacing alone. Highly clustered void distributions promote aligned localization paths, stronger strain localization, and earlier failure, while more uniformly distributed voids tend to delay coalescence. These findings suggest that statistical descriptors of void clustering and spatial heterogeneity should be incorporated in micromechanical and continuum-scale fracture models.

Modelling inhomogeneous materials by the contribution tensor approach and the boundary element method

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KEYWORDS: *effective elastic properties, inhomogeneous materials, contribution tensors, boundary element method, 3-D linear elasticity.*

The work presents an analytical-numerical approach to model composites with arbitrary shapes of inhomogeneities (particles or pores). The approach employs calculating compliance or stiffness contribution tensors. These tensors relate uniform stress or strain boundary conditions to extra strains or stresses caused by a single inhomogeneity [1]. The change in overall compliance or stiffness of the composite depends on the contribution tensors and the volume fraction of the inhomogeneities. Primarily introduced for non-interaction approximation, the approach can be combined with interaction-approximation schemes, e.g., the Mori-Tanaka assumption, to improve its accuracy [2]. The literature shows applications of the finite element method and a meshless method to model the single inhomogeneity problem, which require the discretisation of the domain [3]. Here, to solve the problem and calculate the contribution tensors, we apply the boundary element method (BEM) for 3-D elasticity. The approach requires only the discretisation of boundaries. The BEM employs 8-node boundary elements with quadratic shape functions and an adaptive numerical integration scheme to ensure high accuracy of the calculated stresses and strains [4]. In modelling single-inhomogeneity problems, the BEM eliminates the excessive discretisation of the domain that approximates the matrix, as well as the particle [5]. Numerical examples illustrate the proposed approach.

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- [1] S. Nemat-Nasser, M. Hori, *Micromechanics: Overall Properties of Heterogeneous Materials*, Elsevier, 1993.
- [2] O. Eroskin, I. Tsukrov, *Int. J. Solids Struct.*, **42**(2), 409–427, 2005. <https://doi.org/10.1016/j.ijsolstr.2004.06.045>
- [3] A. Trofimov, B. Drach, I. Sevostianov, *Int. J. Solids Struct.*, **120**, 157–170, 2017. <https://doi.org/10.1016/j.ijsolstr.2017.04.037>
- [4] G. Beer, I. Smith, C. Duenser, *The boundary element method with programming for engineers and scientists*, Springer–Verlag, 2008. <https://doi.org/10.1007/978-3-211-71576-5>
- [5] J. Ptaszny, *Comput. Math. Appl.*, **82**(15), 148–160, 2021. <https://doi.org/10.1016/j.camwa.2020.10.024>

Multiscale prediction of the elastic response of NiAl-based materials using atomistic and micromechanical calculations

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KEYWORDS: *Multiscale modeling, Molecular Dynamics, EBSD reconstruction, NiAl-based materials.*

The presented work proposes a multiscale framework for the numerical/analytical determination of the elastic constants of the intermetallic nickel-aluminate (NiAl) material at the microscopic scale. Molecular dynamics (MD) calculations have been employed to evaluate the stress tensors of a single NiAl monocrystalline body with cubic Pm3m symmetry (B2-NiAl). Moreover, the NiAl amorphous structure was generated and simulated to reproduce the mechanical performance of the grain boundary [1]. The atomistic results were transferred to the upper scale as an input to micromechanical models. Here, the finite element modeling (FEM) was utilized to simulate the elastic behavior of NiAl polycrystalline with special attention to grain anisotropy. The microstructural features of the heterogeneous body were evaluated using electron backscatter diffraction (EBSD) and next generated by Dream3D software, preserving the realistic distributions of grain orientations and grain sizes. The reconstructed NiAl polycrystal was subjected to uniaxial tensile test simulations using FEM to evaluate the effective Young's modulus (E) and Poisson's ratio (μ). The numerical results were confronted with the experimental values of E and μ , indicating a satisfactory agreement with an error of around 7%. To minimize the discrepancy, a modified FEM model was proposed that accounts for the effect of grain boundaries by introducing a weakened phase in the region of crystal bonding. The width of the weakened phase, and as a result its volume fraction, was estimated from SEM images of the NiAl sample, and the elastic properties were obtained from MD simulations of the amorphous structure. With these model assumptions, a nearly perfect correspondence between numerical and experimental results was achieved. Finally, the numerical results were compared with analytical estimates based on the Voigt, Reuss, and Hill bounds, as well as more complex bounds [2]. The analysis assessed the applicability of both numerical and analytical approaches, highlighting their strengths and weaknesses.

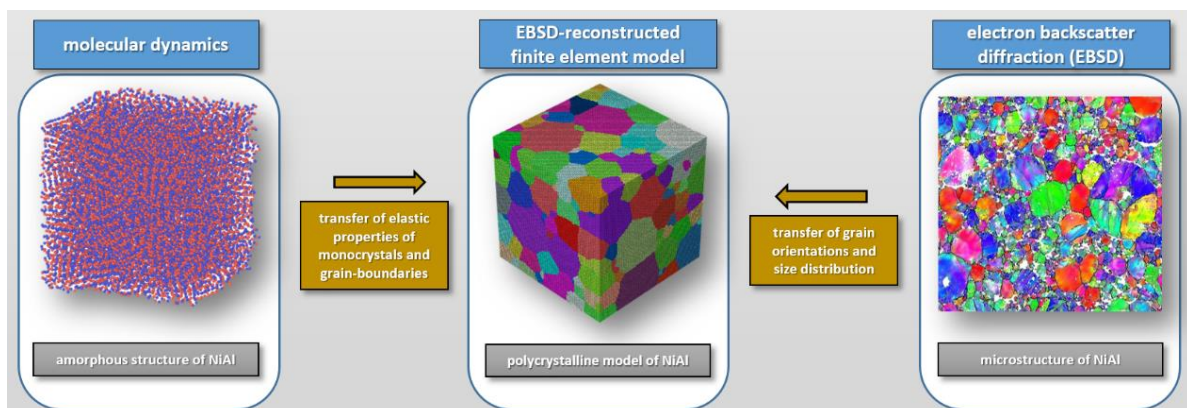


Figure 1. Summary of the multiscale framework.

ACKNOWLEDGEMENT: The authors would like to acknowledge the financial support of the National Science Centre, Poland, under Grant Agreement No. OPUS 2020/37/B/ST8/03907.

- [1] Maździarz M., Nosewicz S., Eng. Fract. Mech. **298**, 109953-1-109953-21, 2024.
<https://doi.org/10.1016/j.engfracmech.2024.109953>
- [2] Kowalczyk-Gajewska K., Maździarz M., Int. J. Eng. Sci., **157**, 103393-1-21, 2020.
<https://doi.org/10.1016/j.ijengsci.2020.103393>

Effect of kinematic hardening on the polycrystalline plasticity of FCC materials, under cyclic deformation

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KEYWORDS: *Crystal plasticity, finite-element method, cyclic loading, kinematic hardening*

A crystal plasticity finite element method (CPFEM) has been implemented to investigate the effect of kinematic hardening on the cyclic stress-strain response of face-centered cubic (FCC) materials. We have employed a rate-dependent crystal plasticity constitutive model that incorporates latent hardening due to slip interaction in the 12 slip systems of the FCC crystal [1]. Kinematic hardening due to scalar back-stresses has been defined, assuming pure self-hardening, which restricts the initiation of slip, by modifying the resolved shear stress, at individual slip systems [2]. The back-stresses have been defined using a hardening-dynamic recovery law, by Armstrong-Frederick (AF), and a Ohno-Wang (OW) type evolution law, introduced by McDowell. Cyclic loading simulations were performed in a representative volume element (RVE) consisting of 1000 grains with random orientation. The size of our RVE is 10 units with an element size of 1 unit. Preliminary results from the CPFEM model, using a single cycle of strain with an amplitude of 1.8 %, predicts the stress-strain hysteresis loop reported in [2]. Analysis of the stress-strain response for multiple strain cycles, and sensitivity of our CPFEM model predictions to the hardening and dynamic recovery coefficients in the AF and OW type laws, is currently underway. Additionally, validation of our model predictions with the stress-strain response and hardening behavior of FCC materials under cyclic loading experiments, would be performed. A predictive micromechanical CPFEM model would be instrumental in understanding the gradual degradation of mechanical strength in FCC materials due to accumulated inelastic deformation under fatigue loading conditions.

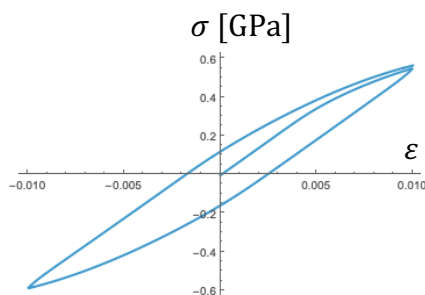


Figure 1. Cyclic stress-strain response for one strain cycle, using the AF type hardening-dynamic recovery law.

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References

- [1] S. Virupakshi, K. Kowalczyk-Gajewska, Cylindrical void growth vs. grain fragmentation in FCC single crystals: CPFEM study for two types of loading conditions, *International Journal of Solids and Structures* 280 (2023) 112397. DOI: 10.1016/j.ijsolstr.2023.112397
- [2] C. Hennessey, G. M. Castelluccio and D. L. McDowell, Sensitivity of polycrystal plasticity to slip system kinematic hardening laws for Al 7075-T6, *Materials Science & Engineering A* 687 (2017) 241–248. DOI: <http://dx.doi.org/10.1016/j.msea.2017.01.070>

Computational homogenization of porous metals and analysis of local stress fields at the microscale

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KEYWORDS: *Micromechanics, Effective properties, Stress concentration, Finite element method.*

Porous metals are a class of engineering materials characterized by a system of pores within a metallic matrix, enabling the achievement of unique structural and functional properties. Pores may be regarded as a functional phase that contributes to optimizing material performance [1]. This work focuses on investigating the influence of the material's microstructural features on local stress distributions, as well as on the prediction of effective properties. The considered factors include the pore volume fraction, as well as their shape and spatial distribution. Digital models of the microstructures accounting for these factors have been generated. The finite element method is employed to compute strain and stress fields within these models, followed by computational homogenization [2]. During the conference, the obtained effective elastic constants and stress distributions will be presented and discussed, along with remarks on modelling in the elastic–plastic regime.

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- [1] P. Liu, G.-F. Chen, Porous Materials: Processing and Applications, Butterworth-Heinemann, 2014.
<https://doi.org/10.1016/C2012-0-03669-1>
- [2] F. Fritzen, S. Forest, T. Böhlke, D. Kondo, T. Kanit, Computational homogenization of elasto-plastic porous metals, International Journal of Plasticity, 29, 102-119, 2012.
<https://doi.org/10.1016/j.ijplas.2011.08.005>

Multiscale Modeling of Creep Behavior in Eutectic NiAl-(Cr,Mo) Composites

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KEYWORDS: *crystal plasticity, homogenization, high temperature, creep*

The macroscopic mechanical response of composite materials depends on the properties of the constituents as well as the microstructure, i.e., the spatial arrangement of the constituents. In this talk we focus on the high temperature creep response of a eutectic NiAl-(Cr,Mo) composite [1], which forms domains (eutectic colonies) within which two metallic phases are arranged as ultrafine lamellar structures (see Fig. 1). Mesoscopic creep experiments of individual colonies showed that the minimum creep rate spans several orders of magnitude depending on the load direction relative to the lamination direction. The apparent Norton exponent also shows a strong anisotropy. Both effects are due to an inhomogeneous stress partitioning between the two phases which originates from the lamellar morphology and the high material contrast. In order to model the macroscopic mechanical response of the material system, we make use of a three-scale homogenization scheme involving two length scale bridges. For this, we describe the lamellar microstructure as a periodic rank-1 laminate, which allows for an efficient evaluation of the effective behavior of a single colony. To account for the interaction between different colonies, we use numerical homogenization techniques, e.g., the description of the mesostructure as a Laguerre tessellation [2] with prescribed interface orientation distribution [3] and its discretization using finite elements. After identification of the constitutive laws of the single phases, we investigate the influence of different interface orientation distributions on the macroscopic creep response.

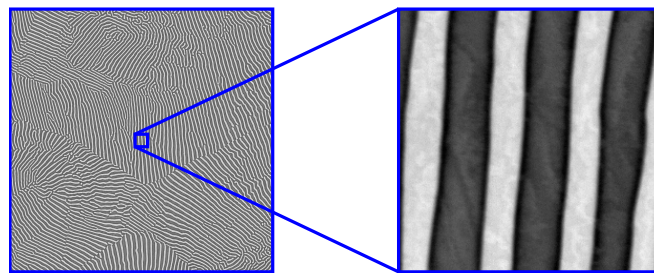


Figure 1. Hierarchical microstructure of NiAl-(Cr,Mo) with eutectic colonies (left) and lamellar structures (right).

- [1] K. Titz, J. Vollhüter, P. Randelzhofer, S. Neumeier, M. Göken, B. Wahlmann, and C. Körner, Design and characterization of a novel NiAl–(Cr, Mo) eutectic alloy, *Advanced Engineering Materials*, 26(9):2302079, 2024. <https://doi.org/10.1002/adem.202302079>
- [2] J. Kuhn, M. Schneider, P. Sonnweber-Ribic, and T. Böhlke, Fast methods for computing centroidal laguerre tessellations for prescribed volume fractions with applications to microstructure generation of polycrystalline materials, *Computer Methods in Applied Mechanics and Engineering*, 369:113175, 2020. <https://doi.org/10.1007/s00466-022-02186-7>
- [3] K.-I. Kanatani, Distribution of directional data and fabric tensors, *International journal of engineering science*, 22(2):149–164, 1984. [https://doi.org/10.1016/0020-7225\(84\)90090-9](https://doi.org/10.1016/0020-7225(84)90090-9)

A general self-consistent clustering analysis for computational homogenization using minimal offline stage

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KEYWORDS: *Micromechanics, Elasticity, Complex random microstructures, Reduced order modeling, Self-consistent clustering analysis.*

Data-driven self-consistent clustering analysis (SCA) [1][2] has emerged as a robust reduced-order modeling framework for efficient computational homogenization of heterogeneous materials. However, its conventional offline stage remains computationally expensive, since it relies on multiple full-field direct numerical simulations (DNS) on finely discretized voxel-based representative volume elements (RVEs) to extract local strain concentration tensors. In addition, the resulting clustering patterns are inherently dependent on the elastic properties of the constituent phases, thereby limiting transferability and necessitating repeated re-clustering when material parameters are altered. In this work, inspired by the fundamental solution [3] for the static linear elastic equation together with the equivalence between polarization stress and eigenstrain [4], a uniform polarization-driven domain decomposition strategy is proposed to overcome these limitations. Six unit orthogonal polarization stress tensors are sequentially applied within each individual material phase, whereas zero polarization stress is imposed in the remaining phases. Induced strain fields inside each material phase are assembled into feature representations for unsupervised k-means clustering analysis [5]. The resulting clustering patterns depend solely on the underlying microstructural geometry and the Poisson ratio for a given choice of prescribed reference medium, thus ensuring enhanced generality and eliminating the need for phase-dependent recomputation. The proposed approach is systematically validated on a diverse set of representative microstructures, including periodic body-centered cubic (BCC) lattices (both percolating and non-percolating), as well as more complex random matrix-inclusion systems such as high-volume fraction Boolean–Poisson media and randomly distributed short-fiber composites. Effective elastic properties are computed by solving the Lippmann–Schwinger equation at the cluster level with a self-consistent scheme that involves iterative updates of the reference medium. The numerical results demonstrate that accurate predictions can be achieved with as few as 64 clusters per phase, even for complex phase distribution microstructures. The proposed method shows excellent agreement with high-fidelity FFT-based homogenization results, while significantly reducing the computational cost of the offline stage compared to the standard SCA framework. Furthermore, the proposed framework outperforms conventional mean-field approaches, as it remains accurate across the full range of volume fractions for RVE/RUC systems.

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- [1] Z. Liu, M.A. Bessa, W.K. Liu, *Comput. Methods Appl. Mech. Eng.* **306**, 319–341, 2016. <https://doi.org/10.1016/j.cma.2016.04.004>
- [2] T.-R. Liu, Y. Yang, O.R. Bacarreza, S. Tang, M.H. Aliabadi, *Int. J. Solids Struct.* **281**, 112407, 2023. <https://doi.org/10.1016/j.ijsolstr.2023.112407>
- [3] T. Mura, *Micromechanics of Defects in Solids*, Springer Dordrecht, 2th ed., 1987. Page 10–12, <https://doi.org/10.1007/978-94-009-3489-4>
- [4] J.D. Eshelby, *Proc. R. Soc. Lond.* **241**(1226), 376–396, 1957. <https://doi.org/10.1098/rspa.1957.0133>
- [5] S.P. Lloyd, *IEEE Trans. Inf. Theory* **28**(2), 129–137, 1982. <https://doi.org/10.1109/TIT.1982.1056489>

Numerical simulation of dynamic failure using an instability based ductile fracture model

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KEYWORDS: *porous metal plasticity, ductile failure, void distortion, void coalescence in shear, plastic instability.*

The ductility of metals subjected to dynamic loading conditions is affected by several constitutive effects such as strain hardening, strain rate sensitivity, thermal softening, and damage softening due to microscopic void growth. Phenomenological ductile failure models such as the Johnson-Cook (JC) damage model [1] include several heuristic parameters to account for the above effects, although their values are difficult to calibrate uniquely from a standard set of experiments for a given material. This leads to non-transferability of the fracture parameters from lab scale specimens to structural components subjected to more complex non-proportional loading paths. In this study, a micromechanics-based model of ductile failure under dynamic loading conditions [2] is used to predict fracture in dual-phase steel specimens subjected to a range of loading paths from quasi-static and dynamic tension, shear and low velocity projectile impact [3]. Crack initiation at a material point is assumed to coincide with the onset of a plastic instability as a result of the competition between strain and strain rate hardening and thermal and void softening effects. Predictions obtained using the JC and the instability-based (IB) models mentioned above are compared with the experimental data under both quasi-static and dynamic loading conditions. It is shown that the IB model is able to quantitatively predict fracture in most specimen types and loading conditions using only the parameters related to the material's plastic stress-strain response and void nucleation as inputs, which can be calibrated from standard tests. Some discrepancies between the predictions of the isotropic model and experiments are observed under low triaxiality loading conditions such as shear. A relatively simple modification of the crack initiation criterion accounting for the effect of void shape changes is shown to improve the model predictions at low triaxialities.

- [1] Johnson, G. R., & Cook, W. H. *Eng. Frac. Mech.*, **21**(1),31–48, 1985. [https://doi.org/10.1016/0013-7944\(85\)90052-9](https://doi.org/10.1016/0013-7944(85)90052-9)
- [2] Tripathy, A., & Keralavarma, S.M. Strain localization in rate sensitive porous ductile materials. *J. Mech. Phy. Solids*, **195**:105957, 2025. <https://doi.org/10.1016/j.jmps.2024.105957>
- [3] Gruben, G., Langseth, M., Fagerholt, E., & Hopperstad, O. S. *Intl. J. Impact Eng.*, **88**, 153–171, 2016. <https://doi.org/10.1016/j.ijimpeng.2015.10.001>

Static recrystallization of biodegradable zinc alloy using in situ and ex situ heating experiments

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KEYWORDS: *zinc alloys. SEM/EBSD, OM/TEM*

Zinc is recognized as a promising candidate for biodegradable bone implants and cardiovascular stents due to its suitable corrosion rate. However, there remains a lack of comprehensive research quantifying how factors such as annealing temperature, alloying elements, and second-phase particles affect the recrystallization behavior and mechanical properties of zinc-based alloys. Furthermore, it is crucial to assess the thermal stability of low-alloyed zinc after undergoing plastic deformation, especially considering body temperature and the potential exposure to higher temperatures during transportation and storage of the final products.

The primary aim of this study was to examine the thermal stability of pure zinc and zinc alloys after hydrostatic extrusion.

Ex-situ microstructural studies were carried out on samples heated in a Memmert UNE 400 drying oven at 50°C, 100°C, and 150°C for 1 hour, followed by air cooling. Additionally, the 4D-STEM TESCAN TENSOR was used to obtain orientation maps of samples before and after heating up to 200°C for 1 hour through precession assistance, allowing the characterisation of the intermetallic phase ($\text{Mg}_2\text{Zn}_{11}$), as well as the grain size and orientations of the eutectic mixture.

In-situ SEM/EBSD studies were performed using the TANIST TESCAN system. Samples were maintained at 100°C for 48 hours, with repeated electron backscatter diffraction (EBSD) analysis to monitor grain nucleation and growth.

Mechanical properties of materials were investigated in the initial state and heating at 50, 100, and 150 °C using static compression and tensile tests.

The results demonstrated that zinc alloys have greater thermal stability than pure zinc. The presence and distribution of second-phase particles during recrystallisation significantly influence the material. Advanced microstructural characterisation allowed both qualitative and quantitative assessment of the changes in the materials during heating at high temperatures. Microstructural changes were correlated with mechanical properties,

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On Range of Values of Cosserats' Material Parameters

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KEYWORDS: *Cosserats' Theory, Size Effect, Material Parameters, Pure Bending, Virtual Experiments.*

The early work of Gauthier and Jahsman [1] is among the first to expose a seemingly unexpected behaviour of granular materials whereby smaller specimens exhibit a softening, rather than stiffening behaviour predicted by the manner in which Cosserats' theory of elasticity has been postulated. Bigoni and Drugan [2] have later performed a detailed theoretical analysis to explain such a behaviour as in fact expected when the material inclusions are stiffer than the embedding matrix, which is exactly what they are in the tests performed in [1].

When this is regarded through the prism of the material parameters in Cosserats' elasticity, it turns out that such a behaviour disqualifies the theory from being a viable mechanical model as it necessarily implies that they fall outside of the range necessary for the strain-energy density of the material to remain positive. While numerical tests, such as e.g. those in [3], confirm that they do, there remains an unanswered question as to why such a mechanical problem remains stable indicating a positive accumulated strain energy upon application of a positive external work increment?

In our recent work [4] we have addressed this controversy by performing a detailed eigenanalysis of the problem and checked if the eigenvectors of the Cosserats' constitutive matrices may represent a deformed shape of the specimen/finite part thereof, i.e. if they may exist on a non-infinitesimal scale. If not, the fact that a strain-energy *density* may drop to zero at some point in a specimen does not necessarily imply a zero strain-energy *over a finite volume* (whole specimen or its representative volume element).

Taking pure bending of a unit strip of thickness h and Poisson's ratio n as a test case, it may be shown that the condition for a stable solution imposed on the characteristic bending length l_b is not $l_b > 0$ as would follow from the condition of positive strain-energy density, but in fact

$$l_b > -\frac{h}{24(1-n)}.$$

By pursuing the methodology presented in [5] it may be demonstrated that this is indeed the limiting value of the characteristic bending length that may be obtained in real periodic structures of the type analysed in [4] for any Poisson's ratio and any matrix-to-inclusion stiffness ratio.

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- [1] R.D. Gauthier, W.E. Jahsman, *ASME J. Appl. Mech.* **42**(2), 369–374, 1975.
- [2] D. Bigoni, W.J. Drugan, *ASME J. Appl. Mech.* **74**(4), 741–753, 2007.
- [3] Z. He, H. Zhu, X. Wang, S. Ma, *Composite Struct.* 251, 112667, 2020.
- [4] E. Papa Dukić, G. Jelenić, *Acta Mech.* (submitted), 2026.
- [5] E. Papa Dukić, L. Grbac, G. Jelenić, *J. Mech. Mat. Struct.* 19 (3), 515–530 (2024)

Inverse Homogenization-Based Design of Canonical Microstructures

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KEYWORDS: *inverse problem, canonical microstructure, homogenization theory, numerical simulation*

Inverse problems in homogenization theory have recently attracted considerable attention, particularly in the context of optimal design of multifunctional materials. In this context, one seeks to determine a microstructure that realizes prescribed effective (homogenized) properties, i.e., to reconstruct a spatial distribution of phases such that the corresponding homogenized response matches given target data.

In this work, we consider the problem of reconstructing the microstructure of a two-phase composite from a sequence of macroscopic measurements. The analysis focuses on effective properties associated with heat flow problem in a heterogeneous medium. The inverse problem is formulated as the minimization of a cost functional defined as the mismatch between target and computed effective responses. The optimization is carried out using a simulated annealing (SA) algorithm, in which the design variables correspond to phase indicators at the pixel level. The microstructure is iteratively updated by modifying the phase assignment of individual pixels, and convergence is assessed through the evolution of the cost functional.

Due to the non-uniqueness of admissible solutions, the problem is inherently ill-posed, exhibiting both non-uniqueness and instability. To address this issue, a regularization term is incorporated into the objective functional, penalizing the interfacial measure (specific surface area). This promotes geometrically simpler configurations and imposes additional structural constraints. Numerical results indicate that, across a broad class of microstructural types, the reconstructed microstructures converge toward configurations consisting of a single irregularly shaped inclusion embedded in a matrix phase. This observation motivates the introduction of the concept of a *canonical microstructure*, defined as a reduced representation that is macroscopically equivalent—within the homogenization framework—to more complex heterogeneous media. Within this framework, the canonical microstructure acts as an effective surrogate for the underlying heterogeneous material, allowing for a substantial reduction in geometric complexity while preserving the essential macroscopic response.

The results suggest that, under suitable regularization, complex multi-inclusion microstructures can be effectively replaced by a single connected inclusion without significant deviation from the target effective properties. This finding sheds light on the structure of solutions to inverse homogenization problems and points toward reduced-order representations in material design. This is particularly relevant in the context of additive and advanced manufacturing technologies, where simplified geometries are advantageous for fabrication and optimization.

Superelasticity generated by instability

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KEYWORDS: *Fe- based shape memory alloys, molecular dynamics, elastic eigen-subspaces*

Fe-based shape memory alloys (SMAs) are a promising class of smart materials; their low cost and large reversible strain—driven by martensitic phase transformation (MPT) and twinning-detwinning processes—make them suitable for diverse applications. The key areas of use are civil engineering and infrastructure, due to their significant stress-strain hysteresis and compatibility with structural steel, as well as high-strength aerospace components designed for compact, hydraulic-free actuation. Despite their excellent damping and positioning capabilities, Fe-based SMAs exhibit a functional decrease in superelasticity (SE) resulting from dislocation activity, martensite-variant cross-blockage, and residual deformations.

Experiments performed on austenitic steels show that strain front mobility is achieved through the junction of the hard-to-deform (111) orientation and the compliant (110) orientation [1, 2]. To transfer this effect to Fe-based SMAs, a molecular dynamics (MD) simulation was performed. The application of a modified embedded atom method (MEAM) interatomic potential [3] revealed that the martensitic phase transformation (MPT) starts within elastic eigen-subspaces on both sides of the boundary; however, due to energetic advantages, martensite propagates primarily within the (110)-oriented part of the SMA bicrystal under tension. The (111) component serves as a trigger area, resulting in the formation of large reversible strains. This process is driven by the reduction of the Gibbs free energy of the unstable, traveling martensite-austenite interface as it returns toward the coherent (111) || (110) junction. To further investigate this instability-driven SE, additional bicrystals featuring coherent boundaries were analyzed. The underlying mechanisms identified in this work offer a pathway toward mitigating functional fatigue in Fe-based SMAs.

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- [1] K. Nalepka, J. Tabin, J. Kawałko, A. Brodecki, P. Bała, Z. Kowalewski, *International Journal of Plasticity* 183, 104159, 2024. <https://doi.org/10.1016/j.ijplas.2024.104159>.
- [2] J. Tabin, K. Nalepka, J. Kawałko, A. Brodecki, P. Bała, Z. Kowalewski. *Metallurgical and Materials Transactions A* 54, 4606-4611, 2023. <https://doi.org/10.1007/s11661-023-07223-5>.
- [3] H. Sharifi, C.D. Wick, *Computational Materials Science* 248 113595, 2025. <https://doi.org/10.1016/j.commatsci.2024.113595>.

Understanding stress and strain partitioning in polycrystalline materials using statistical machine learning

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KEYWORDS: *Strain partitioning, polycrystal plasticity, statistical machine learning, crystal plasticity FEM, Molecular dynamics.*

How does a macroscopic applied stress or strain field distribute or partition into individual grains of a polycrystalline material? This is a long-standing question in the field of (poly)-crystal plasticity. The well-known Taylor and Sachs models provide bounds in this regard, with the Taylor model enforcing iso-strain – i.e., all grains obtain the same macroscopic applied strain – and the Sachs model enforcing iso-stress; the response of real materials lies somewhere in between.

In a recent work, we developed a methodology using statistical machine learning to understand strain partitioning in nanoscale polycrystalline thin films [1]. Such films constitute interesting material systems since they often display enhanced mechanical properties in comparison to their bulk counterparts. We perform atomistic simulations of the molecular statics/dynamics kind to understand the deformation mechanisms in thin film structures. Subsequently, we apply statistical machine learning algorithms to understand the inhomogeneity in the distribution of total strain, elastic strain and orientation in the structure. The results show a lognormal-like distribution of the elastic strain which is in contrast to the normal distribution observed for coarse-grained materials. Whilst the distribution of the elastic strain is unimodal, the distribution of total strain (and microrotation) is multimodal consisting of distinct peaks. We use a Gaussian mixture model to identify these peaks, and furthermore, correlate the individual peaks with deformation events occurring in individual grains.

We extend the methodology to analyze strain partitioning in crystal plasticity finite element simulations, and compare the results with those from atomistic simulations. Furthermore, we study the partitioning behavior over the entire trajectory of deformation. The results are finally discussed in the context of homogenization models and bridging length scales towards continuum frameworks.

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[1] A. Prakash and S. Sandfeld [2022], *Advanced Engineering Materials*, 24(12), 2200574

Session TS11

Multiphysics and coupled problems

Chemo-mechanics of biodegradable polymers

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KEYWORDS: *Hydrolysis, Reaction, Diffusion, Viscoplasticity, Constitutive modelling.*

Biodegradable polymers are materials designed to degrade and ultimately disappear after having completed their structural function. They are increasingly developed for engineering and biomedical applications, where simultaneous control over mechanical performance and degradation behaviour is critical. Many biodegradable polymers primarily degrade via hydrolysis, in which water molecules react with susceptible backbone bonds (e.g. esters), leading to chain scission. Chain scission in turn impacts the thermo-mechanical properties and causes mass loss. Conversely, mechanical stress can also impact the degradation kinetics [1].

In this talk, I will describe our recent experimental and modelling efforts to investigate the coupled chemo-mechanical behaviour of various degradable polymer systems in aqueous environments, including glassy polymers, semi-crystalline polymers, and biodegradable hydrogels. In particular, I will present a constitutive modelling framework for amorphous polymers, incorporating a mechanistic description of the chain scission process and its influence on the elasto-viscoplastic behaviour through the concept of effective temperature [2, 3]. We show that the behaviour of wet, degraded polymer can be accurately captured by evaluating the response of the dry, undegraded polymer evaluated at an elevated temperature and reflecting the reduction in glass transition temperature due to chain scission and water uptake.

ACKNOWLEDGEMENT: This research is supported by a Future Leaders Fellowship of UK Research and Innovation (MR/W006995/1).

- [1] H. Chen, Z. Pan, G.S. Sulley, C.K. Williams, L. Brassart, *Polym. Degrad. Stab.* **243**, 111751, 2026. <https://doi.org/10.1016/j.polymdegradstab.2025.111751>
- [2] Z. Pan, L. Brassart, *Acta Biomater.* **167**, 361–373, 2023. <https://doi.org/10.1016/j.actbio.2023.06.021>
- [3] Z. Pan, H. Chen, L. Brassart, *Int. J. Plasticity* **178**, 103996, 2024. <https://doi.org/10.1016/j.ijplas.2024.103996>

Thermodynamic regularization based computational framework for strain-induced crystallization

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KEYWORDS: *Thermodynamic regularization, Strain-induced crystallization, Loss of ellipticity*

Strain-induced crystallization (SIC) represents a type of phase transition in natural rubbers triggered by deformation. This is evident from the heterogeneities in temperature distribution observed in unfilled natural rubbers subjected to homogeneous uniaxial tension [1], as temperature variations in natural rubber are attributed to SIC. These heterogeneities become pronounced following the onset of SIC, particularly within the stretch ratio range of $4 \lesssim \Lambda \lesssim 5.5$ (see Fig. 1). Interestingly, prior to the onset of SIC ($\Lambda_1 \lesssim 4$) and following the stress upturn ($\Lambda_1 \gtrsim 6$), the temperature distribution remains homogeneous. This observation further implies that this behavior does not stem from coupling instabilities, as observed in electroactive elastomers, but rather from the loss of ellipticity associated with phase transitions.

