Modeling delamination of FRP laminates under low velocity impact

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Abstract. Fiber reinforced plastic laminates (FRP) have been increasingly used in various engineering such as aeronautics, astronautics, transportation, naval architecture and their impact response and failure are a major concern in academic community. A new numerical model is suggested for fiber reinforced plastic composites. The model considers that FRP laminates has been constituted by unidirectional laminated plates with adhesive layers. A modified adhesive layer damage model that considering strain rate effects is incorporated into the ABAQUS/EXPLICIT finite element program by the user-defined material subroutine VUMAT. It transpires that the present model predicted delamination is in good agreement with the experimental results for low velocity impact.

1. Introduction
Fiber reinforced plastic (FRP) laminates have been widely used in engineering such as aeronautics, astronautics, transportation, naval architecture due to their high specific strength, high specific stiffness, design flexibility and high durability. However, during manufacturing or in service FRP laminates may be subjected to impact by dropped objects such as tools or fragments generated from a nearby accidental explosion or even by a military projectile. Hence, the response and failure of FRP laminates under impact loading are a major concern both for academic community and industry.

Delamination is a major damage pattern of FRP laminates subjected to impact loadings and it is still difficult to simulate this damage pattern so far. Olsson [1] proposed an analytical method to predict the delamination initiation and growth of composite laminates struck transversely by large masses at low velocities. Espinosa et.al [2] examined the dynamic delamination in GFRP laminates using a 3D finite deformation anisotropic viscoplastic model in conjunction with contact/cohesive laws whilst Johnson et.al [3] studied the dynamic response of a woven GFRP composite structure utilizing a simple 2D damage model in conjunction with cohesive elements. Singh and Mahajan[4] proposed a 3D elasto-plastic damage model combining the surface based cohesive interaction to simulate the delamination behavior of graphite/epoxy laminates under low velocity impact and reasonable agreement was obtained between the numerically predicted delamination patterns and the experimental observations [5]. Aymerich et.al [6] investigated the usefulness of cohesive interface elements for damage prediction in cross-ply composite laminates subjected to low velocity impact. Francesconi and Aymerich [7] also conducted numerical simulation of the effect of stitching on the delamination resistance of laminated composites subjected to low velocity impact.

The objective of this paper is to formulate an FE model which can be used to predict the delamination of fiber reinforced plastic (FRP) laminates subjected to impact loadings.
1.1 Formulation of an FE model

An FE model will be constructed in the following. A recently developed progressive damage model for fiber reinforced plastic (FRP) laminates subjected to impact loadings is first briefly described and then a modified adhesive layer damage model in some more details.

1.1.1 A progressive damage model. A progressive damage model for unidirectional laminated plates under impact loadings was developed recently by Xin and Wen[8]. The model includes three parts, namely damage initiation, damage evolution and strain rate effects.

Quadratic stress based damage initiation criteria were given to predict the onset of various damage modes. When one of the failure mechanisms takes place, the properties of the material may reduce gradually until to complete failure. This new CDM model introduced a concept of stiffness degradation which is controlled by damage variables and the values of damage variables suggested to be between zero (undamaged state) and one (fully damaged state). The fracture energy approach in terms of stress-displacement relationship was adopted to compute the damage variables under different failure modes.

In the meantime, the strain rate effects on the strengths as well as moduli were considered in the model by introducing the dynamic increase factor (DIF), which is defined as the ratio of dynamic to static values.

Due to space limitation the detailed information about damage evolution and strain rate effects will not be given here. Interested readers are referred to Ref.[8] for more details.

1.1.2 Adhesive layer damage model. To simulate the delamination of FRP laminates, one of the common and successful methods is cohesive zone method (CZM) which was suggested by Barenblatt[9]. This method first uses failure criterion that combine aspects of strength based analysis to predict the onset of the damage of the interface and then fracture mechanics to describe the delamination propagation. However, the cohesive zone method (CZM) and nearly all its subsequent developments[1]-[7] took no consideration of strain rate effects on the strengths as well as moduli of FRP laminates. In the following a modified CZM method that considers strain rate effects is proposed.

1.1.3 Traction-separation law. Adhesive layers damage model are employed to simulate the delamination between layers of FRP laminates. The basis of the method is the cohesive behavior interaction of two adjacent surfaces. The traction stress and separation displacement of the nodes on the surfaces are governed by traction-separation law as shown schematically in Figure 1 which consists of initial elastic response, delamination initiation and delamination propagation.

