Design of Composite ENF Specimens and Conduct Three-Point Test to Calculate Mode II Fracture Toughness

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ABSTRACT

Fiber reinforced composite laminate have tremendous potential in weight critical applications. However, a serious concern in designing with these laminate is their inherently poor damage tolerance for delamination. The resistance of composites to delamination can be well characterized by the delamination fracture toughness. Delamination in composites can occur due to tensile stress (mode I), in-plane shear stress (mode II), and out-of-plane tearing stress (mode III). In this report, the end-notched flexure (ENF) specimen is designed and performed the test for measuring the resistance to delamination under mode II loading. Students have to understand the characteristics of composite materials first, and then they have to learn how to design and make the ENF specimen. At the same time, they have to learn how to operate the INSTRON test machine and how to record the loading-deflection curves for calculating the mode II fracture toughness. Students also have to design and make fixtures for three-point test referred to ASTM standards. I-Lan university is pursing an in-depth study of the composite ENF test in which the effects of matrix material, strain rate, specimen dimensions, stacking sequence, and environment are being investigated. Through this learning project, students will have the capabilities to design and make the ENF specimen and can measure mode II delamination fracture toughness under different loading and environmental conditions. Presentation of the deformation shape in the class, we found that students can understand easily the ENF specimen manufacture procedures and the mechanical meaning of Mode II fracture toughness.

KEYWORDS: composite material, delamination, fracture toughness, ENF, three-point test, virtual simulation technology

Introduction

Delamination (separation of adjoining plies) is an important failure mode in fiber-reinforced laminate composites. Delaminations can result from manufacturing defects or impact by a foreign object [1-4] and can cause significant reductions in stiffness and strength. It is therefore extremely important to understand the behavior of laminated composites containing delaminations. Energy-based linear fracture mechanics has been extensively used for delemination modeling of composites. To determine the loading to cause delamination growth using this approach the strain energy release rate (G) is tested in some criterion involving the critical strain energy release rate (G_c) of the material [5]. In general, the delaminated composite failure is mixed with the three different failure modes (mode I, mode II, and mode III). These three modes can be classified to be (1) opening mode (mode I), (2) shearing mode (mode II), and (3) tearing mode (mode III), The critical energy release rate corresponding to these three modes will be G_{IC}, G_{IIC}, G_{IIIC}. Delamination growth of composite laminate may cause by single failure mode or mixed failure modes. For understanding the failure behavior of composite material, the fracture toughness of the corresponding failure mode and critical energy release rate has to be obtained to become the base of the failure criterion.

The use of end notched flexure (ENF) specimen to study the shear mode (Mode II) of composite was first proposed by Russell [6]. Murri, O"Brian [7] and Carlsson et al. [8] have utilized the ENF test to examine the effects of specimen preparation and data reduction technology on the Mode II interlaminar fracture toughness, $G_{IIC.}$ Russell and Street [9,10] also employed the ENF test geometry to investigate the influence of moisture and temperature on $G_{IIC.}$ Similey and Pipes [11] employed the ENF test geometry to perform Mode II experiments which were tested at room temperature over a range of crosshead speeds from $4.2x10^{-6}ms^{-1}$. In this research, the stitching fiber just reinforced at some locations through the thickness before the prepreg laminate was cured. The stitching conditions are difficult to simulate by using the theoretical formula. Therefore, the compliance method with the experimental data and 3-D finite element method is employed to study the work. In addition, more experimental tools such as optical microscope, ultrasonic C-scan are employed to study the laminate before and after loading.

Theory of the Compliance Method

The development of the strain energy release rate is to evaluate the failure behavior proposed by Griffith [12] that he developed the energy balance to explain the behavior of crack growth. Griffith submitted the theory that the required energy to get an extra crack length (da) can be supplied by the structure. It means that the reduced strain energy will be equal to increment of the surface energy as the crack length is increasing. The released energy of the unit area during the crack growth is called the strain energy release rate that is equivalent to the change of the strain energy. From the Griffith proposal, the crack propagation conditions for the unit thickness of the plate are:

$$\frac{d}{da}(U - F + W) = 0 \quad \text{or} \quad \frac{d}{da}(F - U) = \frac{dW}{da} \tag{1}$$

where a: the crack length.

