XFEM-based model for simulating zigzag delamination growth in laminated composites under mode I loading

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Abstract: Interfaces adjacent to a 90° ply in laminated composites show a typical zigzag path during the mode I delamination propagation process, which is considered to be closely related to high propagation values of fracture toughness. DCB (double cantilever beam) tests of specimens with a starter crack inserted into two 90° mid-layers were carried out, during which the zigzag delamination growth and pronounced *R*-curve behavior were obtained. To simulate the zigzag delamination propagation path, four XFEM-based delamination growth models were proposed which are comprised of a crack initiation model and a crack propagation model, respectively. In the framework of the delamination growth model, a new crack initiation model was developed, which took a quadratic criterion as the crack initiation criterion and the direction orthogonal to the maximum principal stress as the crack growth direction. Based on the mechanism of the delamination resistance, four crack propagation models considering whether the delamination follows a pure or mixed mode damage evolution law and whether a constant or varying critical fracture toughness dominates the damage evolution were introduced. By comparing the predictions from the four delamination growth models and the experimental results, the mode I delamination mechanism with a zigzag path was investigated. The delamination growth model that adopted a critical fracture

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toughness function and the mixed mode damage evolution law showed the best agreement with the experimental results and was recommended.

Keywords: Carbon/epoxy composites, Delamination, Zigzag path, XFEM.

1 Introduction

Due to the weak interlaminar mechanical property of composite laminates, delamination is a hidden peril for composite structures in engineering practice, which attracts significant attention in composite structural designs. Delamination in composite laminates always show *R*-curve behavior, thus the complete failure of the multidirectional laminates depends on the delamination propagation behavior instead of the initiation of the delamination because the increasing resistance with increasing delamination length will hinder subsequent delamination propagation. Accordingly, it is important to study the mechanism of delamination resistance in composite laminates. Compared with unidirectional laminates, multidirectional laminates are more widely used in practical engineering application, which show far more prominent *R*-curve behavior during the delamination process than unidirectional ones. And there is a high tendency for delamination propagating out of the origin crack plane during the delamination growth process in multidirectional laminates, which further triggers extraordinary crack propagation behaviors, such as stair-shape propagation, zigzag propagation, crack jumping and double cracking [1,2]. Among various multidirectional interfaces, the interfaces adjacent to a 90° ply, such as the 90°/90° and 0°/90° interfaces shows most significant *R*-curve behavior with a high propagation fracture toughness value and typical zigzag delamination propagation trajectory during mode I delamination [3,4]. A comprehensive experimental study has been undertaken by a technical committee of the European Structural Integrity Society to investigate the mode I delamination at the 90°/90° and 0°/90° interfaces. A total of three times round robin tests on cross-ply laminates were conducted and some works of which have been published [2,5-7]. It is considered that the

zigzag delamination path is the root of highly pronounced *R*-curve behavior presented in the interfaces adjacent to a 90° ply. Laksimi et al. [3] noted that the change in the propagation plane during the delamination at the interface adjacent to a 90° ply would dissipate more energy. Brunner and Flueler [7] summarized three mechanisms relevant to the high apparent G_{Ic} , which were the increase in fracture surface, mixed mode I/II contributions, and extra energy dissipation from fiber-bridging and micro-cracking. Farmand et al. [8] indicated that the fiber bridging in the cross-ply specimens was the main cause of their highly pronounced delamination resistance.

To investigate the resistance mechanism of the delamination at the interface adjacent to a 90° ply, much attentions have been paid to the simulation of delamination migration behavior within the 90° layer. Morais et al. [2] adopted the virtual crack closure technique (VCCT) to simulate the intralaminar crack propagation within the 90° layer neighboring the interface with a previously specified crack path. Bouvet et al. [9] used the cohesive element to model the crack migration in laminates with 90° plies, where the interface delamination and matrix cracking were simulated based on fracture mechanics and failure criterion, respectively. Both the VCCT and CZM (cohesive zone model) based method need a prescribed path, to alleviate this limitation Carvalho et al. [10] proposed a novel modeling approach that combined the floating node method (FNM) with the VCCT to capture the delamination migration in cross-ply tape laminates tested in a special delamination migration test designed by Ratcliffe et al. [11,12]. The same delamination migration behavior at the 0°/90° interface in the cross-ply laminates was also accurately simulated by Zhao et. al. [13] with the extended finite element method (XFEM). The XFEM approach shows a distinct advantage in simulating the initiation and propagation of a crack along an arbitrary, solution-dependent path, which has attracted a lot of attentions in delamination simulation of multidirectional laminates [14-16]. In fact, the deviation of the delamination into the neighboring 90° plies led to a delamination