The elastic part of the traction-separation law can be written by the following expression, viz.

$$
\mathbf{t} = \begin{pmatrix} t_n \\ t_s \\ t_t \end{pmatrix} = \begin{pmatrix} K_n & 0 & 0 \\ 0 & K_s & 0 \\ 0 & 0 & K_t \end{pmatrix} \begin{pmatrix} \delta_n \\ \delta_s \\ \delta_t \end{pmatrix} = \mathbf{K} \mathbf{\delta} \quad (1)
$$

where \( \mathbf{t} \) is nominal traction stress vector, \( t_n \) is the out-of-plane normal stress, \( t_s \) and \( t_t \) are the transverse shear stresses; \( \mathbf{K} \) is the penalty stiffness vector, \( K_n \), \( K_s \), \( K_t \) are the normal, shear and tearing stiffnesses, respectively; \( \mathbf{\delta} \) is relative displacement vector, \( \delta_n \), \( \delta_s \), \( \delta_t \) are the normal, shear and tearing displacements, respectively.

The delamination initiation of the traction-separation law can be expressed by the quadratic failure criterion, namely

$$
\left\{ \frac{t_n}{t_n^0} \right\}^2 + \left\{ \frac{t_s}{t_s^0} \right\}^2 + \left\{ \frac{t_t}{t_t^0} \right\}^2 \geq 1 \quad (2)
$$

Where \( t_n^0, t_s^0, t_t^0 \) are peak values of the tractions, respectively. It is noted that the compressive normal tractions do not cause delamination to occur and the effective separation displacement corresponding to the peak stress is used in this paper to predict the initiation of delamination. Thus, the effective
displacement corresponding to the onset of the delamination (\(\delta_m^0\)) can be expressed by the following equation [10]

\[
\delta_m^0 = \begin{cases} 
\frac{\delta_n^0 \delta_s^0}{\sqrt{\left(\frac{\delta_n^0}{\delta_s^0}\right)^2 + \left(\frac{\beta \delta_n^0}{\delta_s^0}\right)^2}} & \text{if } \delta_n^0 > 0 \\
\delta_s^0 & \text{if } \delta_n^0 \leq 0
\end{cases}
\]  

(3)

in which \(\beta = \frac{\delta_{\text{shear}}}{\delta_n}\) with \(\delta_{\text{shear}}\) being defined as \(\delta_{\text{shear}} = \sqrt{\delta_s^2 + \delta_t^2}\) and \(\delta_n^0, \delta_s^0, \delta_t^0\) are the separation displacements corresponding to the peak values of the tractions \(t_{n}, t_{s}, t_{t}\), which are defined as follows:

\[
\delta_n^0 = \frac{t_n^0}{K_n}, \delta_s^0 = \frac{t_s^0}{K_s}, \delta_t^0 = \frac{t_t^0}{K_t}
\]  

(4)

It can be seen clearly from equation (12) that when \(\beta = 0\) (i.e., \(\delta_{\text{shear}} = 0\)) \(\delta_m^0 = \delta_n^0\) implying delamination is caused by crack opening mode (mode I) only and that when \(\beta \to \infty\) (i.e., \(\delta_n = 0\)) \(\delta_m^0 = \delta_s^0\) implying delamination by either shear or tearing mode.

On the basis of assumption that the fracture toughness for tearing mode (Mode III, \(G_{IIIc}\)) is equal to the fracture toughness for shearing mode (Mode II, \(G_{IIc}\)), namely \(G_{IIIc} = G_{IIc}\), Benzeggagh and Kenane [11] proposed a criterion for delamination of FRP laminates which can be written as

\[
G_{IIc} + (G_{IIc} - G_{IC}) \left(\frac{G_{shear}}{G_{T}}\right) = G_C
\]  

(5)

where \(G_{IC}\) is the fracture toughness for crack opening mode (Mode I) and \(\eta\) is an empirical constant dependent upon material system and in the present paper it is taken to be unity; \(G_{shear} = G_{II} + G_{III}\) and \(G_T = G_I + G_{shear} = G_I + G_{II} + G_{III}\) with \(G_I, G_{II}, G_{III}\) being defined by the following equations

\[
G_I = \int_0^{\delta_f^0} t_s d\delta_s, \quad G_{II} = \int_0^{\delta_f^0} t_s d\delta_s, \quad G_{III} = \int_0^{\delta_f^0} t_s d\delta_s
\]  

(6)

\(G_C\) in equation (14) is the critical energy release rate which is determined by

\[
G_C = \frac{1}{2} K \delta_m^0 \delta_m^f
\]  

