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Progressive damage of laminated cylindrical/conical panels under meridional compression

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ABSTRACT

The objective of this paper is to investigate the progressive failure behaviour of laminated cylindrical/conical panels under meridional compression considering geometric nonlinearity and evolving material damage. The evolving microscopic damage such as fiber breakage, matrix cracking, fiber matrix debonding etc. is modeled through a generalized macroscopic continuum theory within the framework of irreversible thermodynamics. The analysis is carried out using field consistent finite element approach based on first-order shear deformation theory. The nonlinear governing equations are solved using the Newton–Raphson iterative technique coupled with the adaptive displacement control method to trace the equilibrium path. The damage evolution equations are solved at every Gauss point using Newton–Raphson iterative technique within each iteration of a loading/displacement increment. To accurately model the transverse shear strain energy, shear correction factors are calculated using layers' properties and lamination scheme. The detailed study is carried out to highlight the influences of evolving damage, span-to-thickness ratio, lamination scheme, radius-to-span ratio, boundary conditions and semi-cone angle on the postbuckling response and failure load of laminated panels.

1. Introduction

Composite laminated curved panels, increasingly being used as load-bearing members in space shuttles, supersonic/hypersonic vehicles, rockets, missiles, nuclear reactors, engine components etc., may often be subjected to compressive meridional loading. For the efficient and safe design of curved panels under meridional compression, it is necessary to study their response and failure characteristics incorporating geometric nonlinearity and damage evolution. The process of progressive damage in fiber reinforced composites, due to nucleation and growth of defects such as matrix cracks, fiber breakage, fiber matrix debonding and inter-layer delamination, can be incorporated through the degradation of material properties.

The studies on the buckling/postbuckling characteristics of laminated composite panels under compressive loading have been reviewed by Leissa (1987a, 1987b, 1992), Noor (1995), Zhang and Yang (2009) and Xu et al. (2013). Some of the studies are concerned with critical buckling load and load versus displacement relationship of laminated panels under uniaxial/biaxial compression and in-plane shear loads without considering progressive damage/failure.

In progressive failure approach based on failure criteria, the elastic properties are taken as zero or reduced by a factor depending upon the failure index (Kim et al., 1995; Kong et al., 1998; Gummadi and Palazotto, 1998; Ganapathy and Rao, 1998; Baranski and Biggers, 1999; Singh and Kumar, 1999; Spottswood and Palazotto, 2001; Xie and Biggers, 2003; Ambur et al., 2004; Lanzi, 2004; Maksimovic, 2006; Oh et al., 2006; Zimmermann et al., 2006; Chen and Soares, 2007; Orifici et al., 2008a,b; Degenhardt et al., 2008a,b; Kumar and Singh, 2010; Wagner and Balzani, 2010; Lauterbach et al., 2010; Boni et al., 2012; Shi et al., 2014).

The failure characteristics and postbuckling ultimate load of stiffened composite cylindrical panels using progressive failure analysis based on the maximum stress criterion have been investigated and compared with the experimental results (Kim et al., 1995; Kong et al., 1998). Lanzi (2004) has studied the postbuckling characteristics of stiffened composite panels under axial

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compression employing Tsai–Hill failure criteria to predict the onset of the first-ply failure. Zimmermann et al. (2006) presented a numerical study on the buckling and post-buckling behavior of stiffened CFRP curved panels using nonlinear finite element analysis and compared the predicted results with experimental results. Chen and Soares (2007) performed progressive failure analysis for prediction of post-buckling compressive strength of laminated composite plates and stiffened panels using finite element code coupled with the Tsai–Wu failure criterion. Orifici et al. (2008a,b) conducted experiments and numerical analysis to investigate the post-buckling damage growth and collapse behavior of composite stiffened panels. Their numerical model was based on a global–local technique that uses a strength-based criterion to predict the initiation of interlaminar damage, a degradation model for interlaminar crack growth. Degenhardt et al. (2008a) carried out the analysis of stringer-stiffened CFRP panels including post-buckling and collapse using stress-based failure criteria to simulate material property degradation, skin–stringer separation and delamination in the stringer blade.

Wagner and Balzani (2010) presented a numerical model to predict the postbuckling response of stringer-stiffened curved composite airframe panels under axial compression including fiber fracture, matrix cracking, and fiber–matrix debonding by means of extended Hashin criteria and compared the numerical results with the experiments (Degenhardt et al., 2008b). The damage sensitivity of axially loaded stringer-stiffened curved CFRP panels was studied by Lauterbach et al. (2010) using in-plane failure model based on the extended Hashin criteria as proposed by Goyal et al. (2004) and virtual crack closure technique (VCCT) to simulate the progress of delamination of initial debonded areas. Boni et al. (2012) compared the experiential and numerical results on postbuckling behaviour of flat stiffened composite panels without considering progressive failure of the material. Shi et al. (2014) have carried out the post-buckling and failure analysis of stiffened composite panels subjected to hygro/thermal/mechanical loading incorporating quadratic strain criterion for damage initiation and mixed mode failure criterion for the damage evolution.

