A SUB-LAMINATE BASED DAMAGE MODEL TO SIMULATE INITIATION AND GROWTH OF CRACKS IN LAMINATED COMPOSITES

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ABSTRACT. *A damage mechanics based model is proposed to simulate initiation and growth of intra-laminar damage in fibre-reinforced laminated composites. Some examples are presented to show the performance of the proposed approach in predicting crack paths in notched tensile coupons of multi-directional laminates.*

INTRODUCTION

Prediction of failure in laminated composite structures has posed many challenges for researchers. In recent years, numerous papers have been published in this area to address the complex damage behaviour of laminated composites ([1-4] among others). However, there are still several issues that require further investigations.

A popular approach in simulation of laminated composites is the so-called ply-based approach where the damage behaviour in each and every ply of a laminate is modelled in isolation. Plies are usually connected to each other by a cohesive interface (e.g. [1-3] and [5, 6]). The advantage of this approach is that the resulting damage models are relatively straightforward to formulate and calibrate. However, the unrealistic assumption that each ply behaves independently of its neighbours is a major disadvantage of this methodology.

The sub-laminate based approach proposed by Williams et al. [4], on the other hand, considers a repeated unit volume (sub-laminate) as the basis for the damage model and in so doing implicitly accounts for the interaction between the neighbouring layers.

The current investigation involves further enhancements of the Composite Damage Model (CODAM) [4] within the framework of the sub-laminate approach.

Composite Damage Model

The damage model proposed here is based on the concept of smeared cracking where crack/damage is smeared over an area with a certain size, and damage is simulated as the degradation in the secant stiffness of the material.

The smeared cracking and damage models derived from it are widely used in the simulation of isotropic quasi-brittle materials such as concrete [7, 8].

The same concept has been adopted in the simulation of damage and failure in orthotropic media such as laminated composites (e.g. [2-4]).

The damage model proposed in this paper further enhances the previously developed Composite Damage Model (CODAM) [4] and intends to simulate the overall behaviour of a sub-laminate under in-plane loading. Therefore each element in the finite element simulation represents a stack of plies (sub-laminate) through its thickness. To study the behaviour of such a complex system, we assume that a laminated composite consists of a base isotropic material (the matrix) that is reinforced in certain directions with fibres. Based on this assumption, the matrix and the embedded fibre system are subject to the same strain field (iso-strain condition).

The behaviour of the laminate under the ultimate loading condition will be determined based on contributions of the matrix and fibres. The first step is to additively decompose the stiffness of the ply into an isotropic part and an orthotropic part as shown in Equation (1) below.

$$K_{ply} = \left(K_m\right)_{isotropic} + \left(K_f\right)_{orthotropic} \tag{1}$$

Table 1 shows an example of decomposition of the stiffness matrix of a ply of IM7-8552 CFRP material.

The laminate's stiffness matrix is built-up by superposing the matrix and layers of fibres with the consideration of the orientation of fibres. For example, Equation (2) shows the stiffness of a [0/45/-45/90] quasi-isotropic laminate written in terms of the fibre and matrix components and the rotation tensor.

$$K_{Laminate} = K_m + \frac{1}{4} T_{90}^{*T} K_f T_{90} + \frac{1}{4} T_{45}^{*T} K_f T_{45} + \frac{1}{4} T_{-45}^{*T} K_f T_{-45} + \frac{1}{4} T_{0}^{*T} K_f T_{0} \tag{2}$$

where T and T^* are rotation matrices for 2D stress and strain vectors, respectively.

Failure of the fibres and the matrix is modelled by strain-softening laws assigned to each constituent. Here it is assumed that damage in the matrix is a function of the maximum principal strain while damage in the fibre depends on its longitudinal strain. Figure 1 shows a schematic view of the fibre configuration in a quasi-isotropic laminate and a typical governing strain-softening curve.

Predictions of the Proposed Damage Model

In this paper, predictions of the proposed damage model in terms of direction of growth of the crack/damage in laminated composites are presented. The proposed damage model is employed in the simulation of crack growth in an Overheight Compact Tension (OCT) specimen [9] as shown in Figure 2. The predictions of the crack path in unidirectional lamina, cross-ply and angle-ply laminates are presented here.

Table 1. An example of decomposition of a ply's stiffness matrix into isotropic and orthotropic parts.