(7)

where \(K\) is the effective stiffness. Substituting equation (16) into equation (14) and rearranging yields[10]

\[
\delta_m^f = \begin{cases} 
\frac{2}{K \delta_m^0} \left[ G_{IC} + (G_{IIc} - G_{IC}) \left(\frac{\beta^2}{1 + \beta^2}\right)^\eta \right] & \text{if } \delta_n^0 > 0 \\
\frac{2G_{IIc}}{K \delta_m^0} & \text{if } \delta_n^0 \leq 0
\end{cases}
\]  

(8)

after using expressions for \(G_{shear}\) and \(G_T\) and equations (15) and (10), together with the assumption that \(K_n = K_s = K_t\). \(\delta_m^0\) is estimated by equation (12) and \(\delta_m^f\) in equation (17) is the critical effective
separation displacement at which two adjacent surfaces separate from each other or delamination occurs.

The critical effective separation displacement \( \delta_m^f \) can be utilized to calculate the damage variable \( D \) which can be expressed as

\[
D = \delta_m^f \left( \frac{\delta_m^{\text{max}} - \delta_m^0}{\delta_m^{\text{max}} - \delta_m^0} \right)
\]  

(9)

where \( \delta_m^{\text{max}} \) is a state variable which is defined as

\[
\delta_m^{\text{max}}(t) = \max\left\{ \delta_m(t), \delta_m^{\text{max}}(t-\Delta t) \right\}
\]  

(10)

in which \( \delta_m^{\text{max}}(t) \) is the value of effective separation displacement \( \delta_m \) at current time step while \( \delta_m^{\text{max}}(t-\Delta t) \) is the value of previous time step. Thus, by using this state variable, the irreversibility of damage is taken into account.

The traction-separation law, as shown in Figure 1, can be described by the following equation

\[
t = \begin{cases} 
K\delta & (\delta_m < \delta_m^0) \\
(1-D)K\delta & (\delta_m^0 \leq \delta_m \leq \delta_m^f) \\
0 & (\delta_m > \delta_m^f) 
\end{cases}
\]  

(11)

Figure 1 Schematic diagram of the traction-separation law.

1.1.4 Strain rate effects. The rate dependency of strength as well as modulus can be described within a unified framework by introducing dynamic increase factor (DIF)[8], namely

\[
t_i^0 = t_i^f \times \text{DIF}, \quad K_i = K_i^f \times \text{DIF}, \quad (i = n, s, t)
\]  

(12)

Where \( t_i^0, K_i \) are the dynamic strength and modulus respectively and \( t_i^f, K_i^f \) are the corresponding static values. The dynamic increase factor (DIF) can be expressed in the following form [8]

\[
\text{DIF} = \left\{ \tanh \left( \log \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) - A \right) \times B \right\} \times \left[ \frac{C}{(C+1)/2} - 1 \right] + 1 \times \frac{C+1}{2}
\]  

(13)

in which A, B and C are empirical constants to describe the rate sensitive behavior of FRP laminates.

2. Results and discussion

The progressive damage model for unidirectional laminated plates and the adhesive layer damage model
described above are implemented in ABAQUS finite element code as user defined materials (VUMAT). In the following a low velocity impact is given to demonstrate the validity and accuracy of the FE model developed in section above.

Table 1 cohesive interface properties used in adhesive layer damage model.

| Parameter | Data | Parameter | Data | Parameter | Data |
|-----------|------|-----------|------|-----------|------|
| $t_0$ | 11(Mpa) | $t_1$ | 17(Mpa) | $t_2$ | 17(Mpa) |
| $G_{IC}$ | 0.3(N/ mm$^{[4]}$) | $G_{IC}$ | 0.8(N/ mm$^{[4]}$) | $G_{IC}$ | 0.8(N/ mm$^{[4]}$) |
| $K_{ns}$ | 850(MPa$^{[12]}$) | $K_{ns}$ | 850(MPa$^{[12]}$) | $K_{ns}$ | 850(MPa$^{[12]}$) |
| As | 2.5$^{[8]}$ | Bs | 0.9$^{[8]}$ | Cs | 3.7$^{[8]}$ |
| Am | 1.85$^{[8]}$ | Bm | 0.5$^{[8]}$ | Cm | 1.3$^{[8]}$ |

Table 2 Parameters for graphite/epoxy laminates$^{[5]}$ used in the progressive damage model .