In this contribution, we extend the recently developed thermodynamic regularization technique [2] to the context of strain-induced crystallization in natural rubbers and formulate a novel computational framework based exclusively on the laws of thermodynamics and a single thermodynamic potential. The predictions of the computational framework with the four coupled fields (displacement, temperature and two nonlocal interactions) is then demonstrated through multiple numerical benchmarks and comparison with experimental data. Specifically, the average nominal stress, calculated from the ratio of force and initial cross-sectional area, is demonstrated in Fig. 1 (left). In can be seen a good agreement with the experimental data and also there is no stress plateau observed after the onset of SIC due to regularization. The predicted heat source at the center of the specimen is plotted versus time in Fig. 1 (right). It can be observed that, initially, the heat source increases with crystallinity. Near the end of the loading phase, the heat source decreases due to the inflection point in the evolution of crystallinity.

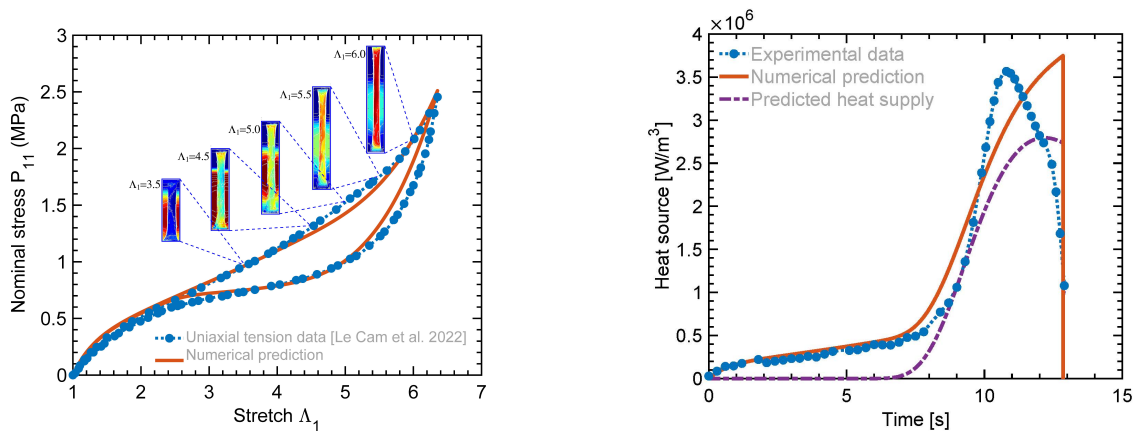


Figure 1: Left: Average nominal stress in the uniaxial tension; **Right:** Heat source evolution at the center of the specimen.

- [1] J.B. Le Cam, A. Tayeb, S. Charlè, *Polymer* **255**, 125120, 2022.
<https://doi.org/10.1016/j.polymer.2022.125120>
- [2] V.N. Khiêm, M. Jabareen, R. Poudel, X. Tang, M. Itskov, *J. Mech. Phys. Solids* **193**, 105874, 2024.
<https://doi.org/10.1016/j.jmps.2024.105874> 2024.

Potential method in the steady vibration problems for the coupled theory of Moore-Gibson-Thompson thermoporoelasticity

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KEYWORDS: *Thermoporoelasticity, Moore-Gibson-Thompson Law, Steady Vibration, Potential Method.*

The first theory of poroelasticity, based on Darcy's law, was formulated by Biot (1941), who developed an elasticity framework describing the mechanical behavior of fluid-saturated porous solids. Moreover, the linear theory of poroelasticity, based on the volume fraction concept was first presented by Cowin and Nunziato (1983). Evidently, theories based on Darcy's law account for variation of the pore fluid pressure but neglect change of the pore volume fraction. Conversely, theories grounded on the concept of volume fraction incorporate change of pore volume fraction while disregarding variation of fluid pressure. Both approaches, however, capture only part of the physical picture. In reality, deformation of a porous body inevitably induces simultaneous changes in both the pore volume fraction and the pore fluid pressure. This limitation highlights the necessity of coupled models that treat these effects in a unified framework.

To overcome this limitation, Svanadze (2020) developed a coupled theory of poroelasticity, in which both physical effects are incorporated within a unified framework. This coupled approach generalizes Biot's and Cowin-Nunziato's theories by introducing additional field variables and interaction terms. Based on Fourier's classical law of heat conduction, Svanadze (2019) introduced a coupled linear theory of thermoporoelasticity.

In this work, based on the Moore-Gibson-Thompson (MGT) law of heat conduction, the coupled linear theory of thermoporoelasticity is proposed in which the combination of the following four mechanical phenomena is considered: the deformation of elastic porous material, Darcy's law for fluid flow in pore network, the concept of the volume fraction of pores, and the MGT law of heat conduction. On the basis of this theory the basic boundary value problems (BVP) of steady vibrations are investigated using the potential method (the boundary integral equations method). Namely, the fundamental solution of the system of steady vibration equations is constructed explicitly by elementary functions. Green's identities are obtained and the uniqueness theorems for the classical solutions of the BVPs are proved. Some useful singular integral operators are introduced and the basic properties of these operators are presented. Then, the above-mentioned BVPs of steady vibrations are reduced to the equivalent always solvable singular integral equations for which Noether's theorems are valid. Finally, the existence theorems for classical solutions of the BVPs of steady vibrations are proved by means of the potential method and the theory of singular integral equations.

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Transformation front kinetics in deformable ferromagnets

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KEYWORDS: *magneto-mechanics; stress-induced phase transitions; magneto-structural phase transitions; phase boundary kinetics; cut-finite-element method; magnetic shape-memory alloys.*

Materials such as magnetic shape-memory alloys possess an intrinsic coupling between material's magnetisation and mechanical deformation. These materials also undergo structural phase transitions, with phase boundaries separating different phases and the kinetics of the phase boundaries governed by the magnetic field and the mechanical stresses. There is a multiplicity of other materials revealing similar phenomena, e.g. magnetic perovskites.

To model the propagation of the phase boundaries in deformable magnetic materials at the continuum scale, three ingredients are required: a set of governing equations for the bulk behaviour with coupled magnetic and mechanical degrees of freedom, a dependency of the phase boundary velocity on the governing factors, and a reliable computational method. The expression for the phase boundary velocity is usually obtained within the continuum thermodynamics setting, where the entropy production due to phase boundary propagation is derived, which gives a thermodynamic driving force for the phase boundary kinetics. For deformable ferromagnets, all three elements (bulk behaviour, interface kinetics, and computational approaches) have been explored, but under a number of limitations.

The talk will demonstrate novel derivation of the thermodynamic driving force for transformation fronts in a general magneto-mechanical setting, adaptation of the cut-finite-element method (CutFEM) for transformation fronts in magneto-mechanics, which allows for an exceptionally efficient handling of the propagating interfaces, without modifying the finite-element mesh, and application of the developments to qualitative modelling of magneto-mechanics of magnetic shape-memory alloys.

Historically, this problem was considered in [1], but only for non-linear elasticity, magnetostatics, and absence of electric fields. The present work does not make these assumptions. The adapted CutFEM method generalises the results of [2], implementing the method for multi-physics, with the code available via GitHub [3]. The preprint of a paper summarising the results included in the talk is available at arXiv [4].

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- [1] G. A. Maugin, A. Fomethé, *Meccanica* 32(4), 347-362, 1997.
- [2] M. Poluektov, L. Figiel, *Comput. Methods Appl. Mech. Eng.* 388, 114234, 2022.
- [3] <https://github.com/mpoluektov/cutfem-multiphys-2d>
- [4] M. Poluektov, arXiv:2602.03745, 2026.

Thermo-Electro-Mechanical Modelling of Spark Plasma Sintering within Discrete Element Framework

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KEYWORDS: *Discrete element method (DEM), Spark Plasma Sintering, conductive materials, thermoelectromechanical model*

Spark Plasma Sintering (SPS) is a powder consolidation process that combines mechanical pressure with rapid Joule heating induced by electric current. This facilitates the consolidation and densification of particulate materials, making SPS a sustainable and energy-efficient technique. Initially, the powder consists of loosely bonded particles. As the process progresses, the particles become connected through necks, which grow over time due to diffusion and mass transport. The complexity of the SPS process lies in the strong interdependence of electrical, thermal and mechanical phenomena. Accurate modelling of this process requires a fully coupled multiphysics approach.

In this work, a microscopic thermo-electro-mechanical model is developed within the Discrete Element Method (DEM) framework. DEM enables microscopic analysis by treating each particle as a discrete element, thereby enabling precise representation of microscopic interactions. The model is based on sintering geometry, assuming cylindrical neck formation between spherical particles. Individual models for electrical, thermal, and mechanical behaviour are first validated separately, and then integrated into a fully coupled model. Thermal and electrical models were presented in [1, 2], in which effective properties were evaluated and validated against experimental measurements. A coupled thermo-electric model was presented in [3], where it was shown that Joule heating, generated due to current flow, tends to concentrate in smaller particles but is effectively conducted throughout the sample, leading to a relatively uniform temperature rise. Finally, the effect of densification on heating rate was analysed. Herein, the coupled thermo-electric model will be integrated with the mechanical model to study the multiphysics phenomena during the SPS process.

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- [1] F. Nisar, J. Rojek, S. Nosewicz, K. Kaszyca, and M. Chmielewski, “Evaluation of effective thermal conductivity of sintered porous materials using an improved discrete element model”, *Powder Technology*, 437, 119546 (2024).
- [2] F. Nisar, J. Rojek, S. Nosewicz, J. Szczepański, K. Kaszyca, and M. Chmielewski, “Discrete element model for effective electrical conductivity of spark plasma sintered porous materials”, *Computational Particle Mechanics*, 11, 2191-2201 (2024).
- [3] F. Nisar, J. Rojek, S. Nosewicz, K. Kaszyca, and M. Chmielewski, “Coupled thermo-electric discrete element model for spark plasma sintering”, *Powder Technology*, 458, 120957 (2025).

Thermo-Electric Phenomena in Spark Plasma Sintering

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KEYWORDS: *Spark plasma sintering, overheating, Joule effect, Thermo-electric coupling*

SPS is a powder consolidation process that employs electric current to generate heat (Joule effect) while simultaneously applying pressure to achieve densification. In conductive powders, as current flows through the network of particles, it can concentrate at interparticle contacts/necks due to high resistance. This may result in high current densities and local temperature increase (overheating). Such thermo-electric effects can influence microstructure and hence properties.

In this work, thermo-electric phenomena during SPS are investigated through a combined experimental and numerical study. NiAl powder is consolidated at different temperatures. The resulting microstructures are characterised using XRD, SEM and EBSD, with particular focus on particle contact regions that are most susceptible to local overheating. To complement the experiments, thermo-electric finite element simulations are performed using representative three-particle geometries with different neck sizes.

The combined experimental and numerical results indicate that the resulting overheating in NiAl is limited and insufficient to induce partial melting or microstructural changes under the investigated conditions. These findings contribute to a clearer understanding of thermo-electric phenomena in SPS and suggests that a numerical model of SPS can be simplified.

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- [1] F. Nisar, J. Rojek, S. Nosewicz, K. Kaszyca, and M. Chmielewski, “Evaluation of effective thermal conductivity of sintered porous materials using an improved discrete element model”, *Powder Technology*, 437, 119546 (2024).
- [2] F. Nisar, J. Rojek, S. Nosewicz, J. Szczepański, K. Kaszyca, and M. Chmielewski, “Discrete element model for effective electrical conductivity of spark plasma sintered porous materials”, *Computational Particle Mechanics*, 11, 2191-2201 (2024).
- [3] F. Nisar, J. Rojek, S. Nosewicz, K. Kaszyca, and M. Chmielewski, “Coupled thermo-electric discrete element model for spark plasma sintering”, *Powder Technology*, 458, 120957 (2025).

Advances in Computational Aeroelasticity of Plates with Acoustic and Thermal Effects

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KEYWORDS: *Aeroelasticity, Vibro-Acoustics, Plates, Flutter, Supersonic Flow.*

The aeroelastic behavior of plates has been extensively studied as a model for flight vehicle skin panels [1]. In supersonic flow, plates can experience flutter and transition into a post-flutter limit cycle oscillation (LCO) without causing immediate structural failure. This behavior contrasts with larger structures, like wings, where flutter must be strictly avoided. Consequently, understanding the mechanisms of flutter onset and post-flutter LCO is important. Often, one side of the panel encloses a cavity of non-convecting fluid, where structural vibrations generate acoustic pressure perturbations that can couple with the aeroelastic system. Although frequently simplified or ignored, this creates a coupled aero-acoustic-elastic (AAE) problem. Recent findings suggest that the vibro-acoustic coupling can affect flutter, potentially triggering instability at significantly lower dynamic pressures than without a cavity [2].

This presentation outlines a computational approach for analyzing this coupled AAE system along with recent and current developments. **For the structural dynamics** of a thin elastic plate, we employ a Rayleigh-Ritz (RR) formulation that includes geometric nonlinearity [3], recently enhanced by using finite element method (FEM) eigenmodes as basis functions in the RR scheme to accommodate arbitrary transverse boundary conditions and geometry. The hybrid FEM-RR approach efficiently balances the need to capture both global fluid-structure interactions (which in many cases requires only several leading modes to resolve) and localized structural effects while keeping the relatively easily computed nonlinear stiffness terms in modal coordinates. **On the acoustic side**, we use a coupled vibro-acoustic model in modal coordinates, focusing on scenarios where the primary acoustic and structural modes are closely spaced [2]. We also address a recent development in modeling acoustic medium with non-uniform temperature and density fields (e.g., due to wall heating or cooling) which lead to acoustic wave bending that affects the vibro-acoustic coupling. Similar to the structural model, FEM is used to obtain the acoustic eigenmodes for a modal formulation. Finally, to account for aerodynamic heating in high-speed flow, we introduce an ongoing development of **a coupled aero-thermal-elastic analysis scheme**. Building upon literature in this area [4], our scheme aims to loosely couple the timescales of thermal and aeroelastic responses by using steady-state Reynolds Averaged Navier-Stokes (RANS) simulation results as input to transient heat transfer and nonlinear aeroelastic stability analysis. In this setting, the plate may start to flutter and reach LCO while its temperature gradually increases until buckling causes it to stabilize.

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- [1] E. H. Dowell, *Aeroelasticity of Plates and Shells*, Noordhoff International Publishing (now Springer) 1974.
- [2] M. Freydin, *Aero-acoustic-elastic flutter of plates*, Journal of Fluids and Structures, **137**, 2025. <https://doi.org/10.1016/j.jfluidstructs.2025.104368>
- [3] M. Freydin and E. H. Dowell *Nonlinear Theoretical Aeroelastic Model of a Plate: Free to Fixed In-Plane Boundaries*, AIAA Journal, **59**(2), 2021. <https://doi.org/10.2514/1.J059551>
- [4] D. Huang and P. P. Friedmann, *An aerothermoelastic analysis framework with reduced-order modeling applied to composite panels in hypersonic flows*, Journal of Fluids and Structures, **94**, 2020. <https://doi.org/10.1016/j.jfluidstructs.2020.102927>

Atomistic Investigation of Size and Temperature Effects on the Compressive Behavior of Cracked Silicon Nanopillars

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KEYWORDS: *Buckling, Silicon, Molecular Dynamics Simulations, Size and Temperature Effects.*

The performance, sensitivity, and reliability of many MEMS and NEMS devices are directly governed by the mechanical behavior of their structural components. Silicon nanobeams and nanopillars are widely used in MEMS and NEMS devices as sensors and actuators. These structures must function reliably under varying thermal conditions, from low to elevated temperatures [1]. Experimental and atomistic simulations have shown that the mechanical response of silicon nanostructures is size-dependent [2]. This size-dependent behavior is further influenced by temperature and structural defects such as cracks [3]. Therefore, it is essential to investigate the size-dependent mechanical response of silicon nanostructures under the combined effects of crack defects and temperature variations.

In this study, molecular dynamics (MD) simulations are used to investigate the compressive behavior of cracked silicon nanopillars across a range of sizes and temperatures. Particular attention is given to how crack defects influence buckling loads. The atomistic results are compared with continuum-based models reported in the literature. The findings show that current continuum models fail to accurately capture the size-dependent compressive response of cracked silicon nanopillars. The underlying physical mechanisms responsible for these discrepancies are analyzed. In particular, the analysis reveals that conventional kinematic continuity conditions used to model cracked cross-sections may not be valid at the nanoscale and require further refinement.

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- [1] Z. Zhang, H. Zhang, Y. Hao, H. Chang, J. Microelectromech. Syst. 33, 174–208, 2024. <https://doi.org/10.1109/JMEMS.2024.3354235>
- [2] H. Darban, Int. J. Mech. Sci. 296, 110316, 2025. <https://doi.org/10.1016/j.ijmecsci.2025.110316>
- [3] K. Kang, W. Cai, Int. J. Plast. 26(9), 1387–1401, 2010. <https://doi.org/10.1016/j.iplas.2010.02.001>

Computational Modelling of Heat Sinks Enhancement with Triply Periodic Minimal Surface Structures

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KEYWORDS: *heat sink, porous TPMS, fluid flow, heat transfer, numerical method*

Efficient thermal management is a critical challenge in modern electronic systems, where increasing power densities and device miniaturization demand advanced cooling solutions [1–3]. Conventional fin based heat sink device, often fail to meet demand for compactness and enhanced heat dissipation [4,5]. In this study, the effects of different triply periodic minimal surface (TPMS) structures on thermal performance of heat sink devices are investigated using finite element simulations conducted in COMSOL Multiphysics. The computational model consists of a fluid channel, a uniform heat source applied through copper base plate and three different TPMS heat sink geometries: gyroid, diamond and I-WP. The generated heat is conducted to the TPMS structure and subsequently dissipated to the surrounding fluid via convection at the outlet surface. The outlet boundary is defined as a pressure outlet, while the outer channel walls are assumed to be adiabatic with a no-slip condition. Water is used as the working fluid in the analysis.

Computational fluid dynamics (CFD) simulations were employed to analyze fluid flow and thermal performance subjected to cell size, structural arrangements and the inlet velocities. The fluid flow and heat transfer are governed by the Navier–Stokes and energy equations, respectively. The results of performance evaluation criterion (PEC), which combines heat transfer and friction factor, indicates that gyroid TPMS heat sink achieves the balanced thermo-hydraulic efficiency. This is due to smooth and continuous channel of gyroid structure, which promotes helical flow paths and ensures uniform fluid distribution. Furthermore, the results of Nusselt number is decreased along the channel length for all configurations due to thermal boundary layer development, while increasing inlet velocity improves overall heat transfer performance. In conclusion, TPMS based porous heat sinks, particularly gyroid geometry, offer effective solution for advanced thermal management applications.

ACKNOWLEDGEMENT: The work was supported by ‘PhDBoost’ Program for doctoral students of the Doctoral School of Poznan University of Technology (in 2026) from the University’s subsidy financed from the funds of Ministry of Science and Higher Education (0610/SPHD/2604).

- [1] W. Iticha, T. Stręk, *Materials* 18(23), 5280, 2025. <https://doi.org/10.3390/ma18235280>
- [2] M.Z. Saghir, M.M. Rahman, *Fluids* 9 (12), 297, 2024. <https://doi.org/10.3390/fluids9120297>
- [3] S. Samson, P. Tran, and P. Marzocca, *Applied Thermal Engineering* 235, 121296, 2023. <https://doi.org/10.1016/j.applthermaleng.2023.121296>
- [4] S. A. Jajja, W. Ali, H. M. Ali, A. M. Ali, *Applied Thermal Engineering* 64(1–2), 76–82, 2014. <https://doi.org/10.1016/j.applthermaleng.2013.12.007>
- [5] Q. Wang, J. Tao, Z. Cui, T. Zhang, G. Chen, *Int. Commun. Heat Mass Transf.* 155, 107580, 2024. <https://doi.org/10.1016/j.icheatmasstransfer.2024.107580>

Shear Stress-based Air Speed Indication System

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KEYWORDS : *Air Speed Indication (ASI), Shear Stress, Cantilever Beam, Strain.*

The conventional air speed indication (ASI) systems rely on Pitot-static pressure differentials, which remain vulnerable to blockages from contaminants and icing, compromising measurement reliability, necessitating robust sensing alternatives. We present a novel shear stress-based airspeed indication system, designed for aircraft applications. The proposed airspeed indicator employs a cantilever type slender, T- beam, rigidly anchored at its base, free at the opposite end [1]. The floating head of T-beam translates in response to velocity-induced wall shear stress (illustrated in Fig. 1), bending the slender beam. Strain gauges positioned near the base of the cantilever beam capture the bending-induced strain. A transient structural analysis was carried out using the *ANSYS 2022 R2 Transient Structural module* to evaluate the strain response for different air speeds. The wall shear stress is subsequently determined from the strain obtained through simulation studies on the cantilever beam.

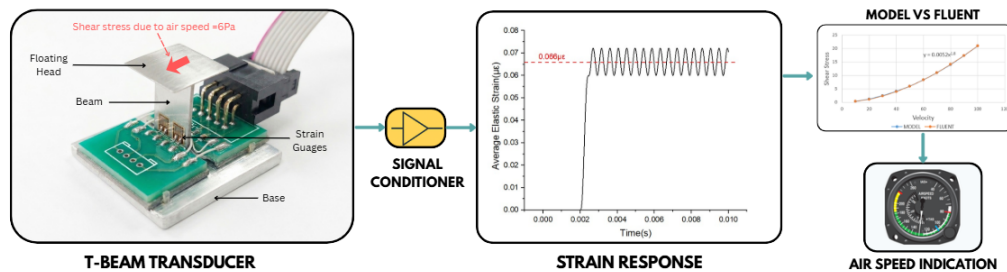


Figure 1. Shear stress-based air speed indicator (ASI) Model

The free-stream velocity is correlated to wall shear stress through a mathematical model given by Eq. (1).

$$u = k_c \tau_w^{5/9} \quad (1),$$

where, turbulence effect is taken into account through k_c ($k_c = 18.4747$), which is an empirical constant; u is the freestream velocity and τ_w is the wall shear stress.

The mathematical model was validated through numerical simulations carried out using *ANSYS 2022 R2 FLUENT*. The results obtained from the mathematical model are in good agreement with the numerical simulations (*ref. Fig. 1, inset Model vs Fluent*). The results demonstrate the feasibility of shear stress-based airspeed indication, offering a simple, cost-effective alternative to conventional Pitot-static probe-based systems, with improved robustness and reduced susceptibility to blockage.

[1] S. Pathan, M. Kshetrimayum, V. Menezes, C.S. Yerramalli, *Sādhana* 50, Article 128, 2025.
<https://doi.org/10.1007/s12046-025-02767-1>

Data-Driven Models for Fast Prediction of Steel Property Distributions

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KEYWORDS: *steel, stochastic modeling, hot deformation process, cooling process, machine learning.*

Stochastic models developed for the cooling process after hot deformation in the rolling process have enabled accurate and reliable prediction of the final properties of steel [1][2]. However, their use in industrial settings is difficult due to the computational complexity of the models and the techniques used, such as the Monte Carlo method. The stochastic models used take into account the uncertainties of process parameters, heterogeneities, and the probabilistic nature of the process, which further increases the complexity.

Data-driven models come to the rescue here, using high-performance computing to provide sufficient training data. Proper development of these models translates into a significant reduction in the time required to predict property distributions at the end of the hot rolling and cooling processes. Initially, stochastic models are identified for a specific selected steel (S355J2) using inverse analysis techniques, which allows for the determination of model coefficients. Next, a methodology utilizing the MLP architecture was proposed to create models that can quickly predict final property distributions for experimental roll configurations. These ML models use input parameters such as strain, strain rate on subsequent rolls, as well as heating temperature, heating time, and cooling rate. The output of these models allows for the preservation of the distributions of microstructural parameters such as phase fractions and material properties. The obtained results (see Fig. 1) demonstrate that the approach provides accurate predictions at significantly reduced computational cost compared to traditional approaches, providing a starting point for real-time process optimization.

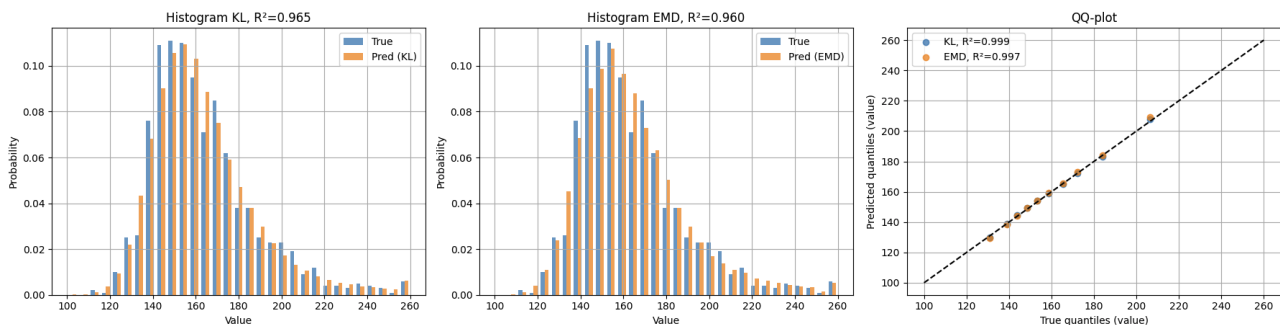


Figure 1. Comparison of impact toughness energy (E_{imp}) distributions from the ML model and the stochastic model for two different loss functions: Kullback–Leibler Divergence and Earth Mover's Distance.

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- [1] D. Szeliga *et al.*, *Inverse problem in the stochastic approach to modeling of phase transformations in steels during cooling after hot forming*, J. Mater. Eng. Perform. 33(24), 13787–13802, 2024. <https://doi.org/10.1007/s11665-024-10458-x>
- [2] D. Szeliga *et al.*, *Stochastic model of accelerated cooling of eutectoid steel rails*, Model. Simul. Mater. Sci. Eng. 33(2), 025008, 2025. <https://doi.org/10.1088/1361-651X/ada81c>

Modeling Surface Roughness and Tool Wear using Particle Methods

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KEYWORDS: *Machining, finishing operations, surface roughness, tool wear, coupled problems, particle methods, PFEM.*

Machining of metal parts involves two key challenges that have driven modeling research in recent decades: optimizing cutting strategies and parameters, and balancing productivity with tool longevity. From the perspective of the workpiece, industry seeks reliable predictions of process parameters that yield optimal surface finish while minimizing energy consumption and machining time. Simultaneously, attention must be given to tool performance, particularly in extending tool lifespan by reducing wear under optimal cutting conditions.

In this work, we present two numerical approaches to predict the surface roughness of the workpiece and the surface topography of the cutting tool. The objective is to characterize the final surface and the residual stresses induced in the material, enabling a more complete assessment of machining performance. This information supports the identification of optimal process conditions.

To address the complexity of machining, we combine fast search algorithms with the Particle Finite Element Method (PFEM) [1, 2], capturing both the geometrical aspects of the process and the thermo-mechanical behavior of the material [3].

The approach is applied to additively manufactured parts, which allow the production of complex geometries but often lack the required surface quality. Machining is used as a finishing step to achieve tighter tolerances and improved surface finishing, helping to reduce overall production time, material use, and energy consumption.

ACKNOWLEDGEMENT: This research has received funding from the European Union’s Research Fund for Coal and Steel (RFCS): project num. 101112346.

- [1] J.M. Carbonell, J.M. Rodríguez and E. Oñate. “Modelling 3D cutting problems with the Particle Finite Element Method”, *Computational Mechanics*, 66, 603-624, (2020).
- [2] Bakhshan, H., Oñate, E. and Carbonell, J.M. “Microstructure evolution modeling of Ti6Al4V alloy during cutting using the Particle Finite Element Method and homogeneous field distributions”. *Journal of Manufacturing Processes*, pp.73-92. (2024).
- [3] Bakhshan, H., Oñate, E. and Carbonell, J.M. “A Review of the Constitutive Modelling of Metals and Alloys in Machining Process”. *Arch Computat Methods Eng* (2023).

Modeling hydrogen redistribution in steels containing retained austenite

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KEYWORDS: *Chemo-mechanical coupling, hydrogen embrittlement, martensitic transformation*

Hydrogen embrittlement remains a critical challenge limiting the reliability and durability of advanced high-strength and duplex steels with multiphase microstructures containing retained austenite. The susceptibility of such steels to hydrogen-assisted crack initiation and propagation is strongly governed by microstructural heterogeneities, phase interactions, and grain boundary characteristics evolving across multiple length and time scales. Because direct experimental observation of hydrogen at the microscale is difficult due to its small atomic size and high mobility, physics-based computational modeling provides an essential pathway for understanding and predicting the hydrogen redistribution processes.

In this work, a multiscale, multiphysics finite element framework is developed to systematically investigate hydrogen transport and accumulation in steels with complex austenite–martensite and ferrite–austenite microstructures, respectively. The modeling approach integrates stress-assisted hydrogen diffusion, reversible and irreversible trapping mechanisms [1], grain boundary diffusion, and orientation-dependent interface properties within a unified numerical formulation implemented in Abaqus. In addition, strain-induced martensitic phase transformation is incorporated to capture the strong coupling between evolving phase fractions and hydrogen redistribution. Particular emphasis is placed on hydrogen redistribution during transformation of metastable retained austenite to martensite, where differences in hydrogen solubility between phases promote local enrichment and increased embrittlement susceptibility. The framework is further extended to include three-dimensional grain boundary effects, enabling microstructure-resolved representation of transport pathways and interface-controlled accumulation processes. The latter are governed by the energy landscape across the interface, which is determined by means of ab initio calculations.

The modeling strategy is supported by in-situ hydrogen charging experiments performed at the synchrotron [2], where lattice expansion measurements provide indirect quantification of hydrogen uptake in austenite. These observations are reproduced using microstructure-resolved simulations that explicitly account for trapping and grain boundary transport, and are validated by X-ray diffraction measurements of hydrogen redistribution during charging.

- [1] F.D. Fischer, J. Svoboda, E. Kozeschnik, *Model. Simul. Mater. Sci. Eng.* Vol. 21, 025008, 2013.
<https://doi.org/10.1088/0965-0393/21/2/025008>
- [2] T. Pogrietz, M. Eichinger, A. Weiser, J. Todt, A. Hohenwarter, A. Ascii, B. Sarac, D. Brandl, G. Ressel, M. Jary, A. Dlouhy, G. Mori, J. Keckes, *Scripta Mater* Vol. 248, 116142, 2024.
<https://doi.org/10.1016/j.scriptamat.2024.116142>

A coupled BEM-FEM aproach for nonlinear electro-elastostatics of CNT-based MEMS structures

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KEYWORDS: Coupled 3D BEM–FEM analysis, Isogeometric analysis, Van der Waals, Pull-in instability

Numerical simulation of electrostatic field–structure interactions is of significant interest in computational engineering [1]. Multiphysical problems of this type become cumbersome when treated using the finite element method (FEM), due to challenges such as mesh deformation, re-meshing, and the treatment of unbounded domains. The boundary element method (BEM) provides an efficient alternative, as it requires discretization only of the domain boundary [2]. When combined with FEM, it offers an effective framework for solving coupled multiphysical interface problems using boundary discretization alone.

In this work, a coupled BEM–FEM framework is employed to investigate the nonlinear electro-elastostatic behavior of carbon nanotube (CNT)-based capacitive MEMS switches. The primary focus is on the deformation and pull-in instability of CNT beams suspended above a grounded conducting substrate. The CNT is modeled as a perfectly conducting structure and described using a geometrically nonlinear shell formulation [3]. A monolithic strategy is adopted to solve the resulting nonlinear system, and its convergence behavior is compared with a staggered approach, as shown in Fig. 1(a), showing better efficiency. The effect of van der Waals (vdW) interactions is also incorporated, and its influence, quantified through the mid-point deflection under a Dirichlet boundary condition with prescribed surface potential V , is illustrated in Fig. 1(b). Furthermore, the influence of CNT length, electrode gap, boundary conditions, and mesh discretization on the nonlinear electro-elastostatic response is investigated. This framework successfully captures pull-in instability and provides a computationally efficient approach for analyzing material structures under coupled multi-field effects.

