Delamination fracture study on Glass-Carbon-Epoxy hybrid composites

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Abstract - **Delamination between the layers is one of the primary weaknesses in composite material structures and is a major cause of failure. The methods to improve the delamination fracture toughness of composite structures have attracted a great deal of interest due to their wide spread applications. The mode I fracture toughness of composite, made of woven glass fiber as reinforcement phase and epoxy resin as matrix phase, is experimentally evaluated. The effect of introducing a carbon epoxy layer in glass-epoxy DCB specimen, on the delamination behavior, is studied numerically and validated through experiment. This method can be successfully used for improving the mode I fracture toughness of the composite structures. Cohesive zone model using the ANSYS package is used for the numerical analysis.**

Keywords—mode I fracture; composite; delamination; cohesive zone model.

I. Introduction

Composite materials are those structural materials, made by combining two or more constituents at a macroscopic level. One constituent is called the reinforcing phase and the one in which it is embedded is called the matrix phase. The fiber reinforced composite materials are widely used because of their high strength to weight and stiffness to weight ratios as compared to many traditional metallic materials.

Delamination is the principal mode of failure of layered composites. The delamination often buried between the layers and can begin to grow in response to an appropriate mode of loading. This will drastically reduce the stiffness of the structure and the life of the structure.

The fracture toughness is the property of material that offers resistance to the growth of crack. The double cantilever beam (DCB) test is the traditionally accepted test for characterizing the mode I delamination. The DCB test has been standardized by ASTM D5528.

Due to wide spread applications of composites, the methods to improve the fracture toughness of composites have attracted a great deal of interest. Reinforcing with nanofibers and nanoparticles, toughening of the matrix and stitching are some of the methods to improve the delamination fracture toughness of the composite but are complex in nature. In this research, the effect of addition of carbon fiber layer on the mode I fracture toughness and the failure behavior of glass epoxy composites is studied.

II. Experimental Work

A. Specimen Preparation

The glass fiber in the form of woven fabric is used as the reinforcement phase and the epoxy resin is used as the matrix phase. The hand layup technique is used for manufacturing of the composite specimens. Rollers are used to ensure proper compaction. The specimens are cured under atmospheric temperature and pressure. As per ASTM D5528 standards [1], the double cantilever beam should have minimum length of 125 mm. Also the specimen should satisfy the following requirements.

$$a_0 \le \sqrt{\frac{(2h)^3 E_{11}}{G_{IC}}} \quad (1)$$

$$2h \ge 8.28 \sqrt[3]{\frac{G_{IC} a_0^2}{E_{11}}} \quad (2)$$

Based on the above requirements, the DCB specimen were produced with dimensions 200 × 30 × 6 mm. Initial crack was introduced by placing a thin film of PVC of thickness 13μm in between the fabric sheet layers during the stacking procedure. The surface of the specimens is scrubbed with sand paper. For better bonding, the surface of the brass piano hinge is also scratched with file. The piano hinge is then bonded on to the DCB surface by applying a thin layer of adhesive. The Fig. 1 shows the DCB specimen with hinges.

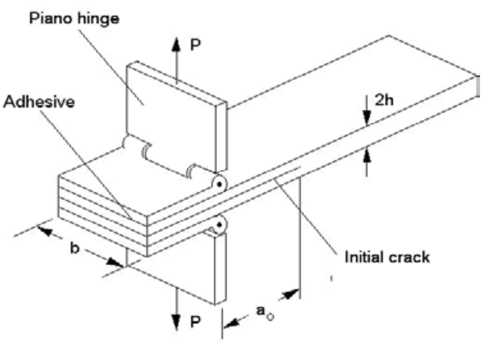

Fig. 1. Model of the DCB specimen.

B. *Material Testing*

1) *Flat wise Tension Test* (FWT)

Fig. 2. Flat wise tension test.

Interfacial normal strength is one of the parameter which is required while modeling the interfacial cohesive zone. The test was conducted on KALPAK (100kN) machine and the peak load was obtained. The specimen is held in between the jaws of the UTM with the help of supporting fixtures as shown in Fig.2. The surface of Aluminium blocks of cross sectional area 50 × 50 mm was first scratched with file and then treated with acid to remove the oxide coating. The blocks are then bonded together using the resin. The test yielded a result of 14MPa as the interfacial normal strength.

2) *Mode I Fracture Test*

The mode I fracture toughness of the composite specimens are experimentally evaluated by the DCB test. The test is performed on the static tension testing machine with constant cross head movement rate of 2mm/min.The hinges of the DCB specimen are clamped to the jaws of the UTM and are then pulled apart. Fig. 3 shows the mode I fracture toughness test being conducted. The critical load at which the unstable crack propagation observed from the test is used for the calculation of mode I fracture toughness.

