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Modelling impact damage in composite laminates: A simulation of intra- and inter-laminar cracking

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ABSTRACT

In this work, stress- and fracture mechanics-based criteria are developed to predict initiation and evolution, respectively, of intra- and inter-laminar cracking developed in composite laminates subjected to a relatively low energy impact (⩽15 J) with consideration of nonlinear shear behaviour. The damage model was implemented in the finite element (FE) code (Abaqus/Explicit) through a user-defined material subroutine (VUMAT). Delamination (or inter-laminar cracking) was modelled using interface cohesive elements while splitting and transverse matrix cracks (intralaminar cracking) that appeared within individual plies were also simulated by inserting cohesive elements along the fibre direction (at a crack spacing determined from experiments for computing efficiency). A good agreement is obtained when the numerically predicted results are compared to both experimentally obtained curves of impact force and absorbed energy versus time and X-ray radiography damage images, provided the interface element stiffness is carefully selected. This gives confidence to selected fracture criteria and assists to identify material fracture parameters that influence damage resistance of modern composite material systems.

1. Introduction

Composite structures usually exhibit a relatively brittle behaviour and complicated damage patterns that develop internally and are thus difficult to detect [1,2]. Internal damage occurs in the form of resin cracking and delamination that leads to loss of stiffness and eventually load-carrying capability when fibres break. Thus, it is important to understand and model the progressive damage of composite laminates in the design and fabrication of aircraft structural components [3].

A finite element (FE) model that is carefully developed can accurately predict in relatively short time the complex internal damage pattern that is formed in composite laminates when subjected to impact loading. It is a desirable approach to avoid the considerably expensive and time consuming process of performing the physical experiment. Composite material failure criteria have been proposed to predict damage initiation and evolution, for different damage modes [4–6]. Continuum damage mechanics (CDM) models have been reported to model damage evolution in composite laminates subjected to impact [7–10]. In addition, a theoretical approach known as the Equivalent Constraint Model (ECM), based on a 2-D shear lag analysis was developed to successfully predict matrix cracking and matrix crack induced delamination responsible for stiffness degradation in laminates under multi-axial in-plane loading [11–14]. Although methods have been published that predict the extent of the damaged area, there are few methods that simulate the process of matrix cracking within a damaged region.

In this paper, the impact induced damage was modelled by implementing a user-defined 3D damage model into the VUMAT subroutine of the finite element code Abaqus/Explicit. Interface cohesive elements are inserted between neighbouring plies to simulate delamination, and also between adjacent elements along the fibre direction within the individual layer; it is assumed to have equally spaced internal cracks to simulate splitting (0°) and transverse matrix cracking (90°) for a cross-ply laminated composite plate. A general contact algorithm is defined with appropriate contact pair properties to represent the contact between the impactor and the composite plate surface, as well as the contact between layers. Results from the simulation of matrix cracking and splitting as well as delamination have been compared to experimental measurements and observations in

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order to assess the capability of the proposed damage model to predict the impact induced damage.

2. Material damage model

2.1. Damage formulation

The Hashin failure criterion [4,5] has been widely applied to predict the initiation of damage in a unidirectional composite by performing a ply-by-ply analysis. However, the matrix compressive damage cannot be accurately modelled, since fracture may occur at an angle through the ply thickness. Thus, in the present study, the Puck damage model [6] was used for its prediction, while the Hashin criteria [4,5] were selected to estimate the initiation of fibre breakage and tensile matrix damage modes, i.e.,

Fibre tensile failure ($\hat{\sigma}_{11} \geq 0$):

$$F_{ft} = \left(\frac{\hat{\sigma}_{11}}{X^T}\right)^2 + \kappa\left(\frac{\hat{\sigma}_{12}}{S_{12}}\right)^2 = 1 \tag{1}$$

Fibre compressive failure ($\hat{\sigma}_{11} < 0$):

$$F_{fc} = \left(\frac{\hat{\sigma}_{11}}{X^C}\right)^2 = 1 \tag{2}$$

Matrix tensile failure ($\hat{\sigma}_{22} \geq 0$):

$$F_{mt} = \left(\frac{\hat{\sigma}_{22}}{Y^T}\right)^2 + \left(\frac{\hat{\sigma}_{12}}{S_{12}}\right)^2 + \left(\frac{\hat{\sigma}_{23}}{S_{23}}\right)^2 = 1 \tag{3}$$

Matrix compressive failure ($\hat{\sigma}_{22} < 0$):

$$F_{mc} = \left(\frac{\sigma_{TN}}{S_{23}^A + \mu_{TN}\sigma_{NN}}\right)^2 + \left(\frac{\sigma_{LN}}{S_{12} + \mu_{LN}\sigma_{NN}}\right)^2 = 1 \tag{4}$$