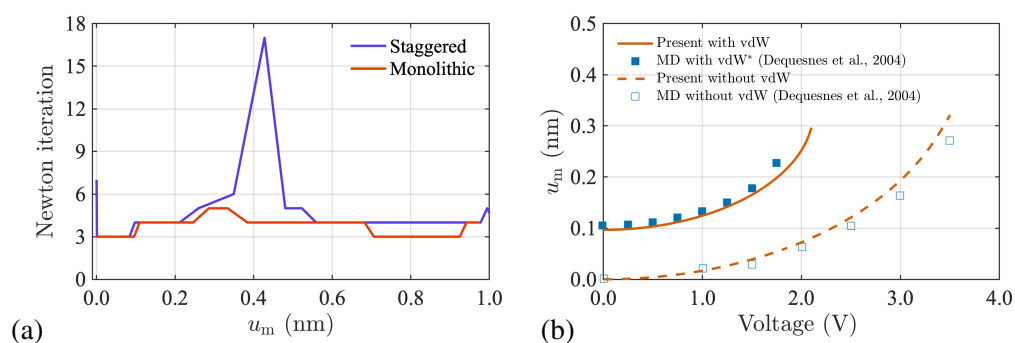


Figure 1: (a) Comparison of monolithic and staggered schemes with arc-length continuation for a 1 nm electrode gap. (b) Mid-point deflection u_m of a 20.7 nm long fixed–fixed CNT (10,10) at a 1 nm gap, compared with molecular dynamics (MD) results from [1] (* using vdW parameters from [1]).

- [1] M. Dequesnes, Z. Tang, N. R. Aluru, *J. Engrg. Mat. Tech.*, **126**(3), 230–237, 2004.
<https://doi.org/10.1115/1.1751180>
- [2] D.K. Vu, P. Steinmann, *Comp. Methods Appl. Mech. Engrg.*, **201**, 82–90, 2012.
<https://doi.org/10.1016/j.cma.2011.08.024>
- [3] R. A. Sauer, T. X. Duong, *Math. Mech. Solids*, **22**, 343–371, 2017.
<https://doi.org/10.1177/1081286515594656>

A Novel DEM-based Coupled 3D Thermo-Hydro-Mechanical Mesoscopic Model with Phase Changes for Modelling Concrete Behavior

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KEYWORDS: *Concrete, DEM-CFD, Heat Transfer, Phase Changes, Fracture.*

Concrete is one of the most widely utilized construction materials, employed in several environmental contexts. The majority of concrete constructions are generally subjected to a temperature range that does not exceed that of the surrounding environment. They may, however, also be exposed to extremely high temperatures (e.g., during a fire) [1]. This work numerically examined the effect of increased temperatures on the uniaxial compressive and tensile behavior of plain concrete.

A unique DEM-based pore-scale 3D thermo-hydro-mechanical (THM) model of two-phase fluid flow and heat transfer in fluids and solids was employed to investigate the concrete behavior at the meso-scale. The model also accounted for phase transitions (evaporation/condensation) in the fluid. Heat transmission was associated with fluid dynamics (diffusion and advection), bound granular particles (conduction), and phase transitions. The model used a direct numerical simulation methodology, comprising two coexisting domains: a three-dimensional discrete (solid) domain and a three-dimensional continuous (fluid) domain. Both domains were discretized using a coarse tetrahedral mesh. The DEM-based THM model was put into the open-source software package YADE, utilizing the soft-particle technique [2]. The THM model's efficacy was demonstrated by a thermal contraction test utilizing a bonded particle assembly during cooling, leading to the formation of a macro-crack. Subsequently, numerical simulations of uniaxial compression and tension tests on concrete specimens were conducted. Concrete was regarded as a four-phase material comprising aggregate, mortar, interfacial transition zones (ITZs), and macropores. The concrete mesostructure was derived from laboratory micro-CT images [3]. The computations examined the influences of strain rate, temperature, aggregate fragmentation, fluid saturation, and viscosity. A technique termed clump breakage was utilized to simulate intra-granular disintegration of aggregates [3]. The numerical results were directly compared with relevant experiments in the literature [1], [4].

- [1] D. J. Naus, The effect of elevated temperature on concrete materials and structures - a literature review, Report for the U.S. Nuclear Regulatory Commission Office, Office of Nuclear Regulatory Research (2005).
- [2] M. Krzaczek, M. Nitka, J. Tejchman, A novel DEM-based pore-scale thermal-hydro-mechanical model for fractured non-saturated porous materials, *Acta Geotechnica* **18**, 2487–2512, 2023.
- [3] M. Krzaczek, J. Tejchman, M. Nitka, Impact of strain rate, free water, and aggregate fragmentation on the dynamic behavior of concrete in compression regime using a unique coupled DEM/CFD technique, *Granular Matter* **27**, 79, 2025.
- [4] J. Shen, Q Xu, Effect of elevated temperatures on compressive strength of concrete, *Construction and Building Materials* **229**, 116846, 2019.

Electromechanical Buckling and Postbuckling of Periodic Patterns of Stiff Film on a Compliant Dielectric Substrate - Analytical and Numerical Analyses

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KEYWORDS: *Electromechanical Buckling, Dielectric Compliant Substrate, Wrinkling, Periodic Patterns.*

The work presents and discusses analytical and numerical solutions for the electromechanical buckling and postbuckling states of a planar stiff film bonded to a compliant dielectric substrate. The thin metal film forms an upper electrode. The compliant substrate is attached to a bottom rigid, and fixed electrode. The film is simultaneously subjected to in-plane compression stresses and to out-of-plane electrostatic attraction forces. The electrostatic forces can be induced by applying a voltage difference between the upper elastic electrode and the lower fixed electrode. Electromechanical buckling instability stems from the coupling of mechanical buckling instability and electromechanical pull-in instability. As revealed, such instability coupling can be employed to instigate mechanical buckling [1]. This work establishes an analytical approach to study the electromechanical critical and post-buckling behavior of one-dimensional square checkerboard, hexagonal, and herringbone periodic buckling patterns, illustrated in Fig. 1.

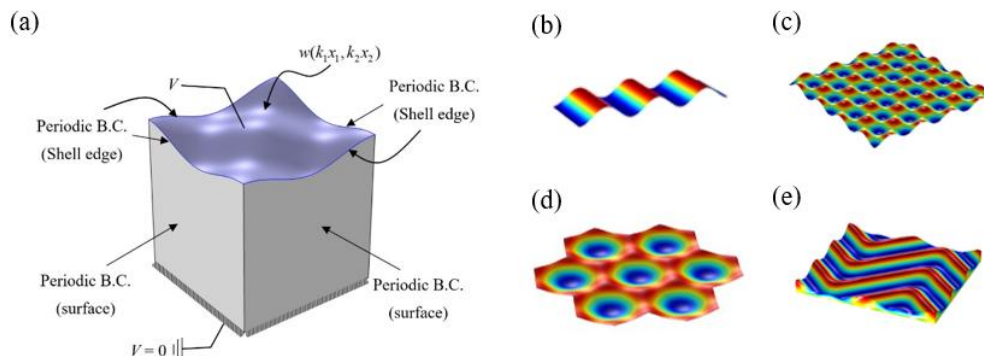


Figure 1. (a) One cell of a system of a film electrode on a compliant dielectric substrate. (b) – (e), 1D, square checkerboard, hexagonal, and herringbone periodic patterns.

Unlike previous works, the electrostatic attraction force and energy contributions are derived from the analytical solution of the electric potential function. A modified version of von-Karman plate equations is formulated and used along with the upper-bound energy method to derive analytical solutions for the critical and post-electromechanical buckling states of the considered patterns. The analytical, critical, and postbuckling solutions, as well as the energy state of periodic patterns, are validated through a rigorous finite element analysis conducted in COMSOL Multiphysics software. It has been revealed that the buckling stress and periodicity wavelength strongly depend on the applied voltage. The ability to determine the buckling stress by varying the applied voltage enhances the potential for microsystem applications.

- [1] Abu-Salih S., Journal of the Mechanics and Physics of Solids 197 (106062), 2025.
<https://doi.org/10.1016/j.jmps.2025.106062>

Evolution of residual stresses in polymer composites having porosity

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KEYWORDS: *Polymer composites, Porosity, Homogenization, Residual stress*

Polymer composites are often produced by curing an uncured liquid monomer, which gradually transforms into a cross-linked solid polymer that bonds the fibers. The development of residual stresses in polymer composites during curing is well reported [1]. The widespread usage of these materials demands an efficient and defect-free curing process. Pores may form during the curing process due to trapped gases or air bubbles in the matrix. As complete elimination of pores in the matrix is extremely expensive and unrealistic, it is essential to understand the influence of porosity on curing-induced residual stresses. The effect of porosity on residual stress evolution in a pure polymer system has been reported by modelling the material as linearly elastic [2]. However, polymer exhibits a viscoelastic constitutive response, and the magnitude and nature of residual stresses in polymer composites are very different from those generated in an isotropic polymer system. Hence, the present study aims to understand the effect of porosity on the evolution of residual stresses in polymer matrix and the laminated polymer composites, capturing their viscoelastic constitutive response. The effective viscoelastic properties

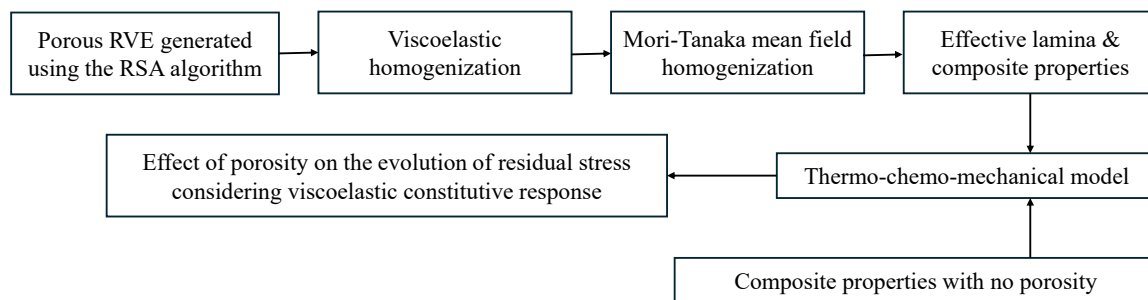


Figure 1. A schematic diagram illustrating the workflow.

of the polymer matrix composite are characterized by using a generalized Maxwell model. A two-step homogenization approach is adopted to calculate the effective viscoelastic properties, which comprise the elastic constants and relaxation times of the porous polymer composite. Firstly, the properties of the porous polymer are determined using a finite element (FE)-based computational homogenization technique. A representative volume element (RVE) of the porous matrix is created, and the homogenization is performed based on the Hill-Mandel macro-homogeneity condition. Appropriate periodic boundary conditions are applied to simulate the relaxation response of the RVE. Finally, the effective properties of the polymer composite are determined using the Mori-Tanaka method. An FE-based thermo-chemo-mechanical model is developed to predict the evolution of the temperature field, curing fraction, and residual stresses. The influence of porosity on the evolution of temperature and cure fraction is investigated. The complete computational workflow is shown in Fig. 1. The evolution of residual stresses in the domain is compared for the porous and non-porous cases, considering both isotropic matrix and orthotropic laminated composite cases.

- [1] Yuan, Z. *et al.*, *Mech. Compos. Mater.*, **155**, 49–61, 2018. <https://doi.org/10.1016/j.compositesb.2018.08.012>
- [2] Dewangan, B., & Chakladar, N. D., *Mater. Today Commun.*, **35**, 105711, 2023. <https://doi.org/10.1016/j.mtcomm.2023.105711>

Homogenization-Driven Acoustic Performance Modeling in Particulate Composites for Noise Mitigation

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KEYWORDS: *Multiscale Modeling, Computational Homogenization, Acoustic Wave, Effective Material.*

Lightweight particulate composites (LPCs) are engineered materials that incorporate low-density fillers into cementitious matrices to achieve reduced weight, improved thermal insulation [1], and enhanced acoustic properties [2]. When embedded in calcium aluminate cement (CAC) matrices, fly ash cenospheres (FACs) not only lower the composite density, but also introduce controlled porosity, which is critical for noise reduction applications [3].

Accurate prediction of acoustic behavior in such heterogeneous materials remains challenging due to complex microstructures [4], [5] and the high computational cost of detailed simulations [6]. This study proposes a homogenization-driven finite element method (FEM) framework for multiscale modeling of heterogeneous LPC composed of FACs and concrete matrix. The approach accounts for inclusion morphology and spatial distribution while maintaining computational efficiency.

The model links microscale features with macroscale acoustic response, enabling reliable prediction of effective mechanical and acoustic properties. Results show good agreement between heterogeneous simulations and their homogenized equivalents, confirming the validity of the approach. The framework demonstrates strong potential as an efficient design tool for LPC optimization. Future work will include experimental validation and comparison with analytical models.

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- [1] D. Mačiūnas, S. Nosewicz, R. Kačianauskas, R. Boris, R. Stonys, Numerical Simulation of Thermal Conductivity and Thermal Stress in Lightweight Refractory Concrete with Cenospheres, *Materials*, **16**(1), p. 190, 2023. <https://doi.org/10.3390/ma16010190>
- [2] Q. Liu, X. Liu, C. Zhang, F. Xin, A Novel Multiscale Porous Composite Structure for Sound Absorption Enhancement, *Compos. Struct.*, **276**, p. 114456, 2021. <https://doi.org/10.1016/j.compstruct.2021.114456>
- [3] H. Xie, Y. Li, E. Kahya, B. Wang, X. Ge, G. Li, Physical Properties and Environmental Impact of Sound Barrier Materials Based on Fly Ash Cenosphere, *Buildings*, **12**(3), 2022. <https://doi.org/10.3390/buildings12030322>
- [4] W. Lee, S. Kim, H. Shin, Accelerated Multiscale Data-driven Finite Element Analysis Using Mean-field Homogenization Method with Knowledge Transfer, *J. Comput. Phys.*, **558**, 2026. <https://doi.org/10.1016/j.jcp.2026.114870>
- [5] A. Elbana A. Khennane, Development of Generalized Yield Surface of Fly Ash Microbubble Composites Using Nonlinear Multiscale Analysis, *Mechanics of Materials*, **212**, 2026. <https://doi.org/10.1016/j.mechmat.2025.105532>
- [6] V. T. Nguyen, V. H. Nguyen, S. Naili, Deep Learning-based Multiscale Prediction of Composite Aerogels' Effective Thermal Conductivity, *Int. J. Mech. Sci.*, **304**, 2025. <https://doi.org/10.1016/j.ijmecsci.2025.110617>

Modelling of granular matter behaviour in an external temperature field using an advanced CFD-DEM method

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KEYWORDS: *CFD-DEM, XDEM, Particles, Porous Media, Heat and Mass Transfer*

This work presents the results of numerical simulations of the heating process in a packed bed of solid particles. For this purpose, an advanced model that couples the Eulerian-Lagrangian approach (CFD-DEM) known as the XDEM method [1] was employed. It was assumed that heat exchange with the surroundings influences the particles' structure, as a consequence of chemical reactions acting inside and on their surfaces. Due to changes in the mass and shape of the particles, the bed shrinks, and the particles displace. The calculations account for particle collisions, and their translational and rotational motion, as well as changes in the material properties within each particle. Practical applications of using the XDEM software are presented. These relate to predicting the behaviour of solid fuel beds in reactors or burners. The various operating conditions of such devices, as well as the different sizes and shapes of the bulk material particles, are taken into account. The results are then compared with experimental data [2, 3].

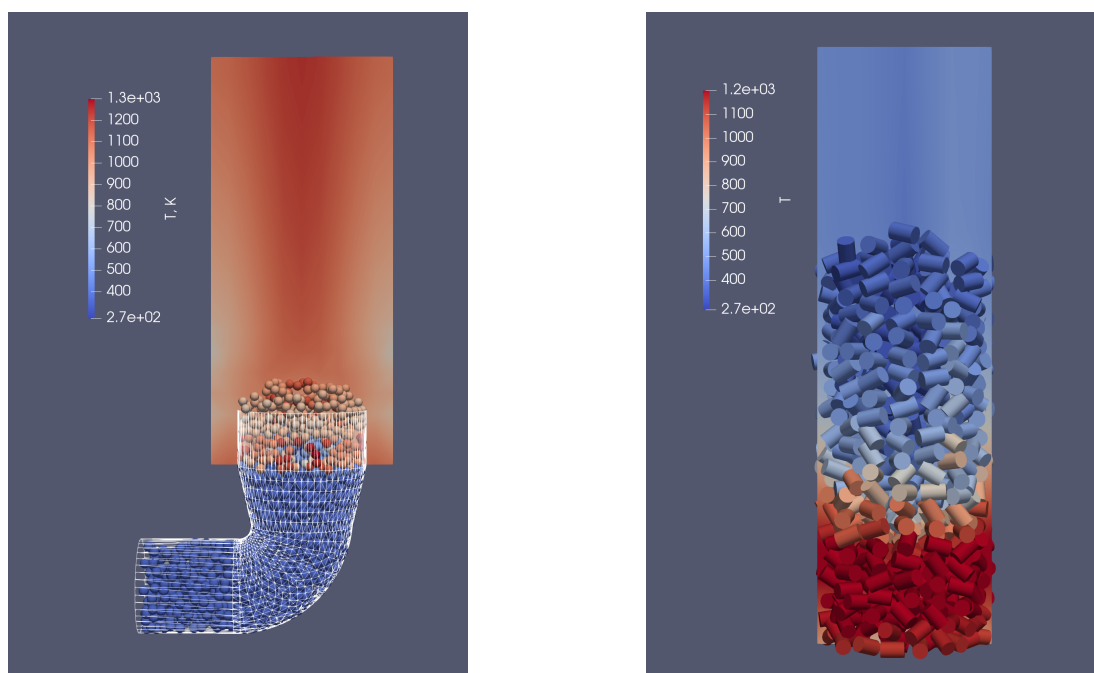


Figure 1. Temperature distribution in biomass burner (left) and thermal conversion reactor (right).

ACKNOWLEDGEMENT: This research is supported by the computer centre CI TASK.

- [1] B. Peters, M. Baniyadi, M. Baniyadi, X. Besseron, A.E. Donoso, M. Mohseni, G. Pozzetti. *Particuology* **44**, 176–193, 2019. <https://doi.org/10.1016/j.partic.2018.04.005>
- [2] D. Kardaś, D., M. Wantuła, S. Pieter, P. Kazimierski. *Energies* **14**, 4648, 2024. <https://doi.org/10.3390/en17184648>
- [3] T. Turzyński, J. Kluska, M. Ochnio, D. Kardaś. *Materials* **14**, 2484, 2021. <https://doi.org/10.3390/ma14102484>

Earthquake-Induced Response of Cylindrical Liquid-Containing Tanks

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KEYWORDS: *Earthquake, Liquid, Tank, Fluid -Structure Interaction, FEM.*

Liquid-containing cylindrical tanks are widely used in water distribution systems as well as in various industrial sectors for the storage of potable water, fire protection water, crude oil, chemicals, and other liquids, including toxic and flammable substances. The seismic response of liquid-containing tanks differs significantly from that of conventional buildings. During seismic excitation, the liquid inside the tank generates additional hydrodynamic forces acting on the tank walls and base. These forces arise from the interaction between the structure and the contained fluid. The dynamic behavior of the liquid can be described as a superposition of two main components: an impulsive (rigidly moving) component and a convective component associated with the sloshing motion of the free liquid surface [1].

The finite element method (FEM) is widely used to analyze fluid-structure interaction in liquid-containing tanks, particularly under seismic loading. The tank is modeled using structural elements, while the fluid domain is represented by fluid elements. Their interaction is captured through coupling conditions at the interface, ensuring displacement compatibility and force equilibrium [2].

Figure 1a illustrates the hydrodynamic effect of the fluid on the structural domain of the tank. The total pressure acting on the tank structure is evaluated as the sum of the hydrostatic pressure p_s and the hydrodynamic pressure p_d . Figure 1b presents results from a numerical simulation carried out using the finite element method (FEM), showing the distribution of total pressure in the fluid domain within the tank under seismic loading condition.

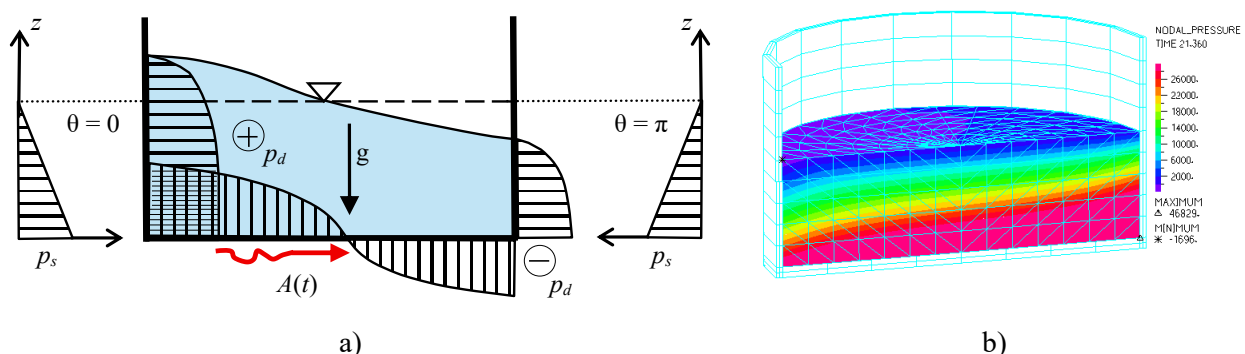


Figure 1. Liquid-containing tank, a) scheme of structure of fluid pressure, b) total pressure distribution in the fluid domain during earthquake.

ACKNOWLEDGEMENT: This research was supported by the Slovak Research and Development Agency under Contract No. SK-PL-25-0094, and by the VEGA Grant Agency under Project No. 1/0307/23.

- [1] E. Kormanikova, K. Kotrasova, Multiscale modeling of liquid storage laminated composite cylindrical tank under seismic load. Compos Part B Eng. 146, 189–97, 2018.
<https://doi.org/10.1016/j.compositesb.2018.03.011>.
- [2] O.C. Zienkiewicz, R.L. Taylor and J.Z. Zhu, The Finite Element Method: Its Basis and Fundamentals. Elsevier Butterworth-Heinemann, 6th ed., 2005.

Homogenization of nonlinear effects in poroelastic media with large contrast in skeleton elasticity and self-contact at pore level

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KEYWORDS: *Homogenization, Poroelasticity, Fluid-Structure Interaction, Geometric Nonlinearity, Dynamic Permeability, Unilateral Contact*

The paper contributes to the asymptotic homogenization-based multiscale modelling of some nonlinear effects in fluid-saturated porous structures consisting of a strongly heterogeneous elastic skeleton and one, or more fluid pore systems. Periodic microstructures are constituted by elastic skeleton composed of a stiffer core supporting very soft parts interacting directly with a viscous fluid flowing in the pore systems. The aim is to explore influence of the "large contrast" in the skeleton elasticity on the fluid-structure interaction (FSI) affected also by possible collapse of the pore lumen (at the microscopic level). The latter phenomena requires to consider the unilateral "self-contact" at the pore level [1]. The large contrast is related to the so-called scaling ansatz in the context of the asymptotic homogenization (AH); in the soft part of the skeleton, the elasticity is proportional to the scale parameter which is involved in the AH. Such a scaling ansatz of the mesoscopic material parameters can be justified using different micromodels associated with the two mesoscopic components [2]. By the consequence, in the "homogenization limit" the FSI is represented at the micro-scale (in contrast with the "standard" case of a given fixed elasticity), affecting also the (friction-less) unilateral formulation involving also the local pore pressure fluctuations. It is shown that the dynamic hydraulic permeability depends on the pore geometry and also on the soft elastic structure response, such that the derived homogenized model describing visco-poro-elastodynamics is featured by a strong wave dispersion. The model is extended for the nonlinearity due to respecting the equilibrium in the deforming configuration, c.f. [3, 4]. The considered porous material is motivated by the situation in perfused tissues under pulsating flow causing peristaltic deformation and, thereby, inducing a secondary pore fluid flow. Numerical issues and related model-order reduction challenges are discussed.

ACKNOWLEDGEMENT: The research has been supported by the grant project GA 24-12291S of the Czech Science Foundation.

- [1] Rohan E., Heczko, J. *Homogenization-based modelling of self-contact and fluid-structure interaction in the microstructure of poroelastic materials*. Computers and Structures, 322 (2026) 108089. DOI: 10.1016/j.compstruc.2025.108089.
- [2] Rohan E., Nguyen V-H., Naili S. *Homogenization of fluid saturated double porosity media with a new type of the contrast in the Biot mesoscopic model*, Applied Mathematical Modelling, 125:750-777, DOI: 0.1016/j.apm.2023.10.008.
- [3] Rohan E., Lukeš V. *Homogenized model of peristaltic deformation driven flows in piezoelectric porous media*. Comput Struct, 302:107470, 2024. DOI: 10.1016/j.compstruc.2024.107470.
- [4] Rohan E., Lukeš V. *Modeling nonlinear phenomena in deforming fluid-saturated porous media using homogenization and sensitivity analysis concepts*. Appl Math Comput, 267:583–595, 2015.

Gaussian Process Framework for Bayesian Inference of Hydrogen Permeation in Polymer Composites

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KEYWORDS: *Polymer composites; Hydrogen permeability; Bayesian inference; Gaussian Process surrogate modelling; Machine Learning-assisted composite design.*

Reliable modelling and prediction of hydrogen permeation in fibre-reinforced polymer composites are essential for the safe and efficient design of hydrogen infrastructure. However, key material parameters — such as in-situ matrix, fibre, and fibre–matrix interphase permeabilities — remain extremely challenging to determine and are inherently uncertain [1]. Furthermore, high-fidelity three-dimensional (3D) microstructure-resolved finite element (FE) simulations required to capture transport mechanisms are computationally expensive, limiting their direct use in design optimisation and inverse parameter identification.

This work introduces data-driven probabilistic framework that integrates Gaussian Process (GP)-based surrogate modelling with three-dimensional Representative Volume Element (RVE) mass transport simulations and hydrogen permeation experiments on composites to enable efficient Bayesian inference of constituent parameters, including interphase [2]. The likelihood entering Bayes' theorem is formulated as a joint GP marginal likelihood of an augmented dataset, combining high-fidelity simulation outputs with experimental observations through the GP covariance structure. In this formulation, both forward-model responses and experimental measurements are treated as noisy observations of a shared latent function, allowing uncertainty to be naturally propagated via the GP covariance matrix.

Hydrogen permeation tests are conducted on the neat polymer specimens, and the measured permeabilities are used to define the prior distribution for the in-situ matrix permeability within the Bayesian framework. For the fibre–matrix interphase permeability, two physically motivated prior regimes are considered: (i) reduced molecular mobility near the fibre surface leading to decreased local transport, and (ii) microvoid-induced enhancement of local permeability. The prior distribution for interphase thickness is constructed using experimentally measured interface dimensions reported in the literature.

Posterior sampling of the uncertain parameters is performed using Hamiltonian Monte Carlo via the No-U-Turn Sampler (NUTS), enabling efficient exploration of the high-dimensional parameter space [3]. Owing to the GP-based probabilistic emulator, thousands of Markov Chain Monte Carlo (MCMC) evaluations can be carried out at negligible computational cost compared to direct finite element simulations. The joint GP marginal likelihood formulation ensures that forward-model uncertainty, surrogate (GP) uncertainty, and experimental measurement noise are consistently incorporated within the Bayesian inference process. The resulting posterior parameter distributions are subsequently propagated through the GP forward model, yielding uncertainty-aware predictions of composite hydrogen permeability which can be used to derive confidence-based permeability limits for design specification. The framework is readily transferable beyond mass transport (e.g., hydrogen permeability in here), enabling solution of other multi-parameter inverse problems in data-driven composite material design.

- [1] M. Okumuş et al. *Composites Part A*, 199, 109213, 2025.
- [2] A. Angus et al. *Composites Part C*, 18, 100630, 2025.
- [3] M. D. Hoffman and A. Gelman, *J. Mach. Learn. Res.*, vol. 15, pp. 1593–1623, 2014.

Session TS12

**Nonlinear dynamics, structural control
and monitoring**

Multistable Shells Design for Energy Harvesting from Mechanical Vibrations

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KEYWORDS: *Geometric Nonlinearities, Multistable Structures, Nonlinear Dynamics, Energy Harvesting.*

Growing demand for self-powered sensors and autonomous monitoring systems has increased the need for robust vibration energy harvesters capable of operating under broadband and variable excitation (in both frequency and amplitude). However, classical linear resonant harvesters, such as cantilever beams or plates, suffer from narrow bandwidth and high sensitivity to frequency detuning, limiting their effectiveness in real-world conditions. To address these limitations, nonlinear approaches can be exploited, including nonlinear resonances, parameter tuning, and multistable designs. In this context, orthotropic multistable shells proposed in [1], characterized by one-sided clamped boundary conditions are promising. The shell mid-surface is defined in the (x_1, x_2, x_3) domain using two pseudo-radii $r_0(x_1 = 0)$ and $r_f(x_1 = L_1)$, see Fig. 1 and Eq. (1).

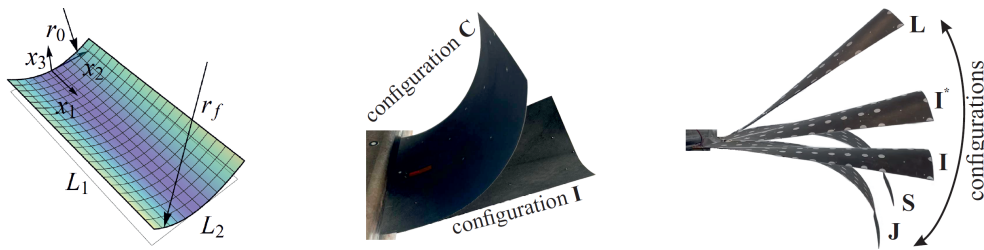


Figure 1. The shell geometry definitions (left), stable configurations for prototype **A** (center), and prototype **B** (right).

$$w_0(x_1, x_2) = \left[\frac{1}{r_0} + \left(\frac{1}{r_f} - \frac{1}{r_0} \right) \frac{x_1}{L_1} \right] \frac{x_2^2}{2}, \quad 0 \leq x_1 \leq L_1, \quad -\frac{1}{2}L_2 \leq x_2 \leq \frac{1}{2}L_2. \quad (1)$$

Energy harvesting from an MFC patch embedded in a bistable shell of type **A** ($r_0 = 0.1045$ m, $r_f = 0.08493$ m, $L_1 = 0.18$ m, $L_2 = 0.15$ m) is experimentally investigated [2]. The structure exhibit two distinct configurations **I** and **C** with significantly different natural frequencies in the linear regime. For moderate response amplitudes, the system shows nearly linear behavior in configuration **C** and pronounced softening behavior in the configuration **I** during in-well oscillations. At higher amplitudes, reversible snap-through transitions occur, significantly enhancing energy harvesting performance. In the second case, nonlinear dynamics and energy harvesting performance of a pentastable shell of type **B** ($r_0 = 0.114$ m, $r_f = -0.07$ m, $L_1 = 0.45$ m, $L_2 = 0.15$ m) are presented [3]. The latter sheds the light on effective placement of a piezoelectric transducer location based on criteria: stress distribution, strain distribution, frequency bandwidth, excitation framework and MFC patch integration in the structure. The results are summarized in maps of RMS power versus excitation frequency, highlighting the advantages of cross-well oscillations. A reduced-order model capturing both local and global dynamics of the multistable structure, including the piezoelectric coupling, is currently under development.

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- [1] M. Brunetti, A. Vincenti, S. Vidoli, *Int. J. Solids Struct* **194**, 388–397, 2018. <https://doi.org/10.1016/j.compstruct.2018.04.009>
- [2] A. Mitura, M. Brunetti, L. Kloda, F. Romeo, J. Warminski, *Mech. Syst. Signal Process* **206**, 110890, 2024. <https://doi.org/10.1016/j.ymssp.2023.110890>
- [3] L. Kloda, *Mech. Syst. Signal Process* **244**, 113825, 2026. <https://doi.org/10.1016/j.ymssp.2025.113825>

Robust semi-active control for energy transfer between structural vibration modes: methodology and experiments

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KEYWORDS: *Semi-Active Modal Control, Lockable Joints, Modal Energy Transfer, Robust Vibration Control, Experimental Validation, Model Updating.*

Vibration remains one of the key challenges across mechanical engineering, motivating ongoing advances in damping and control. Since dissipated energy is typically lost as heat, recent research increasingly explores the integration of vibration suppression with energy harvesting [1].

This work proposes a semi-active modal control strategy that enables precise energy transfer between selected vibration modes by locking or unlocking rotational joints (see: Fig. 1a), effectively switching the structural stiffness. This induces modal coupling and imposes directed energy flow. Such an approach can be employed for two functional objectives: **damping**, by shifting energy from low-frequency modes to higher, more strongly damped ones (see: Fig. 1b), and **energy harvesting**, by concentrating energy in a target mode tuned to a harvester. The approach shows excellent performance in simulations and experiments [2]. Here, the focus is placed on robustness with respect to modeling errors, demonstrating that the controller remains effective despite substantial stiffness deviations. Experimental results are compared with those obtained using a finely calibrated model with 17 adjusted stiffness parameters.