U: the elastic energy of unit thickness of plate.

F: the work applied by the external force.

W: the energy required for crack growth.

The external force P shown in Fig. 1 applies a cracked plate with the thickness of B. Under the apply force, P, the corresponding displacement V can be observed when the crack length increment is da, the displacement is also increased a value of dV, therein, the work produced by the external force will be PdV. The Esq. (1) can be rewritten to be:

$$G = \frac{d}{da}(F - U) = \frac{1}{B}\left(P\frac{dV}{da} - \frac{dU_t}{da}\right) \tag{2}$$

where B: the thickness of the plate.

P: the applied force.

U_t: the total elastic energy of the plate.

V: the displacement at the applied force point.

In elastic deformation range, the displacement V is proportional to the applied force, V=CP, C is the compliance of the plate. For a plate that has a length of L, width of W, and thickness of B and the compliance will be C=L/(WBE), E is the Young’s modulus of the material. The total elastic energy of the cracked plate would be:

$$U_t = \frac{1}{2}PV = \frac{1}{2}CP^2 \tag{3}$$

Substituting Esq. (2) into Esq. (3), the energy release rate can be derived:

$$G = \frac{1}{B}\left(P^2\frac{\partial C}{\partial a} + CP\frac{dP}{da} - \frac{1}{2}P^2\frac{\partial C}{\partial a} - CP\frac{dP}{da}\right) = \frac{P^2}{2B}\frac{\partial C}{\partial a} \tag{4}$$

The theoretical analysis of fracture toughness (G) of sliding mode (Mode II) is derived below. The ENF specimen is shown in Fig. 2.

Where a is the crack length, L is the distance from center to the supporter, H is the half thickness, P is the applied force, and B is the width of the specimen.

The formula of C of ENF [11] is listed in the following.

$$C = \frac{(2L^3 + 3a^3)}{8E_1Bh^3} \qquad (5)$$

Therefore,

$$\frac{\partial C}{\partial a} = \frac{9a^2}{8E_1Bh^3} \qquad (6)$$

Substituting Esq. (6) into Esq. (4), G_{II} can be obtained:

$$G_{II} = \frac{9a^2P^2}{16E_1B^2h^3} \qquad (7)$$

If P is the critical force P_c, the Mode II critical energy release rate G_{IIC} can be found.

$$G_{IIC} = \frac{9a^2P_c^{\ 2}}{16E_1B^2h^3} \qquad (8)$$

The critical force can be derived as the following.

In the experiment, Mode II test can be thought a simple support beam subjected a central load at the center of the beam, the deflection δ (shown in Fig. 3) will be:

$$\delta = \frac{PL^3}{48E_xI} \Rightarrow P = \frac{4\delta E_xBh^3}{L^3} \qquad (2\text{-}9)$$

The above equation can be expressed by using the symbols employed in Fig. 3:

$$P_c = \frac{4\delta E_xB(2h)^3}{(2L)^3} \qquad (2\text{-}10)$$

The theoretical critical load can be obtained.

Experimental Work

In this research, the end notched flexure specimens with and without fibers was made and tests were conducted to calculate the second mode energy release rate. The specimens are manufactured by the graphite/epoxy prepreg and have 16 0^o layers. The geometric dimensions and the stitching fiber locations are plotted in Fig. 4. During the test, the test conditions and supporter are plotted in Fig. 5. The loading tests are conducted on the 10KN hydraulic test machine to perform the loading and unloading processing. According to ASTM-D5528-94a rules, the loading speed is 1 mm/minute, and acoustic emission system [13] is connected to the hydraulic system to detect the delamination initiation and propagation. The curves of the loading and sound intensity level (SIL) versus time are recorded in Fig. 6. With reference to these curves, the critical load, the deflection at different crack length can be obtained. In addition to the above equipment, the ultrasonic scanning system is also used to observe the delamination area before and after loading. For completely understanding the stitching fiber through the thickness of the laminate, the optical microscope is employed to study the microstructure around the stitching fibers.