and intra-ply matrix cracking coupled damage pattern, which is a typical damage mechanism of composites [17-20]. On consideration of the different mechanisms of delamination and matrix cracking, the combined XFEM-CZM method is increasingly prevalent [8,21-27]. For instance, Grogan et al. proposed a combined XFEM-SCZM methodology, which simulated intra-laminar failure in multidirectional composite laminates using XFEM and delamination growth between plies using a surface-based cohesive zone model [22,23]. Farmand et al. [8] established a numerical model for the mode I crack growth in cross-ply carbon-epoxy laminates, in which the crack deviation from the originally pre-defined plane into the adjacent 90° layer was simulated with XFEM, and subsequent crack propagation along a neighboring interface was simulated with the cohesive element.

Although various numerical methods have been successfully applied to delamination simulation along the interfaces of 0°/90° and 90°/90°, the zigzag delamination growth path resulted from oscillating crack migration, which is usually observed in the case of interfaces adjacent to a 90° ply has not yet been simulated accurately. The accurate simulation of the zigzag delamination fashion is important to investigate the delamination resistance mechanism of the interface adjacent to a 90° ply. The delamination with a zigzag path within the 90° ply is a matrix-cracking dominated behavior, which propagated along a path dependent of the stress field of crack tip. For this reason, the XFEM technique was adopted in current work, which was used in conjunction with a cohesive segments method to govern the damage evolution after crack initiation.

The goal of this paper is simulating the periodical crack migration during the mode I delamination with a zigzag path, to realize that four XFEM-based delamination growth models for mode I delamination with the typical zigzag path were established based on different assumptions of the delamination resistance mechanism. The corresponding simulations were carried out, in which an XFEM-based cohesive segment method was

adopted to model the crack initiation and subsequent propagation. DCB specimens made of T800 carbon/epoxy (CYCOM X850) composites and with a starter crack between two 90° mid-layers were designed and tested. By comparing the simulations with the experimental results, the models were validated and the zigzag delamination growth mechanism was also revealed.

2.1 Specimens and Experiments

Two DCB specimens were designed according to ASTM D 5528-01 [28] which are numbered as D-1 and D-2, respectively. The specimens are made of unidirectional T800 carbon/epoxy (CYCOM X850) composites prepreg with a fiber volume fraction of about 57.6% manufactured by CYTEC. The stacking sequence of the tested specimen is (90°/0°₁₀/90°)/(90°/0°₁₀/90°). Table 1 lists the material properties of the unidirectional lamina with an average thickness of 0.185mm [29]. Two non-dimensional parameters, D_c and B_t , are

calculated according to the formulas of $D_c = \frac{D_{12}^2}{D_{11}D_{22}}$ and $B_t = \frac{|D_{16}|}{D_{11}}$ [30]. D_{11} , D_{12} and D_{22}

are the elements in the flexural-stiffness matrix of the legs of the DCB specimen. Based on the classical laminated theory the value of D_{11} , D_{12} and D_{22} are calculated, which are 1350.0 MPa·m³, 33.4 MPa·m³, and 1010.0 MPa·m³, respectively. Substitute the value of D_{11} , D_{12} and D_{22} into the above formula, and the value of the D_c and B_t are obtained, which are 8.22×10^{-4} and 7.53×10^{-19} , respectively. D_c characterizes the difference in strain energy release rate (SERR) at the edges and the center of the specimen due to the longitudinal-transverse bending coupling of specimen legs, and B_t characterizes the asymmetry of the SERR about the specimen center due to the bending-twisting coupling of specimen legs. Because the values of D_c and B_t are quite small, which indicates that the SERR distribution along the delamination front of the test specimen is uniform, so the delamination front can maintain a straight shape in the width direction.

