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A Comparative Study of the Behavior of CFRP and GFRP Laminates in a Plate Specimen Using Modified Virtual Crack Closure Technique (MVCCT)

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Abstract

The applications of polymer composites in aircraft industry have exponentially increased in the recent years due to their high strength to weight ratio. Presence of delaminations in composites is inevitable which affects the structural stability due to reduction in structural stiffness and strength. The degradation of a structural component depends on the geometric characteristics of delamination, nature of loading and material characteristics. Damage tolerance study is thus essential to determine the extent of degradation of the structure due to the presence of delamination. The present paper brings about a comparision between the behaviour of a standard plate specimen made up of Carbon Fibre Reinforced Polymer (CFRP) and Glass Fibre Reinforced Polymer (GFRP) laminates with circular delaminations of varying diameters and subject to compressive load.

A constant compressive load in terms of initial displacements was applied on a quasi-isotropic square plate specimen of dimensions 200 mm x 200 mm with a thickness of 2.88 mm of both CFRP and GFRP configurations. A circular delamination was introduced at the centre of the plate and its diameter and position along the thickness direction were varied and studied. Using ABAQUS codes of practice, Strain Energy Release Rate (SERR) was computed. The principles of Modified Virtual Crack Closure Technique (MVCCT) was used to compute SERR. Delamination propagates when the computed mixed mode energy release rate exceeds the critical value, G_C. Depending on the external loading and material properties, Total strain energy release rate, G_T ($G_T=G_I+G_{II}+G_{III}$) was used to predict growth of delamination. The onset of delamination growth was determined by plotting the values of (G_T/G_C) across various delamination sizes along the thickness of the plate and reported.

Keywords: Virtual Crack Closure Technique, Strain Energy Release Rate, CFRP, GFRP, Delamination.

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1. Introduction

Composite material is a combination of two or more materials mixed together in a suitable proportion to obtain the desired structural properties. Usually, the components in composites can be identified physically since they interface with one another. The properties of composite materials are superior to that of the individual materials used in their composition. A composite material is generally made up of a fibrous material oriented in alternating directions which are embedded in a resin matrix. This arrangement is responsible for the high strength to weight ratio in composites. Composites are friendly and flawless but damages are inevitable, especially the presence of delamination, which can be defined as an interlaminar disbond. Presence of delamination between various layers that are oriented in different directions is one of the prevalent outcomes of low velocity impact in composites. Low velocity impact events can take place during working of the material or during maintenance and can be considered as one of the major threats on composite laminates. The presence of delamination reduces residual strength and stiffness of the structure causing structural degradation. This calls for the designers and researchers to study the significance of delamination, especially in laminate structures. The damage tolerance study may be useful to understand the structural behaviour of the delaminated structure. The pioneer works in Fracture Mechanics were carried out by Rybicki and Kanninen taking into consideration, the crack tip forces and relative displacement of the cracks in order to calculate SERR [Kanninen, (1973)]. This was further extended to 3D specimens, thus the 3D Virtual Crack Closure Technique was developed [Shivakumar et. al., (1998)]. An overview to the history, approach and applications of VCCT was presented by Krueger [Krueger, (2004)]. The concepts of VCCT were later applied to study delamination growth and its behaviour in Carbon Fibre Composite Laminate when subjected to spectrum fatigue loads [Raju et. al., (2014)].

In the present study, principles of Finite elemental Analysis are applied on square plates made up of Carbon Fibre Reinforced Polymers (CFRP) and Glass fibre Reinforced Polymers (GFRP). Critical Energy Release rates in the three modes of fracture; $G_{I,}$ G_{II} and G_{III} are determined. It is assumed that these values of energy release rates are material specific properties and are independent of the stacking sequence and geometry of the specimen. Total Energy Release rate G_T is computed and considered as the major criterion for the growth of delamination in composites.

