Modelling the interfacial damage of carbon fiber reinforced polymer composite laminate under the low-velocity impact loading

M S Meon1*, J B Saedon1, S Shawal1, H Husain1, M F Othman1, M N Rao2 and K-U Schröder2

1Faculty of Mechanical Engineering, Universiti Teknologi MARA (UiTM), 40450 Shah Alam, Selangor, Malaysia.
2Institute for Structural Mechanics and Lightweight Design, RWTH Aachen University, Germany

*msuhairil@uitm.edu.my

Abstract. This paper presents the performance of three-dimensional Puck failure criteria emphasising on the gradual degradation law to predict the structural responses, as well as the onset and propagation of failure due to different interface modelling technique. The proposed damage model is performed using Abaqus explicit analysis. Four different cohesive models are analysed using three-dimensional finite element model based on low-velocity impact loading. The structural responses are compared with experimental data taken from literature to measure the performance of such damage model. It is found out that the model adopted here responses well with test curves and demonstrates the high capability of predicting the damage in the direction of in-plane as well as out-of-plane in a composite laminate. The simplified model using combination of tie-cohesive layer technique demonstrated the balance performance between the quality of the result as well as calculation time.

1. Introduction
The wide application of composite material especially carbon fibre reinforced polymer (CFRP) in many engineering fields such particularly in aerospace industry are due to its high strength, strength to weight ratio as well as design quality. However, many reports show that the material is susceptible to impact loadings which can reduce the integrity of the structure [1]. A low-velocity impact (LVI) event is one of the silent contributors to the composite structure due to its invisible nature and reduce the damage tolerance and safety of the composite laminates [2]. Therefore, it is very crucial to understand the behaviour of laminated composite under the LVI loading.

Numerical simulation has been adopted by many scholars to analyze the characteristic of the damages occur in laminates because of high cost of experimental procedures [2-5]. The research evolves with the implementation of failure criteria and degradation law to predict the initiation and growth of the crack, respectively when the LVI event occurred. Han et al. [6] and Lou et al. [7] simulated the progressive damage on CFRP composite plate using multi-scale criterion. Cui et al. [8] provided a benchmark study on IM7/8552 composite laminated plate using Puck and LaRC failure criteria. Gliszczynski [9] conducted his numerical investigation using Hashin failure criteria, where this damage formulation was frequently adopted by other researchers in assessing the damage occur due to impact loading [3, 10, 11].
Another consideration to model the LVI event in composite structure is to incorporate the out-of-plane damage. Delamination is one of the common inter-laminar damage modes. Studies on composite delamination in the event of drop-weight impact can be found in many literatures. Long et al. [10] performed the cohesive contact method to model the delamination damage. A cohesive mixed-mode damage law was applied by Amaro et al. [12] to investigate the correlation between the inter-laminar damage and the presence of holes. Wang et al. [11] predicted the interface damage by surface based cohesive behaviour which utilized the traction-separation law. The approach was proved efficient to capture the interfacial failure. Many approaches have been proposed to predict the intra- and inter-laminar damages in composite laminate. However, the modeling strategy of delamination is rarely found in the literatures. Furthermore, the research in failure criteria of laminates still inconclusive and widely open for improvement because no universal criteria like metal which can works well with almost all type of loading and environment.

In this study, the low-velocity impact simulation is carried out on CFRP composite plate, which experimental data was obtained from selected publication. The in-plane damage, which cover the fiber breakage and matrix cracking is predicted using Puck failure criteria while the cohesive contact formulation is used to detect the delamination damage provided internally in Abaqus software. Several strategies in modelling the cohesive in each interface was conducted to identify the most efficient and reliable technique as well as produced the acceptable results.

2. Progressive damage model

2.1. Intralaminar failure criteria and evolution law

The prominent Puck failure criteria [13] is used as failure criteria to predict the onset of damage in composite laminate. The damage modes are distinguished by fiber failure (FF) and inter-fiber failure (IFF)/matrix failure both in tension and compression direction. Table 1 shows the complete failure formulation for Puck and the validity functions.

