COMPUTATION FOR THE DELAMINATION IN THE LAMINATE COMPOSITE MATERIAL USING A COHESIVE ZONE MODEL BY ABAQUS

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Abstract. In this paper, a damage model using cohesive damage zone for the simulation of progressive delamination under variable mode is presented. The constitutive relations, based on linear softening law, are used for simulating the delamination onset and propagation. The implementation of the cohesive elements is described, along with instructions on how to incorporate the elements into a finite element mesh. The model is implemented in a finite element formulation in ABAQUS. The numerical results given by this approach are compared with experimental results.

Keywords: cohesive strength, cohesive element, debonding, Abaqus, delamination.

Classification numbers: 5.4.3, 5.4.5, 5.6.

1. INTRODUCTION

Delamination is one of the most common types of damage in laminated fiber-reinforced composites due to their relatively weak interlaminar strengths. The existence of delamination can reduce the strength, stiffness and load-bearing capacity of the laminate under compressive loads [1]. Delamination occurs when the bonds between layers of the laminate fail due to debonding in the plane of the interface adhesive [2]. Stress-based method has been applied to predict the initiation and growth of delamination damage in material [3]. The virtual crack closure technique (VCCT) is based on linear fracture mechanics problems, originally developed by Rybicki [4], has often been used to evaluate both Mode I and Mode II stress intensity factors after the delamination onset. A major drawback of the VCCT method is that it requires the presence of an initial crack in the finite element mesh prior to the analysis, which makes the method useful for cases where the exact location of the delamination crack is explicitly known. For cases involving large structures where delamination crack location is unknown, the method becomes less favorable.

Delamination can be also analyzed by using cohesive damage models. The concept originally proposed by Dugdale [5] and Barenblatt [6], which the assumption that the stress transfer capacity between the two separating faces of a delamination is not lost completely at damage initiation. A cohesive damage model implements interfacial constitutive laws was
defined in terms of damage variables and a damage evolution law. Numerical tools such as Abaqus, which base on the finite element method, have been widely used to study the delamination by using cohesive element that can be used to model crack initiation and propagation in laminate composite.

In this paper, the implementation of cohesive elements for studying delamination propagation under variable-mode is presented using a delamination initiation criterion developed by Camanho [7]. The specimen double cantilever beam (DCB) and mixed-mode bending (MMB) are computed and the numerical results are compared with the experimental results.

2. MECHANICAL MODEL FOR DELAMINATION

2.1. Geometrical model

Unidirectional AS4/PEEK carbon-fiber reinforced composite specimen is used to simulate that shown in Fig. 1 and Fig. 2. The simulated specimen is long 102 mm, wide 25.4 mm and thick $2 \times 1.56$ mm. The material properties shown in Table 1 and the initial crack length shown in Table 2. The penalty stiffness $K = 10^6$ N/mm$^3$ is used [7]. A displacement rate of 12 mm/sec is applied to the appropriate point of the model.

![Figure 1. Model of DCB test specimen.](image1)

![Figure 2. Model of MMB test beam specimen.](image2)

**Table 1. Properties for AS4/PEEK composites.**

| $E_{11}$  | $E_{22} = E_{33}$ | $G_{12} = G_{13}$ | $G_{23}$ | $\nu_{12} = \nu_{13}$ |
|-----------|------------------|-------------------|---------|---------------------|
| 122.7 GPa | 10.1 GPa         | 5.5 GPa           | 3.7 GPa | 0.25                |
| $\nu_{23}$ | $G_{1c}$         | $G_{1c}$          | $\sigma^0$ | $\tau^0$ |
| 0.45      | 0.969 kJ/m$^2$  | 1.719 kJ/m$^2$   | 80 MPa  | 100 MPa             |
Computation for the delamination in the laminate composite material using a cohesive …

Table 2. The initial delamination and lever length [7].

|                  | G_{II}/G_T | 0% (DCB) | 20% | 50% | 80% | 100% (ENF) |
|------------------|------------|----------|-----|-----|-----|-----------|
| a₀ [mm]          |            | 32.9     | 33.7| 34.1| 31.4| 39.2      |
| c [mm]           | 109.4      | 44.4     | 28.4|     |     |           |

2.2. Constitutive equation

2.2.1. Single mode delamination

Cohesive zone approaches can be related to Griffith’s theory [8] of fracture that the area under the traction – separation \((\sigma - \delta)\) curve is equal to the corresponding fracture toughness \(G_c\) \((\delta_c\) is crack displacement):

\[
\int_0^{\delta_c} \sigma d\delta = G_c
\]

