Numerical simulation of Failure Behaviors of CFRP laminates on Hashin model coupled with cohesive elements

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Abstract. The failure modes of carbon fiber reinforced composites (CFRP) was investigated in this study. A method of combination of Hashin model and cohesive elements was proposed to predict failure behaviors in T300/PR319 and AS carbon/epoxy laminates by FE model, while executing three-point bending test. The result shows that there are differences between the response of two materials during bending test. Fiber compression and matrix tension in T300/PR319 and AS carbon/epoxy appears first relatively. Subsequently delamination occurs in AS carbon/epoxy as a result of cohesive elements. A evaluating method of measuring fracture process displacement was also proposed under new damage criterion.

1. Introduction

Since carbon fiber can provide high strength, stiffness, stiffness-to-density ratios. Carbon fiber reinforced composites (CFRP) plays an important role in aerospace and automobile industries. Mechanical properties of CFRPs are mainly affected by primary factors, including properties of raw materials, manufacturing processes and interfacial properties between fiber and resin [1]. The Hashin model, approved extraordinary precision in the second World Wide Failure Exercise (WWFE-II), is widely used in composite laminates strength prediction. Cohesive elements is another way to predict composite delamination [2, 3].

Many researches described the mechanical properties and response of CFRPs by cohesive elements. Chen [2] used cohesive elements in ABAQUS to predict the mechanical response and failure behavior (Hashin failure criterion was employed) of braided composite T-piece specimens under the pulling force. Tarfaoui [3] studied the viscosity coefficient of cohesive elements used in the description of delamination of CFRP, the force-displacement curves obtained numerically shows a good agreement with the experiments. By using ABAQUS subroutine VUMAT, Wang [5] investigated the residual tensile strength of CFRPs after low-velocity impact, proposed a new approach to evaluate the residual tensile strength which can be used in the numerical computation. Sun [6] has studied the fatigue behavior of braided composite when the three-point bending test was carried out, then used UMAT to calculate the stiffness degradation and the maximum deflection of the specimens during each load.
cycle, the results of computation shows good agreement with experiments.

2. Theoretical modeling and numerical simulation

2.1 Damage criterion
The purpose of Hashin model is to predicting the four damage modes of composites, fiber tension, fiber compression, matrix tension and matrix compression. In this study, Hashin failure criterion (HFC) was employed to predicting the failure modes of two kinds of composite laminates.

2.2 Parameters used in simulation
Cohesive elements represents matrix in the middle of the composite, which is the core of the sandwiches structure and bond the upper laminate and the one below. Properties of laminates were cited from reference [9] and exhibits in table 1. T300/PR319 and AS carbon/epoxy were chosen to study their failure modes in three-point bending test.

| Fundamentals properties | $E_1 = E_2$ (GPa) | $G_{12} = G_{13}$ (GPa) | $G_{23}$ (GPa) | $v_{12}$ | $\rho$ (g/cm³) |
|-------------------------|-------------------|-------------------------|----------------|---------|----------------|
| T300/PR319              | 129.00            | 1.33                    | 1.86           | 0.318   | 1.54           |
| AS carbon/epoxy         | 140.00            | 6.00                    | 3.35           | 0.3     | 1.54           |

| Strength properties | $\sigma_{u,c}^L$ (MPa) | $\sigma_{u,c}^T$ (MPa) | $\sigma_{s,c}^T$ (MPa) | $\sigma_{13}^L = \sigma_{23}^L$ (MPa) | $\sigma_{12}^L$ (MPa) |
|---------------------|-------------------------|------------------------|------------------------|----------------------------------------|------------------------|
| T300/PR319          | 1378                    | 950                    | 40                     | 125                                    | 97                     |
| AS carbon/epoxy      | 1990                    | 1500                   | 38                     | 150                                    | 70                     |

2.3 Cohesive elements
Elements COH3D8 are used to simulate delamination behavior of CFRPs. The damage initiation strain $\varepsilon_n^0$ is defined by equation (1). The linear traction-separation behavior of cohesive elements used in this study shows in Figure. 1. $\delta_n^0$ represents the initiation of failure, when the slash reach the point B where $\delta_n^0$ means the failure displacement. The slope of line OA represents the stiffness of cohesive elements, which symbol is $K_n$ ($K_u$, $K_s$). It is worth noting that figure. 1 is similar with constitutive material, they are the same in essence. But $K_n$, which value doesn’t means elasticity modulus, is related to the efficient thickness of cohesive elements. The peak value of the function is the peak strength of the matrix in composites, which symbol is $N_{max}$ ($S_{max}$, $T_{max}$).

$$\varepsilon_n^0 = \frac{N_{max}}{E_n}$$  \(1\)

where, $N_{max}$ and $E_n$ is interlaminar strength and initial elasticity modulus. The damage initiation is depend on the quadratic formula of equation (2).

$$\left( \frac{\sigma}{N_{max}} \right)^2 + \left( \frac{\sigma_s}{S_{max}} \right)^2 + \left( \frac{\sigma_t}{T_{max}} \right)^2 = 1$$  \(2\)

The linear softening damage law was employed in this study and was shown in figure.1. The displacement in different directions was calculated by equation (3). The fracture toughness in $n$ direction was accounted by equation (4).

$$\varepsilon_n^0 = \frac{\varepsilon_n^0 \cdot T_0}{G_{Ic}}$$  \(3\)

$$\delta_n = \delta_n^0 \cdot N_{max} / 2$$  \(4\)

where, $\delta_n^0$ and $\delta_n^u$ is the ultimate displacement and the displacement at peak strength in $n$ direction, $T_0$ is the thickness of the cohesive element. $G_{Ic}$ and $G_{IC}$ was used the same formula above. Mixed-mode fracture energy equation (5) was employed to calculate the total fracture energy
The exponent $\alpha$ in equation (5) was 2, because it shows a good accuracy with failure load of experiments [2].