From the table mentioned, $\sigma_i$ ($i = 1, 2, 3$) are the scalar components of stress tensor, $X_T$ and $X_C$ are the tensile and compressive strengths of a uni-directional (UD) layer in the longitudinal direction and $v_{12}$ and $v_{12f}$ are the Poisson’s ratio for UD lamina and fibre, respectively. In addition, $E_{11}$ is the modulus of elasticity of the lamina in longitudinal direction, while $E_{11f}$ is the modulus of elasticity for fiber. The mean stress magnification factor, $m_{of}$ is assumed to be 1.3 for glass fibre and 1.1 for carbon fiber [14].

For inter-fibre failure (IFF), also referred as matrix cracking assumes that fracture in the laminate is produced by the stresses acting on the fracture plane ($fp$) ($\sigma_n$, $\tau_{nl}$, $\tau_{nt}$) inclined $\theta_{fp}$ relative to the material plane whereas the classical transformation equations are used to obtain the normal and shear stresses. The parameter $\psi$ denotes the shear angle in action plane, $R_\perp$ is failure resistance normal to fibres direction, $R_{\perp\psi}$, $R_{\perp1}$, $R_{\perp\|}$ are the fracture resistances of the action plane due to the shear stressing, and $p_{\perp\psi}$ and $p_{\perp\|}$ are the internal friction parameters [14]. Other formulation required to fulfill the parameters in the criteria can be found in the original publication of Puck [13-14].
Table 1. Damage initiation criteria according to Puck.

| Damage mode                  | Damage function                                                                 |
|------------------------------|----------------------------------------------------------------------------------|
| Fiber failure (tension)      | $f_{FP}^f = \frac{1}{X_T} \left[ (\sigma_1 - \nu_{12} - \nu_{12f}, m_{sf} \frac{E_{11}}{E_{11f}}) (\sigma_2 + \sigma_3) \right]$ for $[\ldots] \geq 0$ |
| Fiber failure (compression)  | $f_{FP}^c = \frac{1}{X_C} \left[ (\sigma_1 - \nu_{12} - \nu_{12f}, m_{sf} \frac{E_{11}}{E_{11f}}) (\sigma_2 + \sigma_3) \right]$ for $[\ldots] < 0$ |
| Inter-fiber failure (tension)| $f_{IF}^f = \sqrt{\left[ \frac{1}{R_{1\perp}} - \frac{p_{1\psi}}{R_{1\psi}} \right] \sigma_n(\theta)^2 + \left( \frac{\tau_{nl}(\theta)}{R_{1\parallel}} \right)^2 + \left( \frac{\tau_{nl}(\theta)}{R_{1\parallel}} \right)^2 + \left( \frac{\tau_{nl}(\theta)}{R_{1\parallel}} \right)^2 + \frac{p_{1\psi}}{R_{1\psi}} \sigma_n(\theta)}$ for $\sigma_n < 0$ |
| Inter-fiber failure (compression)| $f_{IF}^c = \sqrt{\left( \frac{\tau_{nl}(\theta)}{R_{1\parallel}} \right)^2 + \left( \frac{\tau_{nl}(\theta)}{R_{1\parallel}} \right)^2 + \left( \frac{\tau_{nl}(\theta)}{R_{1\parallel}} \right)^2 + \left( \frac{\tau_{nl}(\theta)}{R_{1\parallel}} \right)^2 + \frac{p_{1\psi}}{R_{1\psi}} \sigma_n(\theta)}$ for $\sigma_n < 0$ |

After failure is predicted using above criteria, the gradual degradation law is applied to the structure to reduce the structural stiffness matrix as shown in Table 2 to promote the reduction of the structural integrity.