$K_{ply} = \begin{bmatrix} 181.8 & 2.9 & 0 \\ 2.9 & 10.1 & 0 \\ 0 & 0 & 7.2 \end{bmatrix} \text{GPa}$	Ply's stiffness matrix
$K_m = \begin{bmatrix} 10.1 & 2.9 & 0 \\ 2.9 & 10.1 & 0 \\ 0 & 0 & 3.9 \end{bmatrix} \text{GPa}$	Isotropic part (Matrix's stiffness matrix)
$K_f = \begin{bmatrix} 171.7 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 3.3 \end{bmatrix} \text{GPa}$	Orthotropic part (Fibre's stiffness matrix)

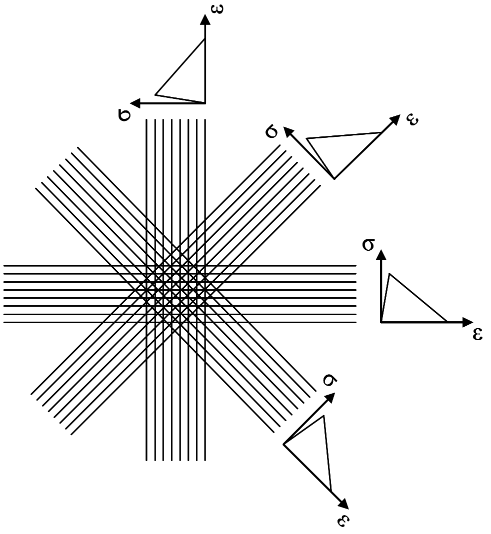


Figure 1. Arrangement of fibres in a [0/45/-45/90] quasi isotropic laminate.

Unidirectional lamina

A unidirectional lamina exhibits a strong orthotropic behaviour. In this case the propagation of crack in a notched tensile specimen not only depends on the direction of the initial notch, but also strongly depends on the orientation of the fibres with respect to the global loading direction.

(a) Fibres parallel to initial notch

When fibres are parallel to the initial notch direction, transverse cracks in the matrix result in the crack propagating in the form of a straight line along the initial notch.

Figure 3a shows the predicted crack path in this case. Dashed lines show the direction of fibres in the material.

(b) Fibres perpendicular to initial notch

In the case when fibres are perpendicular to the initial notch direction, matrix cracks grow along a straight line perpendicular to the initial notch. Figure 3b shows the predicted crack path in this case. This type of failure is known as splitting of the fibres and matrix and it occurs due to the fact that matrix is much weaker than the fibres, and because of the extreme orthotropy of the lamina, crack grows perpendicular to its initial path.

(c) Fibres inclined at 45° to the initial notch direction

In this case the crack propagation is similar to the previous two cases, in the sense that it occurs parallel to the direction of the fibres and splitting of fibres and matrix is observed as shown in Figure 3c.

Multi-directional laminates

The prediction of damage growth in multi-directional laminates is generally difficult due to the presence of multiple fibre directions that affect the stress and strain fields.

(a) Cross-ply laminates

In notched cross-ply specimens, fibres are placed parallel and perpendicular to the initial notch direction. Figure 4a shows the predicted direction of the damage growth, which is parallel to the notch direction, i.e. transverse to the applied load.

(b) Angle-ply laminates

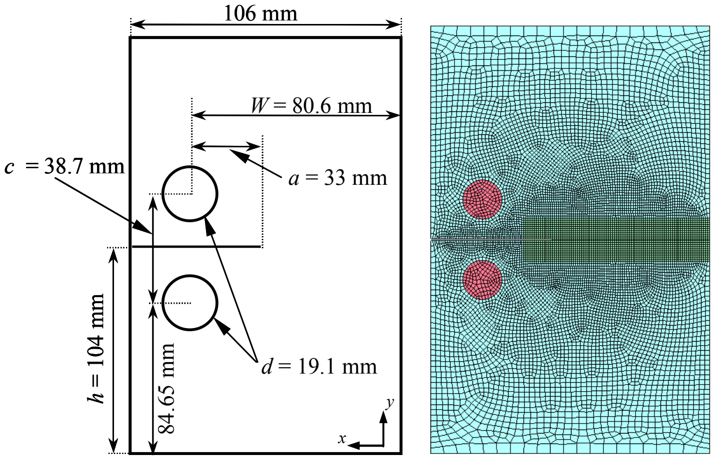
In an angle-ply laminate with ±45° angles with respect to the notch direction the crack branches in two directions each of which is parallel to the fibre directions.