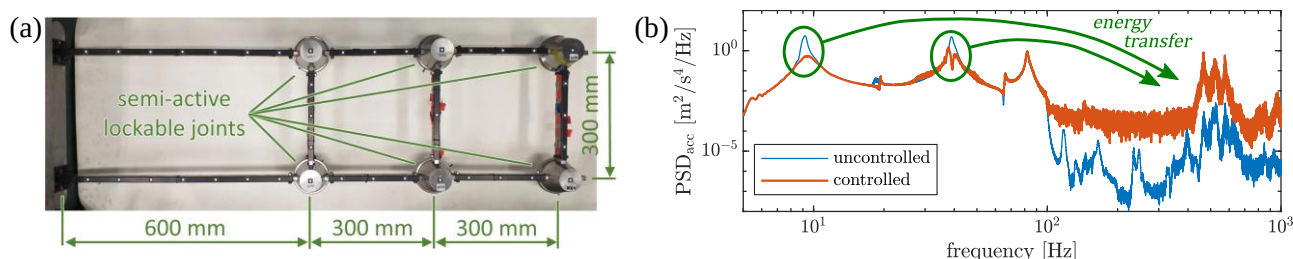


Figure 1. (a) photo of laboratory-scale frame structure equipped with six lockable joints and (b) experimentally obtained power spectral density (PSD) of the structural tip acceleration in log–log scale, demonstrating the transfer of energy from the monitored vibration modes into higher-order, unmonitored modes; the PSD associated with the first mode is reduced by 90%.

Results demonstrate that, despite substantial changes in natural frequencies (up to 80 %) due to stiffness errors in the model used by the controller, the control performance is nearly the same as for the controller based on the calibrated model. Due to these advantages and the high control performance, the proposed control strategy has broad applicability to real engineering structures and is robust to changes in structural properties caused by operational wear.

- [1] T. Yang, S. Zhou, G. Litak, X. Jing, Recent advances in correlation and integration between vibration control, energy harvesting and monitoring. *Nonlinear Dyn.* 111, 20525–20562, 2023.
<https://doi.org/10.1007/s11071-023-08999-2>
- [2] M. Ostrowski, *Semi-Active Control of Energy Transfer Between Vibration Modes in Mechanical Structures*, Institute of Fundamental Technological Research, Polish Academy of Sciences, 2025
<https://doi.org/10.24423/9788365550644>

Improved Shell Quadrilateral for Explicit Dynamics

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KEYWORDS: *Explicit Dynamics, EUROPLEXUS, Shell Quadrilateral, Assumed Natural Strains.*

Shell finite elements are widely used in explicit dynamics codes, such as LS-DYNA, EUROPLEXUS, and RADIOSS, for simulating impact events. Quadrilateral shell elements are generally preferred over triangular ones due to their superior accuracy and stability. Among quadrilaterals, one-point-quadrature formulations (under-integrated with hourglass control) are favoured for their computational efficiency, though they may become unreliable in regions undergoing large deformations. To balance accuracy and computational cost, mixed meshes are commonly employed: more expensive four-point-quadrature (fully integrated) shell elements are applied in areas expected to experience severe deformations, while one-point-quadrature elements are used in regions with mild deformations.

In LS-DYNA, ELFORM 16 is a highly accurate fully integrated quadrilateral shell element with Bathe-Dvorkin transverse shear treatment. It also uses a Hu-Washizu-based hybrid-mixed enhancement along with carefully chosen interpolations for the in-plane strains and stresses. The result is a B-bar formulation briefly described in [1]. As an alternative to this relatively sophisticated approach, we propose a simple yet effective improvement to the standard isoparametric four-point-quadrature quadrilateral shell element with Bathe-Dvorkin transverse shear treatment. Numerical tests show that the improved element achieves performance comparable to—or in several test examples, superior to ELFORM 16. The new element was included in EUROPLEXUS.

The core idea of the proposed formulation is to apply the assumed natural strain (ANS) concept to the membrane strains in a manner that ensures satisfaction of the membrane patch test. Notably, this enhancement affects only the membrane strains of the element, preserving existing code capabilities related to, e.g., material models and parallelization. The membrane ANS approach was originally introduced in [2] and was latter applied in [3] but has not previously been evaluated in explicit dynamics impact simulations. In the Updated Lagrangian framework, commonly applied in explicit dynamic codes, geometric constants of the element are recomputed at each time step to be used in construction of rich membrane ANS strains. The adopted modification softens the membrane response—reducing the highest natural frequency by roughly an order of magnitude—improves representation of near-inextensional bending modes, suppresses parasitic membrane strains, slightly enhances explicit scheme conditional stability in the non-linear regime, and allows marginally larger time steps.

- [1] ANSYS LS-DYNA Theory Manual, ANSYS, Inc., 2025. <https://lsdyna.ansys.com>
- [2] G. M. Kulikov, S. V. Plotnikova, Int. J. Numer. Methods Eng., 83, 1376–1406, 2010. <https://doi.org/10.1002/nme.2872>
- [3] M. Lavrenčič, B. Brank, Comput. Mech., 65, 177–192, 2020. <https://doi.org/10.1007/s00466-019-01759-3>

Modal filter synthesis with use of artificial neural networks

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KEYWORDS: *Modal analysis, Modal filtration, Machine learning, Convolutional neural networks.*

A modal filter is a tool developed in the early 1980s to improve the performance of modal control [1]. In subsequent years, modal filtering has found other applications, such as input identification, modal model comparison, and damage detection and localisation. This last application is particularly interesting, as it effectively identifies damage, lends itself well to automation, and demonstrates low sensitivity to ambient conditions [2]. A significant difficulty in using modal filtering for damage detection is the filter synthesis itself. It requires an identified modal model, and therefore experimental modal analysis. In summary, a modal filter enables the selective extraction of individual vibration modes from the system's dynamic response, whereas its classical synthesis requires knowledge of modal parameters determined by modal analysis methods. Due to the growing demand for automated diagnostic processes, the use of artificial intelligence methods has been proposed as an alternative to classical computational procedures. Convolutional artificial neural networks (CNN) [3] were chosen as a tool for determining modal filter coefficients directly from measurement characteristics.

As part of the research, software was developed to generate training data for variant numerical models of linear mechanical systems with two and four degrees of freedom. Random variation of mass, stiffness, and damping parameters, along with various connection topologies, was considered. Based on this, a dataset was generated comprising spectral transfer functions and corresponding modal filter coefficients determined using classical modal filtering, with a maximum of 10,000 sets. Training data was then prepared, and the architecture of a convolutional neural network (CNN) implementing the regression task was designed. Various network architectures and network parameter settings, along with different training data sizes, were tested. The obtained results did not fully confirm the feasibility of using CNNs for modal filter synthesis.

- [1] L. Meirovitch, H. Baruh, Control of self-adjoint distributed parameter systems, J. Guid. Control Dyn., 8 (6), 60-66, 1982. doi.org/10.2514/3.56140
- [2] A. Deraemaeker, A. Preumont, Vibration based damage detection using large array sensors and spatial filters, Mech. Syst. Signal Process., 20, (7), 1615-1630, 2006. doi.org/10.1016/j.ymssp.2005.02.010.
- [3] X. Zhao, L. Wang, M. Parmar, A review of convolutional neural networks in computer vision. Artif. Intell. Rev, 57, 99, 2024. doi: 10.1007/s10462-024-10721-6.

Two-Stage Identification of a Temperature- and Amplitude-Dependent Nonlinear Fractional Kelvin Model for Viscoelastic Damping Materials

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KEYWORDS: *Viscoelastic materials, fractional Kelvin model, harmonic balance method, WLF equation, vibration damping.*

Viscoelastic materials used in passive damping devices exhibit simultaneous dependence on frequency, temperature, and vibration amplitude, which makes constitutive identification particularly challenging. Temperature effects are commonly described by the time–temperature superposition principle and the Williams–Landel–Ferry (WLF) equation, whereas amplitude dependence can be captured by nonlinear fractional rheological models. However, a compact identification framework capable of accounting for both effects without excessive parameter coupling is still needed.

The present contribution addresses this issue by considering a two-stage identification strategy for a temperature- and amplitude-dependent nonlinear fractional Kelvin model of a viscoelastic damping material. In the first stage, dynamic test data obtained at several temperatures are reduced to a reference temperature by means of horizontal shift factors described by the WLF relation. In the second stage, the parameters of the nonlinear fractional Kelvin model are identified from steady-state force–displacement data using the harmonic balance method. The adopted constitutive law combines a linear elastic term, a cubic elastic nonlinearity accounting for amplitude-dependent stiffness, and a Scott–Blair fractional element representing viscoelastic dissipation.

The proposed decomposition separates thermal shifting from rheological calibration and thus limits the number of parameters identified simultaneously. This is important for maintaining parameter identifiability and numerical robustness when the model includes both fractional-order behavior and nonlinear amplitude effects. Particular attention is focused on the interaction between the fractional rheological parameters and the WLF constants, as well as on the ability of the identified model to reproduce hysteresis loops measured for different excitation frequencies and displacement amplitudes.

The study aims to develop a compact constitutive description suitable for frequency-domain analysis of viscoelastic dampers and damped civil engineering structures. The proposed framework also provides a basis for assessing the practical limits of applying TTSP/WLF-based temperature reduction in nonlinear fractional modeling of damping materials.

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- [1] Z.M. Pawlak, A. Denisiewicz, *Materials* 14(22), 7024, 2021. <https://doi.org/10.3390/ma14227024>
- [2] R. Lewandowski, *Meccanica* 57, 2337–2354, 2022. <https://doi.org/10.1007/s11012-022-01576-8>
- [3] R. Lewandowski, P. Litewka, M. Łasecka-Plura, Z.M. Pawlak, *Buildings* 13(9), 2223, 2023. <https://doi.org/10.3390/buildings13092223>
- [4] R. Lewandowski, M. Słowik, M. Przychodzki, *Struct. Eng. Mech.* 63, 181–193, 2017. <https://doi.org/10.12989/sem.2017.63.2.181>

Theoretical and Experimental Investigation of a Pendulum Absorber-Harvester System

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KEYWORDS: *energy harvesting, vibration mitigation, analytical solution, continuation method.*

The use of mechanical vibrations as a source of electrical energy has attracted increasing attention in recent years. This growing interest is largely driven by the European Union's energy policies, which promote the development of innovative energy-harvesting technologies. While vibrations are typically undesirable in many dynamical systems and are therefore mitigated using various control strategies, integrating an energy harvester into a vibration absorber enables simultaneous vibration reduction and energy extraction. Achieving this dual objective remains a challenging task, as it requires a careful trade-off between effective vibration suppression and maximization of the harvested power.

We propose a pendulum-based vibration absorber system attached to the primary structure (Figure 1). The absorber incorporates an electromechanical energy harvester, consisting of a magnet oscillating inside a coil. The motion of the pendulum induces vibrations of the magnet, which in turn generate an electric current in the coil. This configuration forms an integrated absorber–harvester system (AHS), enabling simultaneous vibration mitigation and energy harvesting [1, 2].

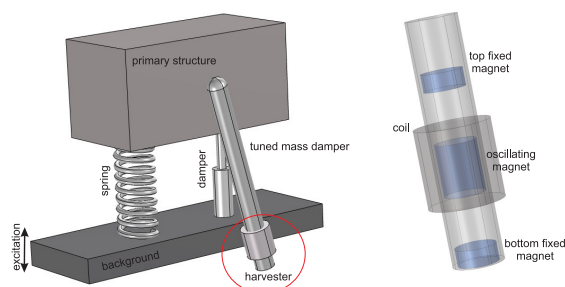


Figure 1. A multifunctional AHS system enabling simultaneous vibration suppression and energy harvesting.

Nonlinear vibration absorbers exhibit effective performance over an extended frequency bandwidth; however, precise tuning of their governing parameters is essential, as nonlinear dynamical systems may display multiple coexisting response regimes. This study investigates the potential of a vibration absorber as a means of energy harvesting. Numerical analysis is performed using a path-following continuation method, enabling systematic tracking of steady state solutions and nonlinear dynamic behavior. The analytical framework is based on the harmonic balance method, which provides closed-form approximations of periodic responses and offers deeper insight into the underlying system dynamics. Finally, the theoretical predictions are validated experimentally using a special designed laboratory test rig.

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- [1] C. Zhang, J. Xu, S. Fang, Z. Qiao, D. Yurchenko, Z. Lai, Z. *Nano Energy* **107**,108126, 2023. <https://doi.org/10.1016/j.nanoen.2022.108126>
- [2] K. Kecik *J. Vib. Eng. Technol.* **10**,2241–2250, 2023. <https://doi.org/10.1007/s42417-022-00536-6>

Robustness of multi-agent reinforcement learning control for a lockable-mass tuned mass damper

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KEYWORDS: *Tuned Mass Damper, Semi-active Control, Reinforcement Learning, Multi-agent Control, Robustness.*

Reinforcement learning (RL) is a class of machine learning methods aimed at solving control-like tasks [1]. Control is learned and applied by an agent that learns to select the best action through a series of interactions with the controlled system.

A potential application area of reinforcement learning is semi-active structural control. In such tasks, the optimal control signals are often unknown and cannot thus be used for training, as required by typical supervised learning techniques. The RL approach is more suitable, as it allows the control agent to progressively improve its decision-making strategy in a trial-and-error manner based on experiencing and received feedback (reward). This interaction-based approach also goes beyond typical unsupervised techniques, as it allows control signals to be actively tested rather than merely exploring pre-prepared datasets. Despite these advantages and remarkable achievements in other fields [2], reinforcement learning methods are still rarely applied in structural control, especially in semi-active control [3].

This contribution continues our earlier work on RL-based control of a seismically excited shear-type building [4], which examined the robustness of a typical single-agent RL controller. Here, the investigation is extended to multi-agent RL control, in which the ultimately applied control action is determined based on the recommendations of a group of independent RL agents. Control is applied via a tuned mass damper whose mass can be locked to or unlocked from the story in an on/off manner. The reward function used for agent training quantifies structural vibrations, and additionally, it includes a penalty term that promotes locking at moments of zero relative velocity, in order to avoid the associated impacts.

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- [1] R.S. Sutton, A.G. Barto, *Reinforcement Learning: An Introduction*, MIT Press, 2nd ed., 2018. <http://incompleteideas.net/book/the-book-2nd.html>
- [2] D. Silver, T. Hubert, J. Schrittwieser, I. Antonoglou, M. Lai, A. Guez, M. Lanctot, L. Sifre, D. Kumaran, T. Graepel, T. Lillicrap, K. Simonyan, D. Hassabis, A general reinforcement learning algorithm that masters chess, shogi, and Go through self-play, *Science* **362**(6419), 1140–1144, 2018. <https://doi.org/10.1126/science.aar6404>
- [3] J.B. Kimball, B. DeBoer, K. Bubbar, Adaptive control and reinforcement learning for vehicle suspension control: A review, *Annual Reviews in Control* **58**, 100974, 2024. <https://doi.org/10.1016/j.arcontrol.2024.100974>
- [4] A. Jedlińska, D. Pisarski, G. Mikułowski, B. Błachowski, Ł. Jankowski, *Semi-active control of a shear building based on reinforcement learning: Robustness to measurement noise and model error*, 18th Conference on Computer Science and Intelligence Systems (FedCSIS 2023), September 17–20, 2023, Warsaw, Poland, pp. 1001–1004. <https://doi.org/10.15439/2023F8946>

Application of deep Q-network for semi-active vibration control of frame structures

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KEYWORDS: *Reinforcement learning, Machine learning, Semi-active control, Vibration attenuation.*

Despite decades of research on semi-active vibration control of mechanical structures, the development of an effective control system for frame structures with multiple lockable joints remains a significant challenge. The primary difficulty arises from the nonlinear operational characteristics of such systems: switching the joint states alters the structural configuration and, consequently, its natural frequency spectrum [1]. In addition, the complex frictional and sliding behavior of lockable joints makes accurate modeling of the system dynamics inherently approximate [2].

In this study, we propose a reinforcement learning (RL)-based semi-active vibration control strategy. Control decisions are determined using a Deep Q-Network (DQN), one of the fundamental algorithms in reinforcement learning [3]. The method is applied to an eight-bay cantilever frame structure equipped with two pairs of lockable joints, operating without prior knowledge of the system dynamics. The joints allow the relative rotational motion between vertical and horizontal beams to be locked or released.

The structure is discretized using a finite element (FE) model with one beam element per bay side, resulting in a total of 24 beam-type finite elements. The RL controller learns through direct interaction with the system by estimating the effect of joint locking on the structural response. The resulting control signals are compared with an instantaneous optimal control strategy, which greedily reduces vibration energy by transferring it from low-frequency to high-frequency modes. The close agreement between the reinforcement learning-based control and the analytical optimal solution demonstrates the capability of RL algorithms to achieve effective vibration mitigation in complex, nonlinear structural systems.

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- [1] Mikułowski G., Popławski B., Jankowski Ł., *Semi-active vibration control based on switchable transfer of bending moments: study and experimental validation of control performance*, Smart Materials and Structures, DOI: 10.1088/1361-665X/abe33b, Vol.30, No.4, pp.045005-1-045005-22, 2021
- [2] Ostrowski M., Błachowski B., Popławski B., Pisarski D., Mikułowski G., Jankowski Ł., *Semi-active modal control of structures with lockable joints: general methodology and applications*, Structural Control and Health Monitoring, DOI: 10.1002/stc.2710, Vol.28, No.5, pp.e2710-1-24, 2021
- [3] Mnih, V., Kavukcuoglu, K., Silver, D. et al. *Human-level control through deep reinforcement learning*. Nature 518, 529–533 (2015). <https://doi.org/10.1038/nature14236>

Ultrasonic Colinear and Vibroacoustic Modulation Shear Wave Mixing for Structural Damage Detection

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KEYWORDS: *Fracture, Damage and Fatigue, Vibro-Acoustic Modulation, Colinear Wave Mixing, NDT, Shear waves*

The presented paper is an experimental study of Vibro-Acoustic Modulation (VAM), and colinear ultrasonic wave mixing using Shear-Horizontal waves (SH) as nonlinear ultrasonic techniques for detecting and localizing damage in metallic structures. The work uses a setup of copper beams containing various crack depths excited by paired piezoelectric actuators: a high-frequency (HF) ultrasonic carrier and a low-frequency (LF) excitation tone. Signals are generated digitally and amplified; in-plane wave motion perpendicular to the beam length to observe modulation effects.

The experiment compares modulation signatures at multiple HF/LF combinations along a sample's length: before, and after a crack at a specific location.

Signal processing focuses on modulation sidebands. For VAM, the expected sideband location is at $HF \pm n \cdot LF$, where n is a sideband modulation harmonic. In collinear mixing, the modulations at $HF \pm LF$ are examined. Metrics that are compared are defined by modulation and sidebands amplitude between samples, sideband orders obtained, and a comparison of the damage index.

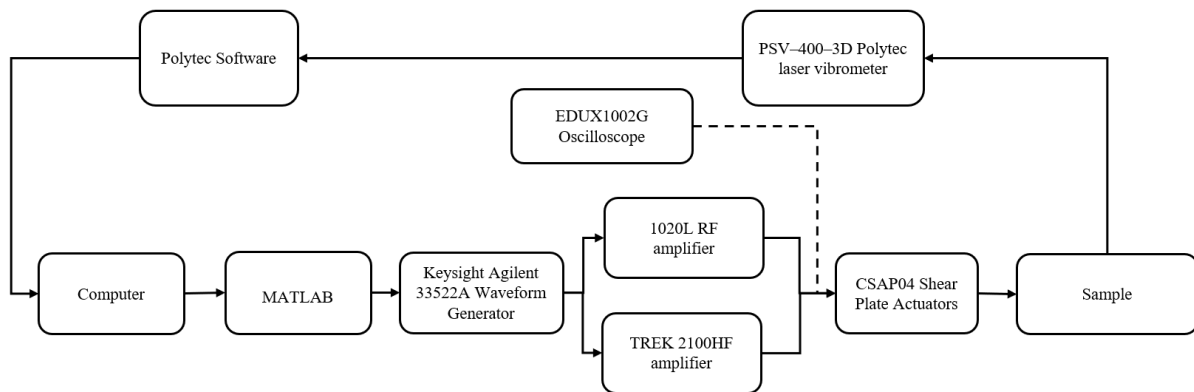


Figure 1. Scheme of experimental setup

From existing literature and theory, it is anticipated that both methods will generate modulation sidebands when nonlinear contact or stiffness changes are present, and that these sidebands will provide localization of damage (increased modulation amplitude near the crack). The paper aims to experimentally expand and verify the behaviour of SH waves in non-destructive structural health monitoring using nonlinear ultrasonic indicators.

Dynamic Analysis and Design Optimization of Washing Machine Suspensions

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KEYWORDS: *Washing Machine Dynamics, Suspension System Optimization, Supercritical Speed Regime, Vibration Analysis.*

The dynamic performance of modern front-loading washing machines is strongly influenced by the behavior of their suspension systems, particularly during high-speed spinning. Increasing demands for higher spin speeds, larger load capacities, and reduced vibration and noise levels impose significant challenges on the mechanical design. Among these, excessive vibrations, structural collisions, and machine walking remain critical issues that directly affect product reliability and the user experience.

This study presents an analytical investigation of the dynamic behavior of a front-loading horizontal-axis washing machine with a particular focus on the supercritical speed regime. In contrast to most existing works, which primarily rely on computationally expensive multibody simulations or focus on transient ramp-up behavior, this research develops a linear six-degree-of-freedom mathematical model derived using Lagrangian mechanics. The model is implemented in MATLAB and validated against a high-fidelity multibody simulation model in ADAMS, showing good agreement in terms of eigenfrequencies and damping characteristics.

The proposed model enables efficient evaluation of steady-state system responses under harmonic excitation caused by rotating unbalance forces. Based on this framework, a comprehensive parameter study is conducted in the supercritical speed range, which is particularly relevant for the spin-drying phase of washing machines. Key suspension parameters—including spring stiffness, spring angle, damping coefficient, damper angle, and damper positioning—are systematically varied to investigate their effects on critical performance indicators, including displacement amplitudes, spring and damper forces, and walking forces.

Unlike traditional optimization approaches that rely on black-box algorithms, this work emphasizes a physics-based, qualitative understanding of parameter sensitivities. The results reveal clear relationships between suspension design parameters and system behavior, enabling the identification of parameter regions that reduce vibration amplitudes, minimize transmitted forces, and mitigate walking tendencies.

The findings provide practical design insights for improving suspension systems in next-generation washing machines while maintaining computational efficiency. Furthermore, the developed analytical framework establishes a foundation for future investigations of nonlinear effects and transient behavior in the critical speed range.

Extended fractional models in the evaluation of dynamic characteristics of plates with viscoelastic layers

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KEYWORDS: *fractional viscoelastic models, layered plates, refined zig-zag theory, homotopy method, time-temperature superposition.*

Laminate plates are frequently used structural elements in many branches of engineering. The understanding of their dynamic behaviour under various service conditions is of great importance. This paper is devoted to the free vibration analysis of such plates containing viscoelastic layers, which are useful in reducing excessive vibrations. This is the continuation of authors' earlier research, e.g. [1].

The viscoelasticity is modelled using four different material descriptions based on the fractional derivatives and including the separation of volumetric and deviatoric parts of deformation. The standard linear solid (or Zener) material model, the 5-parameter model proposed by Pritz [2], the 6-parameter model by Heymans [3] and the most elaborate 10-parameter model proposed by Arikoglu [4] are considered.

Arikoglu showed in [4] that the simpler models containing even 5 or 6-parameter, despite the theoretical possibility to depict the non-symmetric inverted-U-curve relation in the Wicket plot and the limitless storage modulus behaviour in high-frequency limit, are still not capable of sufficiently good representation of real VE materials. Basing on six tested particular materials he proposed the further generalisation of the VE description and introduced the model consisting of two nested 5-parameters segments, showed that its performance is very much superior to the simpler models and proposed an effective identification procedure for the material parameters, based on genetic algorithms and provided the material parameters for those VE materials. In the presented paper these results are effectively embedded into the solution procedure for the layered plates.

The time-temperature superposition is used to include the effect of the ambient temperature. Three methods of thermal shift computation are considered, i.e. the Arrhenius formula based on the activation energy, the Williams-Landel-Ferry proposal and the modified Kaelble method.

The plate kinematics is described with the refined zig-zag theory and the free vibration problem of layered plates is formulated using the principle of virtual work and the finite element discretisation. The solution of the resulting non-linear eigenvalue problem is obtained using the homotopy method.

The results and discussion of several numerical examples solved using the proposed approach will be presented at the conference. Especially, the comparison of the damping performance of six different viscoelastic materials described by four models of viscoelasticity for various sandwich plates will be addressed. The influence of the ambient temperature will be analysed, too.

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- [1] R. Lewandowski, P. Litewka, P. Wielentejczyk, *Compos. Struct.* **2021**, 278, 114547
- [2] T. Pritz, *J. Sound Vib.*, **2003**, 265, 935-952
- [3] N. Heymans, *Rheol. Acta* **1996**, 35, 508-519
- [4] A. Arikoglu, *Rheol. Acta*, **2014**, 53, 219-233

Investigations of rotors supported by passive magnetic bearings with radial magnetization

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KEYWORDS: *Passive Magnetic Bearings, Rubber Damping Elements, Rotors.*

A common requirement on design and operation of rotating machines is minimizing energy losses and wear of the support elements. This is offered by application of contactless passive magnetic bearings [1, 2]. The goal of the research performed was investigation of effect of adding damping elements on the rotor vibration.

The investigated system is a vertical rotor supported by a passive magnetic bearing at its lower end and by a rolling element bearing at its upper end. The magnetic bearing is composed of two permanent magnetic rings with radial magnetization. The outer magnet is connected to a ring coupled with the stationary part by a cage spring and rubber damping elements. When the rotor rotates, it is loaded by unbalance.

In the computational model the shaft was represented by a beam-like body that was discretized into finite elements, the disc and the magnetic rings were regarded as absolute rigid. The rubber elements were represented by beam bodies. The nonlinear magnetic forces acting between the rings of permanent magnets were determined by means of the dipol-dipol method. The laboratory experimental system consists of a stationary part formed by a stiff supporting structure and of a vertical rotor. The magnetic bearing with the rubber elements and the rotor disc can be seen in Fig. 1.

Both computational simulations and experimental research show that presence of the rubber elements suppresses some resonance frequencies and free oscillations induced during passage of the rotor through the resonance areas, which makes the rotor vibration much smoother.

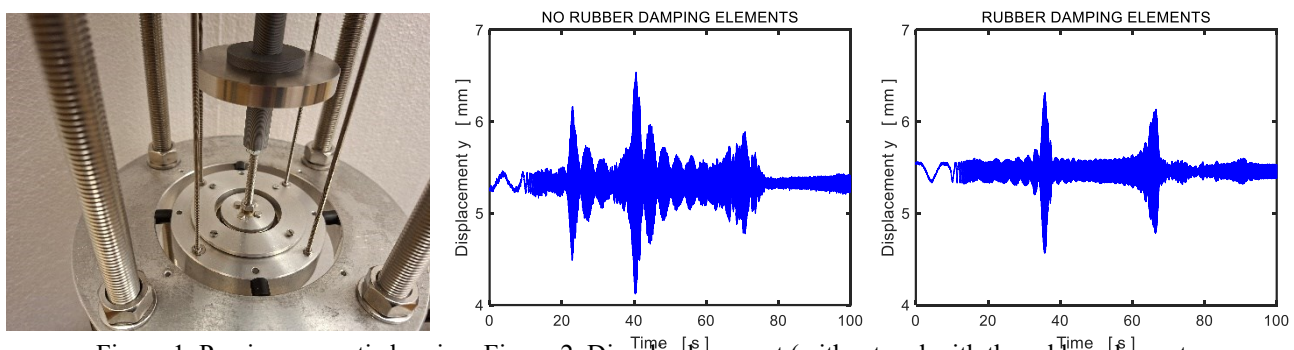


Figure 1. Passive magnetic bearing. Figure 2. Disc displacement (without and with the rubber elements).

ACKNOWLEDGEMENT: The research work was funded by grant projects GAČR 26-21297S and Strategy AV21. The support is highly acknowledged.

[1] A. Vigliani, S. P. Cavallaro, S. Venturini, *Applied Sciences* 15, 2025

[2] S. I. Bekinal, T. R. Anil, S. Jana, *Progress in Electromagnetics Research* 44, pp. 327-343, 2012.

Extension of Reduced Modal Modelling of Turbine Wheel For Suppression of Self-Excited Torsional Vibration by Interblade Dry-Friction Tie-Boss and Shroud Dry-Friction Damping

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KEYWORDS: *turbine blades, dry-friction contact, flutter, travelling wave, Van der Pol model.*

Recently [1-4], the new approach based on modal synthesis method was proposed and has been developing for assessment of dry-friction damping effect on self-excited vibrations due to aero-elastic instability in the bladed turbine wheels. The aerodynamic excitation of the wheel is assumed to arise from the spatially periodical flow of steam through the stator blade cascade creating the travelling deformation waves in the wheel. The neighbouring blades are interconnected by rigid tie-boss and as tip-shroud arms that are on one side fixed to one blade and are in friction contact on their free side with the other blade. Due to relative normal motions in contacts, the prescribed contact forces vary in time. Contact frictions forces in contacts are described by the modified Coulomb friction law. This approach enables to make a numerically effective analysis of the connection parameters, such as placement, length of arms, contact surface angles etc.

In our previous works, we dealt with Van der Pol model linked to absolute motion of the blades [1] and to relative motion between the blades in [2-3]. Furthermore the uniform space distribution of the aeroelastic forces along the blade length was considered. Due to this assumption and choice of number of stator blades the suppression of 2nd flexural mode vibrations of the wheel was mainly tackled. The numerical simulations showed an effectiveness of the tie-boss and shroud damping effect on both types of Van der Pol mode. In this paper we will come from the previous wheel modal model aiming, however, at the suppression of torsional modes of vibration. Based on new experimental results achieved on the torsional blade cascade in our laboratory [5], a new design of aeroelastic forces space distribution will be implemented. As the wheel design, the blade tie-boss couplings are applied on the particular industrial turbine wheel with 66 blades. The effect of the angles of contact surfaces of tie-boss and shroud arm ends on the wheel dynamics and on level of self-excitation suppression will be discussed.

ACKNOWLEDGEMENT: This research is supported by the project of Czech Science Foundation No. 24-12144S "Investigation of 3D flow structures and their effects on aeroelastic stability of turbine-blade cascades using experiment and deep learning approach".

- [1] Pesek, L., Snabl, P., Prasad, C.S. Turbine wheel reduced modal model for self-excited vibration suppression by inter-blade dry-friction damping. Bull. Pol. Acad. Sci. Tech. Sci. 2023, 71(6), e148250.
- [2] Pesek, L., Snabl, P., Prasad, C.S.: Reduced modal model of bladed turbine wheel for study of suppression of self-excited vibration by dry-friction contacts, Proc. of SIRM2021, Gdansk, IMP PAN Publishers, pp.371-380.
- [3] Pesek, L., Snabl, P., Prasad, C.S.: Modal synthesis method for inter-blade dry-friction surface angle design of turbine wheel for vibration suppression, Proc. of the ASME IDETC/CIE2022 Conference, paper DETC2022-88382, 9 pages, August 14-17, 2022, St. Louis, USA.
- [4] Půst, Ladislav, Pešek, Luděk, Byrtus, M. Modelling of flutter running waves in turbine blades cascade. Journal of Sound and Vibration. 2018, 436(December), 286-294. ISSN 0022-460X, doi: 10.1016/j.jsv.2018.08.011.
- [5] Šnábl, Pavel. Analytical Modeling and Analysis of Mistuned Blades in Blade Cascade System. Proc. of Computational Mechanics 2024. Plzeň: University of West Bohemia, 2024.

