Analysis of Macro-damage Evolution in Homogeneous and Inhomogeneous Structures using Localizing Gradient Continuum Damage Mechanics

Abstract

Composite and functionally graded materials (FGMs) have become popular over the conventional engineering materials due to their superior properties and tailorability. However, due to the material inhomogeneity present in these materials at the micro-scales, developing computational methods for their analysis poses significant challenges. In quasi-brittle materials, FGMs and composites, the material's constituents and the inherent micro-defects and damages interact at micro-scales under the action of loading. An accurate understanding of materials' damage mechanisms and failure response is crucial. Therefore, it is imperative that a comprehensive computational framework that is efficient and robust in handling the damage analysis of these high-performance materials be developed. Continuum-based damage mechanics (CDM) models have been very effective in the analysis of damage initiation, evolution, and failure over other methods; but, pose some limitations due to localization and discretization sensitivity Regularization schemes are employed to tackle these computational issues. The localizing gradient damage model is a highly efficient regularization approach that can easily handle micro-macro strain interactions in inhomogeneous materials.

In the present investigation, the localizing gradient damage model is employed to study the evolution of damage in homogeneous and inhomogeneous structures. Characteristically, the material's damage response depends on the choice of damage evolution law and various damage parameters. This work uses exponential damage evolution law to model the material's degradation response beyond the damage initiation. The mixed finite element formulation of the damage model is implemented in the Abaqus finite element package by using a user-defined subroutine (UEL). Various validation studies are performed to validate the model's accuracy, comparing the observed structural response with experimental and numerical data for both homogeneous and inhomogeneous materials. The evolution of damage in homogeneous, quasi-brittle structure is analyzed for various loading and boundary conditions. A quantitative analysis of the influence of damage evolution law parameters on the material's macro-damage response is performed. Effects of variation in specimen size and crack length are also investigated phenomenologically. The novel contribution of the present research work is the development of damage analysis methodology for the macro-damage analysis of inhomogeneous FGMs. The orthotropic and isotropic FGM plates with material property gradation for longitudinal, transverse and shear moduli in *x* and *y* directions are modelled, and the macro-damage response of the structures is examined. Characteristics of proportional and non-proportional material gradation in the material moduli on the structure's damage evolution and relative effects of variation in macro-cracks on the structure's damage response are studied. The outcomes of the present work can be extended to analyze the macro-damage initiation, evolution and failure in the case of other inhomogeneous materials, such as braided composites, textile composites, multi-directional composites, etc., as the scope of future work. The findings of the present research work provide a comprehensive understanding of the macro-damage evolution for homogeneous and inhomogeneous structures, thus offering insights for the development of a better design philosophy with enhanced durability and damage tolerance in critical engineering applications.

Keywords: Macro-damage Evolution; Composite Materials, Functionally Graded Materials (FGMs); Continuum Damage Mechanics (CDM); Regularization; Localizing Gradient Damage Model; Damage Evolution Law