(c) A [30°/60°] laminate

The behaviour of a [30°/60°] laminate is studied here. In this case, the crack path is affected by the direction of the fibres and it propagates in a direction that lies in between the two fibre orientations.

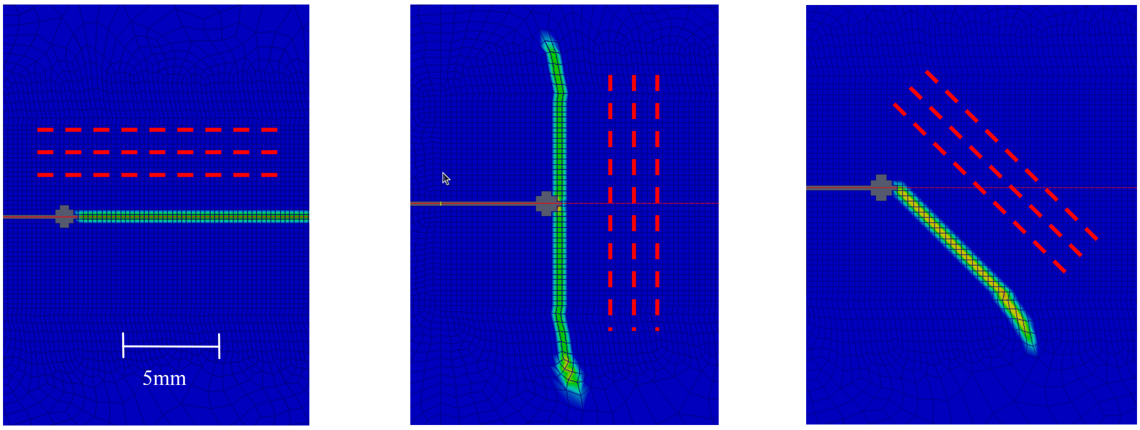
Conclusion

A new damage model based on the sub-laminate concept was proposed in this paper. In this work, ply's stiffness matrix was decomposed into an isotropic base (governed by properties of the matrix) and an orthotropic reinforcement (governed by properties of the fibre). It was shown that the proposed approach is capable of predicting the direction of crack and damage growth in unidirectional as well as multi-directional laminated composites. Without explicitly accounting for fibre orientations (in an otherwise smeared through-thickness resolution in a sub-laminate approach), the predicted crack paths would be erroneous.



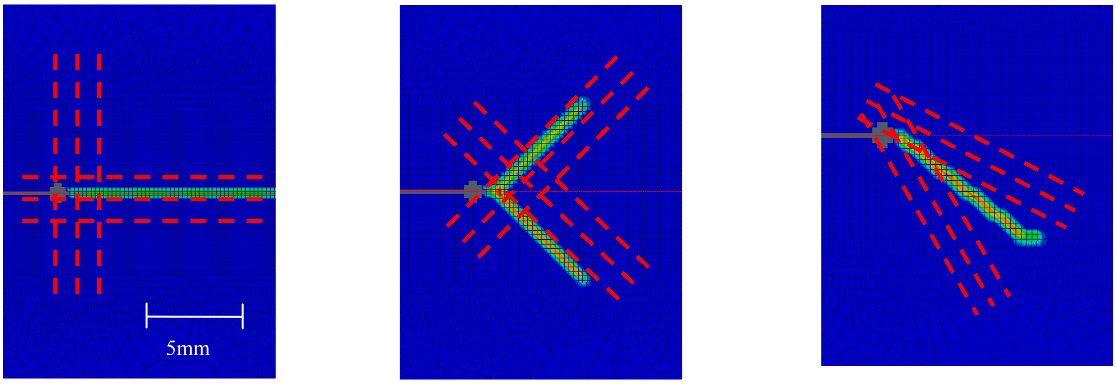
(a) (b)

Figure 2. (a) Schematic diagram of an OCT specimen geometry, and (b) finite element mesh used for its simulation.



(a) (b) (c)

Figure 3. Predicted crack path in unidirectional laminates in an OCT specimen geometry: (a) fibres are parallel to the initial notch, (b) fibres are perpendicular to the initial notch, and (c) fibres are inclined at 45° with respect to the initial notch direction.



(a) (b) (c)

Figure 4. Predicted crack path in multi-directional laminates in an OCT specimen. (a) a [0º/90º] cross-ply laminate, (b) a [+45º/-45º] angle-ply laminate, and (c) a [30º/60º].

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