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Thermodynamically Consistent Modeling of the Nonlinear Damage Behavior of Carbon Fiber Reinforced Thermoplastics

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Abstract

The increasing demand for lightweight structural components in the automotive and aerospace sectors has accelerated the adoption of Thermoplastic Fiber-Reinforced Composites (TPFRCs). Unlike most composites, TPFRCs offer superior recyclability, high specific strength, and rapid processing capabilities. However, the mechanical behavior of the semi-crystalline thermoplastic matrix is highly complex, exhibiting pronounced nonlinearities driven by viscoelasticity, elasto- plasticity, and damage evolution, particularly under cyclic loading conditions [1]. The primary objective of this study was to accurately predict the nonlinear damage behavior of the thermoplastic matrix, while accounting for finite strains and other inelastic phenomena, while maintaining thermodynamic consistency. The developed approach utilized a rheologi- cal framework consisting of a parallel arrangement of intermolecular and molecular network components to decouple viscoelastic and elastoplastic mechanisms [2]. To address the inter- action between inelastic deformation and material degradation, a bipotential formulation was employed; this method introduced two distinct potentials in the intermediate configuration: one

governing the viscoelastic-elastoplastic flow and the other controlling damage evolution. This separation was crucial for ensuring the thermodynamic consistency of the model, specifi- cally when dealing with the non-associative flow rules often required for polymers. The model accounted for isotropic damage but explicitly incorporated Tension-Compression Asymmetry (TCA). This was essential for TPFRCs, where the matrix behavior differs significantly under ten- sile versus compressive loads, influencing the onset of failure mechanisms such as matrix crack- ing. To overcome the pathological mesh dependency inherent in local damage formulations, the frame- work integrated a gradient-enhanced regularization scheme (micromorphic approach) [3, 4]. This introduced non-local field variables that regularized the damage localization zone, ensuring that energy dissipation remained objective and independent of the finite element mesh size. This feature is particularly critical for the subsequent steps of this project, where the matrix model will be employed within Representative Volume Elements (RVEs) for homogenization [5]. The model was validated against experimental data obtained from uniaxial and cyclic tensile, compressive, and shear tests on pure matrix specimens. Preliminary results demonstrated the capability of the model to capture rate-dependent stiffness degradation and permanent defor- mation.

Keywords:

TPFRCs Damage modeling Non-Local

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