Comparative Study of Selected Gradient Damage Model Variants

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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, Politechnico 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.