2. Finite Element Modelling of the Specimen

A standard square plate, 200 mm x 200 mm in dimension with a thickness of 2.88 mm was considered for analysis. A quasi-isotropic lay-up in the sequence $[(+45/-45/0/90)_2]_s$ made up of unidirectional composites was modelled with individual layer thickness of 0.18 mm. The geometric details of the plate are tabulated in Table 1. The material properties of the CFRP and GFRP used was obtained from existing literature [Raju et. al., (2013) and Amaro et. al., (2013) respectively] and are populated in Table 2 and Table 3. Using ABAQUS standard platform, 3-D finite element model of the plate specimen was generated and is shown in Figure 1. The meshing of the specimen was carried out in a way to ensure a smooth propagation of delamination by introducing fine mesh sizes ahead of the delamination front. Regions lying out of the area of interest were coarsely meshed to reduce the number of elements and thus the analysis time. Analysis was carried out by introducing a circular delamination at the centre of the plate by varying the delamination sizes from 10 mm to 100 mm along the laminate thickness. Contact was simulated by introducing BNODES (Bond nodes) throughout the layer except for the considered delaminated area. This absence of BNODES simulated required delamination. The various diameters of delamination considered are shown in Figure 2 and the different cases analysed by introducing the delaminations at different layers are tabulated in Table 4.

Table 1. Geometrical Properties of the plate

Dimensional Properties	
Dimensions of plate : 200 mm x 200 mm	Layer Thickness : 0.18 mm each
Thickness of plate : 2.88 mm	Layup Sequence : $[(+45/-45/0/90)_2]_s$

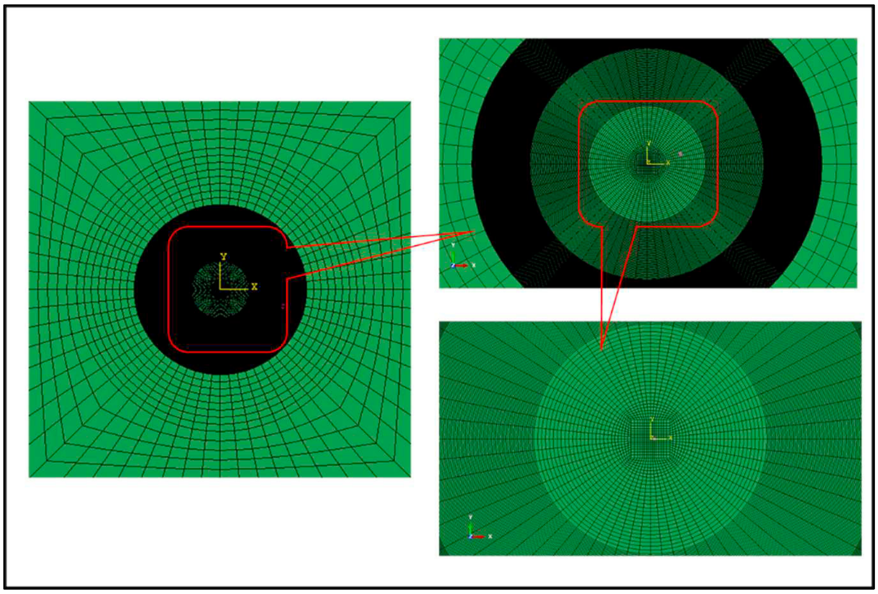

Figure 1. Meshing pattern of the plate specimen

Table 2. Material Properties of CFRP [Raju et. al., (2013)]

Young's Modulus (GPa)	Fracture Toughness (J/m^2)	Poisson's ratio	Shear Modulus (GPa)
$E_{11}=139.4$	$G_{IC}=0.3$	$\nu_{12}=0.3$	$G_{12}=4.6$
$E_{22}=10.16$	$G_{IIC}=0.48$	$\nu_{13}=0.3$	$G_{13}=4.6$
$E_{33}=10.16$	$G_{IIIC}=0.48$	$\nu_{23}=0.43$	$G_{23}=3.5$

Table 3. Material Properties of GFRP [Amaro et. al., (2013)]

Young's Modulus (GPa)	Fracture Toughness (J/m^2)	Poisson's ratio	Shear Modulus (GPa)
$E_{11}=50$	$G_{IC}=0.15$	$\nu_{12}=0.34$	$G_{12}=3$
$E_{22}=10.16$	$G_{IIC}=0.3$	$\nu_{13}=0.34$	$G_{13}=3$
$E_{33}=10.16$	$G_{IIIC}=0.3$	$\nu_{23}=0.38$	$G_{23}=2.79$