| Parameter | Data | Parameter | Data | Parameter | Data |
|-----------|------|-----------|------|-----------|------|
| $E_{11}$ | 143.4(GPa$^{[4]}$) | $Y_1$ | 54(MPa$^{[3]}$) | $v_{23}$ | 0.52$^{[4]}$ |
| $E_{22}$ | 9.27(GPa$^{[4]}$) | $X_c$ | 1650(MPa$^{[4]}$) | $v_{13},v_{12}$ | 0.31[4] |
| $E_{33}$ | 9.27(GPa$^{[4]}$) | $Y_c$ | 240(MPa$^{[4]}$) | $\delta_1^f, \delta_2^f$ | 5.7x10$^{-2}$(mm$^{[8]}$) |
| $G_{12}$ | 3.8(GPa$^{[4]}$) | $Z_1$ | 54(MPa$^{[4]}$) | $\delta_1^f, \delta_2^f$ | 2.7x10$^{-2}$ (mm$^{[8]}$) |
| $G_{23}$ | 3.2(GPa$^{[4]}$) | $Z_2$ | 240(MPa$^{[4]}$) | $\delta_3^f, \delta_4^f$ | 7.65x10$^{-2}$ (mm$^{[8]}$) |
| $G_{31}$ | 3.8(GPa$^{[4]}$) | $S_{12}$ | 100(MPa$^{[4]}$) | $\delta_3^f$ | 5x10$^{-3}$ (mm$^{[8]}$) |
| $X_1$ | 2945(MPa$^{[4]}$) | $S_{31},S_{23}$ | 100(MPa$^{[4]}$) | $\delta_1^f$ | 5x10$^{-2}$ (mm$^{[8]}$) |

Figure 2 shows an FE model for low velocity impact tests which were reported by Aymerich et al. [5]. The specimen was made of Graphite/epoxy laminates (stacking sequence [0$3/90$]$_s$) which had a size of 87.5 × 65mm ×2mm and it was supported in a steel frame and clamped at four corners using G-clamps. The open window (aperture) area was 67.5mm ×45mm. C3D8R solid elements are used to model both the unidirectional laminated plates and the impactor which had a 12.5mm diameter hemispherical end and a mass of 2.3kg. The adhesive layers are created by COH3D8 cohesive elements . The elements in the open window (67.5mm×45mm) are refined with in-plane size of about 1mm ×1mm ,the total number of the elements through the thickness of the sample is four (one element for three plies which aligned in the same direction). COH3D8 cohesive elements are inserted at the interface between the layers with different fiber orientations (0°/90° and 90°/0°) to model delamination damage. The impactor is assumed to remain rigid during impact. A general contact algorithm is employed to model the contact between the impactor and the CFRP laminates. A friction coefficient value $u=0.2$ is included in the contact formulation.
Figure 2 Finite element model employed in low velocity impact

Figure 3 shows comparison of the numerically predicted delamination shape and area with those observed for the 2mm thick CFRP laminates struck transversely by a 2.3kg, 12.5mm diameter hemispherical-ended impactor [5] at three different impact energy of 2.1 J (1.35 m/s), 4.9 J (2.06 m/s) and 9.3 J (2.84 m/s). Here, a state variable is defined in the VUMAT subroutine which represents the stiffness degradation of cohesive elements. The left picture shows the stiffness degradation contour of cohesive elements calculated by the present model at lower 90°/0° interface. When cohesive element’s stiffness degradation is 0 it means no damage at all whilst the stiffness degradation is 1 it means full damage. The fully damaged cohesive elements represent delamination between the adjacent laminate layers. It is clear from Figure 3 that the present model predictions are in good agreement with the experimental observations [5].

Figure 3 Comparison of the numerically predicted delamination area with the experimental observation[5] for the 2mm thick CFRP laminates struck transversely by a 2.3kg, 12.5mm diameter hemispherical-ended impactor.

FRP laminates are prone to delamination under impact loading due to their manufacturing process. They are formed by superposition of anisotropic monolayers through cementing and curing. Under impact loadings, the deformation of the unidirectional layers with different laying direction is not coordinated, which more likely leads to the damage and destruction of the adhesive layer. This model is capable to reflect the non-coordinated deformation of the adjacent unidirectional layers by introducing adhesive layer.
3. Conclusions
A numerical study has been conducted to predict the delamination of fiber reinforced plastic (FRP) laminates subjected to impact loadings. A new FE model is suggested for fiber reinforced plastic composites which considers that FRP laminates has been constituted by unidirectional laminated plates with adhesive layers. A modified adhesive layer damage model that considering strain rate effects is incorporated into the ABAQUS / EXPLICIT finite element program by the user-defined material subroutine VUMAT. It transpires that the present model predicted delamination is in good agreement with the experimental results for low velocity impact.

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