

Experimental and Analytical Investigation on Delamination of Composites

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ABSTRACT: In recent years, extensive research has been conducted on many aspects of delamination failure. In this study, an experimental research was carried out for the characterization of the material's resistance to delamination known as the Interlaminar Fracture Toughness (IFT). The Mode I and Mode II interlaminar fracture toughnesses of the investigated material were characterized with Double Cantilever Beam (DCB) specimen, and End Notched Flexure (ENF) specimen, respectively. Crack propagation analyses of both the specimen were carried out using the Virtual Crack Closure Technique (VCCT) for MARC. Preliminary results showed good agreement of fracture load between the finite element analysis and experimental results.

KEYWORDS: Composites, Delamination, Virtual Crack Closure Technique

I. INTRODUCTION

The most commonly observed failure mode in laminated composites is delamination (interlaminar fracture) which leads to separation of the layers of reinforcement or plies. Although delamination may not cause total collapse of the load bearing properties of the component, it is usually a precursor to such an event. Hence it is crucial to develop a better understanding of delamination. Under the assumption of considering the delamination growth process as a crack propagation phenomenon fracture mechanics concepts can be generally transferred to the analysis of delaminated composite structures.

Experimental evaluation of IFT for Mode I and Mode II is performed using Double Cantilever Beam (DCB) specimen and End Notched Flexure (ENF) specimen, respectively. In these experiments usually the critical value of load and the corresponding crack length at the verge of crack growth are determined. These critical values are then used in analytical formulae to calculate the value of IFT. The calculation of the IFT can also be performed by means of techniques used in conjunction with Finite Element Method (FEM), such as Virtual Crack Closure Technique (VCCT). According to the VCCT, the evaluation of the Strain Energy Release Rate (SERR) can be obtained starting from the assumption that for an infinitesimal crack opening, the strain energy released is equal to the amount of the work required to close the crack. The value of SERR for all the modes of fracture can directly be obtained from the Finite Element Analysis (FEA). In the present study the determination of SERR has been carried out using the four node plane strain composite shell element available in the advanced finite element software package MSC MARC

II. EXPERIMENTAL INVESTIGATION

DCB and ENF specimens have been used for the evaluation of Mode I and Mode II fracture toughness respectively. The specimens used in this investigation have been cut from the same laminate, the preparation and properties of which are explained below.

The specimens used in this study have been made from unidirectional carbon/epoxy prepreg. The prepegs were cut and carefully placed on top of one another with a Teflon film of 25 μm thickness at the mid-plane to make a laminate of size 500 x 250 x 3.3 mm. Teflon film was inserted during the laminate lay-up process to define the initial delamination crack. Total layup consisted of 30 plies aligned with 0° direction for all specimens. The laminate was kept in autoclave and cured at 175° C for 2 hours with vacuum at 4 bar pressure. Final thickness was 3.3 mm. Pneumatic circular saw

was used to cut the laminate into appropriate sizes of mode I and mode II specimens as described in Table 1. Table 2 gives the material properties of the carbon/epoxy material used for the test.

Table 1: Dimensions of the specimens

Specimen	Length, l (mm)	Nominal width, b(mm)	Nominal thickness, 2h(mm)	Initial crack length, a ₀ (mm)
Mode I	150	25	3.3	63
Mode II	140	25	3.3	50

Table 2: Material properties of carbon / epoxy composite

Young's modulus (GPa)	Shear modulus (GPa)	Poisson's Ratio
$E_{11} = 193.382$	$G_{12} = 4.452$	$\nu_{12} = 0.246$
$E_{22} = 6.056$	$G_{23} = 3.5616$	$\nu_{23} = 0.1968$
$E_{33} = 4.500$	$G_{31} = 3.5616$	$\nu_{13} = 0.1968$

Mode I Interlaminar Fracture Toughness Testing

Mode I IFT tests were conducted under quasi static loading conditions with the DCB specimen. DCB test configurations and methods used in this investigation follow the general suggestions by the ASTM standard D5228 [1]. The specimens were loaded by a 100 kN INSTRON machine. The load was measured using a 110 N (25 lb.) load cell and the displacement was measured by the LVDT built into the actuator. Loading was applied to the specimen by means of piano hinges. Before the test, piano hinges were bonded to specimen surface using Araldite 2014 adhesive after rubbing the surface of the hinge with sand paper followed by cleaning with acetone solution. Crack length of 30 mm was used for the present study. Bonded specimens were tested after curing at room temperature for 24 hours. Four specimens were tested in quasi static loading. Test setup is shown in Figure 1.

