CHARACTERIZATION OF PURE MODE I, II AND III DELAMINATION OF LAMINATED COMPOSITE BY USING EDGE RING CRACK SPECIMEN

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ABSTRACT

Edge Ring Crack (ERC) specimen tests are proposed in order to study pure mode I, mode II and mode III delamination behavior of laminated composite. Two experimental devices were designed and realized: one for pure mode II delamination test; the other for pure mode I and pure mode III tests. Virtual crack closure technique in finite element analysis was performed to determine the distribution of strain energy release rate along the crack tip. It demonstrates that the participation of unwanted fracture modes can be eliminated in order to obtain a pure mode delamination by using the ERC specimens. Moreover, the evolution of strain energy release rate along the crack tip is proved to be quite uniform for a given fracture mode. Thus the toughness under three pure modes have been determined on a woven carbon/epoxy composite made from a taffeta fabric prepreg and the results obtained are very close to those measured by well-known delamination tests.

1.Introduction

Delamination is one of the most common and dangerous damage modes in a laminated composite, which generally occurs under mixed mode loading conditions. The criterion for predicting the delamination toughness under mixed mode I+II+III is not yet satisfactory because the investigation of delamination behavior with the participation of mode III is quite limited. Even in the case of pure mode III loading, the determination of the toughness in term of the critical strain energy release rate of, G_{IIIC}, has proven to be a complex issue for laminated polymeric matrix composite materials.

In fact, pure mode III delamination test is not simple to achieve, because it is neither easy to eliminate completely the mode I and mode II components nor to obtain a uniform value of mode III strain energy release rate (G_{III}) along the crack tip. In experimental tests, an average value of G_{III} along the crack tip is generally considered in the determination of G_{IIIC} by a closed-form expression, so high variation of G_{III} along the crack tip would cause excessive error in the measurement of G_{IIIC}. Actually, in most existing tests such as Crack Rail Shear test[1], Split Cantilever Beam test[2] and Edge Crack Torsion (ECT) test[3], even though the evolution of G_{III} along the crack tip can be observed slight in the central region of the crack tip, it becomes more significant at the extremities of the crack tip due to the free edge effects. Moreover, mode II component can never be totally eliminated in most cases, unfortunately.

In this study, a specimen with a circular crack tip called Edge Ring Crack (ERC) specimen was tested. The main advantage of this configuration is the total absence of the edge of crack tip and so no edge effects on the results. With the help of the test devices developed in our study, different loading modes can be introduced so that the behavior of delamination in laminated composites can be investigated under every pure mode loading, even under some mixed mode ones.

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In our previous work, an Edge Ring Crack Torsion (ERCT)[4] test has been realized for the characterization of pure mode III delamination. This work focuses on further improvement of pure mode III delamination by updating ERCT device. Furthermore the ERC specimens are also tested under pure mode I and pure mode II loads.

2.Experimental

2.1.Materials and specimens

In this research work, all ERC specimens were obtained from a woven carbon/epoxy taffeta fabric prepreg (ref: IMP503Z). The properties of the unidirectional laminate are listed in Table 1.

Table 1. Properties of the unidirectional material used in the tested laminates

Fabric weight	200 (g/m^2)
Glass transition temperature: T_g	120 (℃)
Percentage of matrix: V_m	42%
Longitudinal and transverse modulus: $E_{11}=E_{22}$	55250 (MPa)
Out-of-plane shear modulus: $G_{13}=G_{23}$	5400(MPa)
Tensile strength in direction 1 and 2: $X^+= Y^+$	669 (MPa)
Poisson's ratio 12: ν_{12}	0.044
Shear modulus in direction 12: G_{12}	4062 (MPa)
Shear strength in direction 12: S_{12}	117 (MPa)

The composite laminate was manufactured by hand lay-up technique and 32 plies with the stacking sequence: [0/45/45/0/45/0/0/45/45/0/0/45/0/45/45/0]//crack//[0/45/45/0/45/0/0/45/45/0/0/45/0/45/45/0], were used for the whole laminate, where 0 represents a taffeta balanced fabric ply with yarns oriented in 0° and 90° while 45 represents the same fabric oriented in ±45°. A 13 μm thick polyester film was inserted in the mid-plane during the manufacturing process in order to create a pre-crack and it separates the whole laminate into two sub-laminates symmetrically relative to the crack plane.

