Strength-Consistent Structural Optimization Using a Biomimetic Approach

Michał Nowak[1,*], **Dariusz Kurpisz**[1]

[1]Poznan University of Technology, Poznan, Poland
e-mail: michal.nowak@put.poznan.pl

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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.

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