Fracture Behaviour of FRP Cross-Ply Laminate With Embedded Delamination Subjected To Transverse Load

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Abstract

One of the most important damage mechanisms in composite materials is the delamination between plies of the laminate. In industrial applications, composite plates are sensitive to impact and delamination occurs. Many composite components have curved shapes, tapered thickness and plies with different orientations, which make the delamination grow depending on the extent of the crack. It is therefore important to analyze the delamination characteristics of composite structures. The main objective of the present investigation is the characterization of the delamination growth in four layered cross ply (0/90/90/0) fibre reinforced composite laminates along all sides of the delamination. The analysis has been carried out using Virtual Crack Closure Technique (VCCT) in combination with Finite Element Methods (FEM) with the help of commercially available Finite Element Software, ANSYS.

Keywords: VCCT, FEM, Strain Energy Release Rate (SERR), ANSYS.

Nomenclature

E_1 = Young's modulus of the lamina in the fibre direction
$E_2 = E_3$= Young's modulus of the lamina in the transverse direction of the fibre
$G_{12}= G_{13}$= Shear modulus in the longitudinal plane of the fibre
G_{23}= Shear modulus in the transverse plane of the fibre
$\nu_{12} = \nu_{13}$ = Poisson's ratio in the longitudinal plane of the fibre
ν_{23} = Poisson's ratio in the transverse plane of the fibre
G = Strain energy release rate

1. Introduction

Delamination represents a crack like discontinuity between the plies, interlaminar crack, which can propagate under the effect of mechanical, thermal and hygrometric loads. Therefore, fracture mechanics is a useful tool for approaching composite delaminations. In addition fracture mechanics is a suitable approach to deal with material selection and structural integrity when interlaminar cracks are involved. Fracture mechanics of composite materials is mostly based on the measure of the strain energy release rate 'G'. The interlaminar stresses in symmetric laminates under uniform axial extension were first evaluated by Pipes and Pagano[1] by applying a finite difference technique to solve the Navier equations of elasticity for off-axis plies. An experimental and analytical study was conducted by E. F. Rybicky, D. W. Schnussor and J. Fox[2] to examine the free edge delamination mode of failure in a [±30°/±30°/90°/90°]s Boron/Epoxy laminate. Energy release rates were evaluated by a simple computational scheme that does not require special singular element or knowledge of the existence of a stress singularity in the solution. R. B. Pipes[3] determined the boundary layer effects in composite laminates and presented the distribution of interlaminar normal and shear stresses along the width of cross-ply laminate. A. D. Crocombe and R. D. Adams[4] have studied the effect of the interaction between a realistic spew fillet and other joint parameters on the adhesive stress distribution in a single lap joint for a wide range of geometric and material parameters using a linear elastic finite element program.

An approximate semi-analytical method for determination of interlaminar shear stress distribution through the thickness of an arbitrarily laminated thick plate was presented by Reaz A. Chaudhuri and Paul Seide[5]. Erian A. Armanios and Jian Li[6] predicted the interlaminar stresses in a symmetric laminate under extension, bending, torsion and their combined effect using a simple analytical formulation. I. S. Raju, R. Sistla and T. Krishnamurthy[7] have performed fracture mechanics analyses on two debond configurations, flange-ski strip and skin-stiffener. Three-dimensional finite element analyses were performed. Two methods that use the virtual crack closure technique (VCCT) were used to evaluate the strain energy release rate distributions across the debond front. Debagrata Chakraborty and Dr. B. Pradhan[8] have examined the delamination initiation at the interface of broken and continuous plies in case of [0/90/±Ɵ/0]s Gr/E and Gl/E laminates with broken central plies.

A full 3D FE analysis was performed with each layer of the laminate modeled as homogenous and orthotropic. Based on the results of 3D FE analysis, GI, GII & G were calculated at the delamination front using Irwin`s Crack Closer Integral. Dr. B. Pradhan and D. Chakraborty[9] have dealt with the delamination initiation from an existing embedded elliptical delamination at the interface of the FRP composite laminates. A full 3D FE analysis was performed to calculate the inter-laminar stresses at the interface responsible for delamination. Concept of fracture mechanics was used to calculate the components of strain energy release rates at the interface. Effects of important factors like orientation of the adjacent layers, laminate thickness and the aspect ratio of the elliptical delamination on strain energy release rate components was studied. S. K. Panigrahi and Dr. B. Pradhan[10] have performed a three-dimensional finite element analysis and computed the out-of-plane normal and shear stresses in an adhesively bonded single lap joint (SLJ) with laminated FRP composite plates which in comparison to other analytical methods for bonded joint analysis, is capable of handling more general situations related to initiation of damages and its growth. Damage propagation was analyzed by fracture mechanics based strain energy release rate (SERR) approach using virtual crack closure technique (VCCT). In the present analysis, fracture behavior of four layered cross-ply laminates under transverse load having interlaminar embedded delamination at mid span is studied using finite element method through VCCT.