2.4 Modeling in ABAQUS

In this work, cohesive elements in ABAQUS is used to describe the mechanical properties of interface in composite material, which represent delamination failure mode in CFRPs. Hashin model of strength prediction is used for predicting the mechanical response of laminate in CFRPs. The combination of two method above was used to compare the mechanical behavior of CFRPs.

3. Results and discussion

3.1 Mechanical properties of composite laminates

The force-displacement curve of T300/PR319 and AS carbon/epoxy are shown in figure 3, which indicates the maximum force while executing three-point bending experiments. The maximum displacement were observed, From figure 3. It is clear that composite AS carbon/epoxy require greater force at fracture, where the main failure modes occurred. The slope of descending branch of
Figure 3. The Force-displacement curve of T300/PR319 and AS carbon/epoxy

Figure 4. The Strain energy-displacement curve of T300/PR319 and AS carbon/epoxy

T300/PR319 isn’t as violent as AS carbon/epoxy, which can be interpreted as the differences between epoxy resin and PR319, reference to table 2. The elasticity modulus of PR319 and epoxy are 792 MPa and 4464 MPa, while the failure strain, according to the conversion (by equation (3), (4)), at around 15% and 12%. The strength of T300/PR319 and AS Carbon/epoxy are 103.48 and 76.69, then the failure initiation strain of the two were calculated 13% and 1.7% (equation (1)). The huge difference in failure initiation strain between two materials yields diverse slope of descending branch, details in Section 3.2.

The displacement value of maximum strain energy of the two materials shows a little bit less than the maximum force, figure. 3, 4. Thus, the deformation process can be described as three stages. The load of punch is increasing gradually at first stage and descending drastically at third stage. The fracture process appears between the two stages, it’s indicates the failure is a process which can be measured by the difference value in displacement between maximum strain energy and force.

For the AS Carbon/Epoxy, the failure sequence is matrix tension at bottom, fiber compression on the top, fiber tension at bottom and matrix compression at bottom. The failure sequence in T300/PR319 is fiber compression on the top, matrix tension at bottom, fiber tension at bottom and matrix compression on the top. The main failure modes are matrix tension and fiber compression.

3.2 Interfacial strength
The failure initiation and evolution of cohesive elements were based on quadratic stress criterion and BK criterion.
The state variable QUADSCRT means the value in equation (5), the value was varied with displacement of punch, the difference between T300/PR319 (layer 1, 2) and AS carbon/epoxy (layer 1, 2) is illustrated in figure 6. It’s clear that cohesive elements failure occurred in AS carbon/epoxy (layer 1, 2), but didn’t appear in T300/PR319 (layer 1, 2). The phenomenon interprets the difference in slope of descending branch mentioned in Section 3.1. During the process of loading after peak value in figure 3, many of the cohesive elements were failed and didn’t have ability of carry loads. The results of comparison between layer1 and layer 2 in both materials was the same, failure occurs in layer 1 always behind layer 2. From figure 8, layer 2 shows lower maximum stress than layer 1, relatively. But stress in layer 1 is more concentrated, the phenomenon may due to bending load is fanwise along the thickness of the laminates.

4. Conclusion
In this paper, the differences in mechanical properties between T300/PR319 and AS carbon/epoxy composite laminates were compared by a three point bending experiments constructed in ABAQUS, and the force-displacement curve, strain energy and QUADSCRT were checked. The result of simulation shows the main failure modes, for both materials, are matrix tension and fiber compression. fiber compression and matrix tension occurred at first in T300/PR319 and AS carbon/epoxy. It’s may be caused by greater failure strain in T300/PR319. The loading process was divided in three stages. But delamination occurred only in AS carbon/epoxy.
A method, the difference displacement value at peak of force-displacement curve and strain energy-displacement, is proposed to measure the displacement of fracture process stages.

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Reference
[1] Yan Ma, Yuqiu Yang, Toshi Sugahara and Hiroyuki Hamada 2016 J. Composites Part B 99 162
[2] Jiye Chen, Eric Ravey, Stephen Hallett, Michael Wisnom and Marcello Grassi 2009 J. Compos. Sci. Technol. 69 2363
[3] M. Tarfaoui, A. El Moumen and K. Lafdi 2017 *J. Composites Part B* **112** 185
[4] Guang-Min Luo and Ya-Jung Lee 2008 *J. Compos. Struct.* **85** 64
[5] Bing Wang, Lin-Zhi Wu, Li Ma and Ji-Cai Feng 2011 *J. Composites Part B* **42** 891
[6] Baozhong Sun, Ruiqiang Liu and Bohong Gu 2012 *J. Comput. Mater. Sci.* **65** 239
[7] E. Poodts, G. Minak, L. Mazzocchetti and L. Giorgini 2014 *J. Composites Part B* **56** 673
[8] Ireneusz Lapczyk and Juan A 2007 *J. Composites Part A* **38** 2333
[9] Zheng-Ming Huang and Ling Liu 2014 *J. Int. J. Mech. Sci.* **79** 105
[10] E. Poodts and G. Minak 2014 *J. Composites Part B* **56** 673