The strain energy release rate G_I, is basically a function of the load, the displacement, the crack length and the other material and structural parameters used in delamination. From the beam theory analysis, the strain energy release rate for mode I loading is,

$$G_I = \frac{12a^2P_I^2}{b^2h^3E_{11}} \quad (3)$$

Fig. 3. Mode I fracture test.

III. Material Property Evaluation

TABLE 1. CONSTITUENT MATERIAL PROPERTIES

Property	Units	Glass/ Epoxy	Carbon/ Epoxy
Longitudinal modulus E_{11}	GPa	20	300
Transverse modulus E_{22}	GPa	5	6
Shear modulus G_{12}	GPa	2	4.4
Poisson's ratio	-	0.34	0.346

Fig. 4. Type I, II and III DCB specimen.

Mechanical properties of the laminae used for making DCB specimens are shown in Table.1. The type I specimens are manufactured by 16 layers of glass/epoxy laminas. Type II and III specimens are hybrid composites and type II specimens have 14 glass-epoxy layers along with two innermost carbon-epoxy layers whereas type III specimens have 14 glass-epoxy layers along with two outermost carbon-epoxy layers.

IV. MODIFIED CRACK CLOSURE INTEGRAL TECHNIQUE

Strain energy release rate G is the measure of energy available for an incremental crack extension. The work necessary to extend the crack from a to a + Δa is same as that necessary to close the crack tip from a + Δa to a. This is the basic theory of Modified Crack Closure Integral (MCCI) technique. MCCI is a simple and accurate method for calculating strain energy release rates (G) and can be done by finite element analysis in conjunction with experiment. Fig 4 shows the nodal forces and displacements on the crack front. From the nodal forces and displacements, the fracture toughness can be evaluated as per eqn. (4). The main advantage of this method is that it avoids dealing with the details of singular stress fields around crack tips, where there are added complexities of anisotropic material behavior and mode interaction.

$$G_I = \left[{}^{1}/_{2\Delta a\ b}\right]\left[t_j v_{j-2} + t_{j+1} v_{j-1}\right] \quad (4)$$

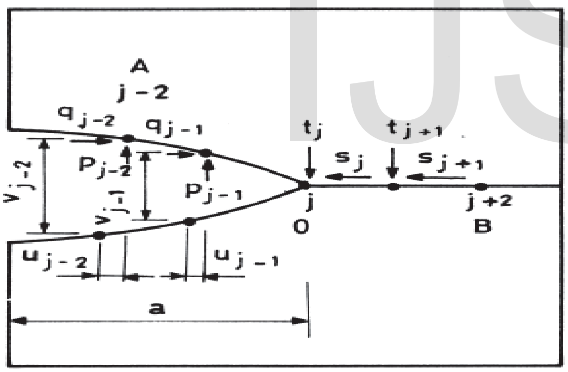

Fig. 5. Nodal forces and displacements on the crack front.

V. COHESIVE ZONE MODELING

Many methods and models have been proposed for the prediction of delamination growth. Cohesive zone modelling (CZM) is a finite element based approach in which the interface between two adherents is modelled using cohesive zone elements. These elements do not have a constant stiffness, but instead incorporate a traction-displacement relation. A damage parameter is used to progressively reduce the stiffness of the element, simulating the growth of damage.

The material behavior at the interface is characterized by the tractions (normal and tangential) and separations (normal and tangential). Cohesive Zone model allows all three modes of separation. This nonlinear analysis technique is integrated in the finite element method and the separation mechanism of two surfaces can be simulated. One method of implementing CZM is by the use of interface elements in which the interface elements are designed specifically to represent the cohesive zone between the components and to account for the separation across the interface. The parameters required for modeling cohesive zone are the interfacial normal strength, normal and tangential separations. Exponential cohesive zone model is used in this study and which is based on a surface potential,

$$\phi(\delta) = e\sigma_{max}\overline{\delta}_n\left[1 - (1 + \Delta_n)e^{-\Delta_n}e^{-\Delta_t^2}\right] \quad (5)$$

$\phi(\delta)$ =surface potential

σ_{max}= maximum normal traction at the interface

δ_n = normal separation across the interface where the maximum normal traction is attained