Table 2. Damaged stiffness matrix based on gradual degradation law

| Reduced stiffness matrix | Damage variables                                                                 |
|--------------------------|----------------------------------------------------------------------------------|
| $C^d$                    | $A = 1 - d_f$; $B = (1 - d_f)(1 - d_m)$; $D = (1 - S_{IF}^f d_{IF}^f)(1 - S_{IF}^c d_{IF}^c)$; $d_f = 1 - (1 - d_{IF}^f)(1 - d_{IF}^c)$; $d_m = (1 - d_{IF}^f)(1 - d_{IF}^c)$ |

Where $C^d$ is the reduced stiffness matrix, while $C_{ij}$ is undamaged stiffness component, and $G_{12}$, $G_{13}$ and $G_{23}$ are the in-plane and out-of-plane shear modulus of composite material. The functions $d_f$ and $d_m$ are the global damage variables corresponding to fibre and inter-fibre failure, respectively. The parameters $d_{IF}^f$, $d_{IF}^c$, $d_{IF}^f$, and $d_{IF}^c$ are the internal damage variables according to each failure modes and directions. The control parameters, $S_{IF}^f$ and $S_{IF}^c$ are 0.9 and 0.5, respectively as successfully used in publication of Lapczyk and Hurtado [15].

2.2. Cohesive Law

In modelling delamination damage, the cohesive surface behaviour is implemented using cohesive contact formulation, where the fracture-separation law is employed to control the interaction between traction stress and separation displacement.

$$ t = \begin{bmatrix} t_n \\ t_s \\ t_t \end{bmatrix} = \begin{bmatrix} K_{nn} & 0 & 0 \\ 0 & K_{ss} & 0 \\ 0 & 0 & K_{tt} \end{bmatrix} \begin{bmatrix} \delta_n \\ \delta_s \\ \delta_t \end{bmatrix} $$

(1)
Where \( t_m, t_s, \) and \( t_t \) are the interface strength under the failure mode I, II, and III, respectively. \( \delta_n, \delta_s, \) and \( \delta_t \) are the peak values of the separation displacement in the normal, the first and the second shear directions, respectively. The delamination progressive failure model is described in table 3.

### Table 3. Failure criteria for delamination used in this article.

| Damage initiation | Damage evolution |
|-------------------|------------------|
| Quadratic nominal stress criterion | Power law fracture criterion |
| \((\frac{t_n}{t_n^0})^2 + (\frac{t_s}{t_s^0})^2 + (\frac{t_t}{t_t^0})^2 = 1\) | \((\frac{G_n}{G_n^c})^\alpha + (\frac{G_s}{G_s^c})^\alpha + (\frac{G_t}{G_t^c})^\alpha = 1\) |

\( t_i^0 (i = n, s, t) \) is the interface strength parameter, \( G_i^c (i = n, s, t) \) is the critical fracture energy needed to cause damage in the normal and two shear directions and \( \alpha \) is the material parameter (i.e. \( \alpha = 1.45 \)). When the delamination initiates, the cohesive stiffness degraded according to power law.

### 3. Material and procedures

Unidirectional carbon fiber reinforced polymer CCF300/epoxy composite laminate was used as simulation material, considering the stacking sequence of [45/0/−45/90]_{4}s. To reduce the computational cost, the laminate was configured to be in sequence of [45/0/−45/90/0/45/0/45/0]. This approach is a so-called global-local approach and was successfully implemented in Han et al. [6] works. The material properties are shown in table 4. The nominal thickness of CCF300/epoxy carbon fiber composite laminates was 4mm.

A 3D-FE model of an LVI specimen was modeled based on Abaqus/Explicit requirement according to ASTM D7136/D7136M-15 standard. The laminate was meshed with enhanced solid reduced integration brick element (C3D8R), while the impactor, rubber clamps and base support were meshed using rigid element (R3D4) since the stiffness of the items are relatively high when compared with the laminate. Boundary conditions were simulated according to figure 1. The initial velocity of LVI was 2577 mm/s. The impactor was fixed in all directions except in the direction of loading. The diameter of the spherical punch was 16 mm, and the lumped mass of 5.36 kg was specified in reference point of the rigid, while the moment of inertia was set to be a large value to prevent rotation of the punch. The general contact was defined between the punch and composite laminate, base-support and bottom ply, rubber-clamps and top ply and be- tween each ply, ignoring the effect of tangential friction force.

