Composites Science and Technology 69 (2009) 937–947

Contents lists available at ScienceDirect

Composites Science and Technology

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

Low-velocity impact damage on dispersed stacking sequence laminates. Part II: Numerical simulations

C.S. Lopes [a,b], P.P. Camanho [b,*], Z. Gürdal [a], P. Maimí [c], E.V. González [c]

[a] Faculteit Luchtvaart- en Ruimtevaarttechniek, Technische Universiteit Delft, Kluyverweg 1, 2629 HS Delft, The Netherlands
[b] DEMEGI, Faculdade de Engenharia, Universidade do Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal
[c] AMADE, Escola Politècnica Superior, Universitat de Girona, Girona, Spain

ARTICLE INFO

Article history:
Received 10 October 2008
Received in revised form 5 February 2009
Accepted 5 February 2009
Available online 20 February 2009

Keywords:
A. Structural composites
B. Delamination
C. Finite element analysis (FEA)
C. Damage tolerance
Low-velocity impact

ABSTRACT

This paper is the follow-up on the previous work by the authors on the experimental evaluation of the impact damage resistance of laminates with dispersed stacking sequences. The current work focuses on the evaluation of the impact performance of the tested laminates by innovative numerical methods.

Constitutive models which take into account the physical progressive failure behaviour of fibres, matrix, and interfaces between plies were implemented in an explicit finite element method and used in the simulation of low-velocity impact events on composite laminates. The computational effort resulted in reliable predictions of the impact dynamics, impact footprint, locus and size of delaminations, matrix cracks and fibre damage, as well as the amount of energy dissipated through delaminations, intra-ply damage and friction. The accuracy achieved with this method increases the reliability of numerical methods in the simulation of impact loads enabling the reduction of the time and costs associated with mechanical testing.

1. Introduction

The present paper corresponds to the second part of our work on impact damage resistance and tolerance of CFRP laminates with dispersed stacking sequences [1]. The previous paper [2] focused on the definition of laminates with dispersed stacking sequences as having nearly the same in-plane and bending stiffness as a traditional laminate based on the traditional 0°, 90° and ±45° fibre orientation angles but with plies ideally assuming any fibre orientation in the 0–90° range. In practice, for higher efficiency of the dispersing algorithm, the allowable fibre orientation angles were restricted to any multiple of 5°. Furthermore, our previous paper reports an experimental programme of impact and compression-after-impact tests on a baseline (traditional) and two alternative (dispersed) stacking sequence laminate specimens produced by the automatised tow-placement method.

The present work consists on the numerical simulation of those tests by means of finite element (FE) tools. A reliable numerical model for the simulation of the impact damage on composite laminates is proposed. Under out-of-plane loads, such as impacts, laminated composites may suffer damage in the form of different mechanisms such as: (i) matrix cracking and fiber failure and (ii) delaminations at interfaces between plies. If acceptable accuracy is to be expected from the numerical impact analyses, these damage phenomena need to be taken into account. Several authors have proposed analytical formulations for the prediction of the impact damage on composite laminates. However, the complexity of the physical phenomena, which includes dynamic structural behaviour and loading, contact, friction, damage and failure, often results in a oversimplification of the problem and limits the analytical models. The numerical approach by means of FE analyses is a more flexible and powerful alternative to the analytical formulations. The possibility of modelling the constitutive behaviour of each material at local (element) level adds to the capacity of simulation of complex structures under seemingly complex external loads and boundary conditions.

Continuum damage mechanics is an accurate framework to predict the quasi-brittle process of failure of composites, where the gradual unloading of a ply after the onset of damage is simulated by means of a material degradation model. Non-linear constitutive models defined in the context of the mechanics of continuum mediums have been developed and implemented in FE codes in the past. The damage model used in this work is an extension to three-dimensional scenarios of the plane stress formulation proposed by Maimí et al. [3,4] for in-plane behaviour which was previously used by the authors to predict the progressive failure behaviour of tow steered composite panels in postbuckling [5], and size effects in notched composites [6]. The main advantages of this formulation in relation to previously developed damage models by other authors are: (i) the use of the physically-based LaRC04 failure criteria [7] for the prediction of the onset of matrix

* Corresponding author. Tel.: +351 22 5081753; fax: +351 22 5081584.
E-mail address: pcamanho@fe.up.pt (P.P. Camanho).

