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Prediction of Fatigue-Driven Delaminations in Composite Laminates Using Cohesive Zone Model

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Abstract

This paper presents an improved strategy based on Cohesive Zone Model (CZM) for prediction of delamination growth in composite laminates under fatigue loading. The fatigue delamination models describe the crack growth rate as a function of the number of cycles using coefficient of the Paris law-like curve, no crack tip tracking algorithm being required. The proposed CZM fatigue models were implemented into ABAQUS/Explicit via a user-written subroutine VUMAT. The developed models were finally used to simulate fatigue-driven delaminations in composite laminates subjected to mode I, mode II and mixed-mode loading scenarios. Numerical predictions was compared with experimental data that are available from open literature, and a good agreement were obtained.

Keywords: composite laminates, fatigue delamination, finite element modelling, cohesive zone model, VUMAT.

1 Introduction

Fibre-reinforced composite materials have been widely used in aerospace applications due to their outstanding mechanical properties such as high specific strength and stiffness, low density, good designability, excellent corrosion resistance etc. In particular, the proportion of composite laminates is increasing in the design of main load-bearing structures of aircraft which are often subjected to cyclic loads, and this leads to fatigue problems becoming a research focus in the design and application of composite structures. Considering that fatigue experiments on composites are often time-consuming and cost-expensive, it is thus highly important to develop numerical models for efficient evaluation of the performance of composites subjected to fatigue loading.

Cohesive zone model (CZM) formulations that combine concepts of damage mechanics and fracture mechanics have been widely used to predict fatigue-driven delaminations in composites. Turon et al. [1] proposed a model to relate the fatigue damage parameters to the Paris criterion, and derived the growth of fatigue damage for this model based on the energy dissipation in damage mechanics. Pirondi and Moroni [2] simplified the Turon fatigue damage model by assuming that the fatigue damage rate keeps constant within the cohesive zone, and calculated the energy release rate of the crack tip based on the J-integral method. Kawashita and Hallett [3] developed a crack tip tracking algorithm for the analysis of composites, which does not require the estimation of the cohesive zone length and is less dependent on the mesh size. Zhang et al. [4] proposed a twin models to effectively simulate fatigue-induced delaminations in composite laminates under loading conditions where one model is loaded with a crest envelope and the other with a trough envelope. Teimouri et al. [5] proposed a trilinear CZM for simulation of mode I fatigue-induced delamination in the presence of large-scale fiber bridging, showing a better simulation accuracy than bilinear CZM curves.

In this paper, an improved strategy of fatigue damage modelling is proposed for the delamination growth in composite laminates under fatigue loading. The developed models are based on the CZM and the Paris law, and no crack tip tracking algorithm or additional parameter fitting is needed. The fatigue models are implemented into the commercial software ABAQUS/Explicit via a user-written subroutine VUMAT and are applied to simulate fatigue-driven delaminations in composite laminates under mode I, mode II, and mixed-mode loading scenarios, respectively. The prediction capability and mesh sensitivity of the developed numerical tool is explored.

2 Methods

The fatigue damage formulations are extensions of bilinear cohesive laws for quasi-static loading [6-7]. The propagation of fatigue delamination is described by a variant of the Paris law:

$$\frac{da}{dN} = \mathrm{C}\left(\frac{G_{\mathrm{a}}}{G_{\mathrm{C}}}\right)^{\mathrm{m}} \tag{1}$$

where a is the length of the fatigue crack, and C and m are two semi-empirical parameters that can be obtained from fatigue delamination experiments. G_a is the maximum strain energy release rate during the loading cycle, which is usually located at the crack tip of the cohesive zone, and G_C is the critical energy release rate.

As illustrated in Figure 1, the amount of static damage acquired by an element at the point of failure can be defined as:

$$D_{\mathrm{s}}^{\mathrm{fat}} = \frac{\delta^{\mathrm{f}}\left(\delta_{\mathrm{fat}} - \delta^{0}\right)}{\delta_{\mathrm{fat}}\left(\delta^{\mathrm{f}} - \delta^{0}\right)} \tag{2}$$

where δ^0 and δ^{f} are the displacements corresponding to damage initiation and complete failure under quasi-static loading, respectively, and δ_{fat} is the complete failure displacement under fatigue loading.

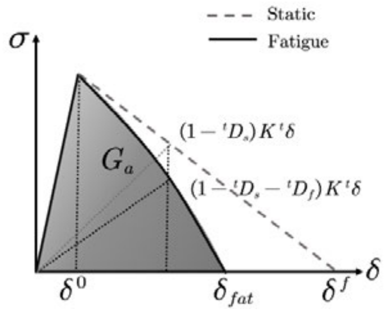


Figure 1: Traction-Separation Law for fatigue modelling.