### Table 4. Mechanical parameters of CCF300/epoxy UD composite [6].

| Reference | Properties | Value |
|-----------|-----------|-------|
| Overall   | Density   | \( \rho = 1.5 \times 10^9 \) tonne/mm³ |
| Intra-laminar | Elastic | \( E_{11} = 123.9 \) GPa, \( E_{22} = E_{33} = 9.72 \) GPa, \( G_{12} = G_{13} = 4.53 \) GPa, \( G_{23} = 2.56 \) GPa, \( v_{12} = v_{13} = 0.288, v_{13} = 0.347 \) |
| Strength  | \( X_T = 1762.3 \) MPa, \( X_C = 1362.2 \) MPa, \( Y_T = 71.1 \) MPa |
| Inter-laminar | Elastic | \( K_{nn} = K_{ss} = K_{tt} = 1 \times 10^4 \) MPa |
| Strength  | \( t_n^0 = t_s^0 = t_t^0 = 80 \) MPa |
| Fracture energy | \( G_n^c = 556 \) J/m², \( G_s^c = G_t^c = 1497 \) J/m² |
Figure 1. Dimension and boundary condition for (a) (top) full model including base support, and (b) (bottom) simplified model.

The contact force between the impactor and the laminate and the reaction force and displacement of compressive reference points were recorded and further analyzed to evaluate the performance of the proposed damage model. Fiber breakage, matrix cracking and delamination were extracted through the user-defined variable (SDV) in Abaqus. The cohesive layers were constructed following figure 2. The complete model description is summarized in table 5.

Figure 2. Modelling cohesive interface with (left) all cohesive contact, (middle) tie-constraint at top, and (right) tie-constraint at bottom. Each layer consists of 4-sublayers.
Table 5. Description of finite element model used in the simulation.

| Reference Name | Size model       | Cohesive model |
|----------------|------------------|----------------|
| FMC1           | Full Model 1     |                |
| SMC1           | Simplified Model 1 | Model 1        |
| SMC2           | Simplified Model 2 | Model 2        |
| SMC3           | Simplified Model 3 | Model 3        |

4. Result and discussion
The numerical simulation is concentrated on composite material of CCF300/Epoxy with impact energy of 6.67 J/mm. Figure 3 shows the comparison of simulated contact force-time and test data. The duration of impact force curves predicted are slightly shorter compared to the experimental result. The simulation results show good agreement in overall curve patterns. The force increases gradually when the impactor touches the top lamina and continues until it reaches its peak value. When the plate swings back upwards, the contact forces decrease rapidly. It is also noted that the full-scale model achieved its peak force at 8400 N, which are significantly higher than other experimental and simulation models. Longer duration of impact contact force indicates more serious damages inside the layers.

| impacted time (s) | impact force (N) |
|-------------------|------------------|
| 0                 | 0                |
| 0.001             | 2000             |
| 0.002             | 4000             |
| 0.003             | 6000             |
| 0.004             | 8000             |
| 0.005             | 10000            |

Figure 3. Comparison of simulated force-time curves with experimental result.

Based on the displacement-time graph in figure 4(a), it is possible to observe that all the models have almost similar magnitude of depth after the impactor penetrates the panel. The boundary condition having the tie-constraint above model obtained the least indentation compare to others. This is because layers of the above panel being tied together to prevent more damage at the other layers. Again, model with full-scale produced highest indentation, due to the boundary condition applied to the plate. The energy-time graph as shown in figure 4(b) shows that all the models has approximately same energy loss due to failure of composite laminates. The pattern of the simulation is almost identical with different maximum energy after the impact. Here, the model having tie-constraint exhibits the maximum energy after the because of simplification made for the interfaces damage. Based on figure 4(c), the
simulated force-displacement curves indicated all models portray the similar curve pattern, except for full model. The increase in number of degrees of freedom for the boundary condition results in not smooth curve.