The specimens were loaded at a constant displacement rate of 0.5 mm/min. The crack growth was measured using a paper scale attached to the lower end of the specimen from the end of the insert film. Instead of one initial loading/unloading cycle and one reloading/unloading cycle as specified in the ASTM standard, the present study used one continuous loading cycle followed by an unloading cycle. The crack tip position was pinpointed using a high speed camera mounted on an instrumented stage with 0.001 resolution. Load and displacement data were recorded continuously for loading cycle, together with the elapsed time from the beginning of the test, by a digital data acquisition system. The distance from each subsequent marking to the first marking, where the initial crack is, was measured by the high speed camera before the test. The crack length at each subsequent marking was calculated by the sum of the initial crack length and the distance to the first marking (initial crack front marking). The elapsed time from the beginning of test to the moment at which the crack propagates to each marking was recorded during the test, so that after the test the crack length could be matched with the concurrent load and displacement based on the data recorded by the data acquisition system.

Mode II Interlaminar Fracture Toughness Testing

Mode II IFT tests under quasi static loading were conducted with the ENF specimen. Four specimens were tested in quasi static loading. A three point bending fixture with a maximum span length of 203.2 mm was used as the loading fixture. Test setup is shown in Figure 2. It consisted of two supporting pins and one loading pin. The specimens were loaded by a 100 kN INSTRON machine. The load was measured using a 110 N (25 lb.) load cell and the displacement was measured by the LVDT built into the actuator.

The specimens were positioned in three point bending fixture and the load was applied to the top of specimen at the mid-span in a displacement controlled mode. A constant displacement rate of 0.5 mm/min was used for loading and unloading. The specimen was loaded until crack initiation was observed, and failure has occurred. The load, centre point displacement and crack length were continuously measured and recorded during the test.



Fig.1: DCB test setup

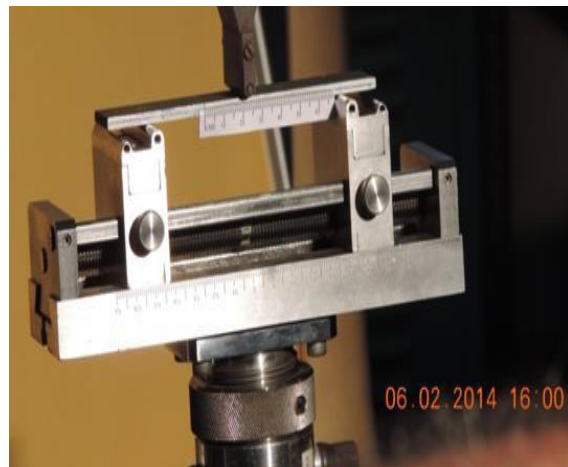


Fig.2: ENF test setup

III. CALCULATION OF INTERLAMINAR FRACTURE TOUGHNESS

Modified Beam Theory for DCB [1]

Classical beam theory will overestimate the strain energy release rate because the beam is not perfectly built –in which means that rotation may occur at the delamination front. One of correcting for this rotation is to treat the DCB as if it contained a slightly longer delamination, $a+|\Delta|$, where Δ may be determined experimentally by generating a least squares plot of the cube root of compliance $C^{1/3}$, as a function of delamination length. Mode I IFT, G_I is calculated by equation

$$G_I = \frac{3P\delta}{2b(a + |\Delta|)}$$

where P is the failure load, δ is the load point displacement, b the width of the specimen and a is the delamination length.

Compliance calibration method for DCB [1]

In this method strain energy release rate is expressed as

$$G_I = \frac{nP\delta}{2ba}$$

where, n is the exponent taken as the slope of a least- square fit of $\log(C)$ versus $\log(a)$. C is the compliance of the beam, defined as δ / P .

Beam analysis for ENF beam

G_{II} can then be calculated from the load for the onset of the nonlinear response, initial crack length and the initial load line compliance based on Beam theory derived by Russell and Street [5].

$$G_{II} = \frac{9a_0^2 P^2 C}{2B(2L^3 + 3a_0^3)}$$

where L is the half span length and a_0 is the initial crack length.

