AN EXTENDED COHESIVE DAMAGE MODEL FOR HIGHLY EFFICIENT PREDICTION OF MULTI-DELAMINATION IN SANDWICH COMPOSITES

X Li and *J Chen

School of Civil Engineering and Surveying, University of Portsmouth
Portland Street, Portsmouth PO1 3AH, UK
*Corresponding address: jiye.chen@port.ac.uk
http://www.port.ac.uk/school-of-civil-engineering-and-surveying/staff/dr-jiye-chen.html

Keywords: ECDM, Damage, Multi-delamination, Sandwich composites, XFEM

ABSTRACT

An extended cohesive damage model (ECDM) has been recently developed by authors for predicting multicrack failure mechanism in fibre composite materials [1-4]. The ECDM is a fully condensed extended finite element method (XFEM) formulation with enriched degree of freedoms eliminated. The effects from enrichment and cohesive force are accounted into the fully condensed FEM formulation. An equivalent damage scalar relating to a strain filed is introduced in terms of energy dissipation during the post-failure process to characterize the damage evolution. This paper briefly presents the basic ECDM formulation and its application of predicting multi-delamination in sandwich composites. This investigation proves the rubout capability of the ECDM in predicting multi-delamination in sandwich composites with great computational efficiency.

1 INTRODUCTION

Predicting the reality of failure behaviour of laminated composites is still a challenge for academics and engineers in composites related societies. Previous numerical approaches have considerable drawbacks in this area. For example, the extended finite element (XFEM) has restraints in simulating multiple different cracks in composites and drawbacks in computational efficiency due to additional enriched degree freedoms. A cohesive zone model (CZM) can be applied in simulating cracks along the element boundaries within which prepared crack paths are required, also its computational efficiency is a considerable issue.

The extended cohesive damage model (ECDM) introduced in this paper aims to meet the challenge in computational damage analysis in composites. The ECDM is a highly efficient modelling approach for accurate predictions of multicrack including matrix crack, debonding, delamination and fibre breakage in composites. Unlike the CZM, this model does not need a prepared crack path, it conducts a solution dependant crack path. This model can effectively and efficiently play a role in predicting multicrack failure mechanism in composites. This capability will help academics and engineers in studying detailed failed mechanism in designing laminated composites.

2 BASIC ECDM FORMULATIONS

The displacement approximation in 2D domain within a cracked element can be expressed by Eq. (1):

$$\begin{Bmatrix} u \\ v \end{Bmatrix} = \sum_{i=1}^{4} N_i(\xi,\eta) \begin{Bmatrix} u_i \\ v_i \end{Bmatrix} + \sum_{i=1}^{4} step_i(\xi,\eta) N_i(\xi,\eta) \begin{Bmatrix} u_i^{'} \\ v_i^{'} \end{Bmatrix} \qquad (1)$$

Where, the shifted Heaviside function can be written as:

$$step_i(\xi,\eta) = \mathscr{H}_{\Gamma_d}(\xi,\eta) - \mathscr{H}_{\Gamma_d}(\xi_i,\eta_i) \qquad (2)$$

Using the weak form of equilibrium equation from Bubnov-Galerkin method, the discrete form of equilibrium equation can be written as shown in Eq. (3).

$$\begin{bmatrix} \mathbf{K}^{uu} & \mathbf{K}^{ua} \\ \mathbf{K}^{au} & \mathbf{K}^{aa} \end{bmatrix} \begin{bmatrix} \mathbf{u} \\ \mathbf{a} \end{bmatrix} = \begin{bmatrix} \mathbf{f}^{u}_{ext} \\ \mathbf{f}^{a}_{ext} \end{bmatrix} \qquad (3)$$

Where, $\mathbf{K}^{uu}$ and $\mathbf{K}^{aa}$ are the stiffness matrices associated with the standard FE approximation and the enriched approximation, respectively; $\mathbf{K}^{ua}$ and $\mathbf{K}^{au}$ account for the coupling between the standard FE approximation and the enriched approximation; $\mathbf{f}^{u}_{ext}$ and $\mathbf{f}^{a}_{ext}$ are the equivalent nodal force vectors for standard FEM DoFs and enriched DoFs, respectively; **u** denotes the standard DoFs while **a** denotes the enriched DoFs. A fully condensed equilibrium equation after eliminating enrichment is given by Eq. (4).

$$\left(\mathbf{K}^{uu} - \mathbf{K}^{ua}\left(\mathbf{K}^{aa}\right)^{-1}\mathbf{K}^{au}\right)\mathbf{u} = \mathbf{f}^{u}_{ext} \text{-} \mathbf{K}^{ua}\left(\mathbf{K}^{aa}\right)^{-1}\mathbf{f}_{coh} \qquad (4)$$