In Eqs. (1)–(4), $\hat{\sigma}_{ij}$ (i, j = 1, 2, 3) is the effective stress tensor that is used to evaluate the initiation criteria, X^T and X^C denote the tensile and compressive strengths of the unidirectional laminate in the fibre direction, Y^T is the tensile strength in the transverse direction, S_{12}, S_{13} and S_{23} denote the in-plane and out-of-plane shear strengths of the composite, respectively. The coefficient κ in Eq. (1) accounts for the contribution of shear stress to fibre tensile failure, which is assumed equal to unity. In Eq. (4), σ_{ij} ($i, j = L, T, N$) is the stress tensor σ_{ij}(i, j = 1, 2, 3) rotated to the fracture plane by using the transformation matrix $T(\alpha)$:

$$\sigma_{LTN} = T(\alpha)\sigma_{123}T(\alpha)^T \tag{5}$$

S_{23}^A is the transverse shear strength in the fracture plane, which can be determined by the transverse compression strength and the angle of fracture plane. The key concept of Puck's failure criterion

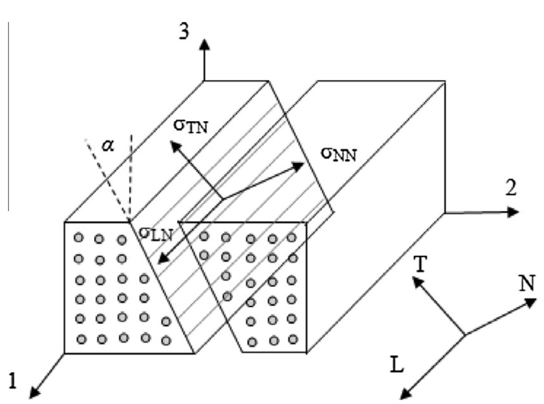

Fig. 1. Fracture plane defined for matrix compressive damage in a unidirectional ply. Local and global coordinates are shown.

is to determine the inclination or orientation of the fracture plane by calculating the angle, α, as shown in Fig. 1 [6]. To predict the different stress states of composites the angle α of the fracture plane should be varied and it could be implemented in FE program by calculating the different fracture angles in the range $-90° \ll \alpha \ll 90°$ and the fracture angle is then determined as which makes the damage initiation index of F_{mc} maximum.

The friction coefficients μ_{NT} and μ_{NL} in Eq. (4) can be defined based on the fracture angle α and material property referring to the Mohr–Coulomb failure criteria.

$$\mu_{NT} = \tan(2\alpha - 90°) \tag{6}$$

$$\mu_{NL} = \frac{\mu_{NT}}{S_{23}^A} S_{12} \tag{7}$$

Once damage occurs, its growth requires defining a stiffness degradation rule. Here, the stiffness is assumed to degrade linearly in terms of represented strain based damage variable that is continuously updated by the FE approach with increasing applied load. For fibre or matrix tensile damage, this is expressed as:

$$d_{1,2}^T = \frac{\varepsilon_{1,2}^{fT}}{\varepsilon_{1,2}^{fT} - \varepsilon_{1,2}^{0T}}\left(1 - \frac{\varepsilon_{1,2}^{0T}}{\varepsilon_{1,2}}\right) \tag{8}$$

where the subscripts 1 and 2 denote parallel and transverse to the fibre direction, respectively; $\varepsilon_{1,2}^{0T}$ is the tensile strain for damage initiation, and $\varepsilon_{1,2}^{fT}$ denotes the tensile strain at final failure where the damage variable reaches one. Due to the irreversibility of the damage variable, the strain tensor $\varepsilon_{1,2}$ in Eq. (8) is updated at each time step and defined as $\varepsilon_{1,2} = \max(\varepsilon_{1,2}, \varepsilon_{1,2}^{0T})$. In order to avoid zero or negative energy absorption values due to damage, the strain at final failure needs to be greater than the initial failure strain, i.e., $\varepsilon_{1,2}^{fT} > \varepsilon_{1,2}^{0T}$. The final failure strain is expressed in terms of the fracture toughness $G_{1,2C}^T$ associated with fibre (1) or matrix (2) tensile failure, the failure strength (X^T or Y^T) and the characteristic length, l^*:

$$\varepsilon_1^{fT} = \frac{2G_{1C}^T}{X^T l^*} \tag{9a}$$

$$\varepsilon_2^{fT} = \frac{2G_{2C}^T}{Y^T l^*} \tag{9b}$$

where l^* is chosen such as to keep an energy release per unit area of crack constant and make the final results independent of the FE mesh size, which is defined in Abaqus manual regarding to different types of elements used [15]. Similarly, for the fibre compressive damage mode, a damage variable for evolution is defined as above, Eqs. (8) and (9), but in terms of fracture toughness and strength related to fibre compressive damage. It should be added that since matrix compressive damage occurs at an angled fracture plane, the strains used to define its evolution should be transferred to that fracture plane.

2.2. Damage laws for cohesive elements

The simulation of delamination in composite laminates is complicated and usually delamination initiation and progression can be performed as separate procedures. Delamination initiation can be modelled based on stress or strain criteria such as the maximum stress/strain criteria or the quadratic laws of the interlaminar stresses/strains to express their interaction effects, while an energy based criterion is generally applied to predict the degradation due to damage evolution [16–18]. The cohesive zone elements are found to be an effective way to capture the form and propagation of delamination at the interface of adjacent plies through the definition of initiation and evolution laws for damage. Camanho