The crack displacement prediction of a composite sample by modelling the mixed mode bending test

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Abstract. One of the main failure modes of laminate structures is interfacial failure by interlaminar failure or debonding. Interlaminar failure can be simulated with a model called cohesive zone approach. A key ingredient of a cohesive zone approach is a traction-separation law that describes the softening in the crack zone near the tip of interlaminar failure. This simulation utilized the implementation of a cohesive zone approach with traction-separation laws, which implemented within the thin elastic layer feature of the Solid Mechanics interface in a COMSOL Multiphysics analysis software’s on a sample of composite material APC-2/AS-4. The capabilities of the cohesive zone approach to predict mixed mode effect in the beginning and propagation of the crack are demonstrated in a model of mixed-mode bending test. Both load and displacement are measured at the crack interface. The maximum load that carried by the sample used was 257.8 N. Whereas the maximum displacement was 6 mm as a load-displacement curve was shown.

1. Introduction

The failure in a bonding agent in different composite/ laminated systems often grows to be as a dominant form of interlaminar damage between matched surfaces. Usually, the influence of both normal and shear stresses has a significant role to form this kind of damages. Therefore, the effects of these two stresses in combined must account for tests of interlaminar damage resistance.

In order to come up with advance test samples has combined normal and transverse stresses on the interlaminar plane, different approaches of samples were applied [1–5]. However, some types of samples were needed to generate toughness statistic's information over range of stress combinations that looked-for. For instance, Johnson and Mangalgiri measured some fracture toughness utilizing different types of interlaminar sample; “double cantilever beam, cracked-lap shear, edge-delamination tension, and end notch flexure” [6]. Accordingly, non-similar variables used can influence on results in ways that are hard to analyze. In this case, it is preferable to tend to use finite element (FE) method or statistical methods, like design of experiments, to investigate the parameters' effects on the results of the tests utilized [7, 8].

Cohesive Zone Approach (CZA) is used as appropriate constitutive equation in the formulation of the decohesion element for an accurate simulation of the crack processing. This approach considered that there is a zone located ahead of the tip of interlaminar damage named cohesive zone [9]. G. I. Barenblatt was the first one proposed the CZA concept which led to remove the crack tip individuality [10]. Physically, the CZA denotes the combination of trends in the layer rich in resin set at the interlaminar damage tip in order to reveal the losing way of load carrying ability of the tested sample. Comparing with the tested sample diminutions, if the size of the process zone is narrow, the behaviour of softening material locates to a thin layer next to the plane of crack is a faithful scheme for the simulation of the CZ and crack growth as reported by T. Ungsuwarungsri and W.G. Knauss [11]. A. Needleman applied the CZA on a boundary value problem and concluded highly applicable to this
approach using standard FE when interfacial strengths are almost low parallel with that of the neighbouring layers in composite materials [12]. This is due to stop developing of high-stress ramps related with cracks.

The aim of this study is modelling the interlaminar damage testing under effect of combined normal/tensile stress (mode A) and transverse/shear stress (mode B) by simulate a CZA in COMSOL Multiphysics to expect beginning of mixed mode softening and propagation of the interlaminar damage on the modelled sample of a double cantilever beam made by composite material under mixed mode bending test (MMBT).

2. The theory analysis

2.1. Definition of the model used

The CZA considered in the current work utilized a “bilinear traction-separation law”. The relation between the stiffness of penalty $Sp$ and the traction is linear until failure initiation displacement $di$ reached of the opening crack. When the crack opens afar $di$, the material become softer permanently, which led to decreases the stiffness as a function of the damage parameter $dp$. Thereby, when the value of the stiffness decrease to zero, the material fails at the maximum displacement $d_{max}$ value. The $di$ and $d_{max}$ values are depending on the separation displacement whether is it tangential or normal with an interface. The displacement of the failure initiation for mode A and mode B could be calculated following equations (1) and (2):

$$d_iA = \frac{\sigma_T}{Sp}$$  \hspace{2cm} (1)
$$d_iB = \frac{\tau_S}{Sp}$$  \hspace{2cm} (2)

Where $\sigma_T$ and $\tau_S$ are tensile and shear strength, respectively. The maximum displacement for each mode is determined based on either critical energy release $E_c$ or fracture toughness [13]:

$$d_{max}A = \frac{2E_cA}{\sigma_T}$$  \hspace{2cm} (3)
$$d_{max}B = \frac{2E_cB}{\tau_S}$$  \hspace{2cm} (4)

The softening in compression is neglected for mode A.