ERC specimen is shown in Figure 1. Before inserting the polyester film, a central disc is cut out with the help of a circle cutter so as to create an edge crack with a circular crack front. It is important to identify the exact position of the center of the hole, because it has to coincide with the axis of the machine to guarantee pure loading mode. In practical, the center of the hole can be determined by the mapping on the surface of the specimens and verified by Ultrasonic C-scan. The loading will be introduced with an axisymmetrical manner, but a finite element analysis has shown that the circular shape of the specimens is not really necessary. Therefore, for practical reasons, the geometry of the ERC specimens tested is square, its side length and thickness are D=120mm and h=7mm, respectively. The diameter of the circular crack tip is d=50mm.

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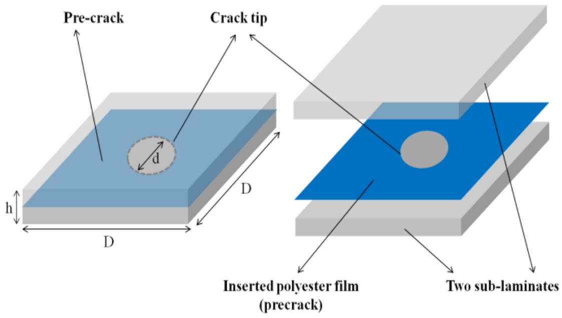

Figure 1. Edge Ring Crack (ERC) specimen

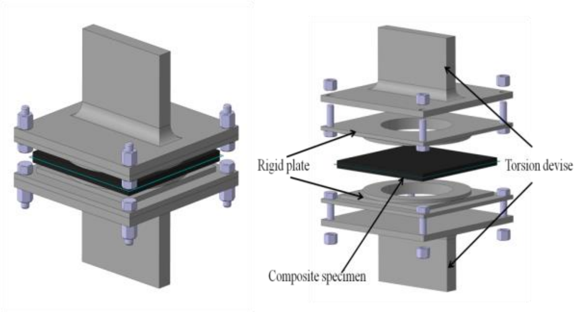

Figure 2. Edge Ring Crack Torsion test device

2.2. Experimental details

In our previous work, the Edge Ring Crack Torsion (ERCT) test device is developed for pure mode III delamination test, shown in Figure 2. Firstly, the surfaces of the composite specimen is pasted to the ring protruding from two rigid plates, so the adhesive surface corresponds to that of the ring with an inner and outer diameter of 80mm and 120mm, respectively. Great care should be taken in order to locate the center of the hole in the sample on the axes of the rigid plate during the gluing process. Secondly the rigid plates are screwed to the torsion devise. Finally, the torsion devise is submitted to an imposed rotation up to the propagation of the crack. Thanks to the holes in the rigid plates, it is also possible to observe the crack propagation by Ultrasonic C-scan. So a delamination under pure mode III loading can be realized with a fairly uniform evolution of G_{III} along the crack tip of the specimen.

In the present work, the original ERCT device has been updated (Figure 3(c)) aiming at further improvements mainly on the evolution of G_{III} along the crack tip. The main modification lies on the axisymmetry of the torsion device. The dimension of the ring protruding is maintained with an inner and outer diameter of 80mm and 120mm, respectively. This pure mode III test on Edge Ring crack specimens is named as ERC-III test in this paper. Moreover, the same ERC specimen can be loaded under pure mode I and pure mode II conditions. The former, called ERC-I test, uses the same device loaded on traction (Figure 3(a)) instead of torsion for pure mode III (Figure 3(c)); the later, named ERC-II test, uses a new device proposed for pure mode II, shown in Figure 3 (b). Herein, the specimen was put on a rigid supporting ring of diameter D=110mm, and then loaded under compression in the centre of the specimen. Note that ERC specimens under pure mode I and under pure mode III loadings have to be pasted to the testing devices, where the adhesive joints must be enough strong to guarantee the crack propagation in mid-plane of the composite specimen, but not in the adhesive joint between the rigid plates and the surfaces of the specimen. A structural adhesive ARALDITE 2012 has been used for this purpose. The pictures of the three tests are shown in Figure 4. For all of these tests, great care was paid to keep the coincidence between the center of the crack of the specimens and the loading axe of the testing machine in order to ensure the wanted pure loading mode.