A polymer insert was placed at the mid-plane serving as a delamination initiator as shown in

Fig. 1. The insert was made of Teflon film, and its thickness was no greater than 13 μm . The folding or crimping of the insert should be avoided during the fabrication of specimens. After curing, the specimens were cut into the desired geometry dimension shown in Fig. 1. A groove was cut at the end of the specimen for assembly with a quick-mounted hinge shown on the right of Fig. 1. One edge of the specimen was painted with a thin layer of water-based typewriter correction for the convenience of delamination front identification.

The static DCB test was run on an MTS 880 servo-hydraulic test machine (load cell capacity of 1.5 kN) with a cross-head displacement rate of 0.1mm/min. A traveling microscope (JCXE-DK) equipped with a digital camera was used to trace the crack tip, which can pinpoint the crack tip with an accuracy of 0.01 mm. In addition, an electronic dial gage was utilized associated with the computer to obtain the delamination length automatically. During the test, the real-time delamination length with its corresponding load and open displacement were recorded. The load-displacement curve was recorded by the computer automatically. Besides, typical images of the delamination front and delamination path during the test were captured.

2.2 Data reduction method

The fracture toughness data, G_I , during the static mode I delamination test were obtained using a modified beam theory (MBT) [31]:

$$G_I = \frac{3Pd}{2B(a + \Delta)} \quad (1)$$

where P is the load, d is the load point displacement, B is the specimen width, and a is the delamination length. Δ is a correction for the delamination length accounting for the rotation occurring at the delamination front, which is determined experimentally by generating a least squares plot of the cube root of compliance, $C^{1/3}$, as a function of delamination length, in which the compliance C is the ratio of the load point displacement d to the applied load P . The data used to generate the above plot are the loads and displacements corresponding to the

visually observed delamination lengths on the edge [28].

2.3 Experiment Results

2.3.1 Load-displacement curve and *R*-curve

Fig. 2 shows the load-displacement curves of two specimens D-1 and D-2, which are in good consistence. The load-displacement response is initially linear up to a point where a slight load drop occurs, which means that the onset of delamination takes place. The load then increases again with an obvious ‘stick-slip’ behavior, which indicates a pronounced resistance-type fracture behavior or *R*-curve during the delamination growth process. The delamination resistance curves for the test specimens under mode I loading are exhibited in Fig. 3, in which the fracture toughness first increases monotonically with increasing delamination growth length a . Clearly, with the increment of a , the fracture toughness eventually stabilizes around a steady-state value. A general mathematical expression is presented [32] to describe the *R*-curve behavior of multidirectional DCB specimens, from which a critical fracture toughness function $G_{Ic}(a)$ is obtained by the experimental data fitting and also shown in Fig. 3. Where G_{init} denotes the initial fracture toughness, which is 350J/m^2 . G_{bz} represents the fracture toughness caused by fiber bridging, which is defined as the difference between the plateau fracture toughness G_{Prop} and G_{init} , and its value is 820J/m^2 . l_{bz} denotes the fiber bridging zone length, which is 16mm .

2.3.2. Zig-zag delamination propagation path

Fig. 4 illustrates typical delamination growth paths during the tests. When the displacement loading was applied to the DCB specimen, the crack propagated along the pre-cracked plane with the interface of $90^\circ/90^\circ$. After passing by the pre-delaminated area, the delamination initiated at the end of the insert (see the vertical red line marked in Fig. 4(a)) and continued to propagate along the mid-plane. When the initial load drop occurred, a transverse matrix crack initiated at the tip of the pre-crack and advanced towards the adjacent 90° layer, which led to

the delamination migration into the lower adjacent $90^\circ/0^\circ$ interface. After that, the delamination propagated a short distance along the $90^\circ/0^\circ$ interface. The delamination path then shifted upward and back to the middle $90^\circ/90^\circ$ interface, as illustrated in Fig. 4(b). With further displacement loading, the delamination periodically wriggled within the two middle 90° plies and finally yielded a zigzag trajectory, as shown in Fig. 4(c).

3. Delamination growth model and numerical simulation

Based on the mode I delamination propagation mechanism shown in specimens with a zigzag delamination growth path, four XFEM-based delamination growth models were proposed. A 2D finite element model was built in the software program ABAQUS[®]. Abaqus/Standard was employed in current work and the user subroutines developed for the delamination growth models were inserted into ABAQUS[®], from which the simulation for the delamination growth behavior in the specimen was implemented.