Robustness of Cross-Well Dynamics in Multistable Energy Harvesters Under Parameter Mismatch

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KEYWORDS: *Energy harvesting, basin stability, parameter mismatch, multistability, nonlinear dynamics.*

This study investigates the influence of parameter mismatch on the stability of cross-well motion in four nonlinear vibration energy harvesters, including two electromagnetic and two piezoelectric designs [1]. Instead of evaluating performance solely through generated power, a basin-stability-based metric with parameter mismatch is employed to quantify the probability of reaching and maintaining the desired high-energy cross-well response. The analysis is conducted in the excitation amplitude-frequency space using Monte Carlo sampling and up to 200,000 simulations per system [2]. Parameter uncertainties of $\pm 2.5\%$, $\pm 5\%$, and $\pm 10\%$ are introduced in damping, electromechanical coupling, stiffness, and potential-related parameters. Results demonstrate that electromagnetic harvesters are substantially more sensitive to parameter mismatch than piezoelectric systems. For the investigated electromagnetic devices, a 10% mismatch may reduce the probability of achieving stable cross-well motion from nearly 1.0 to approximately 0.5–0.7, accompanied by pronounced erosion of safe operating regions. Although the more complex electromagnetic configuration extends the region where cross-well motion can occur, it also introduces wider areas characterized by moderate stability levels. In contrast, piezoelectric harvesters preserve high basin stability even under significant parameter uncertainty, with maximal changes in stability not exceeding approximately 23–30%. The two-degree-of-freedom piezoelectric harvester exhibits the broadest operational bandwidth and the highest robustness. The findings indicate that basin-stability analysis provides an effective framework for assessing practical reliability of nonlinear energy harvesters and identifying excitation conditions that remain safe despite unavoidable parameter uncertainty. The results further suggest that piezoelectric multistable designs offer superior resilience and operational reliability for real-world energy harvesting applications.

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- [1] Burzynski, P. Brzeski, P. Perlikowski, Int. J. Non-Linear Mechanics, 175, 105097, 2025.
<https://doi.org/10.1016/j.ijnonlinmec.2025.105097>
- [2] P. Brzeski, J. Wojewoda, T. Kapitaniak, J. Kurths, P. Perlikowski, Sci. Rep., 7(1), 6121T, 2017.
<https://doi.org/10.1038/s41598-017-05015-7>

Master Stability Function for networks of coupled piecewise-smooth oscillators

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KEYWORDS: *Master Stability Function, piecewise-smooth oscillators, synchronization stability, complete synchronization.*

The Master Stability Function (MSF) [1] has become a standard tool for analyzing the stability of complete synchronization in networks of identical oscillators. This framework offers two main advantages. First, it reduces the stability analysis of a high-dimensional network to the study of a low-dimensional variational equation governing perturbations transverse to the synchronization manifold. Second, the results obtained for a given oscillator model and coupling scheme can be readily extended to networks with different connection topologies. However, applying this framework to piecewise-smooth systems is significantly more challenging, as the variational equation is not defined at points where the vector field is non-differentiable.

To overcome this limitation and enable MSF analysis of piecewise-smooth systems, a novel extension of the MSF framework, based on a previously developed Jacobian estimation technique [2] is proposed. The central idea is to approximate the Jacobian matrix along a system trajectory using the evolution of small orthogonal perturbations. This enables the estimation of perturbation dynamics even when the trajectory passes through non-differentiable points, thereby allowing the computation of the MSF in the absence of a well-defined variational equation. A key advantage of the proposed framework is its straightforward applicability to a broad class of piecewise-smooth systems without requiring system-specific analytical derivations, while still providing quantitative insight into synchronization stability.

The proposed framework is presented and evaluated against existing approaches. Its applicability is demonstrated through the computation of Master Stability Functions for linear and nonlinear impact oscillators, while its accuracy is verified through comparison with an alternative MSF estimation method.

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- [1] L. M. Pecora i T. L. Carroll, „Master stability functions for synchronized coupled systems,” vol. 80, nr 10, p. 2109, 1998.
- [2] M. Balcerzak, A. Dabrowski, B. Blazejczyk-Okolewska i A. Stefanski, „Determining Lyapunov exponents of non-smooth systems: Perturbation vectors approach,” *Mechanical Systems and Signal Processing*, vol. 141, p. 106734, 2020.

Session TS13

Plasticity, damage and fracture mechanics

A new method for solving 3D problems of out-of-plane or out-of-surface crack perturbations, with some applications to mixed-mode propagation of cracks

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KEYWORDS: *3D elastic body, arbitrary crack, out-of-plane perturbation, extended Bueckner-Rice theory, mixed-mode propagation.*

The aim of this work is to propose a new, simple and efficient method for solving problems of 3D elastic bodies containing cracks slightly perturbed *out of their original plane or surface*. It is divided into three parts.

We begin, in a first part, by defining a suitable extension of Bueckner-Rice's theory of 3D weight functions. Rice (1985, 1989)'s re-formulation of Bueckner (1987)'s theory provided the first-order variation of the elastic fields (displacements, strains, stresses) arising from an *in-plane or tangential* perturbation of the crack front, for an arbitrary crack in an arbitrary body. This result is extended here to arbitrary geometric perturbations of the crack front *and* surface, including an *out-of-plane or normal* component to the crack surface. The basis of the treatment is a new, general formula providing the variation of the total energy of the body arising from such an arbitrary crack perturbation. This formula is obtained by adapting and extending reasonings and results of deLorenzi (1982) and Destuynder et al. (1983). It is then used to derive the first-order expression of the full displacement field everywhere in the body. The reasoning here basically follows and extends that in the works of Rice (1985, 1989), which was limited to in-plane or tangential perturbations of the crack front.

In a second part, we illustrate the possible use of the formalism thus defined for the treatment of elastic problems of out-of-plane or out-of-surface crack perturbations. This is done by considering the simplest possible case of out-of-plane perturbation of a semi-infinite plane crack embedded in some infinite body. This problem was solved by Movchan et al. (1998), using an elaborate method specific of the special, infinite geometry considered. In contrast, the method of solution proposed here is general and potentially applicable to *any* cracked geometry. The derivation involves two steps :

- 1) In the general formula providing the variation of the displacement at any point of the body, we let this point of observation go to an arbitrary point on the crack surface, so as to get the variation of the displacement discontinuity there.
- 2) In the formula thus obtained, we let the point of observation on the crack surface go to some arbitrary point on the crack front, so as to get the variations of the stress intensity factors there.

The results obtained in this way fully confirm, and somewhat extend, those derived by Movchan et al. (1998) using a more complex and specific method.

We finally expound, in a third part, the possible applications of these results to the theoretical prediction of crack paths in 3D bodies loaded in mixed-mode conditions. We especially focus on the interpretation of the experimentally well-documented out-of-plane instability of crack fronts loaded in mode I+III. Three cases are considered, in order of increasing complexity :

- 1) That of a mode I+III loading, with a critical energy-release-rate G_c independent of mode-mixity.
- 2) Again that of a mode I+III loading, but with a mode-mixity-dependent G_c .
- 3) That of a general mixed-mode I+II+III loading, with a mode-mixity-dependent G_c .

The results suggest interesting interpretations of both old and recent experiments.

Stress Intensity Factors at the Nanoscale by Atomistic Simulations

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KEYWORDS: *Crack, Fracture Toughness, Molecular Dynamics Simulations, Size Effect.*

This presentation addresses the following question: *Can the available analytical or numerical solutions for stress intensity factors (SIFs), derived from classical continuum mechanics, accurately define SIFs in specimens with micro- or nanoscale dimensions?*

This question arises because, at such small length scales, interactions between atoms on opposing crack surfaces may become significant and influence the deformation field at the crack tip. The extent to which these atomistic interactions affect the validity of classical SIF solutions remains unclear in the literature.

In this work, we aim to provide insight into this issue by investigating the problem using molecular dynamics (MD) simulations. The SIFs will be determined from MD simulations employing an interatomic potential that is carefully validated against Density Functional Theory (DFT) calculations and available experimental data.

The SIFs will be evaluated using two complementary approaches:

1. A global method based on a discretized atomistic formulation of the J-integral, and
2. A local method based on a least-squares fitting of the crack-tip displacement/stress fields.

Finally, the SIFs obtained from the MD simulations will be compared with those predicted by classical continuum solutions.

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An Efficient Implementation of Plasticity for Rollforming Simulations

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KEYWORDS: Rollforming, Kirchhoff-Love Shells, Stress-Resultant Plasticity, Mixed-Euler-Lagrange Parametrization, Stationary Prediction.

Rollforming is a continuous process in which the cross-section of sheet metal is bent incrementally by a number of roll stands along the axial direction x of the forming line to achieve a desired cross-sectional profile. The low thickness of the sheet justifies the use of the nonlinear *Kirchhoff-Love shell* theory with three translational and two rotational degrees of freedom [1]. We apply the finite element method and utilize a *Mixed-Eulerian-Lagrangian* (MEL) description [2] to decouple the downstream motion of the material particles along the forming line from the nodal deflections. Consequently, an advection term with the transport rate v emerges in the material time derivative $\dot{\square} = \partial_t \square + v \partial_x \square$. We seek the steady-state solution with a Newton-Raphson algorithm and employ an operator-split method to divide a time increment into a quasi-static phase and a transport phase to account for the motion of material particles. The quasi-static phase features the iterative solution of the balance equations and a predictor-corrector scheme to establish admissible elastic-plastic states; the transport is carried out with a first-order upwind scheme.

We employ a *stress-resultant plasticity* model [3], which operates directly on the 2D material surface of the shell and mimics the plastification through-the-thickness of the continuum with a *structural work hardening* law. Associative rules are introduced for the material rate of the plastic bending and membrane strains, $\dot{\mathbf{K}}_p$ and $\dot{\mathbf{E}}_p$, and the dissipative power $\dot{A}_p$. The yield surface is not smooth and, thus, requires regularization or active-set strategies [4] for the return mapping. The subsequent transport of the plastic quantities $\mathbf{p} = \{\mathbf{K}_p, \mathbf{E}_p, A_p\}$ creates a disbalance of the system after each increment. We mitigate this effect by applying a *stationary prediction* to provide a qualified guess of the upcoming step j by updating the previously obtained solution after the last increment $j - 1$ with:

$$\tilde{\mathbf{p}}_{j-1} = \mathbf{p}_{j-1} + \frac{\mathbf{p}(t_{j-1}) - \mathbf{p}(t_{j-2})}{t_{j-1} - t_{j-2}} (t_i - t_{i-1}). \quad (1)$$

This estimate is self-improving as the solution gradually approaches the steady state, which results in an increasingly faster convergence of the scheme as the transient simulation progresses. Numerical studies demonstrate a substantial reduction of the computation time, making the stationary prediction a promising tool for the efficient simulation of large industrial models. We compare the results of the stress-resultant model against the established continuum-based treatment of plasticity with a corresponding thickness resolution of plastic states.

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- [1] Eliseev, V. and Vetyukov, Y. In: *Acta Mechanica* 209 (2010), pp. 43–57. DOI: 10.1007/s00707-009-0154-7.
- [2] Vetyukov, Y., Gruber, P.G., and Krommer, M. In: *Acta Mechanica* 227 (2016), pp. 2831–2842. DOI: 10.1007/s00707-016-1651-0.
- [3] E. Kocbay et al. In: *International journal of advanced manufacturing technology* 130 (2024), pp. 781–798. DOI: 10.1007/s00170-023-12544-1.
- [4] Simo, J.C., Kennedy, J.G., and Govindjee, S. In: *International Journal for Numerical Methods in Engineering* 26 (1988), pp. 2161–2185. DOI: 10.1002/nme.1620261003.

Numerical modelling of masonry wall failure by multiple embedded discontinuity finite elements

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KEYWORDS: *Masonry wall, Shear Failure, Continuum model, Embedded discontinuity, Finite elements*

Masonry walls, i.e. structures built by stacking units like bricks or stones bound by mortar, have been used in construction since ancient times. Naturally, the load bearing capacity of masonry structures is of major interest in construction engineering, and has been extensively studied experimentally and, especially during the present computer age, numerically as reviewed by D’Altri et al. [1]. The modeling approaches can be classified as Block-based Models, Continuum Models, Macroelement Models, and Geometry-based Models [1]. The present work adopts the Continuum modelling approach based on the Embedded Discontinuity Finite Element Method (EDFEM) [2].

A Matlab-based method to automatically generate 2D masonry walls with either regular bricks or polygonal stones bound with mortar is developed. The mortar failure is modelled by pre-embedded multiple discontinuity finite elements, while the units (bricks or stones) failure is according to the principal stress criterion (mode I) with a single embedded discontinuity representing a crack. In the present failure model, crack opening is inelastic and the failure process is dealt with similarly to that in the computational multisurface plasticity models.

The modelling approach is demonstrated with numerical examples on in-plane failures of masonry walls found in literature. A simulation example is shown in Fig. 1 where a masonry wall is diagonally compressed with a constant velocity boundary condition. The failure mode is shown as the crack opening magnitude.

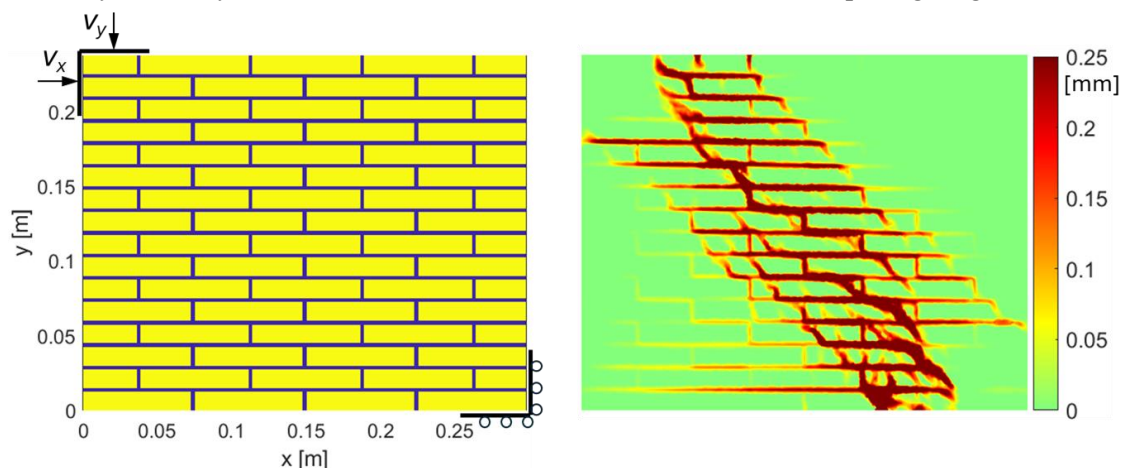


Figure 1. Masonry wall and boundary conditions (left), and the failure mode in terms of crack opening magnitude (right).

- [1] A.M. D’Altri, V. Sarhosis, G. Milani et al. Modeling Strategies for the Computational Analysis of Unreinforced Masonry Structures: Review and Classification. *Arch. Computat. Methods. Eng.* 27, 1153–1185, 2020. <https://doi.org/10.1007/s11831-019-09351-x>.
- [2] T. Saksala. Numerical modelling of concrete fracture processes under dynamic loading: Meso-mechanical approach based on embedded discontinuity finite elements. *Eng. Fract. Mech.* 201, 282-297, 2018. <https://doi.org/10.1016/j.engfractmech.2018.07.019>.

Rheological Models - History, Basics, and Advanced Models

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Historically speaking, people have been thinking about rheology for more than 2,000 years. However, these insights were largely empirical in nature and based on observations of the natural world.

It was not until Robert Hooke and Isaac Newton that the first rheological models emerged, which also led to mathematical expressions. Subsequently, numerous rheological models were introduced, though rheology had not yet been established as a science.

In the 1920s, rheology was established as a scientific discipline on the initiative of the chemist Bingham and the civil engineer Reiner. The latter also authored the first book on rheology. The method of rheological modeling was further developed in the subsequent period, particularly by Palmov.

The article concludes with a brief discussion of current developments in the field of rheological models.

Unexpected Formation of Deformation Bands in the Rate-Dependent Modelling of Single Crystal Plasticity

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KEYWORDS: *Micropolar Crystal-Plasticity, Microstructure Formation, Finite Element Method, 2D Plane-Strain Model.*

The phenomenon of spontaneous formation of deformation bands in metal crystals is investigated using a simple model of crystal plasticity at small strain, with and without the Cosserat-type regularization. A standard and widely used rate-dependent (RD) model has been implemented in a finite element method (FEM). Nevertheless, a laminate pattern emerges spontaneously and is comparable to that obtained using an approach based on incremental energy minimization [1, 2]. It is emphasized that the FEM implementation does not involve any artificial perturbations or geometric imperfections, as well as any predefined laminate kinematics.

The Cosserat model introduces a natural regularization mechanism by inclusion of an internal length scale. The model contains two deformation measures: the relative deformation tensor $\mathbf{e}$ and the curvature tensor $\boldsymbol{\kappa}$. The deformation measures are defined based on two independent kinematic fields of displacement $\mathbf{u}$ and microrotation vector $\boldsymbol{\phi}$. An isotropic Cosserat part of the elastic response is controlled by two parameters of Cosserat elasticity, $\mu_c > 0$ and $\beta_c > 0$.

FEM simulations were performed using a plane-strain model in which the twelve positive fcc slip-systems were reduced to three effective in-plane plastic slip mechanisms, cf. e.g. [3]. The most important condition for the formation of deformation bands is that the latent hardening of slip systems exceeds their self-hardening. The next key factor in the rate-dependent simulations is a sufficiently small strain-rate-sensitivity parameter, highlighting the crucial role of the yield-vertex effect. The results of RD simulations reveal an entire domain filled with a laminate pattern formed by deformation bands with alternating slip-system activity, as illustrated in Fig. 1.

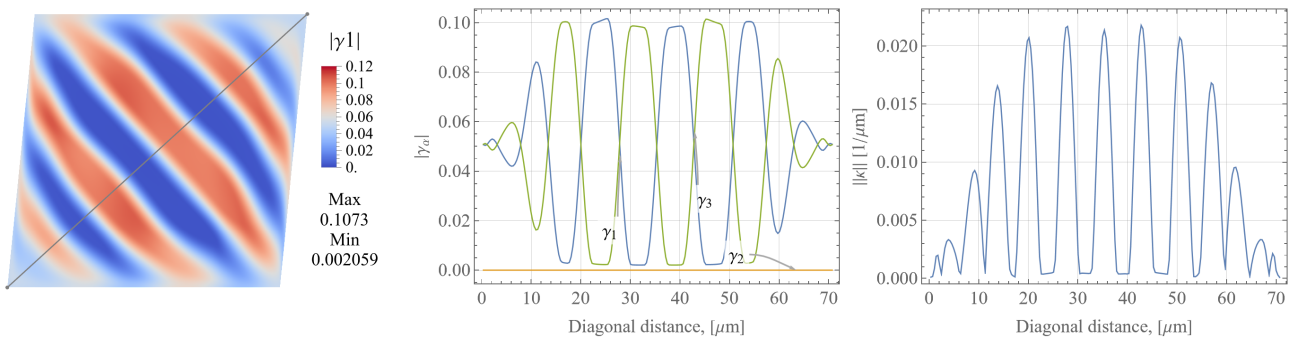


Figure 1: Accumulated slips $|\gamma^\alpha|$ in macroscopically uniform simple shear in case of initial crystal orientation $\omega = \pi/4$, for the Cosserat parameter to hardening modulus ratio $\beta_c/h_0 = 1/2.5$ [mN/GPa] and dimensions $50\mu\text{m} \times 50\mu\text{m}$, profiles of slips $|\gamma^\alpha|$ along the diagonal, and the norm of the curvature tensor $\|\boldsymbol{\kappa}\|$ which is strongly localized at the band interfaces.

- [1] M. Ryś, M. Kursa, H. Petryk, Spontaneous emergence of deformation bands in single-crystal plasticity simulations at small strain, *Comput. Mech.* **75**, 547-574, 2025. <https://doi.org/10.1007/s00466-024-02519-8>
- [2] M. Ryś, M. Kursa, H. Petryk, Selecting deformation patterns in Cosserat crystal plasticity by incremental energy minimization, *J. Mech. Phys. Solids* **212**, 106569, 2026. <https://doi.org/10.1016/j.jmps.2026.106569>
- [3] M.J. Lewandowski, S. Stupkiewicz, Size effects in wedge indentation predicted by a gradient-enhanced crystal-plasticity model, *Int. J. Plast.* **109**, 54–78, 2018. <https://doi.org/10.1016/j.ijplas.2018.05.008>

The energy approach to deformation banding in Cosserat crystal plasticity

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KEYWORDS: *Micropolar crystal plasticity, Microstructure formation, Incremental energy minimization, Finite element method, plane-strain model*

Numerical simulations employing classical crystal plasticity models have encountered two major, long-standing issues: the ambiguity in selecting active slip systems, and the instability of uniform plastic deformation due to deformation banding. To address these challenges, regularization techniques have frequently been applied by introducing a rate-dependent model of crystal plasticity and/or a gradient-dependent enhancement of the continuum framework. However, experimental observations have repeatedly shown that ductile metal crystals tend to develop deformation bands, suggesting that efforts to eliminate this phenomenon in calculations may lack a solid physical foundation. In accordance with that, in a companion presentation at this conference, M. Kursa demonstrates that this phenomenon is not eliminated even if using a standard rate-dependent model, provided that latent hardening exceeds self-hardening of slip systems and the strain-rate sensitivity parameter is sufficiently small. Notably, this does not require any artificial perturbations or geometric imperfections.

The focus of this lecture is the explanation of the deformation banding phenomenon using a rate-independent model of crystal plasticity with the Cosserat-type regularization, applied within the framework of incremental energy minimization [1]. A strictly variational micropolar approach has been implemented in a finite element code. The present study demonstrates that spontaneous emergence of deformation bands is predicted, under the same basic condition that latent hardening of slip systems exceeds their self-hardening, provided the size of the crystal domain is not too small. This is made specific by requiring that the band wavelength exceed the established minimum value, proportional to the square root of the quotient of two factors: the coefficient of the energy density due to the lattice curvature, and the positive difference between the cross-hardening and self-hardening modulus. A nearly perfect agreement has been found between the analytical estimate of the minimal band wavelength and the band interface thickness in full-field finite element simulations in plane strain. It has been demonstrated that the incremental energy minimization is a suitable tool for computing deformation patterns in ductile single crystals with the Cosserat-type regularization.

- [1] M. Ryś, M. Kursa, H. Petryk, Selecting deformation patterns in Cosserat crystal plasticity by incremental energy minimization, *J. Mech. Phys. Solids* **212**, 106569, 2026. <https://doi.org/10.1016/j.jmps.2026.106569>

On the regularization of a tensorial continuum damage model

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KEYWORDS: *Continuum Damage Mechanics, Strain Localization, Visco-damage, Gradient Regularization, Thermodynamics, Free Energy, Dissipation Potential.*

Since the advent of continuum damage mechanics [2] it has developed into an important and active field of continuum mechanics, see e.g. [3, 4]. Progressing degradation of elastic properties will eventually lead to strain softening behaviour, which can result to ill-posedness of the underlying partial differential equation system. In numerical solution the ill-posedness caused by strain softening produces severe mesh size dependency. Several remedies have been proposed to alleviate or remove this deficiency: non-local integral constitutive models, adding spatial gradients, rate-dependency, etc. Research on gradient regularization of elastic damaging models has mostly concentrated on scalar damage approach, see for example [1], and only few papers have been published where tensorial damage models are considered [5, 6]. In this presentation different regularization approaches applied to the tensorial continuum damage model [7] are compared.

ACKNOWLEDGEMENT: This work is partly funded by the Research Council of Finland, project ConSus - Towards sustainable carbon free concrete construction.

- [1] L.M. Kachanov. On the creep fracture time. *Izv. Akad. Nauk SSSR. Otd. Tekhn. Nauk*, (8):26–31, 1958. (in Russian).
- [2] J. Lemaitre. *A Course on Damage Mechanics*. Springer-Verlag, Berlin, 1992.
- [3] S. Murakami. *Continuum Damage Mechanics*, Springer Netherlands, 2012.
- [4] H. Askes, L.S. Sluys. *Eur. J. Mech. A/Solids*, **21**, 2002, 379–390. [https://doi.org/10.1016/S0997-7538\(02\)01214-7](https://doi.org/10.1016/S0997-7538(02)01214-7)
- [5] M. Fassin, R. Eggersmann, S. Wulfinghoff, S. Reese. *Int. J. Solids and Struct.* 167, 2021, 93-126. <https://doi.org/10.1016/j.ijsolstr.2019.02.009>.
- [6] T. van der Velden, S. Reese, H. Holthusen, T. Brepols. *Int. J. Damage Mech.* 35(1), 2026 <https://doi.org/10.1177/10567895251329815>.
- [7] J. Vilppo, R. Kouhia, J. Hartikainen, K. Kolari, A. Fedoroff, K. Caloni. *Int. J. Solids and Struct.* 225: 111048, 2021, <https://doi.org/10.1016/j.ijsolstr.2021.111048>.

Shakedown of Structures Undergoing Plastic Strain Induced Phase Transformation

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KEYWORDS: *Cryogenic Temperatures, Torsion, Constitutive Modelling, Shakedown, Plastic Deformation, γ - α' Phase Transformation*

Selected stainless steel grades are widely used in cryogenic installations, including superconducting particle accelerators cooled with liquid or superfluid helium. Grades such as 304L, 316L, and 316LN are preferred for their favourable mechanical properties and moderate cost. Despite their high ductility, these steels exhibit metastable behaviour due to a plastic strain-induced phase transformation from an fcc to bcc lattice. The primary phase (austenite) is ductile, while the secondary phase (martensite) is relatively brittle and deforms elastically. At extremely low temperatures, the phase transformation progressively replaces the ductile, energy-dissipating phase with a more elastic one, thereby promoting accelerated shakedown. Cyclic torsion tests were conducted at 77 K under torque control to investigate shakedown behaviour in metastable austenitic stainless steels 304, 304L, 316L, and 316LN (Fig. 1). The martensite content was measured on the surface of round-bar specimens during testing to monitor the progression of the phase transformation. The dissipated energy per cycle was analysed, showing that 316LN steel dissipates more energy compared to 304, 304L, and 316L, as its hysteresis loops exhibit only minor narrowing. This fact supports the hypothesis that phase transformation accelerates shakedown. Consequently, more stable steels, such as 316LN, are more resistant to shakedown.

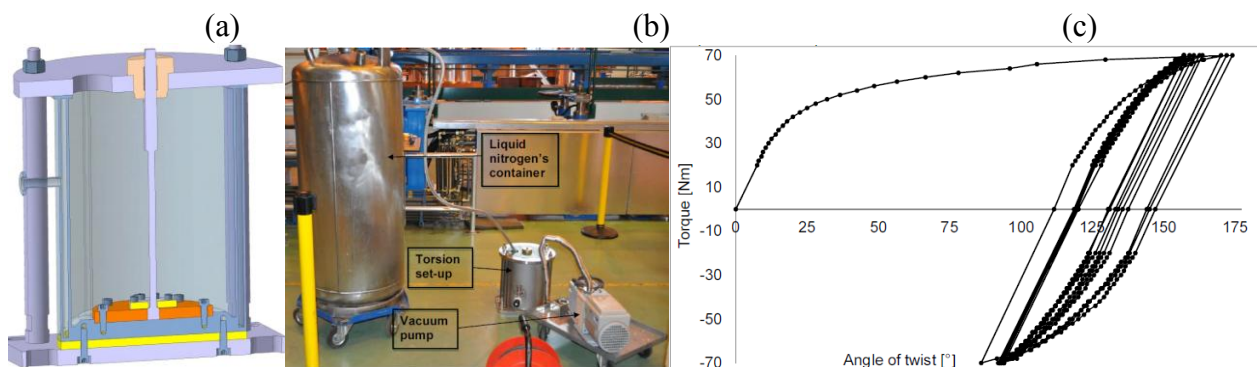


Figure 1. a) Cryostat for torsion tests (bar dimensions: 8 mm diameter, 200 mm length; elastic shear modulus $G_{77K}=75$ GPa); b) Experimental set-up; c) Torque vs angle of twist [1, 2]

To support the experimental findings, a physics-based multiscale constitutive model [1], [2] was developed and implemented in the AceGen/AceFEM tool. The model incorporates hardening mechanisms coupled with plastic strain induced fcc-bcc phase transformation. Cyclic torsion was simulated in 3D for various phase transformation kinetics to assess their impact on cyclic response (shakedown) and martensite content.

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[1] R. Ortwein, B. Skoczeń, J.Ph. Tock, International Journal of Plasticity 59, 152–179, 2014
<https://doi.org/10.1016/j.ijplas.2014.03.006>

[2] R. Ortwein, Constitutive Model of Graded Micro-Structure Obtained via Strain Induced Phase Transformation, PhD thesis, 2015. <https://doi.org/10.13140/RG.2.2.16483.07205>

Influence of applied stress on dynamic strain ageing – experiments and enhanced model formulation

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KEYWORDS: *Dynamic Strain Ageing, PLC Effect, Estrin-McCormick Model, Experimental mechanics, Material modelling*

Dynamic strain ageing (DSA) and the associated Portevin–Le Chatelier (PLC) effect continue to present significant challenges for constitutive modelling, particularly when deformation paths depart from simple monotonic loading. Many established modelling approaches, including those based on the Estrin–McCormick framework, employ an ageing-time variable to represent the diffusion-controlled interaction between solute atoms and dislocations. Although this concept enables the reproduction of key features of DSA, the classical evolution equation proposed by McCormick does not clearly define the mechanical conditions under which the ageing time should accumulate. Consequently, ageing-time evolution is commonly assumed to proceed continuously, which can introduce non-physical hardening contributions in simulations involving holding times, unload–reload sequences, or other non-monotonic loading scenarios.

The aim of this talk is to address this limitation by combining experimental observations with modelling considerations. To this end, tensile tests with prescribed waiting times are conducted on the aluminium alloy AW5083. These experiments are designed to quantify strain ageing during distinct stages of deformation and to evaluate the influence of the applied stress level during short waiting intervals on the subsequent material response.

On the basis of these experimental findings, a modified evolution equation for the ageing time is proposed. The formulation preserves the fundamental structure of the Estrin–McCormick approach but introduces a stress-dependent criterion that restricts ageing-time accumulation, in accordance with the experimental observations. This modification suppresses the unintended growth of DSA-related hardening that can arise in the classical formulation, without adding complexity to the constitutive model.

Comparisons between simulations using the classical and the modified approaches show that both capture the general characteristics of the PLC effect. However, the enhanced model provides more consistent predictions for non-monotonic loading paths and exhibits improved agreement with the experimental results for AW5083. The proposed refinement thus offers a practical improvement for the application of DSA models in finite element simulations that must represent realistic loading histories.

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Numerical verification of stability for large strain thermo-elasto-plasticity

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KEYWORDS: *Material Stability, Large Strains, Thermo-Elasto-Plasticity, Finite Element Method.*

This research addresses the numerical verification of stability in thermo-elasto-plastic materials undergoing large strains. The notion of stability is often associated with the stability of a structure, however, in this paper the attention is paid to the stability of a material at a point. The stability condition derived for a general model formulated in the thermodynamically consistent format is presented in [3]. From a mathematical point of view the stability analysis reduces to a minimization problem of a function dependent on a direction in Euclidean space. Various numerical methods can be employed to solve this problem, such as a search method within the discretized direction space [2] or a multi-start algorithm incorporating a gradient-based method [1].

In the paper the attention is paid to the development of an efficient numerical treatment incorporated into simulations performed using the finite element method. First, methods available in the literature are implemented, tested and analyzed with regard to their applicability to the stability analysis of thermo-elasto-plastic material. Second, a hybrid approach is developed combining different methods and enabling the verification of stability at integration points in complex samples subjected to non-uniform deformation as shown in Fig. 1.

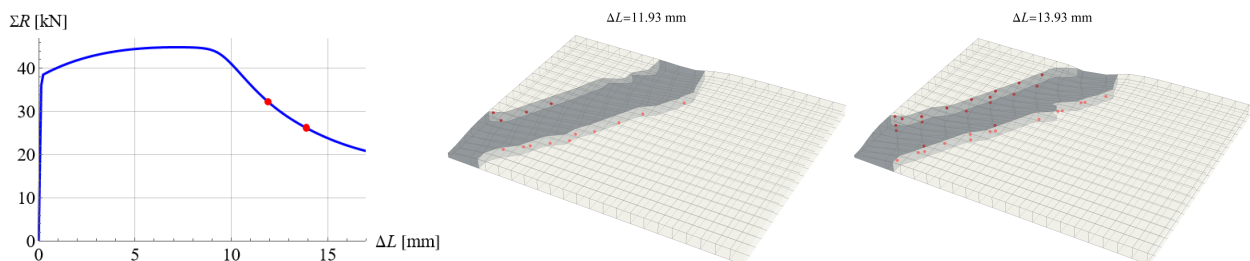


Figure 1: Sum of reactions vs enforced displacement for a tensile plate with a thermo-elasto-plastic material model (on the left) and deformed meshes with plastic zone shown in gray and Gauss points with stability lost marked as red points at load steps $\Delta L=11.93$ mm (in the middle) and $\Delta L=13.93$ mm (on the right).