In this way, the three pure modes toughness measured should be more representatives without any more additional effects on the results dues to geometry change. Note that the distribution of the strain energy release rate along the crack tip is nearly the same between a circular ERC specimen with an outer diameter of 120mm and a square ERC one with a side length D=120mm according to the results from finite element analysis,. Therefore, in this work square ERC specimens were employed.

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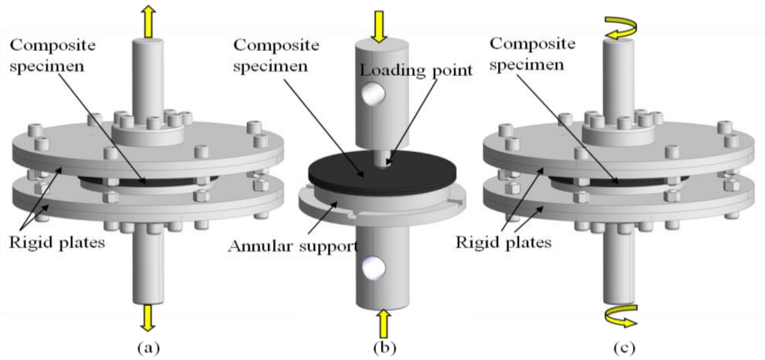

Figure 3. Devices for pure mode I (a), pure mode II (b) and pure mode III (c)

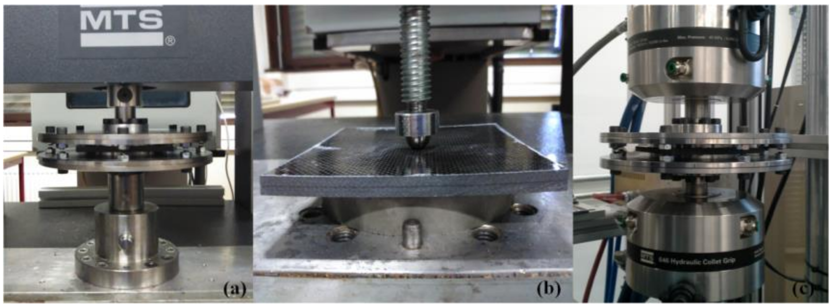

Figure 4. (a) ERC-I test; (b) ERC-II test; (c) ERC- III test

All the tests were carried out at ambient temperature. An axial rotation speed of 0.5 °/min was imposed for mode III delamination test. An axial displacement speed of 2mm/min was imposed for mode I and mode II delamination tests. At least 3 specimens have been tested for each loading mode to obtain an average value.

3.Finite element analysis

In this work, numerical modeling was performed using Ls-Dyna finite element software. The fixtures and specimens were modeled by 3D solid elements. Every ply of the laminate was set up independently according to the stacking sequence. One element was set in the thickness of each ply. The principal mechanical properties of material were set according to Table 1. The mesh along the crack tip was specially refined to guarantee the model convergence. For example, the mesh used for ERC-II modeling is shown in Figure 5. Besides, meshes for ERC-I and ERC-III tests models are shown in Figure 6.

In order to obtain local information at the crack tip necessary to determine the strain energy release rate, spring elements were located along the crack tip. The material model MAT 22 was chosen to simulate the composite laminates due to its better performance where geometry nonlinear shear behavior and Changchang fracture criterion for orthotropic materials have been adopted. Then the virtual crack closure technique (VCCT)[5;6] is performed to determine the distribution of G_I, G_{II} and G_{III} along the crack tip. Contact_automatic_surface_to surface was applied on the two delamination surfaces to prevent interpenetration during the analysis. Relative sliding within the delamination plane between two sub-lamiantes is assumed to be frictionless.

