Composite Structures 108 (2014) 937–950

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

An investigation of matrix cracking damage evolution in composite laminates – Development of an advanced numerical tool

G. Sadeghi [a], H. Hosseini-Toudeshky [a,*], B. Mohammadi [b]

[a] Department of Aerospace Engineering, Amirkabir University of Technology, 424 Hafez Avenue, Tehran, Iran
[b] School of Mechanical Engineering, Iran University of Science and Technology, Narmak, Tehran, Iran

ARTICLE INFO

Article history:
Available online 16 October 2013

Keywords:
Matrix cracking
Progressive damage evolution
General symmetric laminates
Stress transfer
Finite element method

ABSTRACT

In this study, progressive matrix cracking damage analyses are performed for general symmetric laminate with any number of plies under in-plane tensile/shear loading condition. To predict initiation and evolution of matrix cracking in each layer of such laminate, an advanced numerical tool is developed here. The tool consists of, (i) a micromechanic-based damage model to find stiffness reduction of the laminate and damage parameters due to the presence of matrix cracking, (ii) an energy-based evolution law to predict initiation and progression of the damage and (iii) a finite element (FE) basement to implement the constitutive damage law analyzing laminates under complex boundary conditions. The stress transfer method is used to find the displacement and stress fields in a unit cell confined between two consecutive matrix cracks. Then, the degradation of elastic constants and damage parameters are calculated for each damaged layer of the laminate. New formulation is also developed to implement the evolution law at integration points to eliminate the length dependency of the energy-based damage criterion. The crack density is used as the only state variable which controls the damage state. An eight node element is developed using the full layerwise plate theory and the damage constitutive law is implemented in the formulation of a user defined element routine in Abaqus commercial software. The developed procedure is validated favorably with published experimental and numerical results for matrix cracking damage mechanism in general symmetric laminates. Concurrent progressive damage analyses in different plies of various laminates are also investigated and some results which are rarely available in the literature are presented in this paper.

1. Introduction

The application of composite materials has been promoted from secondary to primary structures in different industries particularly in aerospace industry. Despite of the desirable mechanical properties, composites are susceptible to damage from a number of sources, both during manufacturing and in service. The integrity of structural components during their service life is an important design requirement when composite materials are used in load-bearing conditions. But damage occurrence can never be entirely avoided, so composite structures should be designed for safe operation despite the presence of damages.

The first form of damage in composite laminates in the early stages of loading is usually matrix cracks, which are intra-laminar cracks that traverse the thickness of the ply and run parallel to the fibers in that ply. Although this type of damage is not the final failure mode of the laminates, it can degrade their thermo-mechanical properties and trigger the other damage mechanisms such as induced delamination. Usually matrix cracking happens when the tensile load is applied in a direction different from the fiber direction, such as a cross-ply laminate in which the load is perpendicular to 90° plies and in off-axis plies in balanced/unbalanced laminates. In complex in-plane loading condition, the cracks may appear in every laminate ply. Most of the previously performed studies in progressive matrix cracking analyses have been restricted to special layup configurations in which the damage evolution in a laminate layer was investigated [1,2]. Also in most of the previously performed researches, the loading condition was limited to the axial tensile load applied to un-notched laminates that experiencing uniform in-plane stress field.

Fan and Zhang [3] developed the equivalent constraint model (ECM) based on the shear-lag stress transfer method to predict the progressive matrix cracking in 90° plies of $[\pm\theta/90_n]_s$ laminates [4]. The ECM was used to calculate the stiffness reduction of the laminate and the energy-based criterion employed to control the damage initiation and growth. McCartney [5] developed a methodology similar to ECM using a more accurate stress transfer method. He used a homogenization technique to replace the thermo-mechanical effects of fully-developed discrete cracks in one ply by the effective homogenized properties such that the homogenized laminate contains exactly the same properties as the

* Corresponding author. Tel.: +98 21 66405032; fax: +98 21 66959020.
E-mail address: hosseini@aut.ac.ir (H. Hosseini-Toudeshky).

0263-8223/$ - see front matter
http://dx.doi.org/10.1016/j.compstruct.2013.10.007

laminate with discrete ply cracks. This procedure enables the prediction of progressive matrix cracking formation, based on the energy methods, in any ply of a general symmetric laminate. Hosseini-Toudeshky et al. [6–8] developed a damage model on ply level and implements that in a FE based code to find the structural response of the general symmetric laminates having arbitrary lay-up configuration. The major drawback of such damage analyses procedure is that the used rectangular unit cell in the micromechanic model cannot be quite compatible with the finite element discretization around a discontinuity such as a notch or a circular hole. For $[\phi_m/\varphi_n]_s$ laminates containing matrix cracks, Yakozeki and Aoki [9] developed a 2D shear-lag model in an oblique coordinate system along the matrix cracks to find the effective in-plane thermo-elastic properties of the laminates. By fixing the crack density, λ_1, in one ply, the stiffness reduction of the laminate was calculated as a function of the crack density, λ_2, in the neighboring ply. No results were reported to predict progressive matrix cracking in both bunches of the laminate layers in this study. Using Yakozeki's progressive damage concept and based on the shear-lag approach, Barbero et al. [10–13] developed a damage constitutive law to find the laminate stiffness reduction. Using FEM based formulation of a shell element; the model was implemented at integration points to predict the matrix crack evolution in general symmetric laminates. No results were reported for simultaneous progression of damage in multi plies of the laminate in this study. For cross ply laminates having any number of plies and arbitrary stacking sequence, the authors have been developed a model to perform progressive matrix crack analysis [14].

