Abstract

The progressive failure analysis of materials and structures is critical for structural safety, material optimization, and engineering design. Continuum Damage Mechanics (CDM) provides an efficient numerical framework to model the damage evolution in quasi-brittle materials such as concrete and composites. However, accurate damage modeling often requires computationally expensive three-dimensional (3D) modeling, which poses challenges for practical applications.

This thesis develops an efficient computational framework that integrates higher-order beam theories based on the Carrera Unified Formulation (CUF) with CDM for damage analysis of concrete and composite structures. The CUF-based beam model can capture 3D displacement fields at a reduced computational cost. The Component-Wise (CW) allows for the simultaneous consideration of components with different geometries and materials in a complex structure. Additionally, the Node-Dependent Kinematics (NDK) approach ensures accurate damage modeling in critical zones while enabling efficient computation in non-critical zones.

Furthermore, isotropic and orthotropic damage models based on CDM are proposed for concrete and composites, respectively. For composites, the 3D Tsai-Wu failure criterion is employed to independently capture fiber, matrix, and interlaminar failure mechanisms. A fracture energy regularization technique is introduced to mitigate mesh dependency, with different proposed characteristic element length calculation methods for CUF-based beam elements. Additionally, viscous regularization is added to enhance numerical stability.

The proposed framework is validated through numerical damage simulations on experimental benchmarks, including plain concrete, reinforced concrete, and pultruded fiber-reinforced polymer (FRP) composite structures. For plain concrete structures, the CUF-based beam model, combined with the proposed isotropic damage model and regularization technique, effectively reproduces experimental load-displacement responses and consistent damage patterns while mitigating mesh dependency.

For reinforced concrete structures, the CW-enhanced CUF-based model, incorporating the isotropic damage model and regularization technique, effectively captures their tensile, compressive, and shear failure mechanisms. Meanwhile, it is capable of replicating experimental load-displacement responses, demonstrating the accuracy of the proposed framework. Additionally, the NDK approach ensures accurate damage modeling in critical zones with a 35%–50% reduction in computational costs.

For FRP composite structures, the CUF-based beam model with the orthotropic damage model can predict their expected progressive damage behavior. Additionally, this case validates the effectiveness of the regularization techniques and the NDK approach in FRP damage modeling.

Overall, the CUF-based beam model incorporating CDM provides a solution to balance computational efficiency and accuracy in damage modeling of quasi-brittle materials. The regularization techniques ensure mesh independence, while the CW and NDK approaches enable efficient damage analysis of complex structures. These advantages demonstrate the potential of the proposed framework for the damage analysis of practical engineering applications.

Keyword: Carrera Unified Formulation; Finite element method; Isotropic/orthotropic damage models; Tsai-Wu criterion; Regularization techniques; Characteristic element length; Plain/reinforced concrete structure; Composite structure.