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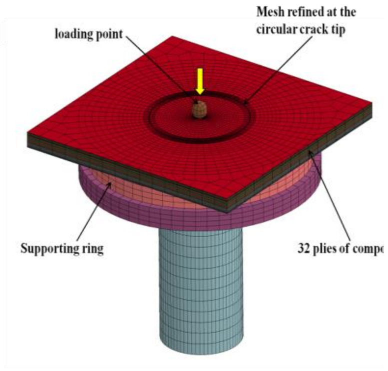

Figure 5. Mesh for ERC-II

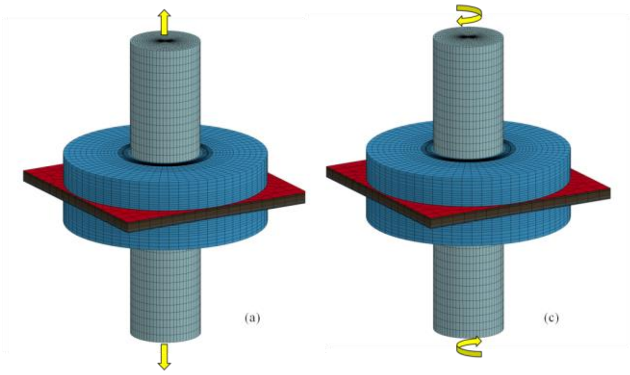

Figure 6. Mesh for ERC-I (a) and ERC-III (b)

4.Results and discussion

4.1. Edge Ring Crack mode III test (ERC-III)

In the ERC-III test, the crack propagates towards the centre in an unstable manner. Figure 7 shows a typical experimental torque/rotation angle curve, where a sudden drop in the torque corresponding to the crack propagation is observed. Note that the experimental curve is not really linear up to the peak load, but the repeatability of the test is relatively good.

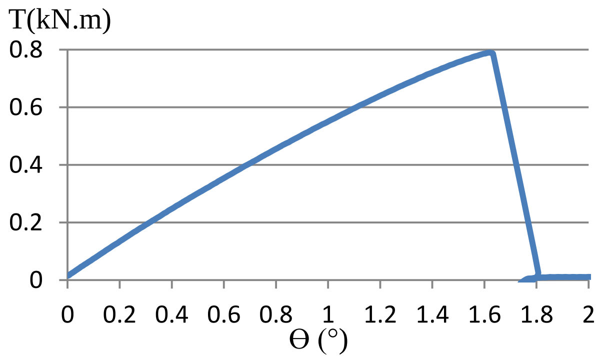

Figure 7. Typical experimental torque/rotation angle curve of ERC-III test

As mentioned above, the ERC-III test has been simulated by a numerical model using finite element analysis to obtain the distribution of the strain energy release rates. Figure 8 compares the evolution of normalized G_{III}, defined as G_{III}/G_{IIIave}, along the crack tip by using the modified mode III device with that by using the original ERCT one. The modification of the mode III device conduces to more uniform distribution of G_{III}, whose relative standard deviation relative to the average value: $\Delta G_{III}/G_{IIIave}$, is less than 1.9%. Moreover, mode I and mode II components relative to the total strain energy release rate: G_I/G_T and G_{II}/G_T with $G_T=G_I+G_{II}+G_{III}$, stay below 1.4% as shown in Figure 9, so can be considered as negligible. Therefore, the interest of this pure mode III test is evident. For comparison, Edge-Crack-Torsion test (ECT) proposed in the literature[7] has been also performed on the same composite with same stacking sequence. The value of $\Delta G_{III}/G_{IIIave}$ in ECT test can arrive

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nearly 22% because the values of G_{III} drop to nearly 0 at the extremities of the crack tip. Moreover the mode II component becomes the principal mode at the extremities of the crack tip.

In conclusion, ERC-III test can be defined as a pure mode III delamination test with uniform distribution of G_{III} along the crack tip. Therefore, by introducing the average critical load obtained by a series of tests, the average value of G_{III} can be defined as G_{IIIC}. In our work, considering the peak load as the critical load, we can obtain the pure mode III toughness for the tested composite: G_{IIIC} =1139(N/m). This value is very close to that measured by the Edge Crack-torsion test (ECT), valued at 1213 (N/m).