Results and Discussions

(1) C-SCAN scanning picture

Due to the delamination embedded between the lay-ups, the specimens after manufacturing would be scanned by using C-SCAN equipment to locate the delamination length. Fig. 7 is the scanning results. In the picture, the green section is the specimen without the delamination, and the red section indicated the delamination embedded here.

There are some small pot red points that represent the defects caused by the air that didn’t kick out before the manufacture. The blue section around the specimen is produced from the water when the specimen is put in the water pool for scanning.

(2) The acoustic emission results

The load-time curves shown in Fig. 6 are for the composite laminate without stitch fibers and obtained by using the acoustic omission system. The load is continuing going up and reaches a peak values that the laminate is propagated abruptly . The lower figure showed the pressure level is a function of time. Through the load increasing processes， the matrix continued broken and caused the noises one detected before the load was down to zero. It is clear that the delamination propagated abruptly caused the highest sound pressure level. Table 1 is the final results for the tests that the critical load for the composite with and without fibers. Due to a few points are enforced by the stitched fibers， the critical load showed that the stitched fibers did not improve the critical load for the 2^{nd} mode of delaminating initiation and propagation. But the theoretical values of the critical load can agree very well with that of the test results. As shown in Fig. 8 indicated that the critical energy release rate for the 2^{nd} mode is not a function of the delamination length. The average critical energy release rate for this material is 7553 J/m^2.

Response from student

This topic combined the theoretical analysis, specimen manufacture, experimental tests, and calculation of critical energy release rate can give the students the whole picture of ENF test and physical meaning of the Mode II fracture toughness. But some students think this topic is too hard and too early offered for the undergraduate students. This topic must have many previous training and covered many mechanical backgrounds. The students said the topic included the basic concept of the composite material, the fracture mechanics and numerical analysis. Those courses are only offered in the senior students or graduate students. The also said that many experimental equipments are used and they don't touch all of these instruments before they touched this topic. The recognized that the topic give them many ideas such as (1) any basic courses took previously may be used in the future: (2) any research will cover or merge different fields:(3) except the class courses, they have to spend more time to learn the other experimental equipments.

Students also suggest that more slides or pictures to present the derivation of the formula and calculation of the Mode II energy release rate. If the topic can present by using the DVD movie to go through the complete experimental procedures, they can easily learn the tests and perform the calculation when they have the opportunity to touch this topic.

Conclusions

1. From C-SCAN scanning picture, the defect inside the laminate specimen due to the air entrapped in there during the manufacture proceeding, this will result in the lower critical delamination force.
2. The sound pressure level was over 100db as the delamination started to propagate, but small sound pressure level (around 60db~80db) was not heard as the matrix produced the small crack or the fibers (not the stitched fiber) are broken, but it can be detected by using the acoustic emission system.
3. The mode II delamination propagation could be happens as the applied load meets the critical load. Once the mode II delamination starts to propagate, the crack propagation cannot stop and why the critical energy release rate is the same for the different delamination length. Therefore, laminate composites must be avoided forming the mode II delamination and if it is found the composite structure must be repaired immediately.
4. From the test results, few stitched fiber reinforced the laminated composites cannot improve the mode II critical energy release rate. The laminated composite has a lower resistance to the shear force compared to the stitched fiber. As the 2^{nd} mode delamination through the specimen, the stitched fiber are still remain in the internal, therefore, even if the composite laminate completely separated two pieces, the stitched fiber still kept two sub-laminates together. As though the

stitched fibers cannot raise the mode II critical energy release rate, it can keep two separated pieces together, so it is still useful to avoid the catastrophic fracture.