0266-3538/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.compscitech.2009.02.015

cracking and fiber fracture under tensile and compressive loads; (ii) the accounting for the in situ effects of ply thickness and surface constraining on the ply transverse tensile and shear strengths [8]; (iii) the modification of Bažants crack band model [9] to ensure a mesh independent solution in scenarios where the fracture planes may have several orientations, and (iv) the simulation of crack-closure effects under load reversal cycles.

The interfaces between the plies are simulated by means of cohesive elements, as proposed by Turon et al. [10]. Cohesive elements constitute a reliable numerical tool in the prediction of delaminations under several loading scenarios.The application of these models is, however, limited to the range of quasi-static loading and low strain-rates situations where low-velocity impact events can be considered to fit [11].

2. Impact damage models

Two distinct formulations are used to simulate the damage phenomena occurring in layered composites under out-of-plane, low-velocity impact loads: (i) a continuum damage model to address the matrix and fibre damage occurring at ply level and (ii) a cohesive damage model to account for delamination. While in the case of delamination the crack plane is known *a priori*, the location and direction of matrix cracks and fibre breakage bands needs to be determined along with the analysis.

The intraply damage model used in this work is an extension to three-dimensional solid elements of the plane stress formulation implemented by Maimí et al. [3,4] in shell elements. The cohesive damage model is based on the explicit implementation [12] of the formulation proposed by Turon et al. [10]. Both constitutive models were coded as Abaqus/Explicit VUMAT user-written subroutines [13]. The models used to simulate ply damage and delamination are thoroughly described in references [3,4,10,12] and will not be elaborated here except for their main aspects which will be briefly described in the following paragraphs.

2.1. Continuum damage model for a 3D ply

For each damage mode, the ply constitutive model used in this work follows the general form schematically represented in Fig. 1. The material response is linear-elastic until the onset of damage and, at higher strains, it softens according to an exponential law.

The proposed complementary free energy density of a transversely isotropic ply ($E_2 = E_3, G_{12} = G_{13}$, and $\nu_{12} = \nu_{13}$) is defined as:

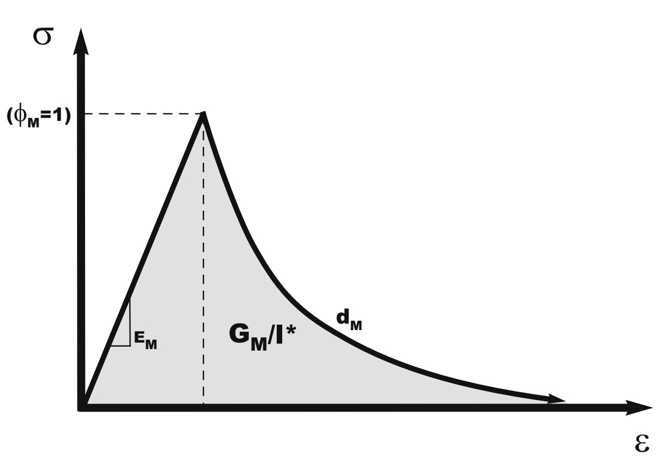

Fig. 1. Parameters of the intraply damage model.

$$G = \frac{\sigma_{11}^2}{2(1-d_1)E_1} + \frac{1}{2E_2}\left[\frac{\sigma_{22}^2}{(1-d_2)} + \frac{\sigma_{33}^2}{(1-d_3)}\right] - \frac{\nu_{12}}{E_1}(\sigma_{22}+\sigma_{33})\sigma_{11} - \frac{\nu_{23}}{E_2}\sigma_{22}\sigma_{33} + \frac{\sigma_{12}^2}{2(1-d_6)G_{12}} + \frac{\sigma_{12}^2}{2(1-d_5)G_{12}} + \frac{\sigma_{23}^2}{2(1-d_4)G_{23}} + [\alpha_{11}\sigma_{11} + \alpha_{22}(\sigma_{22}+\sigma_{33})]\Delta T + [\beta_{11}\sigma_{11} + \beta_{22}(\sigma_{22}+\sigma_{33})]\Delta M \quad (1)$$

where d_1 is the damage variable associated with longitudinal (fibre) failure. The transverse matrix cracking is controlled by d_2, for in-plane loads, and by d_3 for out-of-plane loads. The damage variables d_4, d_5 and d_6 are influenced by longitudinal and transverse cracks. α_{ii} and $\beta_{ii}, (i = 1, 2)$ are, respectively, the coefficients of thermal and hygroscopic expansion in the longitudinal $(i = 1)$ and transverse directions $(i = 2)$. The temperature and moisture content variations with respect to the corresponding reference values are expressed in ΔT and ΔM, respectively.