In the above cited references, thermodynamically consistent continuously evolving damage dependent on current state of damage and/or stress/strain is not considered.

The continuously evolving material stiffness degradation can be modeled in terms of internal state variables within the framework of continuum damage mechanics (CDM). Such an internal state variable was first introduced by Kachanov (1999) to describe inelastic constitutive equations for isotropic solids. The concept of damage variable was utilized by Rabotnov (1969) and Lemaitre (1971) 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 the strain equivalence principle, Sidoroff (1981) proposed the hypothesis of strain energy equivalence. The damage evolution can be modeled based on phenomenological approach (failure mode independent) and/or micromechanics approach (failure mode dependent).

Failure mode independent continuum damage models are based on the principles of thermodynamics of irreversible processes requiring a damage potential function that predicts the occurrence of damage but does not directly identify the failure mode of composites. The damage potential is defined as a function of damage driving forces, overall hardening parameter which defines the damage threshold and damage parameters (Lee et al., 1985). A number of researchers have used quadratic damage potentials as functions of damage driving forces (Kattan and Voyiadjis, 1993a,b; Voyiadjis and Kattan, 1993a,b; Barbero and de Vivo, 2001; Barbero and Lonetti, 2001, 2002; Lonetti et al., 2003) and derived the damage evolution from extremum conditions of damage dissipation power density. The components of anisotropic damage parameters were determined experimentally based on uniaxial tensile tests along the three principal material directions (Kattan and Voyiadjis, 1993a,b; Voyiadjis and Kattan, 1993a,b) whereas Barbero and de Vivo (2001), Barbero and Lonetti (2001, 2002) derived orthotropic damage parameters at the lamina level using strength properties and inplane shear stress versus shear strain curve. The interlaminar damage effect is included by Lonetti et al. (2003).

Ladeveze and Le Dantec (1992) assumed damage evolution law as linear function of equivalent damage driving force and proposed a mesomechanical damage model for single-ply laminate considering matrix microcracking and fiber/matrix debonding represented by two internal state variables. Allix and Ladeveze (1992), Daudeville and Ladeveze (1993) and Allix et al. (1995) extended the approach (Ladeveze and Le Dantec, 1992) to predict the interface delamination by introducing an interface layer between the laminae and three damage variables corresponding to the degradation of three interface stiffness constants. These damage variables are assumed to evolve according to a power law function of equivalent damage driving force (Daudeville and Ladeveze, 1993) and linear function of square root of equivalent damage driving force (Allix and Ladeveze, 1992; Allix et al., 1995). Ladeveze (1992) and Ladeveze et al. (2000) combined the ply and interface damage models to predict the overall damage of laminate under quasi-static and dynamic loadings. Murari and Upadhyay (2012, 2013) proposed a ply-level continuum damage model representing various micro-level damage mechanisms such as fiber breakage, fiber-matrix debonding and matrix cracking and developed a functional continuum representation of stiffness degradation based on a three dimensional micromechanical analysis of a single cell representative volume element considering different fiber volume fraction and damage levels.

Failure mode dependent damage models to predict evolving damage at heterogeneous scale requires the micromechanics study to identify the damage corresponding to different failure modes. Matzenmiller et al. (1995) proposed an anisotropic damage model referred to as MLT (Matzenmiller–Lubliner–Taylor) model for fiber-reinforced composites based on inplane failure modes *i.e.* fiber failure, matrix failure and fiber-matrix shear failure, and established the damage evolution law using the concepts of thermodynamics of irreversible processes. Loading surface is derived from plane stress version of Hashin criterion in terms of damage driving forces. The rate of change of damage variables is expressed as functions of current state of damage/strain, strain rate and relative damage growth parameters in fiber and transverse to fiber directions. Xiao (2009) modified the MLT model to accurately represent unloading and reloading paths in energy absorption modeling of composite structures. Curiel Sosa et al. (2008) modified MLT for 3-D progressive damage analysis of fiber reinforced composite laminates by introducing three additional damage variables. Williams and Vaziri (2001) implemented the plane-stress MLT model in LS-DYNA3D and damage growth model based on experimental results combined with mathematical rigour of continuum damage mechanics was proposed by Williams et al. (2003).

Numerical treatment of CDM based progressive damage models to determine the effect of stiffness degradation on response of composite laminates under different loading conditions has been reported by various researchers. Based on classical plate theory, the effect of damage on nonlinear dynamic response of laminated plates with piezoelectric layers is studied by Tian et al. (2009a,b) considering elasto-plastic deformation, damage evolution law similar to plastic flow rule. Tian et al. (2009a,b) used the stress tensor as the conjugate force to damage which is