3.1. XFEM-based delamination growth model

To drive delamination growth with an XFEM-based method, a crack initiation model and a damage evolution model are required. The former includes a crack initiation criterion used to indicate the beginning of crack growth and a specified crack growth direction. For the waved delamination growth path shown in Fig. 4, in addition to the interface separation controlled by the normal stress, considerable intra-ply damages occurred during the delamination growth. Because the kinking of the delamination into the 90° ply was promoted by the shear stress at the crack tip [12,33], a quadratic criterion proposed by Long [34] that considers the influence of normal stress and shear stress at the crack tip was adopted as the crack initiation criterion. In addition, due to the transverse isotropic performance of composite lamina, a 90° ply behaves macro-mechanically homogeneously and isotropically for the delamination growth. Thus, the crack growth direction within the 90° plies was considered to follow the principal stress trajectory at the crack tip and was specified to be orthogonal to the maximum principal

stress direction in the current work. In summary, the crack initiation model is exhibited in the following equation

$$\left\{ \begin{array}{l} \left(\frac{\sigma_n}{Z_T} \right)^2 + \left(\frac{\sigma_s}{S} \right)^2 = 1 \\ \vec{\varphi} \perp \overrightarrow{\sigma_{\max}} \end{array} \right. \quad (2)$$

where σ_n and σ_s are interlaminar normal stress and shear stress, respectively. Z_T and S are tensile strength and shear strength, respectively. In view of the transverse isotropic performance of the composite lamina, the value of Z_T and S are equal to the transverse tensile strength Y_T and shear strength S_L listed in the Table 1, respectively. $\vec{\varphi}$ denotes the direction vector of the newly extended crack and $\overrightarrow{\sigma_{\max}}$ indicates the maximum principal stress direction vector.

Once the crack initiation criterion is satisfied, the crack propagation will be characterized by a damage evolution model, which uses the damage evolution law to describe the cohesive stiffness degradation behavior of the enriched element. A typical linear traction-separation model shown in Fig. 5 was adopted in the current work to model the cohesive stiffness degradation behavior, in which a damage variable, D , evaluating the average damage level of the cracked element, was used to describe the degradation process of the cohesive stiffness. After the initiation criterion is satisfied, the damage variable, D , will monotonously increases from its initial value 0 to 1 (corresponding to the final failure). The normal and shear stress components of the traction-separation model decrease with the damage evolution according to the following law:

$$t_n = \begin{cases} (1-D)T_n & T_n \geq 0 \\ T_n & \text{otherwise (no damage to compressive stiffness);} \end{cases} \quad (3)$$

$$t_s = (1-D)T_s \quad (4)$$

where T_n and T_s are respectively the normal and shear stress components determined as the

stress corresponding to the separation before damage initiation. They are calculated by the following elastic constitutive relation.

$$\begin{Bmatrix} T_n \\ T_s \end{Bmatrix} = \begin{bmatrix} K_{nn} & 0 \\ 0 & K_{ss} \end{bmatrix} \begin{Bmatrix} \delta_n \\ \delta_s \end{Bmatrix} \quad (5)$$

where K_{nn} and K_{ss} are respectively the normal and tangential stiffness components calculated from the elastic properties of the enriched element in XFEM. δ_n and δ_s are the separations in the normal and tangential directions, respectively.

The linear traction-separation model can be directly determined with the effective displacement $\delta_{\max}$ at the complete failure, or with dissipated energy from damage initiation to complete failure, which is equal to the critical fracture energy G_c . The displacement based method and the energy based method are equivalent in fact, as the value of G_c is determined as the area under the traction-separation curve.

Generally, the eventual failure is described by an energy-based damage evaluation method for the delamination under a pure mode. More frequently, delamination growth usually occurs under mixed mode loading, for which case the B-K law shown in following equation is adopted.

$$G_{Ic} + (G_{IIc} - G_{Ic}) \beta^\eta = G_c \quad (6)$$

where G_{Ic} , G_{IIc} and η are the specified material parameters and $\beta = G_{II} / (G_I + G_{II})$.