In order to obtain the maximum value of energy and displacement in the cohesive zone elements at each moment, it is necessary to introduce global variable commands in the user subroutine VUMAT.

At the beginning of each incremental time step, the energy release rate of all cells in the cohesive zone is stored in a global array so that all cells can share this data. Get the maximum value in this array and assign it to G_a in Equation (1), get the cell where the maximum value is located and assign the displacement value of this cell to δ_{fat} in Equation (2).

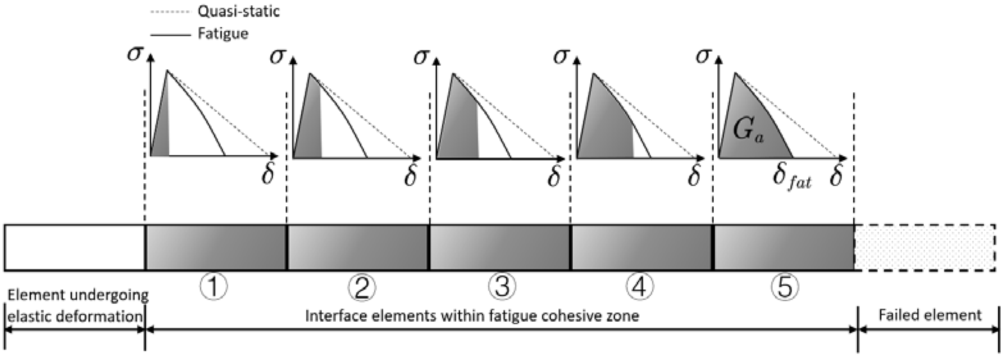


Figure 2: Illustration of fatigue cohesive zone.

The fatigue cohesive zone elements are defined as elements where the displacement is greater than the damage initiation displacement and has not failed completely (see Figure 2.). Delamination propagation can be seen as a process in which the cohesive zone gradually expands forward and the non-cohesive zone elements gradually transform into cohesive zone elements and then fail completely.

Therefore, the number of cycles required for a cohesive zone element to fail completely is:

$$N_{\mathrm{f}} = \frac{L_{\mathrm{cz}}}{da / dN} \tag{3}$$

where L_{cz} is the length of the fatigue cohesive zone and its value can be obtained by defining a binary variable in the subroutine VUMAT for the identification of the cohesive zone elements. The rate of fatigue damage accumulation can thus be calculated as:

$$\frac{dD_{\mathrm{f}}}{dN} = \frac{D_{\mathrm{f}}}{N_{\mathrm{f}}} = \frac{1 - D_{\mathrm{s}}^{\mathrm{fat}}}{N_{\mathrm{f}}} \tag{4}$$

3 Results

To evaluate the performance of the fatigue damage model developed in this paper, numerical simulations were performed on unidirectional HTA/6376C carbon/epoxy laminate [8-9]. The geometry of the HTA/6736C specimen used for mode I DCB, mode II ELS and 50% mode mixity MMB virtual tests is shown in Figure 3. The material properties used in the simulations are obtained from references [8-10] and are listed in Table 1.

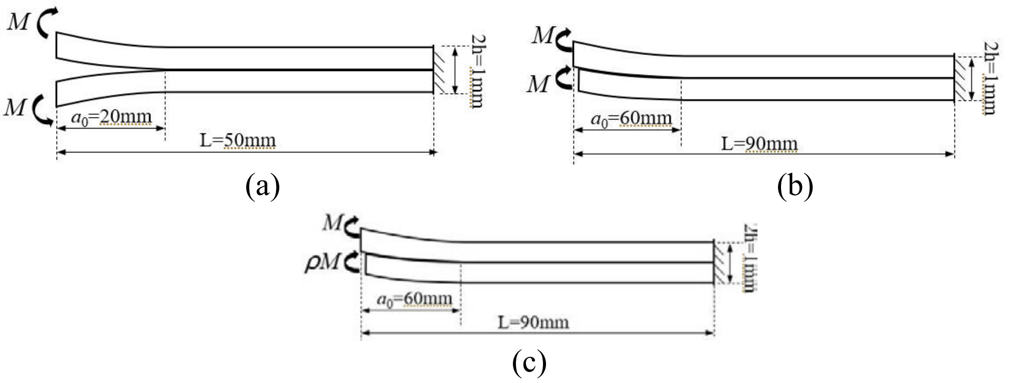


Figure 3: Geometry of the laminate used for
(a) mode I DCB, (b) mode II ELS and (c) 50% mode mixity MMB virtual tests.