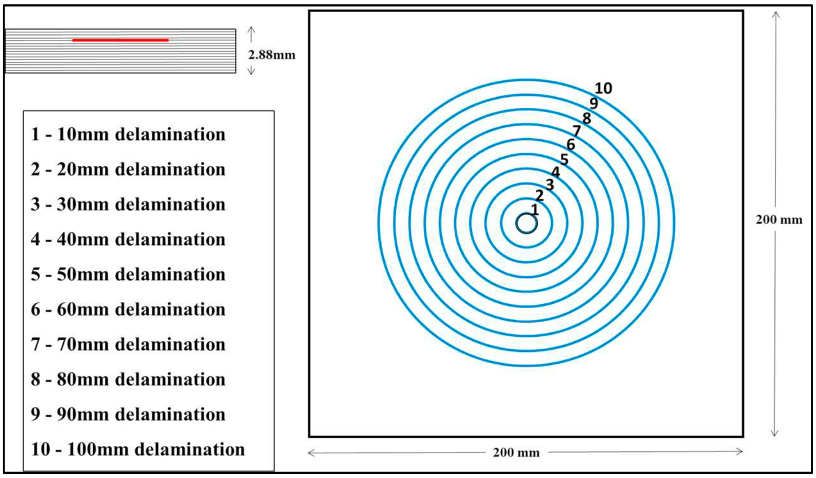

Figure 2. Delamination sizes considered for analysis.

Table 4. Various cases considered for analysis.

Cases of study	**Thickness of Top plate (mm)**	**Thickness of Bottom plate (mm)**	**Figure**
Case 1 (between 90° and 90° plies)	1.44 (8 plies)	1.44 (8 plies)	
Case 2 (between 90° and 0° plies)	1.62 (9 plies)	1.26 (7 plies)	
Case 3 (between 0° and -45° plies)	1.8 (10 plies)	1.08 (6 plies)	
Case 4 (between -45° and +45° plies)	1.98 (11 plies)	0.90 (5 plies)	
Case 5 (between +45° and 90° plies)	2.16 (12 plies)	0.72 (4 plies)	
Case 6 (between 90° and 0° plies)	2.34 (13 plies)	0.54 (3 plies)	
Case 7 (between 0° and -45° plies)	2.52 (14 plies)	0.36 (2 plies)	
Case 8 (between -45° and +45° plies)	2.7 (15 plies)	0.18 (1 plies)	

2.1. Loads and Boundary Conditions

All the degrees of freedoms were held on one of the edges of the bottom plate and a compressive load in terms of initial displacement was applied on to the opposite edge. The remaining free edges were also constrained [Raju et. al., (2014)] such that delamination growth shall initiate from the centre of the plate. A non-linear static analysis was carried out to compute SERR.

2.2. Computation Of Strain Energy Release Rate

The major assumption of VCCT is that the strain energy released during the propagation of crack is always equal to the energy required to close the crack [Krueger, (2004)]. The total value of SERR obtained can be divided into the three corresponding loading modes, opening, sliding shear and tearing shear similar to the Benzeggagh and Kenane criterion [Benzeggagh and Kenane, (1996)] which is used to compute the SERR contributing to the propagation of delamination in the Finite element analysis. The equation for the Critical energy release rate, G_c computed using B-K law.

$$G_C = G_{IC} + (G_{IIC} - G_{IC})[G_S/G_T]^{\eta} \tag{1}$$

Where,
$G_{IC} =$ Critical Energy Release rate in mode I.
$G_{IIC} =$ Critical Energy Release rate in mode II.
$G_{IIIC} =$ Critical Energy Release rate in mode III.
$G_S = G_{II} + G_{III}$
$G_T = G_I + G_{II} + G_{III}$
$\eta = 1.75$, an experimental value obtained from existing literature [Raju et. al., (2014)].