IV. EXPERIMENTAL RESULTS

Typical load displacement behaviour of DCB specimen is shown in Figure 3a. It can be seen that the curve has two parts. In the initial part the load is linearly related to the displacement and hence the curve is linear. During this portion of the test, there is no crack extension in the specimen as loading proceeds. The loading curve for this portion can be

predicted using the simple beam theory. The final part is a nonlinear part where there is crack growth. Failure loads for DCB specimen were estimated from experimental results and used to determine the critical strain energy release rate for mode I fracture.

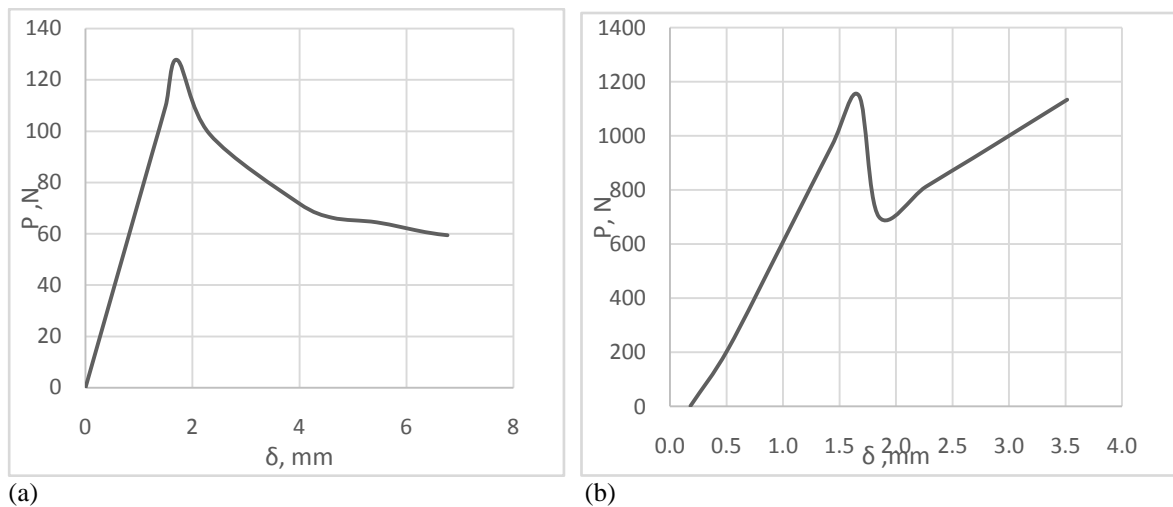


Fig. 3 : Load displacement plot (a) DCB specimen (b) ENF specimen

Figure 3b shows the load displacement plot for ENF specimen. Unlike the DCB specimen load drops rapidly on the onset of delamination propagation in case of ENF specimen which clearly depicts the unstable crack growth. Critical strain energy release rate at crack initiation for mode II, G_{II} can then be calculated from the load for the onset of the nonlinear response, initial crack length and the initial load line compliance. The values of Mode I and Mode II IFT obtained by the experimental procedure are listed in Table 3.

Table 3: Critical strain energy release rate for mode I and mode II specimen

	Mode I	Mode II
G (N/mm)	0.3880 (MBT) 0.3703 (CC)	0.8472

V. NUMERICAL PREDICTIONS

Double Cantilever Beam (DCB) specimen model

Specimen was modelled with plane strain composite element in MARC. Along the length all elements were modelled using 0.5mm size elements. The plane of delamination was modelled as a discrete discontinuity at the centre of the specimen. By VCCT approach the models were created as separate meshes for the upper and lower part of the specimens with identical nodal point coordinates in the plane of delamination. Two surfaces were defined to identify the contact area in the plane of the delamination. Displacement rate of 0.5mm/min was given at the free ends of the initial starter crack. Other end is fully constrained. Figure 4a shows the deformed DCB specimen model.

End Notched Flexure (ENF) beam specimen model

The specimen was modelled in a manner similar to DCB specimen model, the only difference being the boundary condition. Here, either ends of the beam were simply supported. Figure 4b shows the deformed ENF model.