From Fig. 3 and Fig. 4, it can be found that the mode I delamination resistance of test specimens presents obvious *R*-curve behavior and the delamination of the test specimen with a start crack between two 90° plies exhibits the typical zigzag crack growth trajectory. Brunner and Flueler [7] indicated that the resistance of mode I delamination with a zig-zag path within the 90° ply presented a high level for three reasons. First, the wavy delamination path resulted in a longer effective delamination length, which caused the increment in the fracture surface. Therefore, additional energy would be required. That refers to the apparent

effect of the zigzag delamination path itself because the zigzag crack growth trajectory is deemed to cause a larger fracture surface and leads to higher fracture toughness than that of delamination with a straight path. Second, when the delamination path deviated from the middle plane, the specimen would rotate, which induced shear stresses to the crack tip, and the crack sliding mode (mode II) was considered to exist although the specimen was under mode I loading. Consequently, the deviations of the delamination path within the 90° ply caused the pure mode I delamination to become mixed mode delamination, and the mode II contribution was considered to yield a higher fracture toughness value. Third, the wavy pattern with a periodical crossing the 90° ply would trigger serious fiber bridging and micro-cracking, which would dissipate much extra energy. Based on the delamination resistance mechanism during the delamination with a zigzag path, four delamination growth models were established, as follows:

(1) Model 1: Adopting a pure mode damage evolution law

$$\frac{G_I}{G_{Ic}}=1 \quad (7)$$

where G_I refers to the SERR and G_{Ic} is a constant critical fracture toughness.

(2) Model 2: Introducing a critical fracture toughness function into the pure mode damage evolution law

$$\frac{G_I}{G_{Ic}(a)}=1 \quad (8)$$

where $G_{Ic}(a)$ is the critical fracture toughness function obtained by the experimental data fitting, which means that the critical fracture toughness is dependent on the crack growth length.

(3) Model 3: Adopting the B-K law as the mixed mode damage evolution law

$$G_{Ic} + (G_{IIc} - G_{Ic})\beta^n = G_I + G_{II} \quad (9)$$

where $\beta = G_{II} / (G_I + G_{II})$; G_I and G_{II} are the values of SERR under mode I and mode II

respectively; G_{Ic} and G_{IIc} are the constant values of critical fracture toughness under mode I and mode II respectively; η is the material parameters.

(4) Model 4: Introducing the critical fracture toughness function into the B-K law

$$G_{Ic}(a) + (G_{IIc} - G_{Ic}(a))\beta^\eta = G_I + G_{II} \quad (10)$$

The above four delamination growth models utilize the same crack initiation model represented in equation (2), but adopt different crack propagation models to control the damage evolution based on different hypotheses for the delamination resistance mechanism. Model 1 and Model 2 assume that the delamination growth behavior of the specimen under mode I loading can be characterized by the pure mode damage evolution law. Model 3 and Model 4 consider that the zigzag delamination path may introduce the mode II delamination. Therefore, the damage evolution is governed by a mixed mode damage evaluation law (for example, the B-K law). Model 1 and Model 3 assume that the zigzag path itself leads to the increasing resistance during the delamination process as a result of the increased fracture surface, thus, the constant value was adopted for the critical fracture toughness. Model 2 and Model 4 assume that the extra energy dissipation from the serious fiber bridging and micro-cracking, which are indirectly induced by the zigzag path, dominates the increase in delamination resistance. The extra energy dissipation is represented by the *R*-curve behavior or the critical fracture toughness function $G_{Ic}(a)$. Thus, Model 2 introduces the critical fracture toughness function into the energy-based damage evaluation law under the pure mode, and Model 4 introduces the critical fracture toughness function into to the mixed mode damage evaluation law. Because G_{IIc} was considered to show modest *R*-curve behavior according to the previous study [35] and no stable delamination growth was obtained when an ENF (end-notched flexure) test was conducted on the specimens, no critical fracture toughness function was adopted for G_{IIc} .