Laminate properties		Interfacial properties			
E_{11}	120.0 GPa	σ_I^0	30.0 MPa	m_{II}	4.46
$E_{22}=E_{33}$	10.5 GPa	σ_{II}^0	60.0 MPa	G_{IIc}	1.002 kJ/m^2
$G_{12}=G_{13}$	5.25 GPa	C_I	0.0066	C_m	0.168
G_{23}	3.48 GPa	m_I	5.9	m_m	6.28
$v_{12}=v_{13}$	0.3	G_{Ic}	0.26 kJ/m^2	G_m	0.447 kJ/m^2
v_{23}	0.51	C_{II}	0.1392		

Table 1: Material properties for HTA/6376C carbon/epoxy laminate [8-10].

In order to improve the computational efficiency of the fatigue division simulation, the envelope load method is used. As shown in Figure 4, the same load as the quasi-static loading mode is used for the first analysis step. The load of the second analysis step keeps the maximum load constant, and the cyclic load is realized by the frequency parameter set in the subroutine.

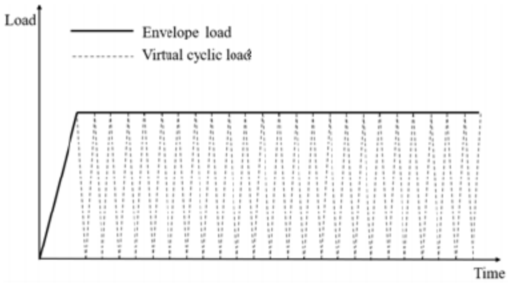
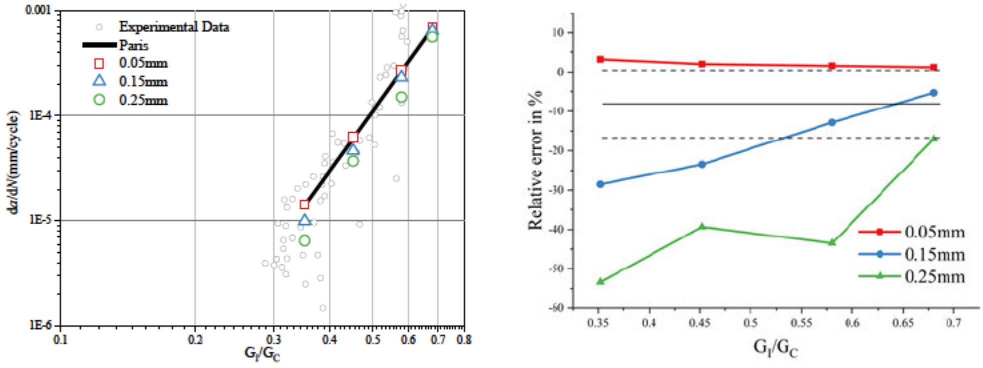


Figure 4: Schematic illustration of envelope load method.

Furthermore, to understand the effect of mesh refinement on the improved fatigue cohesion model, the fatigue expansion rates of mode I, mode II, and mixed-mode were simulated for different sizes of cohesive elements under different constant amplitude load magnitudes. The simulation results and relative error are shown in Figures 5-7. Experimental data are obtained from reference [10].

For mode I DCB virtual test (Figure 5), when the element size is 0.25 mm, it can be clearly seen that the curve deviates from the theoretical Paris law. When the element size is set to 0.15mm or 0.05mm, a good match can be seen between the prediction and the experimental data as well as the theoretical Paris law, and the trend of the predicted results is basically the same as the slope of the Paris curve.

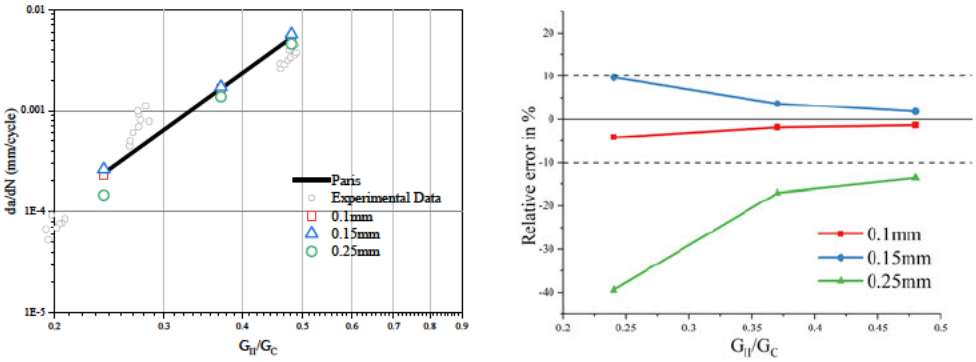


(a) (b)

Figure 5: Numerical results and relative error for mode I DCB virtual test.