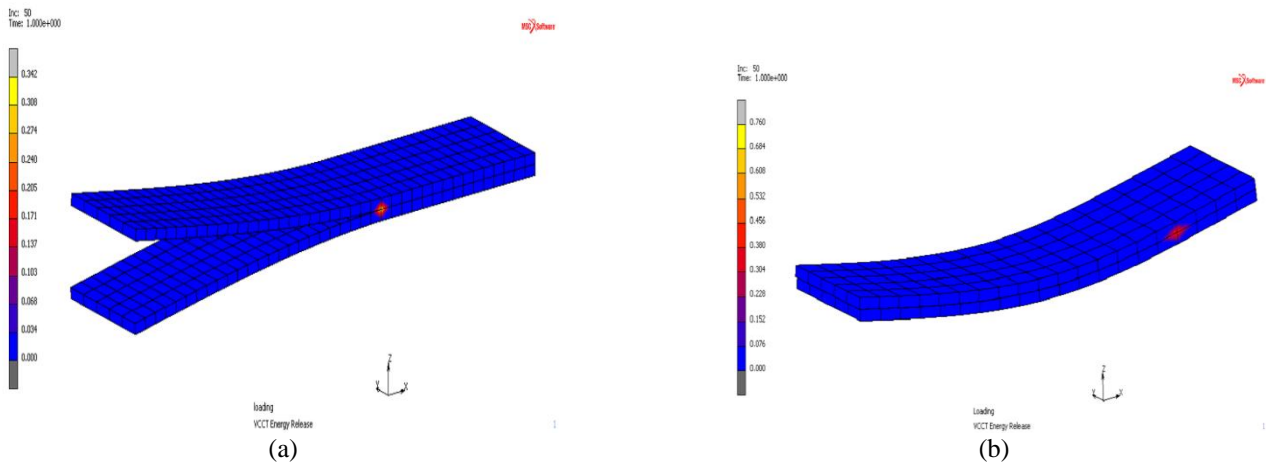


Fig. 4: Deformed (a) DCB model (b) ENF model

Load displacement curve as obtained from the finite element analysis is shown in Figure 5.

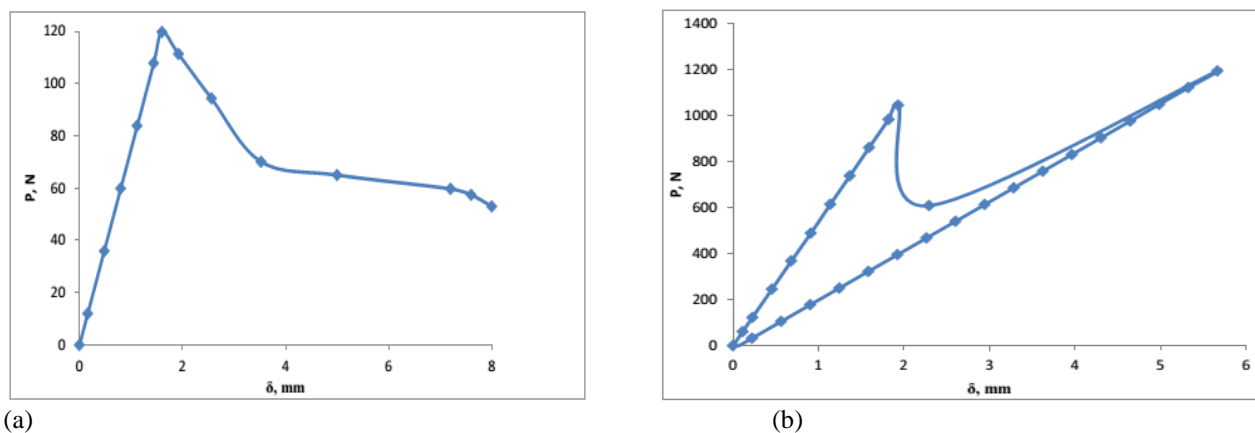


Fig. 5: Load displacement curve (a) DCB specimen (b) ENF specimen

VI. CONCLUSION

Experimental determination of interlaminar fracture toughness has been presented for a carbon/ epoxy composite laminate. A Double Cantilever Beam specimen and End Notched Flexure beam specimen were used to determine mode I and mode II fracture toughnesses respectively. The Virtual Crack Closure Technique (VCCT) was used to model the crack propagation behaviour of the specimens using MARC. By specifying the critical strain energy release rate value as a material property, a good match of fracture load between the finite element modelling results and experimental data was obtained. The fracture load predicted by finite element analysis differed by no more than 10 % for Mode I and Mode II.

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