Delamination is expected to grow when, for a given mixed-mode ratio, the Total Strain Energy Release Rate (G_T) crosses the value of Critical Strain Energy Release Rate (G_C), which is given by B-K law.

$$G_r/G_c \geq 1 \tag{2}$$

3. Results and Discussion

B-K law was used to compute SERR in the finite element analysis using ABAQUS codes. In order to compute the SERR along the delamination front the compressive load was kept constant and the delamination sizes were varied from 10 mm to 100 mm. SERR values in the corresponding three modes of failure were determined from the analysis. Critical Strain Energy Release Rate, G_C and Total Strain Energy Release Rate, G_T were also computed. For Case 1, it was found that the values of G_I, G_{II}, G_{III} and G_{eff} were 0.010 N/mm, 0.421 N/mm, 0.275 N/mm and 1.255 N/mm respectively for a delamination size of 90mm. From these obtained values, G_T and G_T / G_C were computed to be 0.706 N/mm and 1.313 N/mm respectively.

It was found that the propagation of delamination initiated at 88 mm in the CFRP specimen whereas, at 92 mm for the GFRP specimen for Case 1. To better understand the behavior of the crack front in between plies, the values of Strain Energy Release Rates responsible for the propagation of delamination for both CFRP and GFRP specimen were plotted against the various delamination sizes as shown in Figure 3. It was observed that at the surface level (Case 7 and Case 8), the specimen failed even when a delamination of 10 mm diameter was considered for both CFRP and GFRP configurations. As the thickness of the plate reduces, its ability to take load reduces and thus these specimen failed when a delamination of 10 mm was introduced. Failure of the specimen also depends on the orientation of fibres of the layers where delamination is present. In these cases, further analyses were not necessary. The bonding state of the plate specimen after the crack propagation is shown in Figure 4.