3.2. Finite element model

Because the values of D_c and B_t were minuscule, which means that the delamination front can remain straight and parallel to the width direction of the specimen, the delamination stages at the two edges and the interior of the specimen width are uniform. Thus, the delamination of the test specimen can be simplified to a two-dimensional (2D) problem. In this paper, a layer-wise 2D finite element (FE) model of the DCB specimen was established with CPS4 (4-node bilinear plain stress quadrilateral) elements, as shown in Fig. 6. In view of the transverse isotropic performance of the composite lamina, the 90° ply behaviors isotropic in plane of the 2D FE model. Thus, the 90° ply was modelled with isotropic material properties, and the 0° ply was modelled as an anisotropic material in the 2D EF model. The two 90° plies in the middle of the specimen forming the origin delamination interface were modeled as one integrated ply which was discretized with three elements in the thickness direction. Other parts of the specimens were modeled with a ply-by-ply strategy, and each ply was discretized with one element in the thickness direction. A uniform mesh size of 0.15 mm was chosen for the whole FE model in the length direction of the DCB specimen. The enriched feature was specified for the elements in the EF models of the two DCB arms to make them enriched elements with the XFEM property. The insert made of Teflon film was modeled as a bar with a real thickness of 10 μm , which was assembled to the FE model of the DCB specimen and positioned in the middle section of two 90° plies. No property assignation and meshing were implemented on the insert model, as it just indicates the position of the crack tip of the starter delamination. In order to simulate the true loading condition during the DCB test, the bottom point (point A in Fig. 6) at the lower arm of the 2D FE model and on the true loading line was fixed, and a tensile load in the form of displacement with 20mm was exerted on the uppermost point (point B in Fig. 6) at the upper arm of the 2D FE model, which was also on the true loading line. In addition, because the mode I delamination propagation behavior

belongs to a large deformation problem, the geometric nonlinear analysis was adopted, which can be set in ABAQUS[®]. To avoid computational non-convergence during the analysis of the highly discontinuous crack growth problem, a viscosity coefficient with a value of 10^{-5} was used.

3.3 Implementation of the XFEM simulation

Within the XFEM framework in ABAQUS[®], four delamination growth models were developed, each of which consists of a crack initiation model and a crack propagation model. The crack initiation model, which includes the crack initiation criteria and specified crack growth direction, was defined in the user subroutine UDMGINI. The crack growth was governed by the built-in damage evolution law in ABAQUS[®]. The XFEM-based cohesive segments method was adopted to model the crack propagation, which combines the cohesive segments method with phantom nodes. The XFEM-based cohesive segments method used the traction-separation law to simulate the degradation of inter-atomic cohesion, which can avoid the singularity at the crack tip. For the critical fracture toughness function, the user-subroutine USDFLD developed in ref. [36] was used, which provides the variable fracture toughness values with delamination growth length a .

The delamination propagation simulation of the specimen with a start crack between two 90° mid-layers was implemented. Fig. 7 shows the implementation flowchart of the XFEM simulation, and essential steps are described briefly as follows:

- (1) Build a 2D FF model of the DCB specimen with a start crack between two 90° mid-layers.
- (2) Specify the enriched feature for the FE models of the two DCB arms to make them consist of elements that are likely to be intersected by cracks during the delamination propagation.
- (3) Define the crack initiation criterion and specify the crack propagation direction in a user subroutine UDMGINI, and insert the user subroutine into ABAQUS[®].

(4) Set the damage evaluation law, which controls the crack propagation. If varying of fracture toughness is considered, define a user subroutine USDFLD to provide the critical fracture toughness function $G_{Ic}(a)$.

4. Results and discussion

Fig. 8 shows the simulated load-displacement curves of four models and the experimental results of specimens D-1 and D-2. Because all four simulations realized the similar zigzag delamination growth path, a typical one is shown in the bottom of Fig. 8. It can be observed that the predicted results from “Model 2” and “Model 4” are almost identical, both of which show good agreement with experimental results. However, the prediction from “Model 1” and “Model 3” shows a significant low-level load from other two models and the experiment results. This is because “Model 1” and “Model 3” adopt the constant critical fracture toughness instead of the fracture toughness function $G_{Ic}(a)$. When the increasing fracture toughness G_{Ic} is considered, for example, in the cases of “Model 2” and “Model 4”, the delamination resistance will increase after the crack initiation, which represents the continuing increase of the load. Based on the above analysis, it indicates that the fracture toughness function $G_{Ic}(a)$ is suitable to reflect the resistance during the delamination growth process, which should be involved in the simulation. This also verifies the assumption that the extra energy dissipation from serious fiber bridging and micro-cracking is the dominated cause of increasing delamination resistance. Moreover, the distinction of the results from “Model 1” and “Model 3” shows that the introduction of the mode II component does affect the delamination resistance, but the good agreement between the results from “Model 2” and “Model 4” shows that the mixed mode effect is insignificant compared with the extra energy dissipation from serious fiber bridging and micro-cracking, which demonstrates that the crack growth is still dominated by mode I in spite of the occurrence of delamination plane deviation. At the same time, “Model 1” realized the simulation of the typical zigzag path similar to