5. The strain energy release rate is calculated and the mode II critical energy release rate is about 7553 J/m^2

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Table 1: Test and calculation results

Stitched fiber	No	PAN-BASE carbon	Glass	Para-Aramid
Critical force	73.8 Kg	72.4 Kg	74.4 Kg	69.8 Kg
Critical deflection	7mm	6.8mm	7mm	6.5mm
Delamination length	45mm	52mm	49mm	47.5mm
Theoretical critical force	73.1 Kg	70.4 Kg	73.1 Kg	66.0 Kg
Force error pencentage	0.95%	2.76%	1.75%	5.51%

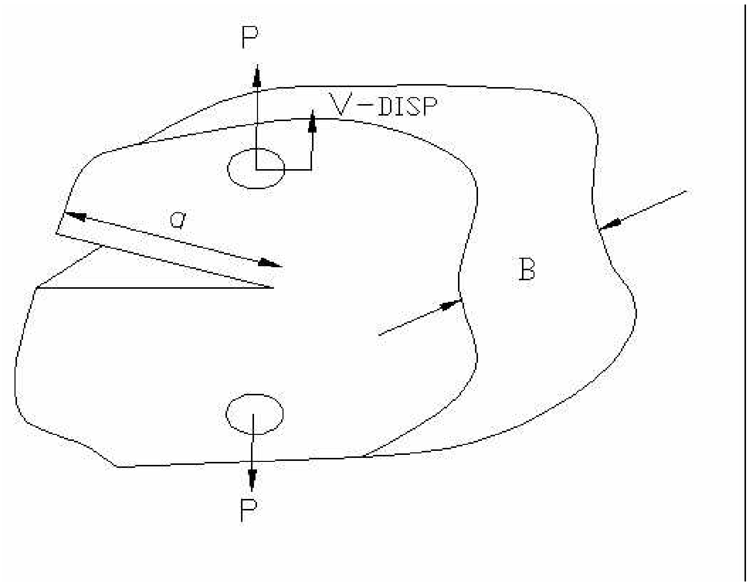

Figure 1: A plate with crack length of a

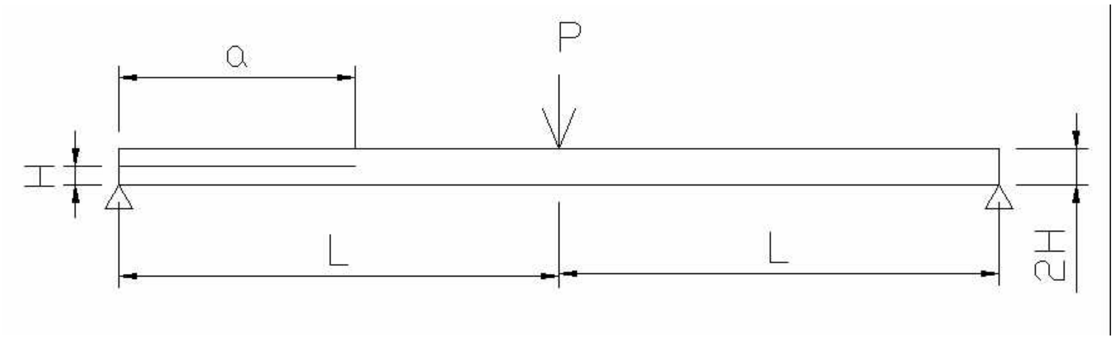

Figure 2: The ENF specimen

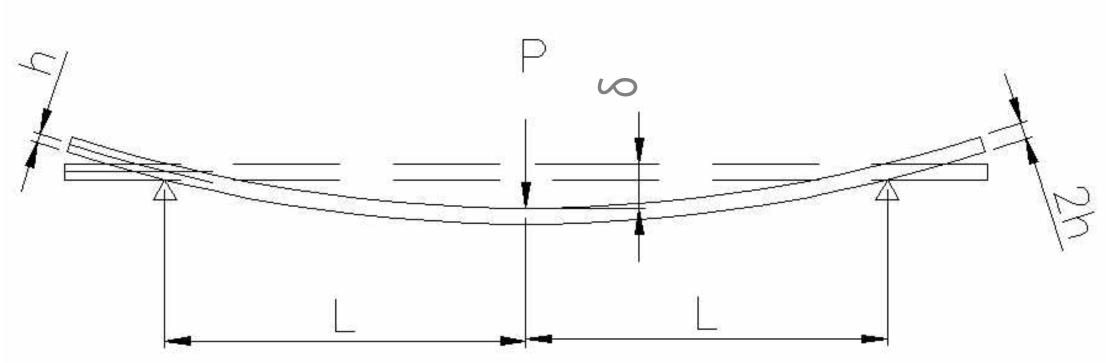

Figure 3: The deformation shape of the ENF specimen with the applied load

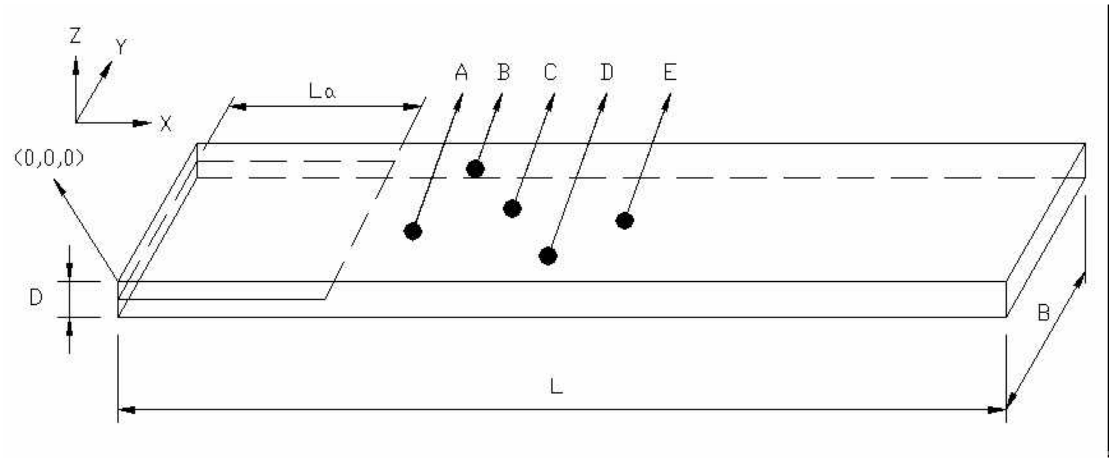

Figure 4: The location of stitched fibers

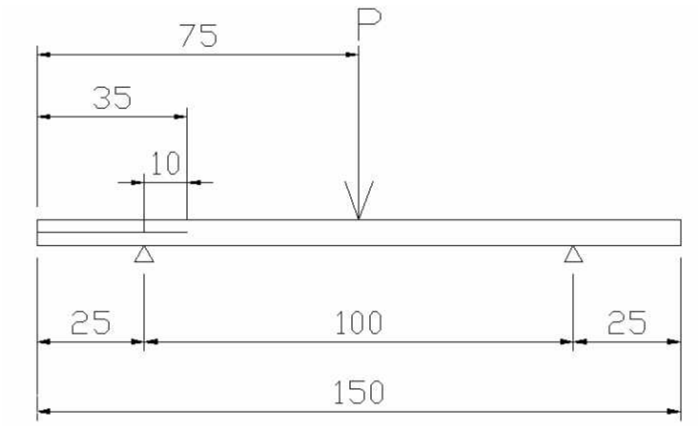