(1)

A traction-separation law, which consists of an initial linear elastic phase, followed by a linear-softening that simulates the de-bonding of the interface after damage initiation is utilized in the finite element cohesive model. The linear-softening constitutive behavior for mode-I loading shown in Fig. 3 can be described (K is material stiffness value) [7]:

\[
\sigma = \begin{cases} 
K\delta, & \delta \leq \delta^0 \\
(1-d)K\delta, & \delta^0 < \delta < \delta^c \\
0, & \delta \geq \delta^c 
\end{cases}
\]

(2)

and \(d\) is damage variable:

\[
d = \frac{\delta^c (\delta - \delta^0)}{\delta^c (\delta^c - \delta^0)}
\]

(3)

2.2.2. Mixed mode delamination

In structure applications of composite, delamination is likely to occur under mixed-mode loading. Therefore, a general formulation for delamination dealing with mixed-mode
delamination onset and propagation is also required. The total mixed-mode relative separation \( \delta_m \) and the mixed-mode ratio \( \beta \) can be defined [7]:

\[
\delta_m = \sqrt{\langle \delta_1^2 \rangle + \delta_2^2 + \delta_3^2} = \sqrt{\langle \delta_1^2 \rangle + \delta_{\text{shear}}^2}
\]

\[
\beta = \frac{\delta_{\text{shear}}}{\langle \delta_1 \rangle}
\]

where the symbol \( \langle \cdot \rangle \) denotes the McCauley bracket:

\[
\langle x \rangle = \begin{cases} 
  x & \text{if } x \geq 0 \\
  0 & \text{if } x \leq 0
\end{cases}
\]

**Delamination onset prediction**

Under pure mode I, mode II or mode III loading, delamination onset occurs when the corresponding inter-laminar traction exceeds its respective maximum interfacial strength \( \sigma_1^0, \sigma_2^0, \sigma_3^0 \). Under mixed-mode loading, an interaction between modes must be taken into account. Few models take into account the interaction of the traction components in the prediction of damage onset. The models that account for the interaction of the traction components are usually based on Ye’s criterion, using a quadratic stress criterion interaction between modes [7]:

\[
\left( \frac{\langle \sigma_1 \rangle}{\sigma_1} \right)^2 + \left( \frac{\langle \sigma_2 \rangle}{\sigma_2} \right)^2 + \left( \frac{\langle \sigma_3 \rangle}{\sigma_3} \right)^2 = 1
\]

**Delamination propagation prediction**

The most widely used criterion to predict delamination propagation under mixed-mode loading, the “power law criterion” is normally established in terms of a linear or quadratic interaction between the energy release rates. However, Camanho [9] shown that, using the expression proposed by Beneggagh-Kenane (B-K criterion) is more accurate for epoxy composites. The propagation criterion can be written as:

\[
\left( \frac{G_I}{G_{Ic}} \right)^\eta + \left( \frac{G_{II}}{G_{IIc}} \right)^\eta + \left( \frac{G_{III}}{G_{IIIc}} \right)^\eta = 0 \text{ or } G_I = G_{Ic} + (G_{IIc} - G_{Ic}) \left( \frac{G_{\text{shear}}}{G_T} \right)^\eta
\]

where \( G_T = G_I + G_{II} + G_{III} = G_I + G_{\text{shear}} \) is the energy release rate under mixed-mode rate.

### 3. NUMERICAL RESULTS AND DISCUSSION

#### 3.1. Double Cantilever Beam (DCB)

The model of the DCB test specimen uses 100 continuum plane strain elements (CPE4I) along the length of the specimen. The finite element mesh which shown deformed in Fig. 4, consists of two layers and 2-D 4-nodes cohesive elements (COH2D). The results of displacement field shown in Fig. 5. Fig. 6 shows the force vs crack opening displacement plot, obtained from \( \sigma_{\max} \) values of 80 MPa, compared to the numerical solution obtained by Camanho [7].
Computation for the delamination in the laminate composite material using a cohesive ...

Figure 4. Finite element mesh for double cantilever beam with displacement $\Delta$.

Figure 5. Displacement of double cantilever beam.

Figure 6. Double cantilever beam load versus crack opening displacement.
In the loading process before the delamination initiation, the load-displacement curves are almost linear. There are some slight noises which are presented in the delamination propagation. Present results are good agreement with the experimental results, with the error 2.15% at the peak load.