2.2. Mixed Mode Loading

The mixed mode relative displacement $dm$ is defined as equation (5) in which $dA$ and $dB$ are the normal and tangential relative displacement, respectively.

$$dm = \sqrt{dA^2 + dB^2}$$  \hspace{2cm} (5)

The mixity mode can be defined as $\phi$ ratio, equation (6).

$$\phi = \frac{dB}{dA}$$  \hspace{2cm} (6)

Thereby, the damage initiation $dm_i$ of the mixed mode was followed by equation (7) [14].

$$dm_i = d_iA \cdot d_iB \sqrt{\frac{\frac{1+\phi^2}{1+2\phi(\frac{d_iA)}{d_iB})^2}}{}}$$  \hspace{2cm} (7)

The exponent of “Benzeggagh and Kenane” criterion $\mu$ was utilized to compute the de-cohesion displacement of the mixed mode [15, 16].

$$dm_{max} = \frac{2}{Sp \cdot dm_i} \left[ E_{cA} + (E_{cB} - E_{cA}) \left( \frac{\phi^2}{1+\phi^2} \right)^\mu \right]$$  \hspace{2cm} (8)

The stiffness at the laminated interface depends on the displacement that captured with the maximum mixed mode displacement $d_f$ at the interface. Based on, the function of damage evolution was defined on equation (9).

$$dp = \frac{dm_{max}(E_{cB} - dm_i)}{d_f(dm_{max} - dm_i)}$$  \hspace{2cm} (9)

Based on previous equations, the stiffness of the normal and transvers displacements components of loads applied becomes as showing in equations (10) and (11), respectively [17].
3. The MMBT and Material Properties

The MMBT is often used to measure interlaminar damage resistance in composite materials [9]. Basically, this test combines both modes A and B by adding additional load on the “Mid-Span” loaded sample (Figure 1), in which tend to separate the arms of the laminate. Moreover, determination of the mixed mode mm ratio could be calculated based on the magnitudes of the two applied loads. The MMBT conducted after applying these loads through a lever, figure 1. The loading position c is important to determine and obtaining different ratios by controls the magnitude of the loads applied on the tested sample [9].

\[
S_A = \begin{cases} 
S_B \Leftarrow dA > 0 \\
S_P \Leftarrow dA \leq 0 
\end{cases} 
\]  \hspace{1cm} (10)

\[
S_B = \begin{cases} 
S_P \Leftarrow d_f \leq dm_i \\
(1 - dp) S_P \Leftarrow dm_i < d_f < dm_{max} \\
0 \Leftarrow d_f > dm_{max} 
\end{cases} 
\]  \hspace{1cm} (11)

![Figure 1. MMBT, test sample and apparatus.](image)

The FE model proposed here implemented via COMSOL software. In order to examine the accurateness of the proposed model, MMBT is simulated conducting a carbon-fiber composite sample of APC-2/AS-4 material with 100 mm × 25 mm dimensions to measures the interlaminar fracture toughness under mixed-modes of loading A and B. The material properties required are shown in Table 1. The experimental results that compared with numerical calculations involved the mixed mode fracture toughness and interlaminar fracture of initial length (a) obtained depend on J.R. Reeder and J.H. Crews work were performed in a reference to input data [18].

