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Multimodal energy-limiter-based continuum damage model and its anisotropic gradient regularisation for progressive damage assessment of fibre-reinforced polymer composites

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Abstract

We propose an energy-limiter-based continuum damage model, along with its anisotropic gradient regularisation, to investigate the progressive degradation in unidirectional fibre-reinforced polymer composite (FRPC) laminates. Based on a chosen form of the Helmholtz free energy density and a postulated dissipation potential incorporating modal energy limiters, thermodynamically consistent evolution equations are established for five local damage variables and other internal variables associated with plastic deformation. The five damage variables represent distinct microscopic modes of lamina failure, namely, fibre tension and compression, and inter-fibre transverse tension, transverse compression, and shear. We implicitly incorporate a stress invariant-based damage initiation criterion into the proposed damage evolution laws. This is achieved by identifying critical modal energy densities —a combination of elastic and plastic work densities at the instant of damage initiation —which determine the effective mode-specific damage driving energies. The damage evolution equation for each mode contains a second critical energy density related to the material's modal fracture toughness, ensuring mesh-objectivity of the formulation. The local damage formulation so obtained is thoroughly investigated and found to have a few limitations in capturing orientation-dependent cracking, fibre-aligned shear failure, and matrix-dominated softening in off-axis plies. To address these issues, each local damage variable is anisotropically regularised using its gradients and the structural tensor of the transversely isotropic lamina. The modified implicit gradient operator introduces dedicated internal length scales leading to smooth non-local damage fields. Stiffness degradation via the non-local damage variables prevents crack growth along incorrect directions, thanks to the introduced anisotropy in damage regularisation. Numerical simulations on unidirectional and multidirectional laminates confirm the model's ability to reproduce fibre-parallel shear failure, orientation-dependent matrix cracking, realistic stiffness degradation, and stable convergence at high damage levels. Compared to classical local damage models and standard gradient damage models, the proposed formulation yields significant improvements in accuracy and robustness. By combining physically interpretable energy limiters with independently regularised gradient evolution for each failure mechanism, the model provides an efficient and reliable framework for progressive failure analysis, making it suitable for implementation in user-defined finite element environments.

Keywords:

Progressive damage of composites Implicit gradient damage Energy limiter Fracture anisotropy