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- [1] M. Al Kotob, C. Combescure, M. Mazière, T. Rose, and S. Forest. A general and efficient multistart algorithm for the detection of loss of ellipticity in elastoplastic structures. *Int. J. Numer. Meth. Engng*, 121:842–866, 2020.
- [2] B. Wcisło, J. Pamin, K. Kowalczyk-Gajewska, and A. Menzel. Numerical analysis of ellipticity condition for large strain plasticity. In *AIP Conference Proceedings 1922*, pages 140008–1–14008–8, Melville, 2018.
- [3] B. Wcisło, J. Pamin, K. Kowalczyk-Gajewska, and A. Menzel. An analytical–numerical approach for the stability analysis of large strain thermo-elastoplastic material models. *Archives of Mechanics*, 77:533–568, 2025.

Modeling of microstructure evolution during creep in metastable materials at extremely low temperatures

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KEYWORDS: *Creep, Cryogenic Temperatures, Phase Transformation, Constitutive Modeling*

Metals and alloys used at extremely low temperatures are expected to exhibit ductile behaviour and significant plastic and creep deformation prior to rupture. While creep has been extensively studied at high temperatures, it has often been overlooked at cryogenic temperatures. Yet, studies show that creep persists even near absolute zero (e.g., 4.2 K), producing measurable strain and largely conventional behaviour [1]. Although strain rates are rather low, they exceed predictions based on simple activation energy extrapolation by several orders of magnitude. Moreover, unlike the diverse plastic flow modes observed at low temperatures (intermittent plastic flow), creep deformation remains continuous. An important question is whether creep in metastable materials, like the austenitic stainless steels, is accompanied by microstructural evolution due to fcc-bcc phase transformation. Another important feature is that creep occurs across the entire temperature range, from absolute zero to room temperature, i.e., from a weakly to a highly excited lattice. Experimental results show significant creep deformation throughout this range. Tests conducted between the boiling points of liquid helium (4.2 K) and liquid nitrogen (77 K) confirm the presence of both primary and secondary creep. Primary creep begins immediately upon loading, and both its duration and obtained strain are stress-dependent, increasing with applied stress. Once the primary stage ends, the creep rate decreases markedly, and steady-state secondary creep is established. To confirm this, preliminary experiments were conducted at room temperature (293 K). Flat, paddle-shaped specimens made of AISI 304 austenitic stainless steel – susceptible to strain-induced phase transformation and widely used at extremely low temperatures – were examined for creep. For the first time, in situ measurements of the ferromagnetic phase content (martensite) were performed. Fifty-hour creep tests were carried out at various prestress levels, both below and above the yield point. Magnetometric results confirm that when the prestress exceeds the material's yield point, a significant increase in the secondary phase content occurs during the test, resulting from creep strain-induced martensitic transformation. Although tests at cryogenic temperatures are planned for the next stage, low-temperature experiments conducted worldwide (primarily in Japan) confirm the occurrence of creep in austenitic stainless steels near absolute zero [2], [3]. The most widely observed type of creep at extremely low temperatures is the so-called logarithmic creep. However, the activation energy at these temperatures is usually much lower than that at intermediate or elevated temperatures [3]. To describe both primary and secondary creep, a more complex approach is required. One possible approach is the strain-hardening model developed in the present paper. In particular, it is assumed that, similarly to plastic flow phenomena, creep processes at low temperatures are accompanied by the phase transformation, which must be taken into account in the constitutive model. For this reason, a new kinetics of creep strain-induced phase transformation is proposed.

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- [1] J. Weertman, Journal of Applied Physics, 29 (12), 1685-1698, 1958. <https://doi.org/10.1063/1.1723025>
- [2] S. Usami, T. Mori, Cryogenics, 40 (2), 117-126, 2000. [https://doi.org/10.1016/S0011-2275\(00\)00016-3](https://doi.org/10.1016/S0011-2275(00)00016-3)
- [3] B. Skoczeń, Creep at extremely Low Temperatures, Encyclopedia of Continuum Mechanics, Springer, Berlin, Heidelberg, 2020. https://doi.org/10.1007/978-3-662-55771-6_159

On physical interpretation of normalized third principal invariant of Cauchy stress deviator and its derivatives Lode parameter, skewness angle – shear stress mode angle

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KEYWORDS: *Third invariant of stress deviator, Degree of orientational (directional) concentration of micro pure shears, Lode parameter, Lode angle, Skewness angle, Pure shears as comparison reference states*

A set of three functionally independent invariants of Cauchy stress tensor σ , i.e. first principal invariant (I_1), second principal invariant of stress deviator (shear stress) (J_2) and normalized third invariant of stress deviator ($\bar{J}_3$) proved to be very useful in modeling behavior of solid materials,

$$\begin{aligned} I_1 &\equiv 3\sigma_m = \sigma_I + \sigma_{II} + \sigma_{III}, & J_2 &\equiv \frac{1}{2}(s_I^2 + s_{II}^2 + s_{III}^2), \\ \bar{J}_3 &\equiv 3\sqrt{6} J_3 / (2J_2)^{3/2} \in <-1, 1>, & J_3 &\equiv s_I s_{II} s_{III} = \frac{1}{3}(s_I^3 + s_{II}^3 + s_{III}^3), \end{aligned} \quad (1)$$

where $\sigma_K, s_K, K = I, II, III$ denote principal stresses of Cauchy stress and its deviator, respectively.

It is vital to know what actually these invariants describe regarding physical phenomena, i.e. identify their rational physical interpretation. Physical interpretation of the first principal invariant of Cauchy stress, as pressure p ($-p = \frac{1}{3}I_1$), is so straightforward that its identification did not require deeper thought. Comprehensive physical interpretation of second invariant of stress deviator (J_2) as a *macroscopic scalar measure* characterizing quantitatively, in an *average manner over all directions on unit sphere*, *shearing forces intensity* (τ_{av}), i.e. effective action of population of *micro pure shears (mechanical dipoles)* generating given *macroscopic stress state* was exposed by Novozhilov in 1951 [1]. The same physical interpretations can be assigned to derivative quantities: shear stress modulus, effective (equivalent) stress, being linearly proportional to τ_{av} ,

$$\begin{aligned} \tau_{av}(\sigma) &\equiv \left((1/\Omega) \int \tau^2 d\Omega \right)^{1/2} = \sqrt{\frac{2}{5} J_2} \quad (\tau^2 = \sigma_I^2 l_I^2 + \sigma_{II}^2 l_{II}^2 + \sigma_{III}^2 l_{III}^2 - (\sigma_I l_I^2 + \sigma_{II} l_{II}^2 + \sigma_{III} l_{III}^2)^2), \\ \tau_{av} &= \sqrt{\frac{2}{5} J_2} \Rightarrow \|s\| \equiv \sqrt{2J_2} = \sqrt{5} \tau_{av}, \quad \sigma_{ef} \equiv \sqrt{3J_2} = \sqrt{\frac{15}{2}} \tau_{av}, \end{aligned} \quad (2)$$

where τ_{av} is the Novozhilov's *shear stress intensity*, τ is modulus of shear stress traction operating on an elementary surface of a unit sphere $d\Omega$, l_I, l_{II}, l_{III} are direction cosines determining orientation of a normal to the surface $d\Omega$ in relation to principal directions of stress tensor σ .

The present work presents physical interpretation, currently non-existing, of the normalized third invariant of stress deviator ($\bar{J}_3$) as the *scalar macroscopic measure* describing *degree of orientational ordering (directional concentration)* in population of *micro pure shears* generating given *macroscopic stress state* around specific directions, see also Lecture 8 in [2]. The same interpretation gain functional derivatives of $\bar{J}_3$, i.e., Lode parameter μ , skewness angle θ_{sk} — *shear stress mode angle* defined with *pure shears as reference comparison states*, Lode angle θ_L ,

$$\theta_{sk} \equiv \frac{1}{3} \sin^{-1}(\bar{J}_3), \quad \mu \equiv 3s_{II} / (s_I - s_{III}) = -\sqrt{3} \tan(\theta_{sk}), \quad \theta_L \equiv \frac{1}{3} \cos^{-1}(\bar{J}_3); \quad \tau_{max} \equiv \frac{1}{2}(\sigma_1 - \sigma_3) = \sqrt{\frac{5}{2}} \tau_{av} \cos(\theta_{sk}). \quad (3)$$

- [1] V.V. Novozhilov, О физическом смысле инвариантов напряжения, используемых в теории пластичности (in Russian), *Prikl. Mat. Mekh.*, XVI, 617–619, 1952.
- [2] A. Ziółkowski, *On symmetric tensors of second order and fourth order in mechanics with focus on Cauchy stress and Hooke tensors*, IPPT PAN, 2025. <https://wydawnictwa.ippt.pan.pl/sklep/on-symmetric-tensors-of-second-and-fourth-order-in-mechanics/b79> (Open access). 978-83-65550-63-7.

Optimized Phase-Field Fracture Models for Monocrystalline Silicon

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KEYWORDS: *Phase-field Fracture, Molecular Simulations, Silicon.*

Reliable silicon devices require predictive fracture models that remain accurate at small length scales, where crystal orientation and surface effects play a dominant role. We present a optimization based calibration strategy for phase-field fracture models based on molecular statics and dynamics (MS/MD) simulations that explicitly resolve atomic-scale fracture mechanisms. Silicon specimens are subjected to controlled loading conditions to initiate and propagate cracks. Thereby, orientation-dependent fracture behavior is characterized through energy release rates, crack trajectories, and traction–separation relations. These atomistic observables are translated into continuum phase-field parameters, including the critical energy release rate G_c , the internal length scale l_0 , the choice of degradation function as well as the crack surface density function, yielding a brittle fracture formulation in single-crystal silicon.

The calibrated phase-field model reproduces some key fracture characteristics across selected crystal orientations, capturing both crack path selection and energy dissipation in good agreement with MS/MD results. Parametric studies highlight the influence of l_0 , G_c , the degradation and surface density functions on crack regularization and dissipation, while crystallographic effects are incorporated through the calibrated constitutive response. Overall, the proposed framework establishes a link between atomistic fracture physics and continuum-scale modeling, providing fracture simulations in silicon-based materials.

- [1] J.A. Hauch, D. Holland, M.P. Marder, and H.L. Swinney. Dynamic Fracture in Single Crystal Silicon, *Physical Review Letters* 82 (1999), 3823–3826.
- [2] B.-J. Lee. A modified embedded atom method interatomic potential for silicon, *Calphad* 31 (2007) 95–104.
- [3] J.-Y. Wu. A unified phase-field theory for the mechanics of damage and quasi-brittle failure, *Journal of the Mechanics and Physics of Solids* 103 (2017) 72–99.
- [4] B. Bourdin, G.A. Francfort, J.-J. Marigo, The Variational Approach to Fracture, *Journal of Elasticity* 91 (2008) 5–148.

Comparative Study of Selected Gradient Damage Model Variants

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KEYWORDS: *Gradient Damage, Regularization, Internal Length Scale, Localization, Damage Zone.*

The objective of the paper is to compare several variants of the gradient damage model that have been proposed and refined over the years. The discussion highlights selected improvements aimed at more realistic simulation of smeared crack zones represented by damage distributions in strain-softening analyses.

The continuum damage approach in its local version, when material instabilities occur, leads to ill-posed problems and pathological mesh sensitivity in simulations of cracking phenomena. Gradient-enhanced models can address this issue by introducing an internal length scale that governs the width of the localization zone. This parameter enters an extra averaging equation, so in the two-field formulation both the displacements and the averaged strain measure are interpolated independently. However, assuming constant length scale causes the obtained results to reveal visibly expanded damage zones [1], which is an undesirable feature of the conventional gradient damage model.

One of the simplest extensions can be a combination of equivalent and averaged strain measures, driven by a damage-dependent weighting function, cf. [2]. It is also possible to introduce a so-called anisotropic gradient matrix as shown in [3], in which the directions of the principal stresses modify the spatial distribution of the nonlocal kernel, effectively rendering the internal length parameter direction-dependent. Alternatively, this parameter can be treated as variable [1]. This version of the model, referred to here as transient gradient damage, was proposed in [4], where the internal length function, reflecting the gradient activity, is moved to the denominator in the averaging equation. Its value grows together with the evolution of the equivalent strain. Moreover, the localizing gradient damage model was introduced in [5], where the damage zone is controlled via a reduction of the gradient activity, which is more consistent with physical observations.

The selected variants of the model are implemented and compared in a tensile bar test as a benchmark, followed by more advanced examples such as the dowel disc test, see [6, 7].

- [1] M. G. D. Geers. *Experimental analysis and computational modelling of damage and fracture*. Ph.D. dissertation, Eindhoven University of Technology, Eindhoven, 1997.
- [2] G. D. Nguyen. A damage model with evolving nonlocal interactions. *Int. J. Solids Struct.*, 48(10):1544–1559, 2011.
- [3] B. Vandoren and A. Simone. Modeling and simulation of quasi-brittle failure with continuous anisotropic stress-based gradient-enhanced damage models. *Comput. Methods Appl. Mech. Eng.*, 332:644–685, 2018.
- [4] S. Saroukhani, R. Vafadari, and A. Simone. A simplified implementation of a gradient-enhanced damage model with transient length scale effects. *Comput. Mech.*, 51(6):899–909, 2013.
- [5] L. H. Poh and G. Sun. Localizing gradient damage model with decreasing interaction. *Int. J. Numer. Methods Eng.*, 110(6):503–522, 2017.
- [6] L. Ferrara. *A contribution to the modelling of mixed mode fracture and shear transfer in plain and reinforced concrete*. Ph.D. dissertation, Politecnico di Milano, Milan, 1998.
- [7] M. di Prisco, L. Ferrara, F. Meftah, J. Pamin, R. de Borst, J. Mazars, and J. M. Reynouard. Mixed mode fracture in plain and reinforced concrete: some results on benchmark tests. *Int. J. Fracture*, 103:127–148, 2000.

Observation of Fracture Behavior of CFRP Laminates with Fiber Discontinuities

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KEYWORDS: *CFRP, Fiber Discontinuities, Cohesive Zone Model, Damage Absorption.*

Carbon fiber reinforced plastics (CFRP) is widely used in aerospace, automotive, and medical devices due to its high specific strength and stiffness. However, its brittle fracture behavior caused by sudden fiber damage and interlaminar delamination poses challenges in ensuring structural reliability. In order to improve energy absorption, techniques for intentionally incorporating fiber discontinuities within the material's internal architecture are increasingly being explored. Tang et al. [1] demonstrated that intentionally introducing fiber discontinuities is a promising approach to achieving pseudo-ductility. To achieve pseudo-ductility in CFRP laminates, this study presents the bending fracture mechanisms via experiments and analysis.

In this study, CFRP laminates with fiber discontinuities are fabricated by applying slit processing to specific layers prior to molding. For comparison, conventional continuous CFRP laminates without fiber discontinuities are also prepared. Bending tests are conducted on each specimen using compact tabletop tester to record the load-displacement relationships and observe damage propagation behaviors. Furthermore, in order to evaluate the complex damage evolution mechanisms—such as delamination and fiber damage in detail, numerical simulations using the finite element method (FEM) are employed. The Cohesive Zone Model (CZM) is applied to the analysis to accurately model the delamination propagation and the progressive stress dropping process originating from the fiber discontinuities.

The bending test result reveals that the continuous CFRP exhibited typical brittle failure, where fiber damage occurred immediately after reaching the maximum load, resulting in an instantaneous loss of load-carrying capacity. In contrast, the specimens with fiber discontinuities do not show a severe stress drop after the peak load. Instead, delamination and interlaminar damage originating from the fiber discontinuities are observed to propagate progressively. Due to this progressive failure, the CFRP with fiber discontinuities maintain a certain level of load-carrying capacity until complete fracture, exhibiting pronounced pseudo-ductile behavior. Additionally, the energy absorption capacity, calculated from the area under the load-displacement curves, is confirmed to be significantly improved compared to the conventional materials.

- [1] J. Tang, Y. Swolfs, M. Yang, K. Michielsen, J. Ivens, S.V. Lomov, L. Gorbatikh, Discontinuities as a way to influence the failure mechanisms and tensile performance of hybrid carbon fiber/self-reinforced polypropylene composites, *Composites, Part A* 107, 354–365, 2018

Multiscale analysis of damage behaviour of sintered NiAl-based materials with ceramic addition

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KEYWORDS: *Spark Plasma Sintering, NiAl-based Porous Materials, Molecular Dynamics, Finite Element Method, Discrete Element Method.*

The present study aims to establish a quantitative relationship between sintering parameters, microstructural evolution, and the resulting mechanical properties of NiAl-based porous composites. Special emphasis is placed on capturing the deformation process and damage mechanisms by accounting not only for the bulk microstructure and macroscopic mechanical response, but also for the evolution of interfacial regions [1]. These include the formation and transformation of metal-metal and metal-ceramic interfaces, which critically influence the effective material behavior.

To achieve this, a comprehensive multiscale framework is employed (see Fig. 1), integrating advanced experimental characterization techniques - such as scanning electron microscopy, X-ray micro-computed tomography, and mechanical testing combined with digital image correlation together with numerical multiscale modeling approach. The latter encompasses finite element and discrete element methods at the mesoscale [2], as well as molecular dynamics simulations at the atomic scale to resolve interfacial phenomena [3]. The inherently heterogeneous microstructure of the porous NiAl composite, reconstructed from experimental observations, and the interfacial constitutive behavior, informed by microscale/atomistic simulations complement elastic-plastic properties of the NiAl material within grains. This integrated approach enables a physically consistent analysis of deformation and damage processes of sintered NiAl-based composites under mechanical loading.

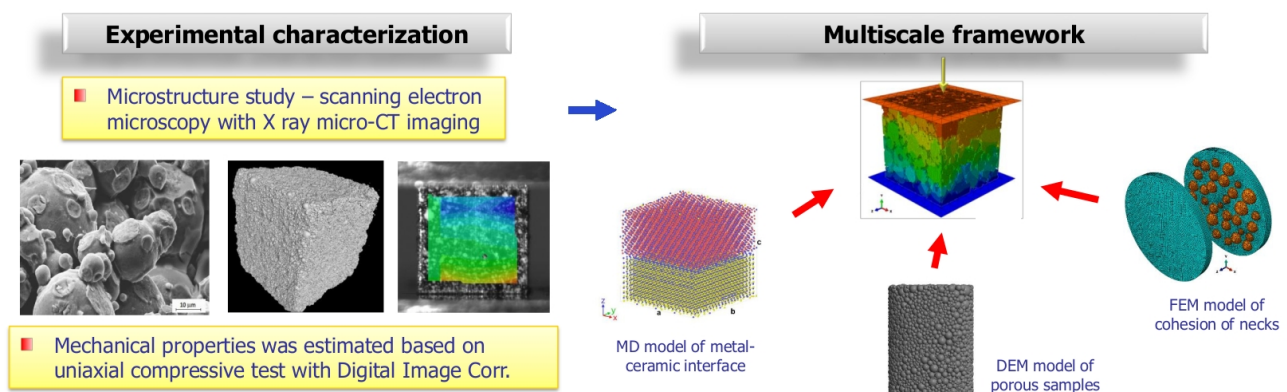


Figure 1. Summary of the multiscale framework.

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- [1] Nosewicz S., Jurczak G., Wejrzanowski T., Ibrahim S.H., Grabias A., Węglewski W., Kaszyca K., Rojek J., Chmielewski M., Int. J. Heat Mass Transf. 194, 123070-1–123070-19, 2022. <https://doi.org/10.1016/j.ijheatmasstransfer.2022.123070>
- [2] Nisar F., Rojek J., Nosewicz S., Kaszyca K., Chmielewski M., Powder Technol. 458, 120957-1–120957-23, 2025. <https://doi.org/10.1016/j.powtec.2025.120957>
- [3] Maździarz M., Nosewicz S., Eng. Fract. Mech. 298, 109953-1-109953-21, 2024. <https://doi.org/10.1016/j.engfracmech.2024.109953>

Prediction of Forming Limits Under Non-Proportional Strain Paths Using a Multi-Surface Plasticity Model

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KEYWORDS: *Localized Necking, Ductile Failure, Void Growth and Coalescence, Plastic Anisotropy, Sheet Metal Formability.*

Predicting the forming limits of sheet metals under complex loading paths encountered in forming operations is a challenging problem because ductile failure strongly depends on the loading path. Conventional forming limit diagrams (FLDs), obtained using proportional biaxial loading experiments, cannot be used to predict failure under strongly non-linear loading histories. Failure in sheet metals occurs by localized necking along a narrow band whose width is comparable to the sheet thickness. Under plane stress conditions, the critical conditions for the onset of localized necking can be obtained using either a bifurcation analysis [1] or an imperfection band approach [2]. However, both approaches have well-known limitations, such as the inability of the bifurcation approach, when used with conventional plasticity models, to predict failure under biaxial tensile strains, and the sensitivity of the imperfection band approach to the choice of initial imperfections. In this study, we show that realistic predictions of the forming limits can be obtained using a recently developed multi-surface plasticity model, based on the micro-mechanics of void growth to coalescence, over the entire range of biaxial plane stress loading paths [3]. The predictive capability of the model is demonstrated by comparison with experimental forming limit diagrams for aluminum sheets subjected to pre-straining along various loading directions [4]. It is shown that the model is able to predict the evolution of the shape of the FLD as a function of the pre-strain history, in good agreement with the experimental data. The effects of plastic anisotropy and thickness imperfections in the sheet metal as a result of manufacturing tolerances are also investigated.

- [1] S. Stören, J.R. Rice, *J. Mech. Phys. Solids* **23**(6), 421–441, 1975. doi:10.1016/0022-5096(75)90004-6
- [2] Z. Marciniak, K. Kuczyński, *Int. J. Mech. Sci.* **9**, 609–620, 1967. doi:10.1016/0020-7403(67)90066-5
- [3] K.N. Morey, S.M. Keralavarma, M. Chouksey, *J. Mech. Phys. Solids* **205**, 106334, 2025. doi:10.1016/j.jmps.2025.106334
- [4] Y. Bai, T. Wierzbicki, *Int. J. Mech. Sci.* **50**, 1012–1022, 2008. doi:10.1016/j.ijmecsci.2008.02.010

Large strain thermo-visco-plastic model for case-hardening steel

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KEYWORDS: *Large Strains, Thermo-Mechanical Coupling, Visco-Plasticity, Gradient Enhancement.*

This work is dedicated to a large strain thermo-visco-plastic material description for case-hardening steel, which is an extension of the small strain model [1]. The alloy is commonly used in machine components due to its favorable mechanical properties. Machine parts are frequently exposed to high temperatures and large temperature differences, hence an important part of modeling is thermo-mechanical coupling. Additionally, around 750 °C the material undergoes phase transformation which affects parameter values. This work includes thermal softening, temperature-dependent parameters and thermo-elastic coupling due to the Gough-Joule effect.

The large strain formulation is based on [2], including a Huber-Mises-type yield function with cold work hardening. Moreover, Perzyna-type visco-plasticity is included. Many parameters are temperature dependent, among others elastic moduli, thermal expansion coefficient, heat capacity, heat conductivity, initial and final yield strength and visco-plasticity related parameters. Some of the parameters are fitted using experimental values from literature.

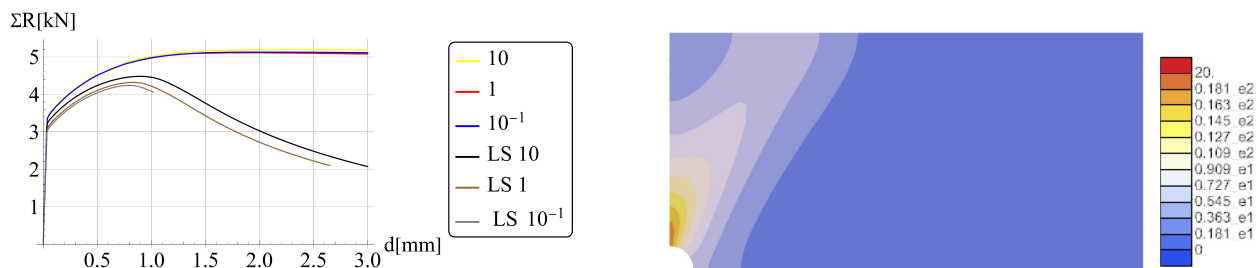


Figure 1: Plate with hole: Sum of reaction forces vs extension for different strain rates (left; strain rate unit in the legend is 1/s). Diagrams related to Small strain model [1] are depicted with primary colors and results based on the large strain (LS) model with dark colors. Distribution of relative temperature (LS) for $\dot{\epsilon} = 1/s$ and $d = 1mm$ (right).

Selected numerical examples, including aspects of localization and regularization are computed. Fig. 1 shows a comparison of the diagrams of the sum of reaction forces vs plate extension for different strain rates for the small and large strain models, as well as the distribution of relative temperature for a selected case (large strain, $\dot{\epsilon} = 1 s^{-1}$) and elongation equal to 1 mm. The plate under tension has a rectangular shape and a hole (d) in the middle, [1]. Simulations presented in Fig. 1 are done for initial temperature T_0 equal to 20°C and 3D model. The computations are performed using AceGen/AceFEM packages of Wolfram Mathematica [3].

- [1] P. Oppermann, R. Denzer, A. Menzel, A thermo-viscoplastic model for metals over wide temperature ranges – application to case hardening steel, *Computational Mechanics*, 69:541-563, 2022.
- [2] J.C. Simo, C. Miehe, Associative coupled thermoplasticity at finite strains: formulation, numerical analysis and implementation. *Computer Methods in Applied Mechanics and Engineering*, 98(1):41–104, 1992.
- [3] J. Korelc, P. Wriggers, *Automation of Finite Element Methods*, Springer, 2016.

Damage evolution in classical and additive materials at cryogenic temperatures

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KEYWORDS: *Continuum Damage Mechanics, Additive manufacturing, Cryogenic conditions, Constitutive model*

Modern engineering materials, particularly metastable austenitic stainless steels, are produced using a range of methods, from traditional plastic working processes to advanced additive manufacturing technologies such as Laser Powder Bed Fusion (L-PBF). The manufacturing process plays a crucial role in shaping the material's microstructure, thereby determining its mechanical properties and resistance to damage, especially under extreme operating conditions such as cryogenic temperatures. The present study focuses on the kinetics of damage evolution in metastable austenitic stainless steels (grades 304 and 316L) subjected to monotonic tensile loading at room (293 K) and liquid helium temperature (4.2 K). To qualitatively assess the degree of structural degradation, microscopic investigations were conducted using a scanning electron microscope (SEM) equipped with EDS (energy-dispersive spectroscopy) and EBSD (electron backscatter diffraction) detectors. The results indicate that the level of micro-damage observed in L-PBF samples is significantly higher than that in samples produced using traditional manufacturing methods. To quantitatively assess the damage level, multiple unloading tests were conducted at room temperature (293 K) and at liquid helium temperature (4.2 K), during which the unloading secant modulus was determined for each cycle. Based on the effective unloading modulus, the evolution of the damage parameter D – defined as the ratio of the damaged surface area to the total cross-sectional area of the representative volume element (RVE) – was evaluated. Furthermore, the kinetics of damage evolution was identified using the Lemaitre–Chaboche [1] and Bonora [2] damage models. Within the framework of this study, a comparative analysis of the identified damage kinetics for both conventionally manufactured and additively manufactured materials is performed. The results are expected to enable a quantitative assessment of differences in the initial damage state and the evolution of damage, with particular emphasis on the influence of process-induced porosity characteristic of additive manufacturing (3D printing) technologies. A key element of the study is the formulation of a constitutive model for damaged material. The model shall describe the coupling between increasing damage and the plastic strain-induced fcc–bcc phase transformation, which is characteristic of metastable materials operating at cryogenic temperatures. A suitable framework is offered by the Garion–Skoczeń model [3], which accounts for the evolution of anisotropic damage, represented by a Murakami-type damage tensor, in the presence of a secondary phase generated by strain-induced phase transformation. The proposed model aims to provide tools for more accurate lifetime prediction of stainless steel components operating in extreme cryogenic environments, highlighting the significant role of manufacturing technology in the structural safety assessment process.

REFERENCES

- [1] J. Lemaitre, *A Course on Damage Mechanics*. Springer Berlin, Heidelberg, 2nd ed., 1996.
- [2] Bonora, N., *Eng. Fract. Mech.*, **58** (1/2), 11-28, 1997. 10.1016/S0013-7944(97)00074-X.
- [3] Garion C., Skoczeń B., *Int. J. Dam. Mech.*, **12** (4), 331-356, 2003. 10.1177/10567890303.

Intermittent Plastic Flow and Microstructure Evolution During Low Cycle Fatigue at Cryogenic Temperatures

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KEYWORDS: *Fracture, Phase Transformation, Serrated Yielding, Cryogenic Temperatures.*

Austenitic steels at cryogenic temperatures, subjected to cyclic loading within the plastic deformation regime, undergo processes governed by the low thermal activation of the crystal lattice [1]. Cyclic deformation leads to strain-induced martensitic transformation, resulting in material hardening. At the same time, at temperatures approaching absolute zero, intermittent plastic flow is observed, manifested as cyclic stress drops at constant total strain. Both mechanisms significantly affect the course of low-cycle fatigue, particularly crack initiation and propagation. On the one hand, the phase transformation leads to material hardening with increasing plastic deformation; on the other hand, intermittent plastic flow may accelerate crack initiation.

Experimental studies carried out over a wide range of cryogenic temperatures have shown that the failure process is largely controlled by microstructural evolution. With increasing number of loading cycles, an increase in force amplitude is observed in crack opening displacement-controlled tests, up to the point of crack initiation. Ahead of the notch tip cyclically opened in Mode I, regions of α' martensite form, which delay crack initiation. At 77 K, crack initiation occurs only after reaching a high volume fraction of martensitic phase, whereas at 4.2 K, under conditions of intermittent plastic flow, initiation occurs at a lower number of cycles and at a lower fraction of this phase. This indicates a detrimental effect of intermittent plastic flow on low-cycle fatigue resistance.

The mechanism of crack propagation also depends on temperature and the character of plastic flow. At liquid nitrogen temperature, crack propagation is continuous, whereas at liquid helium temperature it proceeds in an intermittent manner, correlated with the occurrence of serrations [2]. Despite these differences, fracture surfaces in both cases exhibit fully ductile characteristics, indicating the dominant role of the retained austenitic matrix in the fracture process. During crack propagation, phase transformation continues to occur, and the distribution of the martensitic phase exhibits a bimodal character. Ahead of the current crack tip, a gradient microstructure develops, in which the distribution of martensitic phase corresponds to the stress field described by the Irwin solution, with the maximum volume fraction of the secondary phase decreasing with increasing crack length.

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- [1] R. Schmidt, B. Skoczeń, J. Bielski, E. Schmidt, New double surface constitutive model of intermittent plastic flow applied to near 0 K adiabatic shear bands, *Mechanics of Materials*, 175, 2022. <https://doi.org/10.1016/j.mechmat.2022.104500>
- [2] R. Schmidt, E. Schmidt, B. Skoczeń, Fracture of metastable materials near absolute zero, *International Journal of Plasticity*, 187, 2025. <https://doi.org/10.1016/j.ijplas.2025.104273>

Microstructure Based Constitutive Modelling of Metastable 3D Printed Materials Strained at Extremely Low Temperatures

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KEYWORDS: *Phase Transformations, Microstructural Analysis, Additive Manufacturing, Constitutive Model*

Stainless steels are widely used at extremely low temperatures due to their excellent properties, including high ductility. However, they exhibit metastable behaviour when strained beyond the yield point. The aim of the present work is to observe and analyse the evolution of the material microstructure – particularly the fcc-to-bcc phase transformation [1] – during plastic deformation and fracture in AISI 304 and 316L stainless steels at extremely low temperatures (77 K and 4.2 K). The study focuses on phenomena such as intermittent plastic flow, diffusionless martensitic transformation, and the development of micro-damage and fracture [2,3] in metastable materials manufactured using additive techniques.

The unique cryogenic experiments were conducted using an in-house testing system equipped for both uniaxial and multiaxial loading. The specimens were mounted in a vacuum-insulated cryostat integrated with a dedicated testing machine. To ensure the required temperature, the coolant was transferred from a dewar to the cryostat via a specialized transfer line. The fracture surfaces were examined in detail using magnetometric methods (Feritscope), scanning electron microscopy (SEM), electron backscatter diffraction (EBSD), and X-ray diffraction with synchrotron radiation. The X-ray diffraction studies revealed, among other findings, that the fcc-to-bcc phase transformation extensively accompanies macrocrack propagation. Moreover, the resulting α' martensite undergoes intensive twinning to achieve a good lattice fit with the austenitic matrix. The secondary phase nucleates at the intersections of shear bands – i.e., at the crossings of ϵ -martensite plates or twin lamellae – and subsequently undergoes growth and coalescence.

An extended multiscale constitutive model describing the plastic strain induced fcc-bcc phase transformation will be presented. The model accounts for a multiphase material consisting of an austenitic matrix and Eshelby-type ellipsoidal inclusions corresponding to both martensitic variants, ϵ and α' . Furthermore, based on in-house experimental data, a phase transformation tensor will be incorporated into the constitutive framework, taking into account both volumetric and shear components.