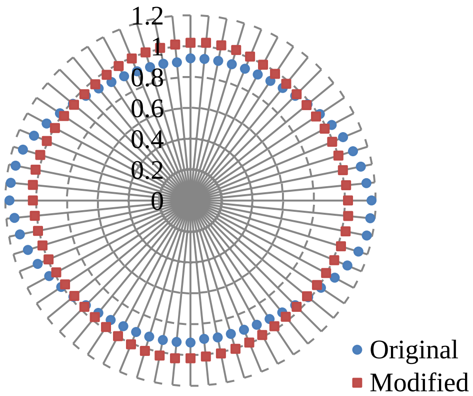

Figure 8. Comparison of the evolution of G_{III}/G_{IIIave} along the circular crack tip between original ERCT test and modified ERC-III test

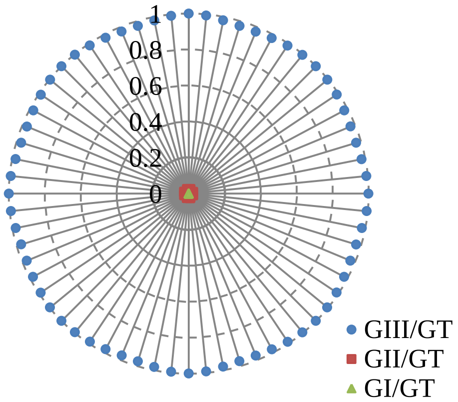

Figure 9. Evolution of normalized G_I, G_{II}, G_{III} along the circular crack tip with new ERC-III device

4.2. Edge Ring Crack mode II test (ERC-II)

Figure 10 shows a typical experimental force/displacement curve from the ERC-II test. After a small non linear part, an unstable propagation of the crack is observed, which is corresponding to a sudden drop in the compression load. Actually, most of the advantages of ERC-III are kept in the ERC-II test. Figure 11 shows the distribution of relative G_I, G_{II} and G_{III} along the crack tip obtained by finite element analysis using the VCCT. It is seen that the distribution of G_{II}/G_T along the crack tip is nearly uniform with $\Delta G_{II}/G_{IIave}$ less than 1.2%. Moreover, the relative mode I and mode III components are less than 1.8%, so can be considered as negligible. As a comparison, the relative standard deviation G_{II}/G_{IIave} can arrive approximately 14% in End Notch Flexion (ENF) mode II test on the same composite with the same stacking sequence.

In conclusion, a pure mode II delamination test with uniform distribution of G_{II} along the crack tip is achieved by using ERC-II test. Therefore, the average value of G_{II} from the VCCT at the critical load can be defined as G_{IIC}. By introducing the average peak load obtained by a series of the ERC-II tests, the pure mode II toughness G_{IIC} of the tested composite is measured as 1121(N/m). However, the value of G_{IIC} measured by ENF test on the same composite is much lower, valued at 750(N/m). The difference can be explained by the much bigger variation of G_{II}/G_{IIave} in ENF test and by the geometry effect.

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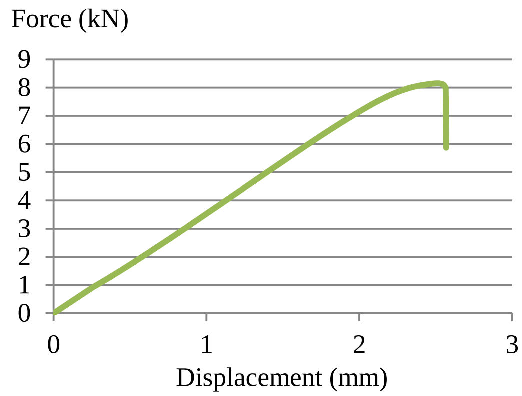