3 A SCHEME FOR SIMULATING MULTICRACK IN COMPOSITES

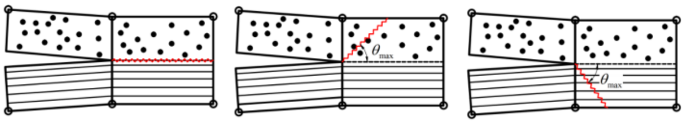
Multiple fracture modes in fibre laminated composites include matrix crack, fibre breakage and delamination as shown in Fig. 1. In the case of matrix crack and fiber fracture, a maximum principal stress based criteria is used to characterize the damage initiation, which means when the maximum principal stress $\sigma_{\max}$ at gauss points of any elements is beyond the cohesive strength S_{matrix} for matrix or S_{fibre} for fibre, the damage onsets. The perpendicular direction to the direction of the maximum principal stress is adopted to be the crack direction within the cracked element, which provides a potential arbitrary crack propagation. It should be noted that a brittle fracture is assumed in the case of fibre breakage. As shown in Fig. 1, the average maximum principal stresses from four Gauss points at the upper layer (90º ply) and the lower layer (0º ply) are calculated for the judgment of matrix crack and fiber breakage, respectively. The fracture directions of matrix crack and fiber breakage are veraciously determined by the $\theta_{\max}$, which is perpendicular to the direction of the maximum principal stress. On the presence of delamination, a stress based criteria given in the Fig. 1 and the stresses of the mid-point at the interface between two plies are used for the judgment of damage initiation. Considering a general mix-mode delamination propagation, a mix-mode criterion proposed by Benzeggagh and Kenane [5], i.e. a total fracture energy as a function of crack mode ratio given in Eq. (5) is used in this investigation.

$$G_f = G_{f,I} + \left(G_{f,II} - G_{f,I}\right)\left(\frac{1}{1+\beta}\right)^{\eta} \qquad (5)$$

Where the mix-mode parameter η is taken as 1.39. $G_{f,I}$ and $G_{f,II}$ are fracture energy corresponding to pure mode I and mode II fracture, respectively. For a normal opening delamination case, the mix-mode ration β is defined as:

$$\beta = \frac{\sigma_n^0}{N} \Big/ \frac{\sigma_s^0}{S} \qquad (6)$$

Where σ_n^0 and σ_s^0 are the normal and shear initial stress, respectively, corresponding to the onset of damage initiation under mix-mode loading; N and S are the material strength corresponding to Mode I and Mode II fracture, respectively. The path of delamination propagation is prescribed along the physical interface boundary when $\theta_{\max}$ is zero.



$$\left(\frac{\langle \tau_n \rangle}{N}\right)^2 + \left(\frac{\langle \tau_s \rangle}{S}\right)^2 \geq 1 \qquad \sigma_{\max} \geq S_m \qquad \sigma_{\max} \geq S_f$$

$$\theta_{\max} = 0 \qquad \theta_{\max} > 0 \qquad \theta_{\max} < 0$$

Fig. 1. A schematic illustration of failure mechanism judgments in fibre composites,
a): Delamination, b): Matrix crack, c): Fibre breakage

4 APPLICATIONS

As an example, the ECDM is applied for predicting multi-delamination in a sandwich composite panel. This sample shown in Fig. 2 is manufactured as a 50mm square plate with 30mm thickness, consisting of three layers: glass fibre laminates (GFLC) on the top and the bottom and the core of polymer foam. Each GFLC layer is a 5mm thick with $0^0/90^0$ woven cross plies. The ECDM based 2D plain strain model is applied to predict its major failure mode: the multi-delamination or debonding along the two interfaces between the core and GFLC on the top and the bottom of the sample under bending. Fig. 3 shows the failed deformation with two delaminations predicted by an ECDM based half model. The corresponding failure response can be seen from Fig. 4. It can be seen from Fig. 4 that the ECDM prediction has a good agreement with test measurement. The CPU time spent by the ECDM model on this example is only 95 second. Therefore, the developed ECDM is a highly efficient and accurate numerical approach, which can be used for fundamental study of failure mechanism of laminated composites and prediction of failure modes in composite structures.

Fig. 2. A sample of sandwich panel

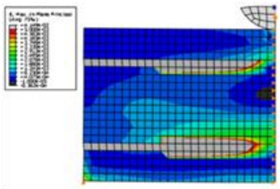


Fig. 3. The failed deformation with two delaminations

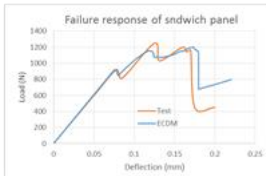


Fig. 4. The failure response

5 CONCLUSIONS

A brief introduction to the ECDM formulation and a scheme for simulating multicrack in laminated composites were given in this paper. An application of the ECDM in predicting two delamination propagations of a glass fibre sandwich sample was presented. This investigation shows that the ECDM is a robust approach in predicting multi-delamination in fibre composite sandwich composites. Especially, the ECDM can guarantee the solution from nonlinear facture analysis with much reduced CPU time, which is a significant issue in conventional numerical approaches. This investigation showed the ECDM can be a promised tool in studying detailed fracture mechanism in laminated composite structures.

REFERENCES

[1] X Li and J Chen, An extended cohesive damage model for simulating arbitrary damage propagation in engineering materials, Comput. Methods Appl. Mech. Engrg. 315, 744–759, 2017.

[2] X Li and J Chen, A highly efficient prediction of delamination migration in laminated composites using the extended cohesive damage model, Composite Structures, 160, 712–721, 2017.

[3] X Li and J Chen, An extended cohesive damage model for simulating multicrack propagation in fibre composites, Composite Structures, 143, 1–8, 2016.

[4] X Li and J Chen, The implementation of the extended cohesive damage model for multicrack evolution in laminated composites, Composite Structures, 139, 68–76, 2016.

[5] Benzeggagh, M. L., & Kenane, M., Measurement of mixed-mode delamination fracture toughness of unidirectional glass/epoxy composites with mixed-mode bending apparatus. Composites science and technology 1996; 56(4): 439-449.