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- [1] G.B. Olson, M.A. Cohen, A mechanism for the strain-induced nucleation of martensitic transformations *Journal of the Less Common Metals*, 28 107-118, 1972. [https://doi.org/10.1016/0022-5088\(72\)90173-7](https://doi.org/10.1016/0022-5088(72)90173-7).
- [2] K. Nalepka, B. Skoczeń, R. Schmidt, M. Ciepielowska, E. Schmidt, R. Chulist, Microstructure evolution in the context of fracture in austenitic steels under complex loads at cryogenic temperatures, *Materials Characterization*, 197, 112654, 2023. <https://doi.org/10.1016/j.matchar.2023.112654>.
- [3] Schmidt E., Plastic flow phenomena in metastable materials subjected to cyclic loading at cryogenic temperatures, PhD thesis, 2025. <https://repozytorium.biblos.pk.edu.pl/resources/51063>.

Modelling Irradiated Metastable Materials for Cryogenic Applications

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KEYWORDS: *Phase transformation, Radiation damage, Cryogenic conditions, Constitutive model*

Metastable materials, such as stainless steels, undergo a plastic strain-induced phase transformation at cryogenic temperatures, transitioning from the parent face-centered cubic (fcc) phase to a secondary body-centered cubic (bcc) phase. Components of superconducting particle accelerators, including high-field magnets, are frequently made of stainless steels. Due to the presence of high-energy particle beams, these components are often subjected to secondary particle flux, which induces nano- and micro-damage resulting from interactions between particles and the crystal lattice. One of the key challenges is predicting the lifetime of these components, considering various dissipative phenomena that occur simultaneously, including inelastic deformation, phase transformation, and the evolution of nano- and micro-damage. To obtain closed-form analytical solutions, constitutive models describing plastic strain-induced phase transformation and micro-damage evolution are needed. In the present work, a constitutive model of metastable austenitic stainless steels operating under combined cryogenic and irradiation conditions is presented. The approach combines plastic strain-induced phase transformation with radiation-induced damage mechanisms to capture the complex evolution of microstructure and mechanical response. The transformation from austenite to martensite is described using a physically based constitutive model referring to a linearized kinetics, based on the classical Olson–Cohen model. Radiation effects are incorporated through the evolution of defect populations, including helium-filled micro-voids, that affect both hardening and softening mechanisms. The growth of porosity is modeled using the Rice–Tracey formulation, enabling the description of void evolution including stress triaxiality. A new model of radiation-induced hardening based on the Orowan mechanism is developed. Building upon the mean-field algorithm, the present work introduces a novel formulation that accounts for the stiffness contribution of helium-filled micro-voids [1] [2]. Unlike conventional approaches that treat voids as compliant defects, the proposed formulation incorporates their internal pressure and effective stiffness, leading to a more accurate representation of the mechanical response. The combined model captures the competing effects of radiation-induced hardening, driven by dislocation–defect interactions, and softening associated with porosity evolution. The resulting framework provides improved predictive capabilities for the behavior of irradiated multiphase materials, and is particularly relevant for the analysis and design of structural components operating in extreme cryogenic environments. The results of the analysis are compared with experimental data to calibrate the models. Furthermore, the evolution of the microstructure accompanying both the plastic strain-induced phase transformation and damage development is thoroughly analyzed. Based on these models, the lifetime prediction of irradiated stainless steel components operating under cryogenic conditions is developed.

[1] Sitko M., Skoczeń B., Wróblewski A., 2010, FCC-BCC phase transformation in rectangular beams subjected to plastic straining at cryogenic temperatures. *Int. Journal of Mech. Sciences*, 52, 7, 993-1007.

[2] Skoczeń, B., Schmidt, E., Schmidt, R., Kaciuba, A., 2026, Phase transformation and radiation induced hardening in austenitic stainless steels at cryogenic temperatures, *Cryogenics* Vol. 153, 104258.

Microstructure evolution during tensile elongation of stainless-steel welded joint in cryogenic conditions

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KEYWORDS: *Stainless steel, Cryogenic temperatures, Deformation induced martensite, Microstructure, Discontinuous plastic flow*

In low temperature BCC materials become brittle thus making them unsuitable for such conditions [1]. Making materials with FCC crystal structure like stainless steel leading contenders for such applications. At temperatures near 0K, in certain modes of deformation an effect called discontinuous plastic flow (DPF) occurs. This effect is sometimes accompanied by Luders like propagation of deformation [2].

Laser welding of stainless-steel is a great method of joining long elements such as mantle for superconducting cables [3]. Unfortunately, such process results in complex microstructure and appearance of internal stresses. Understanding the behaviour of such joints in cryogenic conditions is crucial for developing engineering solutions for such conditions.

The following research was conducted to characterise DPF behaviour and better understand the mechanisms of destruction of welds in cryogenic conditions. Miniature tensile samples were used to examine tensile elongation of such welded joints in temperatures of 77K and 4.2K. Electron microscopy as well as EBSD and eddy currents have been used to characterize the evolution of microstructure. Tensile tests and microhardness measurements have been used to characterize mechanical properties.

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- [1] J. Zhang, T. Zhao, T. Hou, Y. Li, K. Wu. *Metals* 2025;15:743. <https://doi.org/10.3390/met15070743>.
- [2] J. Tabin, J. Kawalko, D. Schob, R. Roszak, A. Brodecki, P. Bała, Ph. Maasch, Z. Kowalewski, M. Ziegenhorn. *Materials Science and Engineering: A* 2026;950:149552. <https://doi.org/10.1016/j.msea.2025.149552>.
- [3] T. Bevilacqua, A. Gumenyuk, N. Habibi, P. Hartwig, A. Klawonn, M. Lanser, M. Rethmeier, L. Scheunemann, J. Schröder. *Results in Engineering* 2025:108827.

Session TS14

**Structural optimization and optimum
material design**

Realizability-Aware Free Orthotropic Material Optimization: From Convex Relaxations to Hashin–Shtrikman Bounds

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KEYWORDS: *Free Material Optimization, Orthotropic Materials, Hashin–Shtrikman Bounds, Sequential Global Programming, Sequential Laminates*

Free material optimization treats the elasticity tensor field itself as the design variable. In classical compliance minimization, admissibility is usually enforced by positive semidefiniteness together with resource constraints expressed in terms of tensor invariants, typically of trace or Frobenius norm type. These constraints control the overall amount of stiffness, but they do not guarantee that an admissible tensor can be realized as the effective property of a composite made from prescribed constituent phases. This work narrows that gap for two-dimensional plane-stress problems with two well-ordered isotropic phases by introducing a hierarchy of realizability-aware admissible sets based on zeroth-order, Voigt, and Hashin–Shtrikman energy bounds.

The proposed hierarchy has several notable structural properties. In the convex setting, the Voigt admissible set is strictly tighter than the zeroth-order one for intermediate phase volume fractions, while the two coincide at the pure-phase endpoints; moreover, the Voigt model reduces to an isotropic variable-thickness-sheet formulation. For the Hashin–Shtrikman model, the energy upper bound can be written as a Voigt term minus a nonnegative correction, which explains both the strict tightening of the admissible set and the loss of joint convexity in the effective tensor and the local volume fraction. In the single-loadcase continuum setting, the resulting relaxation is tight with the classical Allaire–Kohn relaxed problem and is attained in the relaxation sense by orthotropic sequential laminates. In generic multi-loadcase settings, by contrast, it should be interpreted as a lower bound on compliance minimization over general microstructures.

Computationally, the resulting nonconvex free orthotropic material optimization problem is solved by sequential global programming. Numerical experiments illustrate the expected compliance ordering induced by the zeroth-order, Voigt, and Hashin–Shtrikman models and show that the Hashin–Shtrikman formulation remains close to finite-rank laminate reference designs while staying computationally tractable. Overall, these results connect classical homogenization bounds with free material optimization and show how realizability-aware energy bounds can inform structural design.

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- [1] M. Tyburec, M. Stingl, S. Ma, *Hierarchy of bounds in free orthotropic material optimization: From convex relaxations to Hashin–Shtrikman via sequential global programming*, arXiv:2602.23180, 2026.
- [2] G. Allaire, R.V. Kohn, *Explicit optimal bounds on the elastic energy of a two-phase composite in two space dimensions*, *Quart. Appl. Math.* **51**(4), 675–699, 1993. <https://doi.org/10.1090/qam/1247434>
- [3] K. Burazin, I. Crnjac, M. Vrdoljak, *Optimality criteria method in 2D linearized elasticity problems*, *Appl. Numer. Math.* **160**, 192–204, 2021. <https://doi.org/10.1016/j.apnum.2020.10.002>

Material and Prestrain Identification of Spatially Heterogeneous Isogeometric Thin Shells

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KEYWORDS: *Material Identification, Prestrain, Inverse Problems, Finite Element Model Updating Method, Heterogeneous Bodies, Stress-free Geometry.*

Characterizing the prestrain of biological shells and their material properties is crucial for accurate numerical modeling. Prestrain identification belongs to the class of problems involving the recovery of stress-free configuration. In many cases, the external loads acting on a body are known, whereas only the deformed, non-stress-free geometry can be observed. In this study, the previously developed Finite Element Model Updating inverse framework [1, 2, 3] is extended to identify simultaneously prestrain and spatially varying material properties. The thin shells are directly formulated on the mid-surface and adopt Kirchhoff–Love kinematics with large deformations. Three surface configurations are introduced: the reference (unstrained and stress-free), intermediate (prestrained), and current (prestrained and under external loads). This leads to a multiplicative split of the surface deformation gradient into prestrain and load-strained parts [4]. The forward problem is solved numerically with rotation-free isogeometric analysis [5]. The inverse problem assumes that the intermediate and current surface configurations are known, whereas the reference one remains unspecified. The prestrain and material properties fields are described using low-order Lagrange elements, known as the material mesh [1], whose nodal values become the unknowns to be identified. The identification is carried out through PDE-constrained optimization, where the minimized objective function consists of the least square error between experimental full-field displacements and their numerical counterparts. To solve this task, the Trust-Region Interior Reflective approach, supplied by the analytical derivatives of the objective function, is employed. Verification of the proposed inverse approach is performed with numerical examples based on synthetic data corrupted by noise. The results indicate that the presented framework can reconstruct the prestrain and spatially varying material properties provided that certain assumptions are met, such as an appropriate material mesh and full-field data with high information content. The scope of examined constitutive relations includes isotropic ones, in particular Koiter, Neo-Hooke, and Canham models.

ACKNOWLEDGEMENT: The authors gratefully acknowledge financial support from the Research School of Ruhr University Bochum through the PhD Exchange Program.

- [1] Borzeszkowski B, Lubowiecka I, Sauer R A., *Nonlinear material identification of heterogeneous isogeometric Kirchhoff–Love shells*, CMAME, Vol. 390:114442, 2022.
- [2] Łazarczyk B, Sauer R A., *Nonlinear elastodynamic material identification of heterogeneous isogeometric Bernoulli–Euler beams*, CMAME, Vol. 448:118415, 2026.
- [3] Łazarczyk B, Sauer R A., *Material Identification of Heterogeneous Isogeometric Bernoulli–Euler Beams With Pretensioning*, PAMM, Vol. 25:4, 2025.
- [4] Sauer R A., Ghaffari R, Gupta A, *The multiplicative deformation split for shells with application to growth, chemical swelling, thermoelasticity, viscoelasticity and elastoplasticity*, IJSS, Vol. 174–175, 2019.
- [5] Duong T X, Roohbakhshan F, Sauer R A., *A new rotation-free isogeometric thin shell formulation and a corresponding continuity constraint for patch boundaries*, CMAME, Vol. 316:4383, 2017.

Robust Design Optimization of gridshells using the Force Density Method

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KEYWORDS: *form-finding, Force Density Method (FDM), structural optimization, robust design.*

The Force Density Method (FDM) [1] provides a framework for generating the shape of reticulated shells by formulating the equilibrium of forces in terms of force-to-length ratios. Building on this principle, the present work proposes a Robust Design Optimization strategy [2] specifically developed for elastic gridshells. Assuming that fabrication-induced imperfections and fluctuations are sufficiently small compared to the overall dimensions of the truss, the form-finding task is reformulated as an enhanced deterministic problem derived through perturbation techniques, following the approach outlined in [3]. This reformulation circumvents the significant computational burden of probabilistic analyses and Monte-Carlo-based optimization, which typically require repeated assembly and inversion of the global stiffness matrix. To mitigate the impact of stochastic variations, the method identifies the force densities that generate an optimal spatial configuration minimizing a weighted combination of mean compliance and its standard deviation. This optimization is carried out using sequential convex programming. The dependence of both the geometry and the global stiffness matrix on the design variables is efficiently managed by leveraging the formal structure of the FDM, as demonstrated for similar applications in [4]. This representation is particularly advantageous for addressing the elastic equilibrium and for computing the associated sensitivities with respect to the design unknowns. The proposed formulation is assessed through numerical studies involving gridshells subjected to vertical loading and a slender column-like structure representative of components manufactured through metal additive processes. These examples illustrate how optimal configurations respond to uncertainties in material properties. Further extensions to accommodate additional forms of uncertainty are anticipated.

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- [1] H. Schek, *Comput. Methods Appl. Mech. Eng.* 3(1), 115–134 (1974).
[https://doi.org/10.1016/0045-7825\(74\)90045-0](https://doi.org/10.1016/0045-7825(74)90045-0)
- [2] J. Lógó, *Mech. Based Des. Struct. Mach.* 35(2), 147–162 (2007).
<https://doi.org/10.1080/15397730701354633>
- [3] J.K. Guest, T. Igusa, *Comput. Methods Appl. Mech. Eng.* 198(1), 116–124 (2008).
<https://doi.org/10.1016/j.cma.2008.04.009>
- [4] M. Bruggi, C. Guerini, *Compos. Struct.* 354, 118742 (2025).
<https://doi.org/10.1016/j.compstruct.2024.118742>

On regularization of the Isotropic Material Design

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KEYWORDS: *Optimization of structural topology, Free Material Design, Isotropic Material Design,*

The paper concerns the d -dimensional problem of minimization of the compliance of linear elastic structures made of an isotropic material; $d=2$ or $d=3$. The bulk k and shear μ moduli are the design variables, both viewed as non-negative fields on the design domain Ω . The design variables are subject to the isoperimetric condition which is the upper bound of L^p -norm of the elastic moduli:

$$\left(\int_{\Omega} \left[(dk)^{1+e} + \left(\frac{1}{2} d(d+1) - 1 \right) (2\mu)^{1+e} \right] dx \right)^{\frac{1}{1+e}} \leq \Lambda$$

The case of $e=0$ corresponds to the original concept of the *Isotropic Material Design (IMD)* method proposed in the paper by Czarnecki [1]. Then the unit cost represents the trace of the Hooke tensor. The original IMD method leads to the variational problems with integrands of linear growth, hence its correct setting requires the measure-theoretic tools, see [2]. Thus, it is highly recommended to regularize the IMD. In the present paper the IMD method will be extended by assuming the above L^p -norm-based cost condition. At the first step the design variables are eliminated. Thus, the optimum design problem is reduced to the pair of mutually dual problems of the mathematical structure of a theory of elasticity of an isotropic body with nonlinear power-law type constitutive equations. They link the trace of the stress with the trace of the strain and, independently, the deviator of the stress with the deviator of the strain. Both the states of stress and strain determine the optimal layouts of the bulk and shear moduli of the least compliant structure, see [3]. The effective non-linear static problem can be solved by using available commercial codes, e.g. with the help of Abaqus. This paves the way towards solving topology optimization problems on a large scale.

- [1] S. Czarnecki, Isotropic material design, *Computational Methods in Science and Technology*, **21** (2), 49–64, 2015.
- [2] K. Bołbotowski, T. Lewiński, Setting the Free Material Design problem through the methods of optimal mass distribution. *Calculus of Variations* 61, 76 (2022) 39 pp.
- [3] K. Bołbotowski, S. Czarnecki, T. Lewiński, The isotropic material design methods with the cost expressed by the L^p -norm. arXiv preprint arXiv:2502.03161

Implementation of Equivalent Load Scheme for easy prediction of minimal compliance topologies in the presence of random loads

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KEYWORDS: *optimal design, structural topology optimization, compliance minimization, Cellular Automata, heuristic methods, random loads, Equivalent Load Scheme.*

In engineering applications, load randomness is a frequent issue and represents a key aspect that has to be considered in the design process in order to guarantee the required stiffness and durability of structural components. This issue can be addressed in various ways [1], and the convenient approach to deal with this type of the problem is to mimic random loads using multiple deterministic load cases. However, in order to adequately capture the stochastic nature of acting load, it is usually necessary to consider several hundred of load cases, which significantly increases the computational demand. The following article presents an easy to implement alternative concept that could reduce the computational time. The Equivalent Load Scheme (ELS) is a conceptual framework employed for predicting the structural topology of systems subjected to random loads. The ELS proposes a limited number of appropriately selected deterministic load cases that facilitates the replacement of a multitude of random ones. Although this approach is heuristic, it ensures a high degree of consistency with the classical multi-load approach, while allowing for reduction of the computational cost. The efficacy of the method has been validated by performing a multitude of numerical tests, encompassing a broad spectrum of structural complexity. These examples include two-dimensional structures, as well as realistic spatial engineering structures [2,3]. In each analysis, the results obtained based on random loads and their ELS equivalents were compared. The obtained topologies were practically identical, and the differences in compliance values did not exceed a few percent. The results confirmed that the presented ELS concept can be regarded as a useful alternative to the existing techniques, significantly simplifying the design process. This approach offers also an additional advantage, namely the possibility of using any algorithm or commercial software that allows finding topologies with minimum compliance involving multiple load schemes. In this paper the authors employ Cellular Automata as the minimal compliance topology generator. The ELS method is thus a practical, universal, and easily implementable tool that allows for rapid and effective prediction of the topology of structures under loads subject to random changes. Moreover, its adaptability to both simple and highly complex geometries demonstrates that the approach remains robust across diverse engineering scenarios, further enhancing its relevance for practical applications.

- [1] J. Gresia, F. Vasconcelos Senhora, G.H. Paulino, *Struct. Multidisc. Optim.* **67**, 179, 2024. <https://doi.org/10.1007/s00158-024-03882-z>
- [2] B. Bochenek, K. Tajs-Zielińska, *Appl. Sci.* **15**, 12294, 2025. <https://doi.org/10.3390/app152212294>
- [3] B. Bochenek, K. Tajs-Zielińska, *Materials* **18**, 2819, 2025. <https://doi.org/10.3390/ma18122819>

Development of Fe-based mille-feuille materials and evaluation of their mechanical properties

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KEYWORDS: *Fe-based alloy, mille-feuille materials, mechanical properties, kink bands.*

In recent years, the introduction of kink deformation bands and the resulting improvements in strength and ductility have been achieved by subjecting Mg-, Al-, and Ti-based mille-feuille materials to compressive deformation [1-3]. These materials are characterized by an alternating stacking structure of hard and soft phases. In this study, we aimed to create Fe-based mille-feuille materials and introduce kink deformation bands through compression testing, thereby improving strength and ductility, by performing directional solidification on Fe-based alloys, which are widely used as practical structural materials.

Two types of Fe-based eutectic alloys, i.e., Fe-Ti and Fe-Nb, were prepared by arc melting, and microstructural orientation was achieved through directional solidification (DS) using the Bridgman method. Microstructural observations were performed using an optical microscope and a scanning electron microscope (SEM), and the constituent phases were identified using SEM-EBSD and EDS. Compression tests were performed on the prepared alloys at temperatures ranging from room temperature to 800°C, and changes in crystal orientation accompanying deformation were investigated using SEM-EBSD.

In the Fe-Ti and Fe-Nb alloys, layered and rod-like microstructures oriented along the growth direction were observed due to DS. Crystal orientation analysis with EBSD revealed that both the α -Fe/Fe₂Ti and α -Fe/Fe₂Nb phase pairs exhibit an orientation relationship of (110) // (11 $\bar{2}$ 0). The results of the compression tests showed that both the alloys achieved high yield stress of over 1 GPa at room temperature. Although the yield stress decreased with increasing test temperature for both the alloys, the high strengths were maintained at 600°C. In the Fe-Nb alloy, kink deformation bands formed during the test conducted at 800°C, suggesting the possibility of simultaneously improvement of strength and ductility. The yield stress tended to be higher in the Fe-Ti alloy than the Fe-Nb alloy. Although this trend was not reproduced by the short-fiber composite rule, it became possible to estimate values close to the experimental data by incorporating the degree of microstructural orientation defined in this study. This clearly demonstrates that the degree of orientation in the microstructure of mille-feuille materials is critical to their mechanical properties.

- [1] K. Hagihara, R. Ueyama, T. Tokunaga, M. Yamasaki, Y. Kawamura, T. Nakano: Mater. Res. Let., 9 (2021), 467-474. <https://doi.org/10.1080/21663831.2021.1974593>
- [2] K. Hagihara, T. Tokunaga, S. Ohsawa, S. Uemichi, K. Guan, D. Egusa, E. Abe: Int. J. Plast., 158 (2022), 103419. <https://doi.org/10.1016/j.ijplas.2022.103419>
- [3] T. Tokunaga, T. Yonemura, K. Hagihara: Mater. Sci. Eng. A: 900 (2024), 146505. <https://doi.org/10.1016/j.msea.2024.146505>

PINN or SPINN for the topology optimization?

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KEYWORDS: *Physics Informed Neural Networks, Topology Optimization, Numerical Methods.*

Physics Informed Neural Networks (PINNs) [1] are a successful approach to approximate solving of differential equations. Yet, in case of topology optimization, they are barely competitive to traditional methods, like SIMP, in terms of computational effort. Therefore, the search for improvement in efficiency is an active area of scientific research. One of such promising approaches is a so-called Separable PINN. The idea is to use separate artificial neural nets for each coordinate (for instance, in case of 3-dimensional domain – 3 distinct networks are utilized). According to original paper [2], substantial improvement in performance was obtained. It is additionally increased by forward differentiation and reducing differentiation time by calculating only one derivative per net.

The aim of the research is to determine the performance of SPINN w. r. t. its predecessor, i.e. PINN, used as a core for displacements determination in structural topology optimization algorithm. Both methods were also compared to the ground truth, which was taken to be the traditional approach (i.e. SIMP). The topology optimization algorithm used linear elasticity formulation. The aim of the optimization was a structure compliance minimization, with given *a priori* volume constraint condition.

The author examined a 3-dimensional example of beam, fixed at both ends (left and right), loaded with concentrated force, applied at the center of the top surface of the beam, just like shown on the left in Fig. 1.

The preliminary simulations did not confirm the jump in performance for the topology optimization problem, as it was shown by the authors of the idea, based on the several examples of solving 3-dimensional differential equations. Nevertheless, obtaining better results is still potentially possible through hyperparameters optimization, which will be the next step of the author's research.

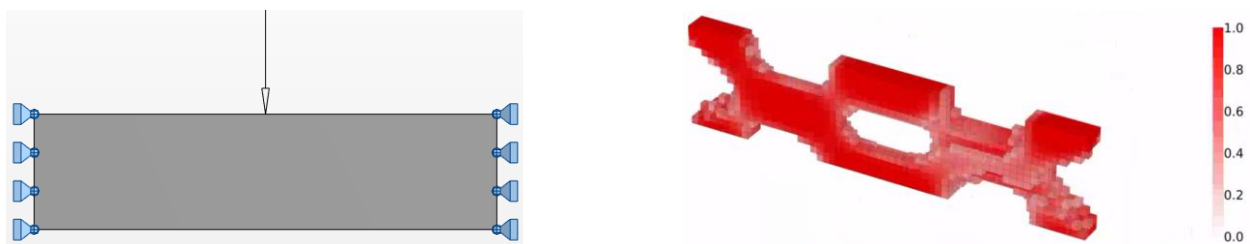


Figure 1. Analysed example and the example PINN solution.

- [1] Raissi M, Perdikaris P, Karniadakis GE. Physics Informed Deep Learning (Part I): Data-driven Solutions of Nonlinear Partial Differential Equations. Preprint 2017. <https://doi.org/https://doi.org/10.48550/arXiv.1711.10561>.
- [2] Cho J, Nam S, Yang H, Yun S-B, Hong Y, Park E. Separable Physics-Informed Neural Networks. 37th Conference on Neural Information Processing Systems (NeurIPS 2023), New Orleans: 2023. <http://arxiv.org/abs/2306.15969>.

A computational procedure for frequency maximization in topology optimization

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KEYWORDS: *Topology optimization, Frequency maximization, Quasi-static approximation*

Maximizing the eigenfrequencies of a structure using topological optimization methods poses a significant computational challenge due to the fact that each optimization step requires a numerical solution to the eigenvalue problem. An additional difficulty during the optimization process is the so-called mode switching phenomenon. To solve this problem, an approach known in the literature as the so-called *bound formulation*, has been proposed. This approach, along with its numerical implementation, can be found in the work of Olhoff and Du [1]. In this implementation, optimization is performed using two nested loops, the first of which is responsible for solving the eigenvalue problem and determining the sensitivity of the frequencies and eigenvectors, while the second determines the increments of the design variables using mathematical programming.

Due to the significant computational cost of the *bound formulation* method, approximate methods for frequency maximization have been proposed, including the approach presented in the work of Yuksel and Yilmaz [2]. In this approach, solving the eigenvalue problem at each iterative step is replaced by a two-stage static optimization. The first stage approximates the basic eigenmode using a unit force, while the second optimizes the structure by introducing quasi-static modal forces.

A similar approach was used in this paper. Instead of two-stage static optimization, a single-stage approach was proposed [3], where the eigenmode is approximated by first solving the eigenvalue problem once at the beginning of the optimization process. The result of this procedure makes the proposed approach more intuitive and eliminates the need to introduce a fictitious unit force. The paper will compare the performance of the three methods using a benchmark example of a simply supported beam modelled as a plate system in a plane stress state.

- [1] N. Olhoff and J. Du, *Topology Optimization in Structural and Continuum Mechanics*, CISM Vol. 549, 275–298, 2014. https://doi.org/10.1007/978-3-7091-1643-2_11
- [2] O. Yuksel and C. Yilmaz, *Efficient topology optimization for maximizing fundamental frequency with design-dependent inertial forces*, *Engineering Computations*, vol. 42, no. 9, 2025, <https://doi.org/10.1108/EC-03-2025-0278>
- [3] P. Tazowski, M. Zawidzki and B. Blachowski, *Quasi-Static Approximation in Topology Optimization of Beam Structure Subjected to Modal Inertial Forces*, *Proc. Civil-Comp 2025*, Vol. 10, Paper 4.4, 2025. <https://doi.org/10.4203/ccp.10.4.4>

Strength-Consistent Structural Optimization Using a Biomimetic Approach

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KEYWORDS: *Mechanical design, Biomimetic structural optimization, Trabecular bone remodeling.*

The conventional approach to mechanical design is primarily based on strength hypotheses, which are typically used to verify whether a given structure satisfies material failure criteria. However, most structural optimization methods do not explicitly incorporate these strength conditions into the optimization process itself; instead, they are often applied only at a later verification stage. This separation can lead to solutions that are mathematically optimal but not fully consistent with the physical limits of the material.

In contrast, biological systems—particularly load-bearing structures such as bone—develop under conditions where material strength plays a fundamental role. In such systems, structural adaptation (e.g., bone remodeling) occurs in response to mechanical stimuli, ensuring that the material is efficiently distributed and utilized within safe stress limits.

Inspired by this phenomenon, the authors have developed an optimization framework modeled on bone remodeling [1]. This approach is grounded in rigorous theoretical studies in the field of continuum structural optimization. A key condition for achieving an optimal solution in this framework is the equalization of strain energy density (SED) over the structural surface. The novel contribution of the presented work lies in establishing a direct relationship between this condition of constant strain energy density and the strength properties of the material. In particular, classical strength (yield) hypotheses are reformulated in terms of strain energy, allowing them to be naturally integrated into the optimization process. As a result, the optimality condition not only reflects efficient material distribution but also inherently respects the material's failure limits [2].

The main objective of the study is to precisely quantify the relationship between a constant surface value of strain energy density and material strength, as defined by standard yield criteria. The numerical examples provided in the paper are compared with analytical results, demonstrating the validity of the proposed approach and highlighting a distinctive feature of the method: its ability to produce strength-consistent optimal designs without the need for separate constraint enforcement. An additional advantage of the method is the introduction of the “insensitivity zone” concept. This concept allows for a controlled range within which variations in strain energy density do not affect the optimal solution. As a consequence, the optimization process becomes naturally regularized, eliminating the need to explicitly determine Lagrange multipliers associated with volume constraints. This improves both the stability and robustness of the numerical procedure.

Importantly, although the method is inspired by trabecular bone remodeling, it is not limited to biological applications. The proposed framework can be applied more broadly as a general structural optimization tool, providing engineers with a physically meaningful and efficient alternative to traditional optimization techniques.

- [1] M. Nowak, J. Polak, O. Napierała, *Springer, PCM-CMM 2023: Theories, Models and Simulations of Complex Physical Systems* pp. 533–568, 2024. https://doi.org/10.1007/978-3-031-73161-7_13
- [2] M. Nowak, J. Sokołowski, A. Żochowski, J. Polak, *Bulletin of the Polish Academy of Sciences Technical Sciences* **74** (1) pp.e155900, 2026. <https://doi.org/10.24425/bpasts.2025.155900>

Shape optimization of nonlinear elastic structures

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KEYWORDS: *Shape optimization, level-set method, nonlinear elasticity, 2d, 3d.*

A classical objective functional in structural optimization is compliance (the work of external loads on displacements). This functional depends on the geometry of the domain as well as on the solution of a boundary value problem of linear or nonlinear elasticity theory formulated on that domain. In such a framework it is convenient to work with the gradient-like method based on a concept of a shape derivative and level-set method. The key idea of level-set method is to represent the structural boundary with zero level-set of given function (level-set function – LSF). Now, changing the shape of a structure under optimization is equivalent to transport the LSF in such a direction that ensures decreasing the value of the objective functional. In this work volumetric form of shape derivative is used together with linear transport equation for evolution equation governing the change of shapes in a process. It is showed that it can be efficiently used to obtain optimal shapes in 2D elasticity shape optimization problems as well as in 3D case (see Fig. 1).

Moreover, influence of nonlinear elasticity of small displacement for shape optimization is studied. A nonlinear theory of elasticity for small displacements, incorporating a nonlinear (more realistic) constitutive relationship between the strain and stress tensors with sufficiently smooth potentials (convex and coercive), makes it possible to formulate structural shape optimization problems that can be solved using well-established mathematical tools, while at the same time addressing scenarios closer to reality (see Fig.2 for benchmark example).



Figure 1. Optimal shape for 3D case of a cantilever in linear elasticity.



Figure 2. Optimal shape for 2D case of a cantilever in nonlinear elasticity (left), first order optimality condition on boundary – constant value of function derived from solution of nonlinear elasticity and adjoint state (right).

Literature:

- [1] Allaire G, Jouve F, Toader AM (2004) *Structural optimization using sensitivity analysis and a level-set method*. J Comput Phys 194(1):363-393.
- [2] Delfour MC, Zolésio JP (2011) *Shapes and Geometries Metrics, Analysis, Differential Calculus, and Optimization* Society for Industrial and Applied Mathematics Philadelphia

Optimization of thin-walled panels with stability considerations

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KEYWORDS: *Structural optimization, Thin-walled, Stability.*

Panel stability has been a longstanding research subject in structural mechanics. When a thin plate (or panel) is subjected to a flow at supersonic speeds it undergoes a loss of stability. This limits the maximum speed of aerospace structures that incorporate such components. Due to the widespread use of these elements and their importance in enabling high-speed aerospace systems, considerable effort has been devoted for optimizing these panels aiming at improving their flutter performance. While early works focus on optimizing the thickness of these elements to reduce their weight, today, composite designs are utilized for the same purpose. However, these works mainly concentrate on optimizing the material layout and fibres in the thickness direction.

Recent advances in manufacturing methods, particularly the integration of automated processes such as 3D printing, have made the design of multi-material components, in which the material is spatially varying, increasingly feasible. To leverage these capabilities, optimization-based design has proven highly valuable due to its ability to produce non-intuitive structures without geometric restrictions.

This work presents an optimization framework for panels operating at supersonic speeds with the goal of enhancing aerodynamic stability. The aim is to investigate the potential for achieving weight reduction while limiting the degradation in flutter stability by designing longitudinally tailored by material structures.