δ_t = shear separation where the maximum shear traction is attained

$$\Delta_n = \frac{\delta_n}{\overline{\delta}_n}$$

$$\Delta_t = \frac{\delta_t}{\overline{\delta}_t}$$

δ_n, δ_t *and* $\overline{\delta}_n, \overline{\delta}_t$ are the displacements and its peak values corresponding to opening and shear modes respectively. By differentiating (5) w.r.t δ_n , the normal traction force can be found out.

$$T_n = e\sigma_{max}\Delta_n e^{-\Delta_n}e^{-\Delta_t^2} \quad (6)$$

For pure mode I, G_{IC} can be obtained from (5) by putting mode II displacements to zero.

$$\phi_n \text{ or } G_{IC} = e\sigma_{max}\overline{\delta}_n \quad (7)$$

Based on the cohesive zone equations and the fracture toughness value obtained, the cohesive zone parameters are calculated. A 3D model of the DCB specimen is created using the SOLID185 layered elements and the INTER205 elements available in the ANSYS package. The displacements are applied on the edges of the specimen and the load-displacement curves are plotted. The numerical and experimental results are then compared.

TABLE 2.COHESIVE ZONE PARAMETERS

Maximum normal traction (σ_{max})	14 MPa
Normal separation (δ_n)	0.02 mm

VI. Results and Discussions

Effect of addition of a high stiff carbon epoxy layer on the fracture failure of glass-epoxy DCB specimens were carried out experimentally and numerically. In mode I fracture test, the peak load in load-displacement curves shows the onset of crack growth and thereafter the load decreases with increase in deflection. The crack growth in type I specimen (glass-epoxy only) was observed at 121N (Fig.7). But addition of carbon-epoxy layers instead of the middle glass-epoxy layers (type II specimen) shows increase in fracture load i.e 164N experimentally. This clearly indicates that the type II specimen has higher fracture toughness than the type I specimen. While adding outer layers of carbon-epoxy i.e. in type III specimen, the peak load obtained is 138N experimentally which is lower than that of type I specimen.

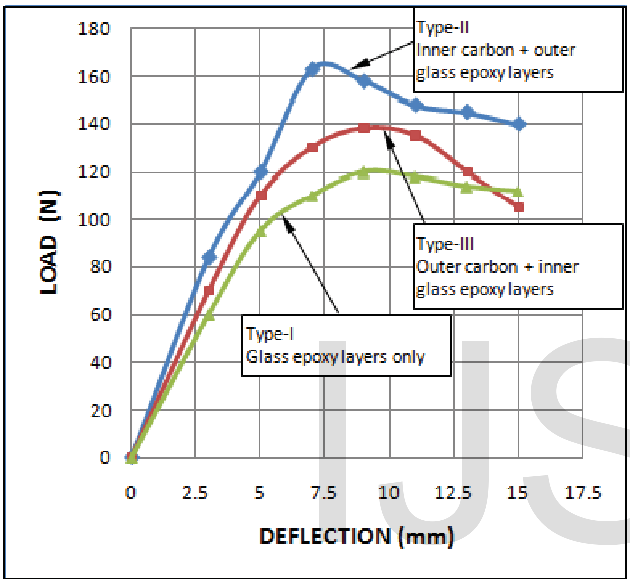

Fig. 6. Load- displacement curve (Experiment)

Table 3. Experimental Results

Specimen	Peak load(N)	G_{IC} (kJ/m^2)
Type I (without carbon layer)	121	0.210
Type II (with inner carbon layer)	164	0.272
Type III (with outer carbon layer)	138	0.250

In numerical analysis, cohesive zone model of the DCB specimen is created and the exact boundary conditions were applied. The load- displacement curves were plotted and the peak loads were obtained. The numerical analysis predicted a critical load of 123N for the type I specimen which is in good agreement with the experimental result. For type II specimen, the numerical analysis predicted a critical load of 152N. In this case, the experimental result is higher than the predicted result. Type III specimen shows a predicted critical load of 142N against the experimental value of 138N. Both experiment and CZM shows reduction in fracture load while keeping the carbon-epoxy layers as outer layers (type III) in comparison with DCB with inner carbon epoxy layers (type II). This may be due to the local buckling of the outer carbon epoxy layer. DCB with inner carbon layer exhibited carbon fiber bridging at the interface and may be a cause of increase in fracture load for type II specimen.