“Model 2” and “Model 4”, but it could not accurately predict the load-displacement response with a pronounced *R*-curve characteristic, which indicates that the zigzag path itself has a small impact on the increased resistance during the delamination propagation. In summary, both the zigzag delamination path itself and the introduced mixed mode effect are not the main cause of the increased delamination resistance. The increasing delamination resistance during the crack growth process is mainly caused by the occurrence of serious fiber birding and matrix cracking accompanying the zigzag delamination growth behavior.

As discussed above, although both “Model 2” and “Model 4” offer good predictions for the load-displacement responds of the specimens, by contrasting with the experimental observation of the delamination path, it is found that “Model 4” can give the best simulation for the delamination growth behavior, including the crack plane alternation evolution during the first stage of delamination and the final regular zigzag path. Herein, only the simulation from “Model 4” is present. To deeply understand the delamination behavior, series of typical fracture events simulated by “Model 4” are depicted in Fig. 9(a) with capital English letters on the load-displacement curve. The fracture status corresponding to each event is shown in Fig. 9(b). Delamination initiated from the end of the insert at event A, which resulted in a slight load drop. The delamination grew along the original $90^\circ/90^\circ$ interface for a short distance until it deviated from the middle plane and kinked downward into the adjacent 90° layer, as presented at the later event B. At the same time, the load began to increase. The downward crack migration led to the increase of the load because it resulted in increased upper arm thickness, and then the bending stiffness of the upper arms would enlarge, which required a raised load to drive the further delamination propagation. Subsequently, the delamination grew within the lower 90° adjacent ply and showed an approximately straight path as shown in event C, during which the load continued to increase. The gradual increase of the load during the above process was derived from the increase in critical fracture

toughness because the critical fracture toughness function $G_{Ic}(a)$ was adopted in the model. The increasing trend of the load continued until event D, when the delamination migrated upward and propagated toward the region close to the upper $0^\circ/90^\circ$ interface, at which point a sharp load drop occurred. In contrast to the above downward crack kinking at event B, the upwards growth of the crack from the original middle plane at event C gave rise to a decrease in upper arm stiffness, which prompted a fast delamination growth and resulted in a typical load drop. Subsequent delamination grew forward with a straight path, as illustrated at event E. During that process, the load continued to increase until it reached the maximum load at event F. The continuing increase of the load during the above process was also related to the use of the critical fracture toughness function. From event F onward, delamination propagated in a zigzag fashion as shown in event G with the load gradually descending until the final state as illustrated at event H. At event F, the critical fracture toughness reached the plateau value, but during the subsequent delamination process, the crack length continued to extend. Accordingly, the load gradually decreased in the process from event F to event H. Moreover, the modest load fluctuating in the above process was related to the regular zigzag path during the final steady delamination propagation stage.

In addition, by contrasting Fig. 9(b) and Fig. 4, the simulated delamination behavior from the delamination growth model (“Model 4”) adopting the critical fracture function $G_{Ic}(a)$ and B-K law presents good agreement with the experimental observation. Because the crack growth direction was specified to be orthogonal to the maximum principal stress direction during the simulation, the shifting of the crack growth plane indicates the change of the maximum principal stress direction. The first crack deviation from the middle plane was considered to be associated with the shear stress at the crack tip induced by the bending of the DCB arms. The subsequent crack path alternated because it was associated with the rotation of the specimens caused by previous delamination plane deviation, which changed the stress

state, especially the maximum principle stress direction [37]. In addition, because of the difference between the identical homogeneous isotropic material in simulation and the actual heterogeneous 90° composite lamina, in which the fibers will affect the crack growth direction, the initial crack deviation angle obtained from the simulation (shown in the second sub-graph of Fig. 9 (b)) is smaller than the experimental observation illustrated in Fig. 4 (a).

Conclusions

This paper conducted a mode I delamination test for DCB specimens with a starter crack inserted between two 90° mid-layers. During the test, the typically periodical crack line alternation was observed, which yielded a zigzag delamination path, and the typical *R*-curve behavior was obtained.