A gradient-based optimization approach is proposed with analytical derivation of the sensitivity analysis. The optimization problem is formulated to determine the spanwise material distribution in the panel, aiming to maximize the aerodynamic pressure under a predefined weight constraint. The linear piston theory is adopted for modelling the aerodynamic forces, and the flutter point is determined by solving a stability problem in the form of an eigenvalue analysis.

The optimal designs of bi-material panels are investigated under various boundary conditions. The results indicate that a substantial weight reduction can be obtained by tailoring two materials in the spanwise direction.

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Optimal Stiffener Configuration for Maximizing Nonlinear Frequencies of Rhombic Laminated Composite Hyperbolic Paraboloids

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KEYWORDS: *Laminated composite, Geometric nonlinearity, Finite Element Method, First order Shear Deformation Theory, Hyperbolic paraboloids*

Laminated composite hyperbolic paraboloids are widely utilized in civil, marine and aerospace structures for their aesthetic appeal, high specific stiffness, and lower susceptibility to decay from weathering. Civil engineering panels experience dynamic excitations due to wind, snow, and seismic actions. Moderately thin panels undergo large amplitudes of vibration, for which a geometrically nonlinear approach is essential. The performance of such panels can be improved by stiffeners, as shown by several research studies. However, stiffened panels are costlier to fabricate and heavier than unstiffened ones. Since dynamic performance is compromised for heavier panels, stiffeners should be applied optimally. The additional cost of stiffeners should also be justified by maximizing frequencies significantly. This study proposes guidelines to optimize stiffeners for laminated composite rhombic hyperbolic paraboloids (Figure 1) using a C^0 continuous geometrically nonlinear finite element code, eight noded elements and first order shear deformation theory. The optimal stiffeners aim for maximizing nonlinear fundamental frequencies within a given weight ratio of stiffened to unstiffened panels.

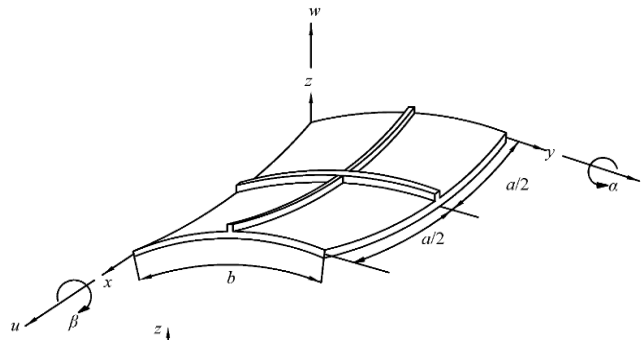


Figure 1. Laminated composite hyperbolic paraboloid with stiffeners.

The governing equation of free vibration is given below. The derivation was reported in [1].

$$[M_{sh}]\{\ddot{\delta}_k\}_g + [K_s]\{\delta_k\}_g = 0 \quad (1)$$

$\{\ddot{\delta}_k\}_g$, $\{\delta_k\}_g$ are acceleration and displacement vectors, respectively. mass and stiffness matrices are

$$[M_{sh}] = \int_A [T]^T [N_i]^T [m] [N_i] [T] dA, \text{ and } [K_s] = \int_A [T]^T [\bar{B}]^T [E] \left([B_L] + \frac{1}{2} [B_{NL}] \right) [T] dA$$

[1] M. Trivedi, K. Bakshi, *Thin-Walled Structures*, 2026, 114600. <https://doi.org/10.1016/j.tws.2026.114600>

Optimization of Stiffened Laminated Composite Rhombic Elliptical Paraboloidal shells for Nonlinear Bending Performance

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KEYWORDS: *Laminated composite, Geometric nonlinearity, Finite element method, First order shear deformation theory, Elliptic paraboloidal shell, Rhombic geometry.*

The literature reveals that research studies on stiffened laminated composite elliptical paraboloids (Figure 1) are scanty, particularly for the rhombic geometries. These panels are often preferred in civil, maritime, and aerospace structures for their ability to cover longer spans with fewer supports. Since the moderately thin panels can undergo large deformations under static overloading, a geometrically nonlinear approach is essential for realistic performance predictions. Performance can be improved by stiffeners. Since stiffened panels are costlier than bare ones, this study presents an optimization analysis which reports deflections and stresses for varying weight ratios of stiffened to the bare panels. The Nonlinear solutions are obtained using an isoparametric C^0 continues finite element code based on von-Karman type nonlinear strains and first order shear deformation theory. The optimization study aims for achieving panels with minimizing the weight ratio while restricting the deflections and stresses within serviceable limits.

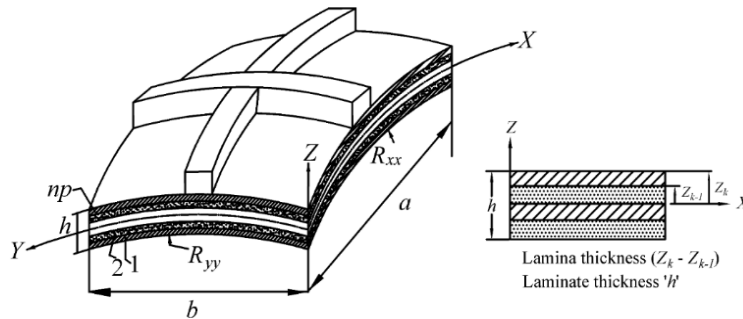


Figure 1: Stiffened elliptic paraboloidal panel

The nonlinear bending problem is solved using Newton-Raphson iterative approach [1]. The incremental displacement for the n^{th} iteration is given as follows,

$$\Delta\{\delta\}_n = [K_T]^{-1} \left\{ \sum_{j=1}^{ne} (\{R\} - [K_s]\{\delta\})_j \right\} \quad (1)$$

The secant stiffness matrix is given in the following:

$$[K_s] = \int_A [T]^T [B]^T \left[[E] \left([B]^L + \frac{1}{2} [B]^{NL} \right) [T]\{\delta\} \right] dA \quad (2)$$

The improved solution can be obtained from the given equation.

$$\{\delta\}_{n+1} = \{\delta\}_n + \Delta\{\delta\}_n \quad (3)$$

- [1] N. Singh and K. Bakshi, Nonlinear bending of laminated composite rhombic stiffened elliptical paraboloids, *Mechanics of Advanced Materials and Structures*, 33(1), 2621138, 2026.
<https://doi.org/10.1080/15376494.2026.2621138>

Application of the Pontryagin's Maximum Principle in shape optimization of Glue Laminated Timber beams and its numerical and experimental validation.

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KEYWORDS: *Structural Optimization, Glue Laminated Timber, Pontryagin's Maximum Principle.*

The problem of shape optimization of a Glue Laminated Timber (GLT) beam of variable height under 4-point bending is posed and solved with the use of the Pontryagin's Maximum Principle (PMP) [1]. For a given reference beam of constant cross-section two optimization problems are stated: 1) minimization of an amount of material used (beam's volume) while preserving the original load carrying capacity (V_{min} beams) and 2) maximization the beam's load carrying capacity (LCC) while preserving the beam's volume (Q_{max} beams).

Governing equations for a beam of variable height were derived from the 1D Timoshenko beam theory and general equilibrium equations for a plane elasticity problem, accounting for boundary conditions on both top (flat) and bottom (oblique) faces of the beam. Author's energy-based limit state condition for anisotropic solids with asymmetric elastic range was used as a measure of material's effort [2]. Values of mechanical parameters of the material were assumed in the design process according to the EN 14080:201 standard. Control theory problem was formulated and solved with the use of the PMP, using the Dircol software which utilizes the direct collocation method. Obtained results were compared with the 3D Finite Element Analysis (FEA) results obtained from the Abaqus CAE software. Theoretical volume savings were approximately equal to 11,4% of the reference volume, while increase of the LCC was ca. 12,2% of the reference LCC.

After appropriate adjustments of the numerically determined beam's optimal shape, nine GLT beams were ordered, 3 of each type (reference beams, V_{min} beams and Q_{max} beams) and examined in the 4-point bending tests. Beam's deflections in nine points as well as the plane strain state near the bottom face in the midspan were recorded with the use of inductive displacement transducers and strain gauge rosette, respectively. Experimental finding only partially confirmed the results of numerical optimization due to large variation of the mechanical properties of GLT. Points of material's failure clearly corresponded with the designed points of maximum material effort.

ACKNOWLEDGEMENT: This research was funded by the Faculty of Civil Engineering, Cracow University of Technology.

- [1] P. Szeptyński, D. Jasińska, L. Mikulski, *Materials*, **17**, 6263, 2024. <https://doi.org/10.3390/ma17246263>
- [2] P. Szeptyński, *Arch. Metall. Mater.*, **62**, 729-736, 2017. <https://doi.org/10.1515/amm-2017-0110>

Session TS15

**Shells, plates, and lattices as macroscopic
or microscopic structures**

Equivalent single layer models of laminated plates and shells: achievements, limitations and future directions

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KEYWORDS: *Multilayered plates and shells, 2D models, Finite element method, Failure*

Over the past decades, numerous theoretical approaches have been proposed to model mechanical behaviour of composite laminated plates and shells. Among the various models developed, two-dimensional Equivalent Single Layer models (ESL) are particularly attractive due to their relatively low computational cost. Being two-dimensional, these models are generally based on theories of homogeneous plates and shells; however, their application to laminated composite structures requires appropriate modelling strategies to capture characteristic phenomena such as high transverse shear flexibility and the variation of stiffness through the thickness [1-3]. In addition, individual layers in laminated composite structures exhibit orthotropic behaviour, leading to markedly different mechanical responses depending on the direction of the applied loading. Variations in stiffness and strength along the fibre direction, transverse to the fibres, and in shear result in distinct deformation patterns and load-transfer mechanisms under different loading conditions. This imposes the use of appropriate constitutive models and failure criteria capable of capturing the direction-dependent, anisotropic response of individual layers.

This keynote lecture provides a comprehensive overview of the current state of the art in ESL modelling of laminated plates and shells, drawing on key contributions from the composite structures' community [1-2] as well as selected developments proposed by the author's research group. Different kinematics descriptions adopted within ESL formulations are examined and their implications for mechanical response prediction are discussed [3]. Particular attention will then be devoted to the capabilities and limitations of ESL models in the analysis of damage and failure in laminated shell structures, including the application of different failure criteria [4].

- [1] E. Carrera, Compos. Struct., 50, 183-198, 2000. [https://doi.org/10.1016/S0263-8223\(00\)00099-4](https://doi.org/10.1016/S0263-8223(00)00099-4)
- [2] A. Tessler, M. Di Sciuva, M. Gherlone, J. Mech. Mater. Struct., 5, 341–367, 2010. <https://doi.org/10.2140/jomms.2010.5.341>
- [3] I. Kreja, A. Sabik, Acta Mech. 230, 2827–2851, 2019. <https://doi.org/10.1007/s00707-019-02434-7>
- [4] J. Chrościelewski, A. Sabik, B. Sobczyk, W. Witkowski, Compos. Struct. 261, 1-15, 2021. <https://doi.org/10.1016/j.compstruct.2020.113537>

Random Static Analysis of Plates Resting on Elastic Foundations Considering One-sides Constraints by the Finite Element, Boundary Element and Finite Difference Methods

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KEYWORDS: *Finite Element Method, Boundary Element Method, Finite Difference Method, Thin Plates, Elastic Foundations, Semi-Analytical Probabilistic Analysis, Stochastic Perturbation Technique, Monte Carlo Simulations.*

The paper presents a random analysis of the statics of a thin plate resting on an elastic foundation of the Winkler type and an elastic half-space. For the foundation of the Winkler type the one-sided constraints are applied too. The problem of bending the plate is independently described by the Finite Element Method (FEM), Boundary Element Method (BEM) and the Finite Difference Method (FDM). For the FEM approach, the plate is discretized using classical four-node rectangular finite elements with three degrees of freedom at each node [1]. In terms of the BEM two boundary and domain integral equations, with the boundary conditions formulated in such a way that it is not necessary to take into account the Kirchhoff forces [2]. Within the plate domain, there are introduced additional collocation points at which the elastic discrete support is realized and the fundamental solution for statics of a pure infinite plate is used. The plate boundary is divided into elements of the constant type. A non-singular approach is used to calculate boundary integrals. This approach allows for a significant simplification of the calculation algorithm. Finally, the formulation of the problem by the FDM allows to easily take into account the variable stiffness of the plate. A random analysis for selected design parameters is presented such as the plate thickness, its material properties, and the properties of the parameters describing the foundation itself. Three approaches were adopted: semi-analytical (SAM), stochastic perturbation technique (SPT) and Monte Carlo simulation (MCs), which can be traced, e.g., in [3, 4, 5]. For these three methods, random moments are defined, the most important of which is the expected value of the solution, e.g. the plate deflection established at selected point, as a function of the coefficient of variation of the selected design parameter. A Gaussian probability density distribution is assumed for the arbitrary design parameter. Since such a distribution is continuous, it is necessary to determine the so-called continuous response function for a finite number of deterministic solutions. Most often, these are 3rd or 4th order polynomials. Higher order polynomials provide some power “reserve” when differentiating them, which is necessary to determine higher order random moments as skewness or kurtosis.

- [1] M. Kuczma, *Foundations of structural mechanics with shape memory. Numerical modeling*, University of Zielona Góra Publishing House, Zielona Góra, 2010, ISBN 978-83-7481-411-9 (in Polish).
- [2] M. Guminiak, P. Litewka, R. Sygulski, *Static analysis of plates on the unilateral foundation by BEM*, Proc. of the 9th Int. Conf. “Modern building materials, structures and techniques”, Vilnius, May 19–21, 2004, selected papers, Vilnius Gediminas Technical University Press “Technika” scientific book 1026, III, 765–768, 2004, eds.: E. K. Zavadskas, P. Vainiunas and F. M. Mazzolani.
- [3] G. Stefanou, *The stochastic finite element method: Past, present and future*, Computer Methods in Applied Mechanics and Engineering, 198 (9–12), 2009, 1031–1051.
- [4] M. Kamiński, *The Stochastic Perturbation Method for Computational Mechanics*, Wiley: Chichester, 2013.
- [5] M. Kamiński, M. Przychodzki, M. Łasecka-Plura, M. Guminiak, A. Lenartowicz, *Random eigenvibrations of beams with viscoelastic layers*, Journal of Theoretical and Applied Mechanics 62(4), 2024, 763–767.

Sensitivity-based interval uncertainty analysis for free vibrations of variable stiffness plates with curvilinear wires

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KEYWORDS: *Variable stiffness plates, Curvilinear wires, Free vibration, Sensitivity analysis, Interval uncertainty.*

This work addresses the problem of free vibrations of thin variable-stiffness plates reinforced with discrete curvilinear wires modeled as one-dimensional inclusions embedded in a two-dimensional plate continuum. The aim is to formulate a numerical model and derive eigenvalue sensitivity measures with respect to parameters describing the wire layout, and then to employ these measures in a non-probabilistic uncertainty analysis. In contrast to classical laminate models, in which variations of wire orientation are incorporated in an averaged sense through local stiffness matrices of individual layers, the proposed approach treats the wires explicitly as discrete one-dimensional elements coupled with the plate kinematics [1].

The plate is discretized by the finite element method within the framework of the classical Kirchhoff theory of thin plates. The global stiffness and mass matrices of the system result from a superposition of the plate contribution and the contributions of individual wires embedded in its domain,

$$\mathbf{K}(\mathbf{p}) = \mathbf{K}_p + \sum_{i=1}^{N_w} \mathbf{K}_{w,i}(\mathbf{p}_i), \quad \mathbf{M}(\mathbf{p}) = \mathbf{M}_p + \sum_{i=1}^{N_w} \mathbf{M}_{w,i}(\mathbf{p}_i) \quad (1)$$

where $\mathbf{K}_p$ and $\mathbf{M}_p$ denote the stiffness and mass matrices of the Kirchhoff plate, whereas $\mathbf{K}_{w,i}$ and $\mathbf{M}_{w,i}$ are the contributions associated with the i -th embedded wire. Such a formulation makes it possible to account directly for both the position of the wires and their curvilinear layout within the finite element model.

This leads to an eigenvalue problem in which the stiffness and mass matrices depend on the vector of parameters $\mathbf{p}$ describing the wire arrangement. Analytical sensitivity measures of the eigenvalues with respect to the design parameters are then determined, which makes it possible to quantify the influence of the wire layout on natural frequencies [2]. These sensitivity measures depend on three main factors: the variation of the wire geometry, the variation of the embedding operator, and the variation of the integration measure along the wire path.

The determination of sensitivity measures then provides the basis for taking parameter uncertainties into account, with the uncertain quantities treated as interval numbers. As a result, lower and upper bounds of the natural frequencies are obtained, which makes it possible to estimate the variability range of the structural response without exhaustive examination of all vertices of the uncertainty space [3].

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- [1] S. Honda, Y. Narita, *J. Sound Vib.* **331**, 180–191, 2012. <https://doi.org/10.1016/j.jsv.2011.08.019>
- [2] R.M. Lin, J.E. Mottershead, T.Y. Ng, *Mech. Syst. Signal Process.* **138**, 106536, 2020. <https://doi.org/10.1016/j.ymssp.2019.106536>
- [3] A. Sofi, G. Muscolino, I. Elishakoff, *J. Sound Vib.* **347**, 79–95, 2015. <https://doi.org/10.1016/j.jsv.2015.02.037>

Influence of Graded Mechanical Properties on Natural Vibrations of Tensegrity-Inspired Cellular Lattices – Computational Approach

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KEYWORDS: *Tensegrity, Graded Cellular Lattice, Natural Vibrations, Computational Approach.*

One unexplored area in mechanics is the design of tensegrity-inspired metamaterials [1, 2] with graded properties, realised by using cells with diverse geometric or physical properties. Modelling dynamic properties of such metamaterials would significantly expand the possibilities of obtaining a variety of extreme properties and improve the controllability of the systems under consideration.

A set of lattices designed from expanded octahedron tensegrity modules [2] with graded mechanical properties is shown in Fig. 1. The lattices are simply supported at the bottom surface. Their dimensions of $6 \times 6 \times 6$ cm correspond to those of planned additively manufactured samples and future experimental studies. Grey cells have struts with a diameter of 1.5 mm and cables of 0.85 mm. Blue cells are thickened with a 4:3 ratio, and red cells with a 5:3 ratio. The green layer consists of rotated cells with significantly lower vertical stiffness.

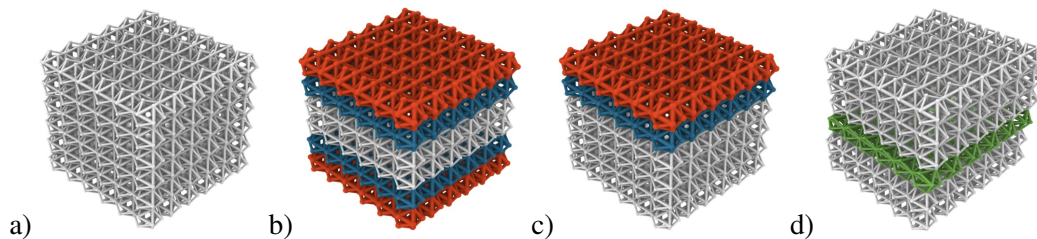


Figure 1. Expanded octahedron lattices: a) periodic, b) top and bottom reinforced, c) top reinforced, d) soft middle layer.

The masses of the lattices are 47.47 g, 87.90 g, 67.69 g, and 48.20 g, respectively. The first six natural frequencies and eigen-modes are analysed. The computational simulations are performed using a 3D frame model in ABAQUS. The natural frequencies of the periodic lattice serve as a reference. These are, respectively, 640 Hz, 663 Hz, 740 Hz, 1833 Hz, 1905 Hz, and 2010 Hz. Mode shapes 1, 2, 4, and 5 correspond to bending in vertical planes of symmetry, with one or two half-waves. Mode shapes 3 and 6 are torsional. Gradation b) does not change the mode shapes, but reduces frequencies 1–3 by approximately 8% and slightly increases frequencies 4–6. The trends are different for gradation c). Mode shapes 1–5 do not change, while mode 6 corresponds to compression/tension in the vertical direction. Frequencies 1–3 decrease by about 25% and 4–6 by about 12%. Gradation d) does not alter the vibration modes and reduces frequencies: 1–3 slightly and 4–6 by about 10%.

An evaluation of lattices designed from other tensegrity modules will be presented at the conference. Computational simulations are promising and indicate the possibility of controlling the level of natural frequencies, as well as the modes of these vibrations, by introducing gradations of mechanical properties.

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- [1] T.J. Cui, D.R. Smith, R. Liu, *Metamaterials: Theory, Design, and Applications*, Springer, 2010. <https://doi.org/10.1007/978-1-4419-0573-4>
- [2] A. Al Sabouni-Zawadzka, *High Performance Tensegrity-Inspired Metamaterials and Structures*, CRC Press, 2022. <https://doi.org/10.1201/9781003343202>

Plates and shells reinforced with embedded shape memory alloy wires

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KEYWORDS: *Plates, Shells, Shape memory alloy wires, Embedded reinforcement, Variational formulation, Hysteresis loops, Numerical analysis.*

Plate and shell structures play a fundamental role in engineering applications. Shells exhibit a high stiffness-to-weight ratio and the ability to carry loads primarily through membrane action. In recent years, increasing attention has been devoted to the modeling of reinforced and smart structures. In particular, embedding one-dimensional reinforcements such as fibres, rebars, or wires into plate and shell structures provides a flexible means of tailoring their mechanical response. While continuous reinforcement is often modelled through homogenization, discrete reinforcements require a coupled multi-dimensional formulation. Shape memory alloys (SMAs) provide an additional level of functionality through their ability to undergo phase transformations and exhibit hysteresis (energy dissipation, damping, re-centring). Variational and energetic approaches to hysteresis modelling offer a mathematically consistent framework for describing such behaviour.

This work presents a variational formulation of thin plate and shell structures reinforced with discrete SMA wires. The plate/shell structure is modeled using Kirchhoff–Love kinematics, while the reinforcement is represented by embedded truss elements. The SMA behaviour is described within a rate-independent energetic framework consistent with hysteresis models ([1, 2]). The formulation naturally leads to a global–local finite element algorithm suitable for nonlinear analysis of adaptive plate and shell structures. The structure is discretized by the finite element method within the framework of the classical Kirchhoff–Love theory ([3]). The global stiffness of the structural system is obtained as a superposition of the plate/shell contribution and the contributions of individual wires embedded in its domain,

$$\mathbf{K}(\mathbf{z}) = \mathbf{K}_s + \sum_{i=1}^{N_w} \mathbf{K}_{w,i}(\mathbf{z}_i) \quad (1)$$

where $\mathbf{K}_s$ denotes the stiffness matrix of the plate/shell structure, and $\mathbf{K}_{w,i}$ are the contributions associated with the i -th embedded wire, that depend on a set of internal variables $\mathbf{z}$ describing the phase transformation process. This formulation makes it possible to account directly for both the spatial distribution of the wires and their evolving stress–strain–phase transformation state within the finite element model. The coupled evolutionary variational inequality is solved incrementally as a sequence of complementarity problems, allowing for an accurate representation of the path-dependent behaviour and the associated hysteresis loops.

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- [1] M. Kuczma, A. Mielke, E. Stein, *Arch. Mech.* **51** (1999) 693–715.
<https://am.ippt.pan.pl/index.php/am/article/view/v51p693>
- [2] C. Erdogan, T. Bode, P. Junker, *CMAME* **429** (2024) 117134. <https://doi.org/10.1016/j.cma.2024.117134>
- [3] T.P. Wu, P.M. Pimenta, P. Wriggers, *Arch. Appl. Mech.* **94** (2020) 2371–2404.
<https://doi.org/10.1007/s00419-024-02591-9>

Wave dispersion modeling for mechanical metastructures with nonlocal connections

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KEYWORDS: *Metastructure, Elastic wave, Dispersion, Homogenization, Nonlocal connection, Nonlocal properties, Computational mechanics.*

The work addresses analytical and numerical investigation on the phenomenon of elastic wave propagation in mechanical metastructures, i.e., meso-scale periodic truss-like structures, that are formed using both local and nonlocal inner connections. Generally, metastructures are the systems in which the resultant behavior depends on the spatial distribution of the construction matter rather than on the material properties [1]. Considerable freedom regarding spatial shaping of metastructures, which is feasible mainly due to the capabilities of additive manufacturing technologies, leads to many interesting physical properties, that are of high importance in practical applications, e.g., quasi-zero stiffness in case of energy harvesters [2]. In the present research, the contribution of nonlocal links defined between the surrounding degrees of freedom results in an unique capability of forming dispersion curves.

The current work focuses on mathematical modelling and computational aspects for designing metastructures of the desired dynamic properties. The developed computational framework assumes definition of an unit cell for the considered periodic system, using finite element (FE) method. All the involved system connections are used to assemble the FE global stiffness and mass matrices, adequately applying the coordinate system transformations. The process of dispersion curves extraction is based on the solution of eigenvalue problem formulated with the Kelvin-Christoffel equation [3]. The relevant part of the resultant governing equation, that corresponding to the unit cell's central node, is used to find the above-mentioned curves. The applied homogenization allows for effective and reliable characterization of the system's dynamic response. The work is complemented with the results of numerical simulations conducted for the initial value problem.

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- [1] N. Chen, A. Zuo, P. Jiang, Y. Xu, Z. Yang, A ring metastructure vibration isolator with thin beams, *International Journal of Mechanical Sciences* **280**, 109528, 2024. <https://doi.org/10.1016/j.ijmecsci.2024.109528>
- [2] J. Margielewicz, D. Gąska, G. Litak, P. Wolszczak, D. Yurchenko, Nonlinear dynamics of a new energy harvesting system with quasi-zero stiffness, *Applied Energy* **307**, 118159, 2022. <https://10.1016/j.apenergy.2021.118159>
- [3] A. Martowicz, W.J. Staszewski, M. Ruzzene, T. Uhl, Peridynamics as an analysis tool for wave propagation in graphene nanoribbons. In: J.P. Lynch, K.-W. Wang, H. Sohn [eds.], *Sensors and smart structures technologies for civil, mechanical, and aerospace systems*, **9435**, 2015; Proc. of the SPIE / The International Society for Optical Engineering, San Diego, USA, 9–12 March 2015, 94350I-1–94350I-8

Initial stability of plates considering internal constraints by the Stochastic Boundary Element Method

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KEYWORDS: *Boundary Element Method, Thin Plates, Initial Stability, Semi-Analytical Probabilistic Analysis, Stochastic Perturbation Technique, Monte Carlo Simulations.*

The work presents the initial stability of plates in terms of the Stochastic Boundary Element Method (SBEM), what the authors discussed in [1] for plates supported only along its edges. It is assumed that the girders are loaded in their plane in a constant or linearly variable manner in one direction. The Boundary Element Method (BEM) is used to solve a single deterministic problem. The boundary and domain integral equations are formulated using e.g. Betti's theorem with fundamental solution applied to plate statics (Green's function). These equations are formulated in a singular approach and, alternatively, in a non-singular approach, where the collocation point is located outside the plate domain and at the same time sufficiently close to its edge. A plate boundary is divided into finite number of elements of the constant type. Internal constraints are considered too. The curvatures within the plate domain must be determined. For this purpose a plate domain is divided into finite number of sub-domains coupled with e.g. one central collocation point. This can be accomplished by using the first boundary and domain integral equation, which must first be differentiated twice with respect to a coordinate parallel to the applied load in the plate plane. This curvature can also be determined by simple difference quotients constructed for three internal collocation points located within a single subdomain – the central one and two others lying on one line before and after it (triple collocation point approach). Eliminating the boundary quantities from the governing equations leads to the standard eigenproblem, whose solution is the eigenvalues and eigenvectors that is the values of the critical multiplier and the corresponding curvature vectors. Alternatively, the second boundary and domain integral equation may be established by the addition second collocation point (double collocation point approach). Then there is no need to use the fundamental solution obtained for a unit moment whose vector is perpendicular to the normal to the plate edge.

The random approach requires a finite number of deterministic solutions obtained for different values of, for example, a single design parameter e.g. Young's modulus or a plate thickness. Based on this, a continuous polynomial response curve of the structure is determined, which will be integrally related to the probability density curve. For each of the design parameters the normal Gaussian probability density distribution is assumed. Three probabilistic approaches are applied: Semi-Analytical Method (SAM), Stochastic Perturbation Technique (SPT) e.g. [2], and Monte Carlo simulation (MCS). Probabilistic moments are defined in the form of curves (for SAM and SPT) or a set of points (for MCS), as a function of the coefficient of variation of the selected design parameter. The random approach allows testing the solution of the problem in the case of a non-singular approach with the use of double and triple collocation point technique.

- [1] M. Guminiak, *Stability of rectangular Kirchhoff plates using the Stochastic Boundary Element Method*, Engineering Analysis with Boundary Elements, 144, 441–455, 2022
- [2] M. Kamiński, *The Stochastic Perturbation Method for Computational Mechanics*, Wiley: Chichester; 2013

Dragonfly-Inspired Flapping Wing Fabrication Using PVDF/CNT Nanocomposite Membranes and 3D-Printed Vein Structures

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KEYWORDS: *Bioinspired, Dragonfly wings, MAVs, Bio-composites, DIC*

Nature has long served as a blueprint for solving complex engineering challenges. Dragonfly is one of the most aerodynamically efficient flyers. Their corrugated wing membranes, hierarchical venation, and ability to exploit unsteady aerodynamic mechanisms inspire the design of next-generation flapping wing micro air vehicles (FWMAVs). In this work, a PVDF/CNT nanocomposite membrane was fabricated by solution casting with varying CNT loading, and a vein structure was generated via VAT additive manufacturing. An integration of a nanocomposite membrane with a vein structure was performed to develop a dragonfly-inspired wing. The developed wing's mechanical and structural dynamic properties were characterized using various techniques, including tensile tests, Dynamic Mechanical Analysis (DMA), vibration tests, and Digital Image Correlation (DIC). An optimal CNT loading of 1.5% was found, yielding the most suitable properties as determined by characterization techniques. Furthermore, the effect of vein integration on deformation modes and their corresponding natural frequencies was found with DIC. For the first time, a PVDF/CNT membrane was used for bioinspired wing fabrication, and VAT 3D printing was used to fabricate the vein structure. Results showed that integrating the nanocomposite membrane into the vein structure could yield significant improvements in structural performance in FWMAVs. This study also demonstrates the significant potential of nanocomposite membranes and additive manufacturing for fabricating bioinspired flapping wings for MAVs.

Influence of the Functionally Graded Material of Three-Layered Annular Plate on Dynamic Response under Thermal Loading

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KEYWORDS: *FGM Composite Plate, Dynamic Stability, Thermal Loading, Numerical Methods*

Presented problem draws attention to the dynamic responses of three-layered, annular plates subjected to constant or time-dependent temperature fields. Using the functionally graded material on the plate outer layers the new composite structure was built, whose dynamic behaviours are some new cognition. The temperature field model in combination with the material and geometrical parameters create a multiparameter problem. Detailed analysis can show plate reactions, whose meaning can be used in practical applications of such composite plates in for example: aerospace industry, mechanical and nuclear engineering, civil engineering or miniature mechanical systems.

The three-layered annular plate is composed of the thin FGM facings and thicker foam core. The plate is loaded thermally with the temperature difference between plate edges: inner and outer. The thermal environment is defined by the temperatures T_i and T_o in the area of plate hole and outer perimeter, respectively. The temperature field is axisymmetric and flat. There is no heat exchange between plate surfaces. The support system of the examined plates is in the form of both edges slideably clamped. Time-dependent thermal loads is formulated as follows:

$$\Delta T = at, \quad (1)$$

where ΔT is the temperature difference, t is the time, a is the rate of temperature loading growth.

The radial changes of the FGM facing material are smooth presented by the following power function:

$$VV = \left(\frac{r_i}{r_i - r_o} + \frac{r}{r_o - r_i} \right)^n, \quad (2)$$

where VV is the rate of material variation in the radial direction, r_i and r_o are the inner and outer plate radii, r is the plate radius, and n is the power-law exponent. The material parameters of the facings are calculated according to the following equation:

$$W = W1 + VV(W2 - W1), \quad (3)$$

where $W1$ and $W2$ are the values of the material parameters, W is the value of the facing material parameters at the plate point determined by the radius r . The facings are composed of two materials located at the plate edges. Between the edges, the facings' material parameters vary according to the selected power-law exponent n . Solution procedure uses two numerical methods: finite difference method in author's programme and finite element method in Abaqus system. The solution process is presented in works [1,2] in detail.

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[1] D. Pawlus, *International Journal of Structural Stability and Dynamics* **20**(12), (35 pages), 2020. <https://doi.org/10.1142/S0219455420501394>

[2] D. Pawlus, *Materials* **19**, 256, 2026. <https://doi.org/10.3390/ma19020256>

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