The strain tensor, $\varepsilon = \{\varepsilon_{11}, \varepsilon_{22}, \varepsilon_{33}, \gamma_{12}, \gamma_{13}, \gamma_{23}\}^T$, results from the differentiation of the complementary free energy density with respect to the stress tensor, $\sigma = \{\sigma_{11}, \sigma_{22}, \sigma_{33}, \sigma_{12}, \sigma_{13}, \sigma_{23}\}^T$:

$$\varepsilon = \frac{\partial G}{\partial \sigma} = \mathbf{H} : \sigma + \alpha\Delta T + \beta\Delta M \quad (2)$$

Here, $\mathbf{H}$ is the lamina compliance tensor represented as:

$$\mathbf{H} = \frac{\partial^2 G}{\partial\sigma \otimes \partial\sigma} = \begin{bmatrix} \frac{1}{(1-d_1)E_1} & -\frac{\nu_{12}}{E_1} & -\frac{\nu_{12}}{E_1} & 0 & 0 & 0 \\ -\frac{\nu_{12}}{E_1} & \frac{1}{(1-d_2)E_2} & -\frac{\nu_{23}}{E_2} & 0 & 0 & 0 \\ -\frac{\nu_{12}}{E_1} & -\frac{\nu_{23}}{E_2} & \frac{1}{(1-d_3)E_2} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{(1-d_6)G_{12}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{(1-d_5)G_{12}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{(1-d_4)G_{23}} \end{bmatrix} \quad (3)$$

The longitudinal and transverse (in-plane and out-of plane) damage variables are calculated as:

$$\begin{aligned} d_1 &= d_{1+}\frac{\langle\sigma_{11}\rangle}{|\sigma_{11}|} + d_{1-}\frac{\langle-\sigma_{11}\rangle}{|\sigma_{11}|} \\ d_2 &= d_{2+}\frac{\langle\sigma_{22}\rangle}{|\sigma_{22}|} + d_{2-}\frac{\langle-\sigma_{22}\rangle}{|\sigma_{22}|} \\ d_3 &= d_{2+}\frac{\langle\sigma_{33}\rangle}{|\sigma_{33}|} + d_{2-}\frac{\langle-\sigma_{33}\rangle}{|\sigma_{33}|} \end{aligned} \quad (4)$$

where $\langle x\rangle$ is the McCauley operator defined as $\langle x\rangle := (x + |x|)/2$. Damage caused by tension loads (d_+) is tracked separately from damage caused by compression loads (d_-). In this way, the eventual closure of transverse cracks under load reversal is taken into account. Depending on the sign of the corresponding normal stress, a damage mode can be either active or passive. The model also assumes that the shear damage variables, d_4, d_5 and d_6 are not affected by the closure effect. Shear damage is caused mainly by transverse cracks and these do not close under shear stresses [14].

2.1.1. Damage activation functions

The elastic domain is assumed to be bounded by four distinct damage activation functions based on the LaRC04 failure criteria [7]: longitudinal and transverse fracture under tension and compression. The four damage activation functions, F_N, associated with damage in the longitudinal $(N = 1+, 1-)$ and transverse $(N = 2+, 2-)$ directions are defined as:

$$\begin{aligned} F_{1+} &= \phi_{1+} - r_{1+} \leqslant 0; \quad F_{1-} = \phi_{1-} - r_{1-} \leqslant 0 \\ F_{2+} &= \phi_{2+} - r_{2+} \leqslant 0; \quad F_{2-} = \phi_{2-} - r_{2-} \leqslant 0 \end{aligned} \quad (5)$$

where the loading functions $\phi_N (N = 1+, 1-, 2+, 2-)$ depend on the strain tensor and on the material constants (elastic and strength