In the present study, a progressive damage analysis procedure is developed to predict matrix cracking in symmetric laminates with arbitrary stacking sequence. In this hypothesis each laminate ply is susceptible to damage and therefore matrix cracking evolution has to be considered for all layers. In this way, transverse and shear damage parameters are defined to consider the degradation of elastic constants of each ply. A micromechanical damage model based on the stress transfer method is used to find the stiffness degradation of the unit cell. The method may leads to more accurate results compared to other shear-lag approaches as it benefits from a three dimensional stress–displacement field of a cracked unit cell [15]. The unit cell which is defined between two consecutive matrix cracks is extracted for each ply with a proper coordinate system transformation. Classical lamination theory is used to find the ply properties in the laminate and transverse and shear damage parameters are calculated for each cracked ply. The finite fracture mechanics and energy based failure criterion are used to predict the initiation and evolution of the damage in all laminate layers. The strain energy, which is calculated using the degraded properties of the laminate at integration points, is decomposed to the related terms according to the normal and shear loading condition. The effect of mixed mode condition on matrix cracking is also considered. To implement the model at an integration point, a fictious plate is considered there and the strain energy release rate is evaluated for such plate as a function of the unit cell degraded properties and crack density. User element definition capability of Abaqus commercial software is used to implement the damage constitutive law. The capability of the standard code to entitle Fortran routines helps us to construct and solve the governing differential equations arising from the micromechanic damage model. This is a key point in the performed progressive damage analysis procedure in the present study. The developed tool can be used to predict the progressive matrix damage of laminates with complex geometry and boundary conditions. It is employed to predict the progressive matrix crack damage for several cross-ply, balanced and general symmetric CFRP and GFRP laminates and the obtained results are compared with the available experimental and numerical results.

2. Micromechanic damage model

The stress transfer model, similar to the other micromechanic-based models, is formulated based on a unit cell which is a representative continuum of a laminate limited between the two consecutive matrix cracks. The goal of such model is to predict stiffness deterioration of cracked laminate using stress–displacement fields of the unit cell. The stress–displacement field of such unit cell is calculated using the constitutive law, equilibrium equation, interface and edge boundary conditions and simplifying assumptions. The main assumptions are piecewise linear form of the out of plane perturbed shear stress components through the thickness and the generalized plain strain condition of cracked laminate due to the complexity of the problem. Also some of the boundary conditions are not met exactly and must be averaged through the thickness of layers. There is no restriction on the number and orientation of plies and by the refinement of layers, the accuracy of the solution can be improved. When the stress and displacement fields of the problem are obtained, the stiffness reduction of the unit cell can be calculated as a function of crack density.

Fig. 1 shows the extracted unit cell from cracked laminate with $N+1$ layer at the structural scale. The matrix cracks may evolve in every layer in accordance with the boundary and loading conditions, but the crack evolution is investigated in only one layer at each calculation step. Suppose that the j^{th} layer is under consideration and damage evolution occurs in that ply only. For more clarity and better understanding of the modeling, the exaggerated cracked layer is shown in Fig. 1. Three coordinate systems are also introduced as depicted in this figure. The structure or global coordinate system (XYZ) which is a fixed system during the analysis is used to define the layers orientations in the laminate. The angles of the plies are measured with respect to the X direction of the global coordinate system. The unit cell coordinate system (xyz) is defined according to the extracted unit cell in which the x direction is normal to the crack face, y direction is in the laminate plane and along the crack direction and the z direction is normal to the laminate plane. It is clear that the unit cell coordinate system varies during the analysis and must be defined in proper rotation with respect to the global coordinate system for j^{th} layer. The last coordinate system is the material coordinate system (123) which is defined for each layer, as direction 1 is along the fibers, direction 2 is in the layer plane transverse to the fibers and direction 3 is normal to the lamina plane. The unit cell is limited to the region in which $|x| \leqslant a, |y| \leqslant b$ of the laminate and due to the symmetry condition, half of the laminate, $0 \leqslant z \leqslant H$ is modeled only. The laminate has $N+1$ perfectly bonded layers with arbitrary stacking sequence. The locations of the N interfaces are specified by $z = z_k$, $k = 1, \ldots, N$. The laminate mid-plane is specified by $z = z_0 = 0$ and the external surface by $z = z_{N+1} = H$ where $2H$ is the laminate total thickness. The thickness of the kth layer is denoted by $h_k = z_k - z_{k-1}$.

The constitutive law for the k^{th} layer ($k = 1, 2, \ldots, N+1$) in the material coordinate system (123) is defined as:

$$\begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \varepsilon_4 \\ \varepsilon_5 \\ \varepsilon_6 \end{Bmatrix}^k = \begin{bmatrix} \frac{1}{E_1} & \frac{-\upsilon_{12}}{E_1} & \frac{-\upsilon_{12}}{E_1} & 0 & 0 & 0 \\ & \frac{1}{E_2(1-d_2)} & \frac{-\upsilon_{23}}{E_2} & 0 & 0 & 0 \\ & & \frac{1}{E_2} & 0 & 0 & 0 \\ & & & \frac{1}{G_{23}} & 0 & 0 \\ & symm. & & & \frac{1}{G_{12}} & 0 \\ & & & & & \frac{1}{G_{12}(1-d_6)} \end{bmatrix}^k \begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{Bmatrix}^k + \begin{Bmatrix} \alpha_1 \\ \alpha_2(1-d_\alpha) \\ \alpha_2 \\ 0 \\ 0 \\ 0 \end{Bmatrix}^k \Delta T \quad (1)$$

By transverse isotropy hypothesis, seven thermo-mechanical constants are only needed to describe the stress–strain relations. The constants are longitudinal and transverse young's modulus E_1 and