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An investigation on nonlocal continuum damage models for composite laminated panels

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ABSTRACT

The performance of nonlocal approaches based on nonlocal strains, damage driving forces and damage variables is investigated for progressive damage analysis of thick/moderately thick laminated panels under uniform transverse loading using eight-noded isoparametric finite element based on a global higher-order shear deformation theory including zig-zag function and first-order theory. The nonlocal variables are obtained from corresponding local variables using layerwise finite element with quadratic through the thickness variation in each layer. The effect of nonlocal parameter on convergence of failure load, maximum deflection and damage variables with successive mesh refinement is investigated. It is concluded that the convergence improvement based on all the three nonlocal models is almost same and the nonlocal scale parameter in the range of 0.5–3% of plate/panel dimensions yields a good convergence rate.

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1. Introduction

Laminated composites are increasingly being used as load bearing members in aircraft, spacecraft, missile, hydrospace, automobiles, marine and medical prosthetic devices etc. due to their tailorability to achieve greater specific stiffness and strength. The process of progressive damage in composites, due to nucleation and growth of defects such as matrix cracks, fiber breakage, fiber matrix debonding and inter-layer delamination, may cause the degradation of material properties and failure. Accurate predictions of failure initiation, progression and failure load are essential for designing reliable, safe and failure proof structures. Continuum damage mechanics (CDM) is a phenomenological approach that represents the macroscopic effects of microscopic cracks/cavities in the material by introducing internal state variables (damage variables). The damage model is based on a generalized macroscopic continuum theory within the framework of irreversible thermodynamics and enables to predict the progressive damage and failure load. Kachanov [1] first introduced the concept of continuum factor to describe inelastic constitutive equations for isotropic solids. The damage variable ranges from zero to unity with zero implying an undamaged material and unity implying a completely damaged material. The concept of damage variable was utilized by Rabotnov [2] and Lemaitre [3] to propose the concept of effective stress and the strain equivalence principle, respectively. To resolve the issue of unsymmetric constitutive matrix involving anisotropic damage based on strain equivalence principle, Sidoroff [4] proposed the hypothesis of strain energy equivalence.

Chaboche [5,6] described different measures of the damage variable, developed damage growth equations within the thermodynamic general framework and also discussed the use of CDM for local approaches of fracture. Matzenmiller et al. [7] established the damage variable evolution law using the concepts of thermodynamics of irreversible processes and proposed an anisotropic damage model for fiber-reinforced composites based on in-plane failure modes *i.e.* fiber failure, matrix failure and fiber–matrix shear failure. Williams and Vaziri [8] developed the plane-stress CDM model by implementing the Matzenmiller–Lubliner–Taylor (MLT) model [7] into LS-DYNA3D. Further, Williams et al. [9] gave a physical treatment of damage growth based on experimental results combined with mathematical rigour of continuum damage mechanics.

Based on strain equivalence hypothesis, Allix et al. [10] and Ladeveze and Le Dantec [11] formulated mesomechanical damage model for single-ply laminate considering matrix microcracking and fiber/matrix debonding represented by two internal state variables. The damage evolution law is assumed to be linear function of equivalent damage energy release rate. Allix and Ladeveze [12], Allix et al. [13], Daudeville and Ladeveze [14] extended the approach [10,11] to predict the interface delamination by introducing an interface layer between the laminae and three damage variables corresponding to degradation of three interface stiffness

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constants. These damage variables are assumed to evolve according to a power law function of equivalent damage energy release rate. Ladeveze [15] and Ladeveze et al. [16] combined the ply and interface damage models to predict the overall damage of laminate under quasi-static and dynamic loadings. Barbero and de Vivo [17], Barbero and Lonetti [18,19] and Lonetti et al. [20] proposed a model for damage initiation, evolution and failure of composite structures at critical values of damage based on the concepts of thermodynamics of irreversible processes. Abdelal et al. [21] extended this model and proposed a micro-mechanics damage approach for fatigue damage evolution of polymer matrix composites (PMCs). A discrete damage mechanics model for initiation/evolution of transverse matrix cracking in laminated composites is proposed by Barbero and Cortes [22] and the moduli of the damaged laminate are expressed as functions of crack densities. Since the evolution of crack density is expressed as function of calculated energy release rate, the model requires only critical energy release rates for the laminae. The procedure to determine material parameters for carbon-epoxy laminate [23] and a robust three-node shell element [24] based on the model have been developed.