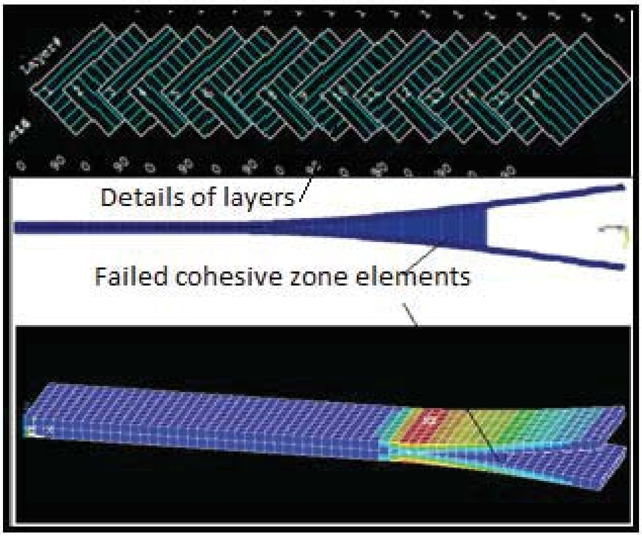

Fig. 7. Failed DCB specimen (mode I CZM)

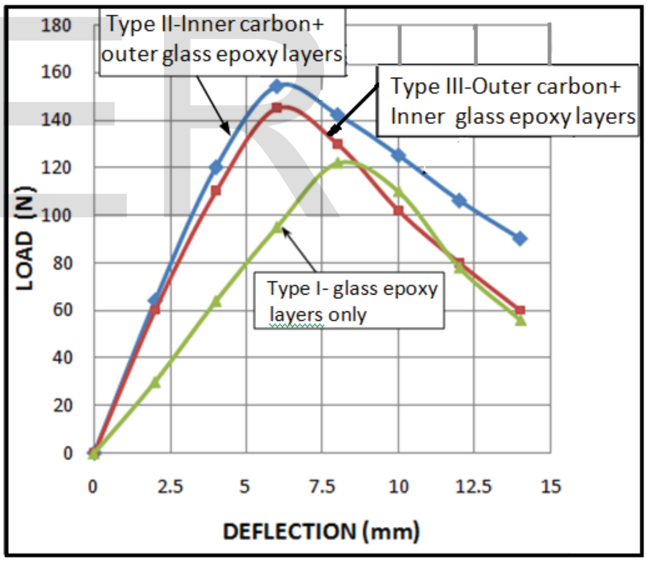

Fig. 8. Load- displacement curve (Numerical using CZM)

Table 4. Numerical Results

Specimen	Peak load(N)
Type I (without carbon layer)	123
Type II (with inner carbon layer)	152
Type III (with outer carbon layer)	142

VII. Conclusions

The mode I fracture toughness experiment has been conducted and the critical loads were obtained for both type of specimens. The type II specimen carried more load than type I specimen. In numerical analysis, the DCB specimen was modeled using cohesive elements and the load displacement curves were plotted. The experimental and numerical results were in good agreement. The results show that the addition of carbon fiber layer in glass epoxy composites increased the fracture toughness of the structure. Addition of carbon layers as inner layers increased the fracture load in comparison to that of specimen with outer carbon layers. The exact reason of this trend is to be analyzed thoroughly before implementing this method for practical applications. Ease of manufacturing glass epoxy structures with carbon fiber layers is one of the advantages of this method.

Acknowledgment

This work was supported by Centre for Engineering Research and Development, Trivandrum, Kerala [CERD grant No: CERD/2010/RSM(15) dated 06/01/2011].

References

[1] R. A. Naik, J.H. Crews Jr and K. N. Shivakumar, Effects of Ttabs and large deflections in DCB specimen tests," Composite Materials, Fatigue and Fracture, T. K. O'Brien, Ed., vol. 3 of ASTM STP 1110, 1991, pp169–186.

[2] Arthur K Kaw, Mechanics of composite materials, ISBN-10: 0-8493-1343-0,Second edition, CRC Press, 2006.

[3] E.A. Bonifiaz, Cohesive zone modeling to predict failure processes, Canadian journal on Mechanical Sciences and Engineering, vol.2, 2011, pp1-13.

[4] Bijan Mohammadi and Davood Salimi Majd, Investigation of delamination and damage due to free edge effects in composite laminates due to free edge effects, Engineering solid mechanics, vol. 2, 2011, pp101-118.

[5] Shun Fa Hwang and Ching Ping Mao, Failure of delaminated interply hybrid composite plates under compression, Composites science and technology, 2001, pp1513-1527.

[6] P.S. Shivakumar Gouda,S.K. Kudari, Prabhuswamy and Dayananda Jawali, Fracture toughness of glass-carbon (0/90)s fiber reinforced polymer composite-An experimental and numerical study, Journal of minerals and materials characterization and engineering, vol.10, 2011, pp671-682.