Figure 5: Geometry and dimension of the ENF specimen

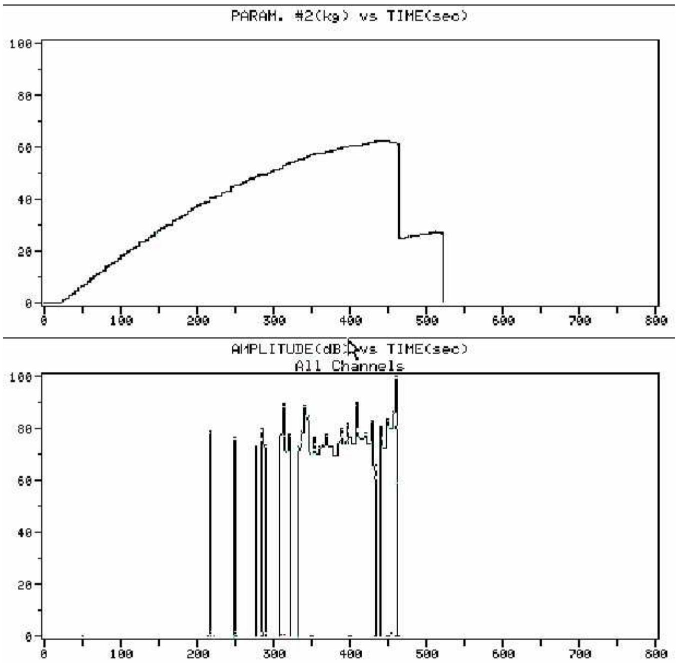

Figure 6: The loading and SIL (sound intensity level) as a function of time

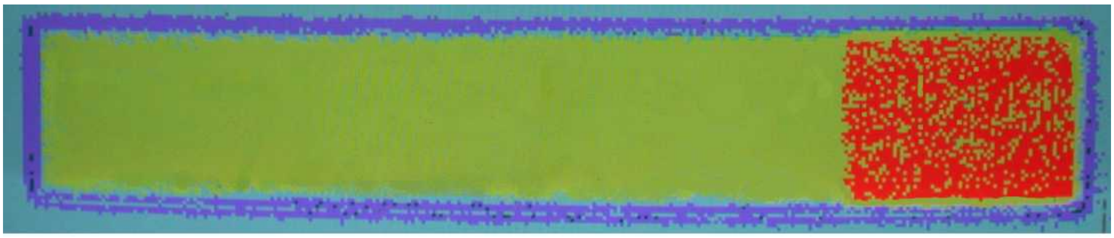

Figure 7: The C-Scan picture for the specimen without the stitched fibers (red color is the delamination area)

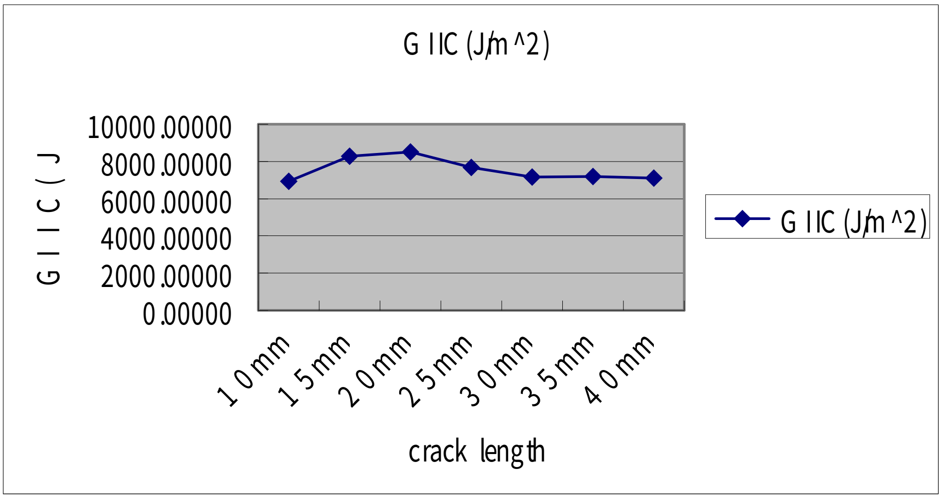

Figure 8: The relationship between G_{IIC} and delamination length