Robbins et al. [25,26] implemented the continuum damage mechanics approach in the finite element model based on the first order [25] and layerwise [26] shear deformation theories of laminates. Gupta et al. [27,28] investigated the effect of evolving damage on static response characteristics of laminated composite shallow cylindrical/conical panels and plates. The nonlinear dynamic response of laminated plates with piezoelectric layers is studied by Tian et al. [29,30] considering elasto-plastic deformation, damage evolution law similar to plastic flow rule and classical plate theory. The elasto-plastic postbuckling of orthotropic plates is studied by Tian and Fu [31] using classical plate theory and continuum damage based on damage flow rule. Tian et al. [29,30] and Tian and Fu [31] have used stress tensor as the conjugate force to damage which is thermodynamically inconsistent [32]. The progressive failure analysis of carbon fiber/epoxy composite laminated cylindrical is carried out using explicit finite element method incorporating viscous damping effect to overcome numerical convergence difficulty [33] employing Hashin failure criterion based damage initiation and fracture energy based damage evolution laws.

Progressive damage is a strain softening phenomenon exhibiting strong spurious mesh sensitivity due to damage localization in a zone of vanishing volume [34]. The energy dissipated through damage tends toward zero with mesh refinement indicating failure of structure at zero energy dissipation [35] which is unacceptable from phenomenological view point. The strain/damage localization to a zero volume and spurious mesh sensitivity can be overcome using nonlocal continuum damage mechanics approach [35–38] wherein growth of damage at a point is no longer governed by the local strains/damage driving forces, but depends on the weighted average of these parameters in a finite neighbourhood of the point. The nonlocal quantities can be evaluated based on integration (averaging) [38] or implicit/explicit gradients [39,40]. Peerlings et al. [41,42] compared the nonlocal and implicit/explicit gradient approach in the framework of elasticity based continuum damage model for an isotropic rod undergoing axial deformation to find out the similarities and intrinsic differences between them. Geers et al. [43] compared implicit gradient-enhanced nonlocal isotropic damage models for axial deformation of a rod and two-dimensional notched plate based on equivalent strain, local history parameter (function of equivalent strains), damage variable with damage dependent characteristics length and strains with damage/strain dependent characteristics length. The damage variable is assumed to evolve according to a power and an exponential law based on local history parameter.

Geers and coworkers [44] determined intrinsic length scale parameter of strain-based transient gradient isotropic damage model based on the comparison of the failure process, load displacement curve and strain distribution in the failure region of glass fiber reinforced polypropylene Compact-Tension specimen with experimental results. The damage evolution is based on power law function of nonlocal equivalent strains. Further, a mixed numerical–experimental approach [45] has been developed to identify the unknown model parameters governing the damage evolution and failure process of fiber reinforced composites.

Kennedy and Nahan [46] proposed a nonlocal damage model for notched composite laminated plate under tensile loading. The evolution of uncoupled damage variables is based on exponential function of nonlocal strains obtained by weighted averaging of local strains. The authors investigated the progressive failure of a pre-cracked composite stiffened cylindrical panel subjected to internal pressure loading with constant [47] and linear [48] through the thickness variation of damage variables. Germain et al. [49,50] proposed anisotropic nonlocal damage model by introducing different internal length scales for each principal material direction. The damage variables were expressed as exponential functions of nonlocal damage driving forces obtained by implicit gradient formulation.

It can be concluded from the literature review that most of the nonlocal damage models are based on isotropic damage with damage evolution law based on power or exponential function of nonlocal strains/damage driving forces. The application of the nonlocal damage theory is mainly dealing with the in-plane loading. The implementation of nonlocal damage models for progressive failure analysis of composite laminated plates/panels under flexural loading has not received the adequate attention of researchers except Kennedy and Nahan [47] and Nahan and Kennedy [48] wherein damage variables are assumed to be constant/linearly varying through the thickness. The progressive damage modeling and global failure load prediction of thick composite structures is strongly affected by interlaminar shear stresses and through the thickness material inhomogeneity. The use of higher-order theories is essential to accurately predict the through-thickness distribution of damage/stress/strain and failure load. To the best of the authors' knowledge, the application of these theories with nonlocal effects for progressive damage analysis of thick composite laminated structures is not explored.

In the present work, a nonlocal continuum damage model for progressive failure analysis of thick/moderately thick laminated composite plates/panels using a global higher-order shear deformation theory including zig-zag function is formulated. The static analysis of laminated plates/panels is carried out considering continuum damage models based on nonlocal strain, nonlocal damage driving force and nonlocal damage variables for prediction of failure load. The detailed study is carried out to investigate the effect of nonlocal parameter on convergence of failure load, maximum deflection and damage variables with successive mesh refinement for thick/moderately thick laminated plates/cylindrical panels subjected to uniformly distributed transverse load.

2. Continuum damage mechanics model

The relation between the Cauchy stress $\{\boldsymbol{\sigma}\}$ in the damaged continuum and effective stress $\{\bar{\boldsymbol{\sigma}}\}$ in the equivalent undamaged continuum can be expressed as [51]:

$$\{\bar{\boldsymbol{\sigma}}\} = [\mathbf{M}]\{\boldsymbol{\sigma}\} \tag{1}$$

where $[\mathbf{M}]$ is the effective damage tensor. The non-zero elements of the effective damage tensor [51] are given by:

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