Figure 10. Typical experimental force/displacement curve of ERC-II test

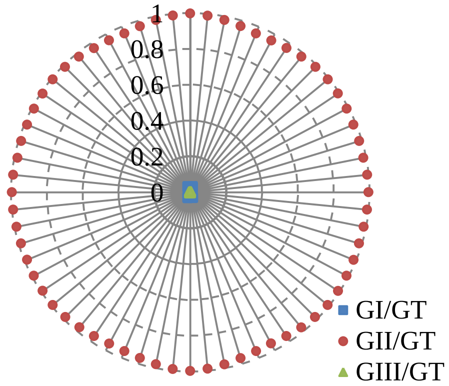

Figure 11. Evolution of normalized G_I, G_{II}, G_{III} along the circular crack tip in ERC-I test

4.3.Edge Ring Crack-I(ERC-I) test

Typical experimental force/displacement curve from the ERC-I test is shown in Figure 12. It is shown that the peak load is very different from the load at the end of linear part, where a stable propagation of the crack could occur before an unstable crack growth. Figure 13 shows that according to numerical simulation by finite element analysis, the distribution of G_I is practically constant and there is no participation of mode II and mode III components. However, in Double Cantilever Beam (DCB) test, the relative standard deviation $\Delta G_I/G_{Iave}$ can arrive 32% when DCB specimens have the same stacking sequence as that of ERC ones.

In conclusion, ERC-I test is a pure mode I delamination test with uniform distribution of G_I along the crack tip. Therefore, with the average critical load measured, we can determine the pure mode I toughness G_{IC}. In this work, if the peak tensile load is defined as the critical load, the value of G_{IC} is given as 305N/m, which is quite closed to the value 330(N/m) measured by DCB test on the same composite. However, the definition of critical load corresponding to the crack onset needs further experimental observations.

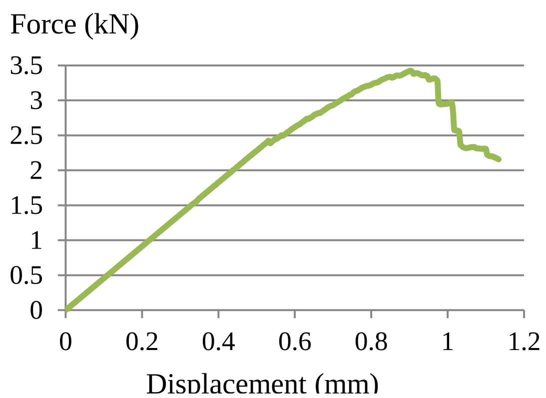

Figure 12. Typical experimental force/displacement curve of ERC-I test

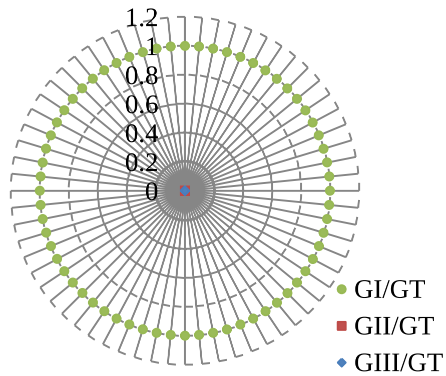

Figure 13. Evolution of normalized G_I, G_{II}, G_{III} along the circular crack tip in ERC-I test

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5.Conclusions

ERC specimen is very promising to characterize delamination behavior of laminated composites: Firstly, by introducing different loadings, the pure mode I, the pure mode II and the pure mode III delamination tests can be performed on the ERC specimens of the same geometry. So the influence of the geometry of the specimens on the toughness measured can be avoided;
Secondly, the evolution of the strain energy release rate along the crack tip is fairly uniform whatever the loading mode is. The average value is more meaningful. Therefore it is important to have a closed-form expression to determine easily the toughness for each of these tests;
Thirdly, if the effect of adjacent fiber orientation on the delamination resistance is important, that means the toughness varies along the crack tip of an ERC specimen, the toughness measured in ERC tests should be the smallest one, which is also meaningful. In this case, we can imagine that the points at the crack tip with the lowest resistance to delamination could be detected by ERC tests;
Finally, the ERC specimens can be also tested under some mixed mode delamination loadings. For example, a mixed mode I+II delamination test can be realized under tensile load if the two sub-laminates are not symmetrical relative to the crack plane, and a mixed mode I+III test can be realized under a combined torsion and tensile load when the two sub-laminates are symmetrical relative to the crack plane.

Acknowledgments

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