Similarly, for mode II ELS virtual test (Figure 6a), the results for the element size of 0.25 mm deviate from the theoretical Paris curve, while those for the element sizes set to 0.1 mm and 0.15 mm are in reasonable agreement with the experimental data and the theoretical Paris law.

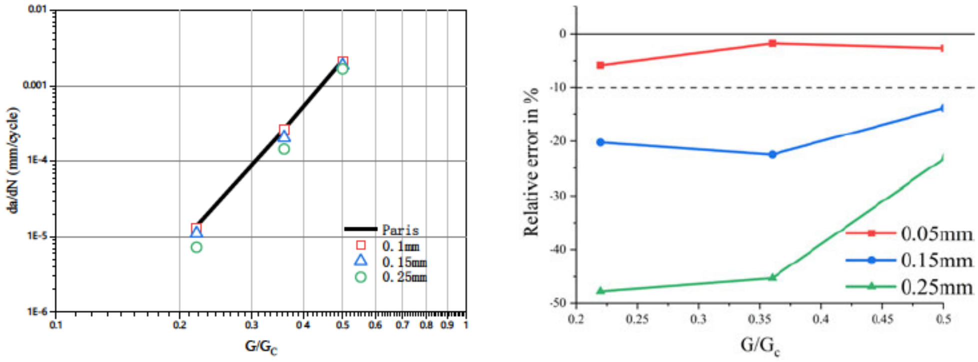
Comparing Figure 5a with Figure 6a, it can be found that the analysis results of mode II are more accurate than those of mode I when the same element size is set for simulation. This can be attributed to the fact that the length of fatigue cohesive zone under Mode II loading is longer than that of Mode I loading.



(a) (b)

Figure 6: Numerical results and relative error for mode II ELS virtual test.

As seen in Figure 7, the simulation for 50% mixed-mode virtual test is similar to the previous two cases. Larger elements sizes lead to the simulation results deviating from the Paris curve. Combining Figure 5b, Figure 6b, and Figure 7b, the relative error of all three finite element simulation results decrease as the applied load increases.



(a) (b)

Figure 7: Numerical results and relative error for 50% mixed-mode virtual test.

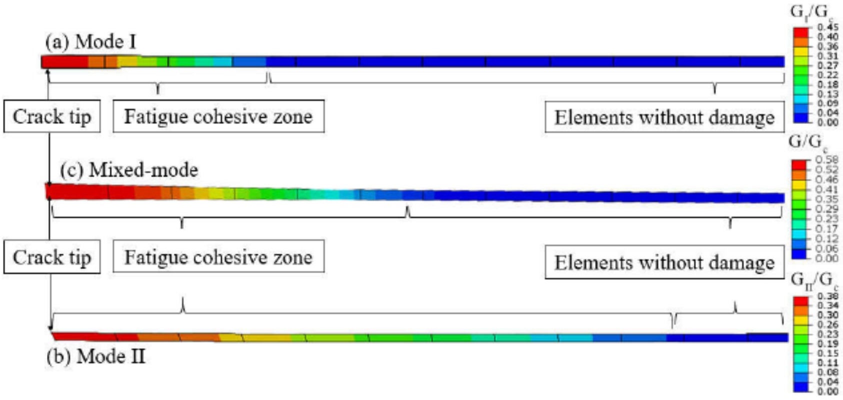


Figure 8: Comparison of fatigue cohesive zone for
(a) mode I DCB, (b) mode II ELS and (c) 50% mode mixity MMB loading cases.

The state of the cohesive zone elements for different loading modes is compared in Figure 8. It can be easily found from the figure that mode II has the longest fatigue cohesive zone length, which demonstrates the weakest mesh sensitivity for mode II.

4 Conclusions and Contributions

The development of an effective finite element tool to predict the fatigue delamination behaviour of composite laminates is of great importance for practical engineering. Although the existing simulation methods can give reasonable prediction results, they still need to be advanced in terms of applicability and ease of use.

In this paper, an improved fatigue damage rate strategy was proposed to predict the fatigue-driven delaminations in composite laminates on basis of cohesive zone model combined with the Paris law. The simulation strategy uses two Paris parameters obtained from experiments, and no additional parameter fitting and calibration are needed. Furthermore, the algorithm to obtain global information about the model ensures that the data used to calculate the fatigue crack growth rate are for the element with the largest current energy release rate, so that no additional complex crack tip tracking algorithms are required either. The proposed models were implemented in ABAQUS/Explicit through a user-written subroutine VUMAT. The developed models were used to simulate the two-dimensional fatigue damage growth in composite laminates subjected to mode I, mode II, and mixed-mode cases. It is found that a reasonable agreement can be obtained between numerical simulations and experimental data and that sufficient cohesive elements must be present in the fatigue cohesive zone to ensure the accuracy of the predictions.

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