3.1. Effects of cohesive properties

In order to investigate the effect of $\sigma_{\text{max}}$ on the numerical solution obtained using 100 elements-mesh, the problem was solved using different values of interfacial strengths $\sigma_{\text{max}}$, while keeping $G_c = 0.969kJ/m^2$ constant. The results of the peak loads for all cases shown in Table 3 and the force versus crack opening displacement plot shown in Fig. 7. When $\sigma_{\text{max}}$ increases, peak loads also increase and more heavy noise in delamination propagation.

Table 3. Reaction force and the displacement in the Onset.

| Normal traction stress | Peak load (N) | Displacement (mm) |
|------------------------|--------------|-------------------|
| $\sigma_{\text{max}} = 40 \text{ MPa}$ | 137.3074 | 4.939 |
| $\sigma_{\text{max}} = 60 \text{ MPa}$ | 146.1113 | 4.92 |
| $\sigma_{\text{max}} = 80 \text{ MPa}$ | 153.9262 | 5.2648 |
| $\sigma_{\text{max}} = 100 \text{ MPa}$ | 205.2538 | 6.3905 |

Experiment (Camanho [7], $\sigma_{\text{max}} = 80 \text{ MPa}$) 150.6838 5.1963

Figure 7. Double cantilever beam load versus crack opening displacement in different maximum normal traction stress cases.
Computation for the delamination in the laminate composite material using a cohesive …

Figure 8. Double cantilever beam load versus crack opening displacement in different critical energy release rates cases.

The sensitivity of the load-displacement plot to $G_{kc}$ when $\sigma_{\text{max}}$ is kept constant equal to 80 MPa shown in Fig. 8. When $G_{kc}$ equal to 0.969, 1.4535 and 1.938 kJ/m², the peak loads increase. This trend is similar to the trend in the effect of $\sigma_{\text{max}}$ on the peak loads.

Figure 9. Double cantilever beam load versus crack opening displacement in case of 400, 200, 100 mesh elements.

In order to investigate the effect of the mesh size on the results, the simulation was repeated using three different types of 100, 200 and 400 mesh elements. Figure 9 shows the force-displacement relation. The value of $\sigma_{\text{max}}$ equal to 100 MPa and was kept constant in all cases.
The chart is the smallest nose when using 400 mesh elements. The onset occurs sooner and the predictability of the peak load is also reduced.

3.2. Mixed Mode Bending (MMB)

The experimental tests were performed at different $G_{II}/G_T$ ratios, ranging from pure mode I and pure mode II loading. The initial delamination and lever lengths are shown in Table 2. Model using of 100 elements along the length of the specimens, the finite element mesh shown in Fig 10. The elements are homogeneous and equal. The different $G_{II}/G_T$ ratios are simulated by applying different loads at the middle and end loads for each mode ratios. The B-K parameter $\eta = 2.284$ is calculated by applying the least-squares fit procedure proposed in [9].

The numerical and experimental results relate the load to the displacement of the point of application of the load P in the lever for all cases shown in Fig. 11. The results of the maximum load shown in Table 4 and compared with experimental results. It can be concluded that a good agreement between the numerical predictions and experimental results are obtained. The largest error (23.5 %) corresponds to the case of an MMB test specimen with $G_{II}/G_T = 20 \%$ and decreases when $G_{II}/G_T$ ratio decrease.
Computation for the delamination in the laminate composite material using a cohesive …

Table 4. Comparison of the maximum load.

| GI/GT | Numerical [N] | Experimental [N] | Error (%) |
|-------|---------------|------------------|-----------|
| 20 %  | 133.5         | 108.1            | 23.5 %    |
| 50 %  | 315.2         | 275.3            | 14.5 %    |
| 80 %  | 474.7         | 518.7            | 8.5 %     |

4. CONCLUSIONS

Modeling for mode I and mixed-mode delamination in laminate composite materials using cohesive elements in the commercially available in ABAQUS software have been successfully implemented. The material properties required to define the element are the interlaminar toughness, the penalty stiffness and the strengths of the interface. Addition, material parameter $\eta$, which required for the B-K mode interaction law. The effects of cohesive properties to delamination onset and propagation are computed and the numerical results are in good agreement with the experiment data. The results show that $\sigma_{\text{max}}$ has a dominant effect on the delamination initiation and the peak load rises as $G_{\text{IC}}$ and $\sigma_{\text{max}}$ increase. They indicate that the proposed criterion can well predict the strength of composite structure with the progressive delamination.

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