| Property                      | Value       |
|-------------------------------|-------------|
| Tensile strength ($\sigma_T$) | 80 MPa      |
| Shear strength ($\tau_S$)     | 100 MPa     |
| “Benzeggagh and Kenane” exponent ($\mu$) | 2.284       |
| Stiffness of Penalty ($S_P$)  | $10^6$ N/mm$^3$ |
| Young modulus $E_X$           | 122.7 GPa   |
| $E_Y, E_Z$                    | 10.1 GPa    |
| $G_YZ$                        | 3.7 GPa     |
| Shear modulus $G_{XY}, G_{XZ}$| 5.5 GPa     |
| $V_{YZ}$                      | 0.45        |
| Poisson ratio $V_{XY}, V_{XZ}$| 0.25        |
As shown in figure 1, the apparatus had two levers; one supported on the lower side of the beam by the outer edges, and the other sat on the upper surface of the beam in order to apply the load. Moreover, the lever itself was attached to the cracked area of the beam with the ability to twists around a contact area at the centre. The apparatus design gives an ability to levers to applying modes A and B load on the tested samples simultaneously with pushing of levers. Thereby, the mixed mode loading ratio can be adjustable by changing the lever length (2L). Instead of existence the levers, the loads were applied directly in the current model. A pulling load \( L_p \) is acting on the cracked edge from the sample. Whereas at the midpoint of the beam, the \( L_m \) load was applied downward. Ignoring lever's weight, both of \( L_p \) and \( L_m \) considered as a function of the total load, and the mixed mode ratio (mr) regulates the ratio of their magnitudes according to equation. \( \frac{L_m}{L_p} = 8 \left( \frac{6 \text{ mr}^2 + \sqrt{3 \text{ mr}(1-\text{mr})}}{3 + 9 \text{ mr} + 8 \sqrt{3 \text{mr}(1-\text{mr})}} \right) \) (12) [9, 18, 19].

4. Results and discussion

Figure 2 showing the meshed sample with sufficiently density consisting of 2416 domain elements, 3084 boundary elements, and 986 edge elements of hexahedral and quadrilateral types.

![Figure 2. The meshed/mapped sample.](image)

In the present, mr ratio of 0.5 was selected. Figure 3 (a-c) shows the develop of stresses at three steps of displacements; 0 mm (before loading), 2 mm, 4 mm, and 6 mm at last step of loading.

![Figure 3. The Von Mises stress distribution through loading steps.](image)

The loading effect at the last step of displacement on the propagation of initial crack is shown along the delamination interface in figure 4.
Figure 4. The intact and failed/laminated parts of the tested sample interface. The load-displacement curve that shown in figure 5 confirms the information could be concluded from figure 4. The beam/tested sample was applied 257.8 N as a maximum load before the failure occurring due to crack propagation.

Figure 5. The Load-displacement curve of the MMBT. Based on the Lp, Lm force on the lever can be determined via the length from the center of the sample to the lever edge ($L_{S-L}$) and sample/beam length $L_b$ as followed in equations (13) and (14) [20]:

$$L_m = L_p \left( \frac{L_b/2}{L_{S-L}} \right)$$

(13)

$$L_{S-L} = \frac{(L_b/2)\left(1/2 \sqrt{3(1-mr) + 1}\right)}{3 - 1/2 \sqrt{3(1-mr) + 1}}$$

(14)

Figure 6 shows the relation between data predicted from experimental results and the built model simulated. Based on the comparison between the experimental and productional results found, a good agreement was mostly obtained with error value of 4.5%.
This fact leads to predict not much difference in toughness between the experimental and the predicted measured could occurs also. Moreover, the predictions obtained reveals dropping in load value at the fractured zone than that found experimentally. This is possibly related to the fracture toughness increasing proportionally with crack lengths due to fiber bridges of the tested sample, which is hard to take into consideration through building of the model.

5. Conclusions remarks
A simulation of MMBT has been simulated for a sample of a double cantilever beam of APC-2/AS-4 composite. The mixed mode of loading was produced and the loading ratio was 50%. The conclusions based on the results can be summarized in the following:
1- A mixed mode of loading combined from normal and shear stresses was successfully simulated and conducted to predict the length of the interlaminar damage by utilizing the CZA in COMSOL Multiphysics.
2- The maximum displacement of the fracture was 6 mm at 257.8 N load applied as a maximum before the failure occurring due to crack.
3- A good agreement was obtained between the experimental results and the theoretical results that obtained from the model with low error value of 4.5%.
4- Applying of the MMBT on thin sheets of different materials is recommended to investigate the agreeability between the experimental and analytical results can be obtaining from the model used in the work.

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