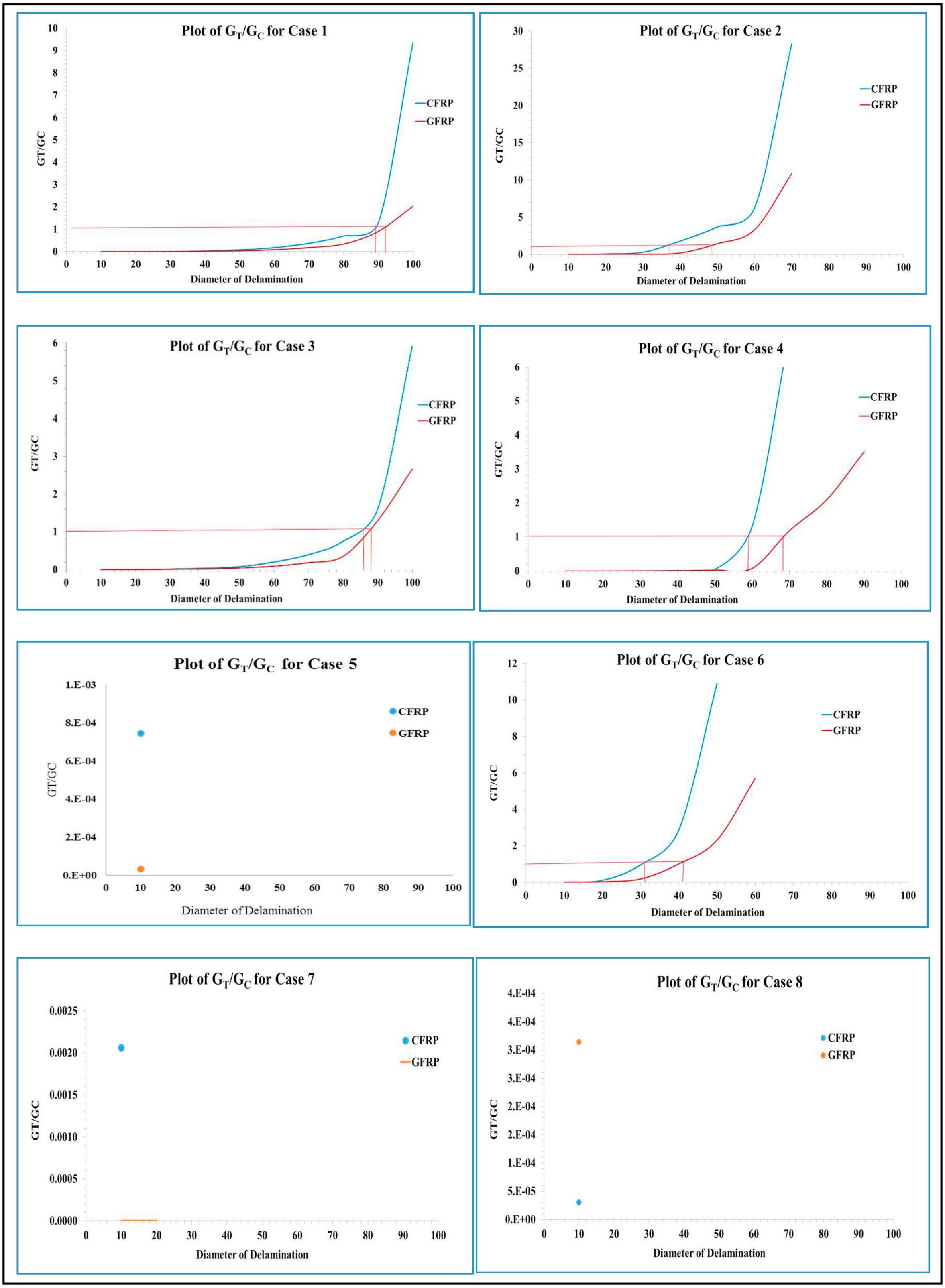

Figure 3. Comparision of G_T/G_C for CFRP and GFRP.

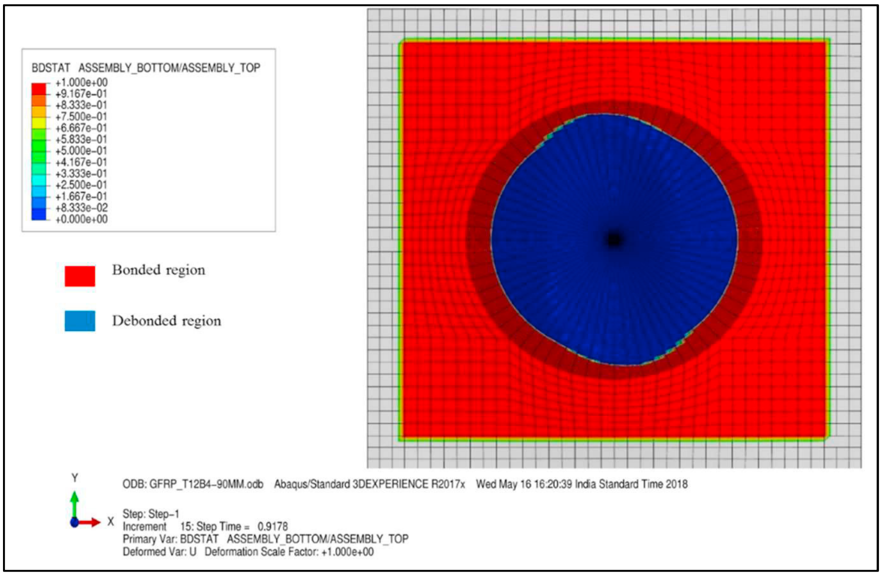

Figure 4. Delamination Growth Pattern.

4. Conclusion

From the results obtained from the analysis of CFRP plate specimen, the values of SERR obtained in both shearing mode and tearing mode (Mode II and Mode III) during the analyses are very close to each another and quite dominant when compared to Mode I. From the results obtained, it is also inferred that smaller delamination sizes at the surface level is sufficient to initiate delamination growth. This implies that surface level delamination causes more damage to the stability of the structure and thus should be avoided. In the next phase of analysis, GFRP plate specimen was studied and the results obtained are compared with the data from CFRP analysis. From the plotted graph it is inferred that crack growth is comparable with both materials and crack propagation is delayed in GFRP laminate as compared to the CFRP laminate.

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