Based on different assumptions for the delamination resistance mechanism, four XFEM-based delamination growth models were developed, which included the delamination growth model considering the delamination follows a pure mode with a constant critical fracture toughness, the model considering the delamination follows a pure mode with the varying critical fracture toughness, the model considering the delamination follows a mixed mode with a constant critical fracture toughness, and the model considering the delamination follows a mixed mode with the varying critical fracture toughness. The four delamination models shared the same crack initiation model, which took a quadratic criterion as the crack initiation criterion and the direction orthogonal to the maximum principal stress as the crack growth direction. All of the four delamination growth models realized the simulation for the zigzag delamination growth behavior, which validates the new crack initiation model proposed in this paper. However, only the two delamination models adopting the critical fracture toughness function $G_{Ic}(a)$ could give a good prediction for the load-displacement response, which indicates that the varied G_{Ic} should be considered in the delamination simulation. Furthermore, among the two XFEM-based delamination models adopting the

critical fracture toughness function $G_{Ic}(a)$, the “Model 4” adopting $G_{Ic}(a)$ and B-K law provided the good simulation for experimental observed delamination behaviors and a prediction for load-displacement curve with the best agreement, which in turn verifies the validity of the model. And from the delamination simulation results from the “Model 4”, it can be concluded that the change of the maximum principal stress direction at crack tip is the cause of crack plane shifting during the delamination growth process.

Additionally, according to the comparisons between the four growth delamination models and the experimental results, neither the zigzag delamination path itself, which is considered to enlarge the fracture surface, nor the mixed mode effect is the main cause of the increased resistance. However, the zigzag path can induce serious fiber bridging and matrix cracking within the adjacent plies, which dissipates extra energy. It is concluded that the increasing delamination resistance during the delamination growth process is considered to be mainly caused by the serious fiber bridging and matrix cracking in the damage zone ahead of the crack tip.

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Figure Captions

Fig. 1 DCB specimens dimension and quick-mounted hinge

Fig. 2 Load-displacement curves of two specimens

Fig. 3 Delamination resistance curve of two specimens

Fig. 4 Side view of the delamination path

Fig. 5 Linear traction-separation response with damage

Fig. 6 FE model of the DCB specimen

Fig. 7 Flowchart of the XFEM simulation

Fig. 8 Comparison of load-displacement responds from simulation and experiment

Fig. 9 Delamination propagation behavior by XFEM simulation

Fig.1 DCB specimens dimension and quick-mounted hinge

Fig.2. Load-displacement curves of two specimens

Fig.3. Delamination resistance curve of two specimens

Fig.4 Side view of the delamination path: (a) transverse crack followed by delamination migration. (b) wriggled crack within two middle 90° plies. (c) stable zigzag delamination path

Fig. 5 Linear traction-separation response with damage

Fig.6 FE model of the DCB specimen

Fig.7 Flowchart of the XFEM simulation

Fig. 8 Comparison of load-displacement responds from simulation and experiment

Fig.9 Delamination propagation behavior by XFEM simulation. (a) Predicted load-displacement response from “Model 4”. (b) Simulated delamination behaviors from “Model 4”. A: delamination initiation. B: crack propagates downward into adjacent 90° layer. C: delamination grows close to lower $0^\circ/90^\circ$ interface. E: delamination grows close to upper $0^\circ/90^\circ$ interface. F: start of zigzag delamination path. G: stable crack grow in a regular zigzag fashion. H: illustration of zigzag path during delamination process.

Table 1 Material properties of the T800 carbon/epoxy composite lamina

Properties	Values
Elastic modulus E_1 (GPa)	195
Elastic modulus E_2, E_3 (GPa)	8.58
Poisson' ratio ν_{12}, ν_{13}	0.33
Poisson' ratio ν_{23}	0.48
Shear modulus G_{12}, G_{13} (GPa)	4.57
Shear modulus G_{23} (GPa)	2.9
Longitudinal tensile strength X_T (MPa)	3071
Longitudinal compressive strength X_C (MPa)	1747
Transverse tensile strength Y_T (MPa)	88
Transverse compressive strength Y_C (MPa)	271
Shear strength S_L (MPa)	143
Mode I interlaminar fracture toughness G_{Ic} (N/m ²)	350
Mode II interlaminar fracture toughness G_{IIc} (N/m ²)	3000
B-K law exponent η	2