Table 6 summarized the performance of proposed damage model based on different boundary condition and cohesive interface. Overall, FMC1 overestimates the peak values, and the trend continues with regards to indentation and energy absorption. It is found that higher absorbed energy contributes to unbalance structure and tends to fail the fibers and matrix structure on composite. The balance performance including CPU time is achieved using model having tie-constraint both SMC2 and SMC3 models. This means that the model is suitable to handle the contact interface interaction generated from low-velocity impact event.

Figure 4. Simulation results based on (a) (top-left) indentation-time, (b)(top-right) energy-time, and (c)(bottom) force-displacement curves.

| Model | Peak force (N) | Indentation (mm) | Energy absorption (J) | CPU time (hour) |
|-------|----------------|------------------|-----------------------|-----------------|
| FMC1  | 8400           | 5.0              | 9.0                   | 90.28           |
| SMC1  | 6900           | 4.9              | 8.4                   | 73.06           |
| SMC2  | 6200           | 4.7              | 7.2                   | 53.55           |
| SMC3  | 6000           | 4.9              | 7.8                   | 52.45           |
As illustrated in the figure 5, the pattern of intra-laminar failure modes is similar for every simulation. The red color indicated the damage, while the undamaged elements are colored with blue. Fiber failures are more dominant in compression due to impact loading from top, while fiber breakage in tension shows less effect on the model because of low initial velocity applied to the plate. Inter-fiber or Matrix failure in compression dominates the highest contribution to the structural failure, while tension IFF occurs at the bottom part of the laminate, due to the bending effect. It is clearly observed that IFF failure mode drives the total failure of the impacted plate.

The delamination morphology is shown in figure 6 for each different finite element models. Delamination spreads away from the location under the impact point and propagates to the outward regions (top to bottom), except for SMC2, due to its tied constraint nature. Once again, the full model (FMC1) exhibits greater delamination regions, and both SMC2 and SMC3 display similar delamination size.

| Layers | FF in tension | FF in compression | IFF in tension | IFF in compression |
|--------|--------------|------------------|---------------|-------------------|
| 7 (45°)| ![Image](image1.png) | ![Image](image2.png) | ![Image](image3.png) | ![Image](image4.png) |
| 6 (0°) | ![Image](image5.png) | ![Image](image6.png) | ![Image](image7.png) | ![Image](image8.png) |
| 5 (-45°) | ![Image](image9.png) | ![Image](image10.png) | ![Image](image11.png) | ![Image](image12.png) |
| 4 (90°) | ![Image](image13.png) | ![Image](image14.png) | ![Image](image15.png) | ![Image](image16.png) |
| 3 (-45°) | ![Image](image17.png) | ![Image](image18.png) | ![Image](image19.png) | ![Image](image20.png) |
| 2 (0°) | ![Image](image21.png) | ![Image](image22.png) | ![Image](image23.png) | ![Image](image24.png) |
| 1 (45°) | ![Image](image25.png) | ![Image](image26.png) | ![Image](image27.png) | ![Image](image28.png) |

*Figure 5. Intralaminar damage morphology of CCF300/epoxy due to LVI loading*
Model | Delamination damage
--- | ---
FMC1 | ![FMC1](image)
SMC1 | ![SMC1](image)
SMC2 | ![SMC2](image)
SMC3 | ![SMC3](image)

**Figure 6.** Delamination patterns according to different modelling technique.

5. Conclusion
In the present study, the numerical validations with four cohesive model are implemented using 3D Puck failure theory incorporated with gradual degradation law. In the FE model, 3D solid elements are widely used to precisely predict the onset of failure as well as the damage accumulation in a composite laminate. The proposed failure model was able to predict the damage behavior of different cohesive method and capture well the damage initiation and progression on composite laminates. It is hoped that this failure formulation can be a great numerical package for future research.

6. References
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