2. Problem statement

In the present analysis, fracture behavior of four layered cross-ply laminates under transverse load having interlaminar embedded delamination at mid span is studied using finite element method through VCCT.

3. Problem Modelling

3.1 Geometric Model

The in-plane dimensions of the laminate considered for the present analysis is as shown in Fig.1. The length and width of the plate are taken as 100 mm with a length/depth ratio of 10. Four layers of equal thickness (10/4=2.5mm) are considered. The delamination is located at the centre of the laminate. The delamination length is taken as 25mm. The virtual crack length is taken as 0.11mm on four sides of the delamination.

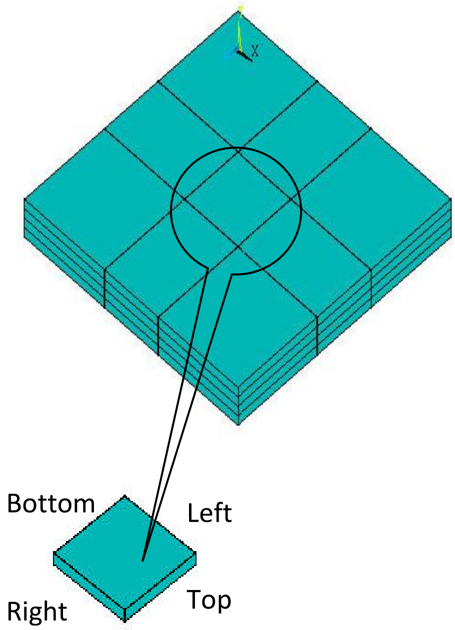

Fig.1Geometric model for centre delamination at the middle interface.

2.2 Finite Element Model

Finite element mesh is generated using 8 node solid element SOLID45 in ANSYS software[12] as shown in Fig. 2. This element is defined by 8 nodes having three degrees of freedom per node: translations in the nodal x, y and z directions. The element may have any spatial orientation. SOLID45 has plasticity, creep, stress stiffening, large deflection, and large strain capabilities. It has the capability to inherit orthotropic material properties and hence, best suited for analysing FRP composites.

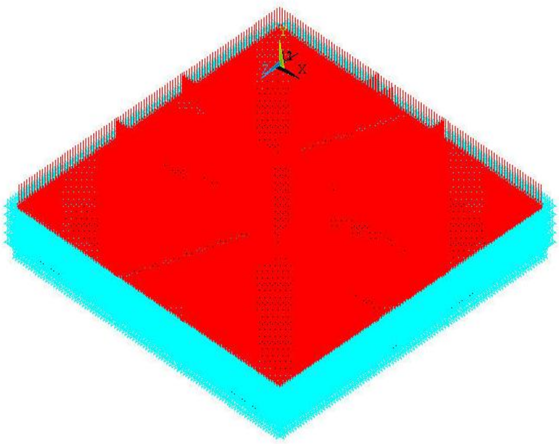

Fig. 2 Finite element model with boundary conditions

2.3 Material Properties

The material selected to carry out the present work is carbon epoxy[11]. The material properties used for the carbon epoxy material are given below:

i) Young's Modulus, E_1 = 147GPa, E_2 =9GPa, E_3=9GPa
ii) Poisson's Ratio, $\nu_{12}= \nu_{13}$ = 0.27, ν_{23}=0.54
iii) Rigidity Modulus, $G_{12}=G_{13}$=7GPa, G_{23}=3.7GPa

2.4 Boundary Conditions and Loading

Fixed boundary condition is imposed along the depth of the plate on four sides of the FE model. A transverse load of 1MPa is applied on the top surface of the laminate at y=10mm of the FE model.

3.0 Analysis of Results

The variation of strain energy release rate in opening mode 'G_I' with respect to the normalized length for a delamination length of 25mm along the four sides of an embedded delamination in a 4 layered laminate subjected to transverse load is shown in figs. 3 to 6. No constant trend is observed in the variation of G_I along the top and bottom edges of the embedded delamination. A maximum value of 0.044871J/m^2 is found at the 6th normalized location from left to right of the top and bottom edges. G_I is found to be maximum 0.017734J/m^2 at the 5th normalized location measured from bottom to top of the left and right edges of the embedded delamination.

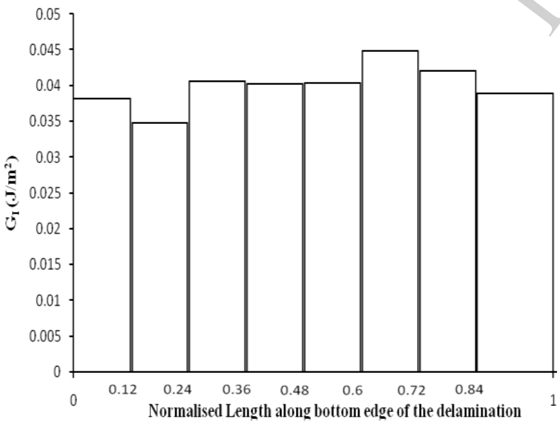

Fig. 3 Variation of 'G_I' with respect to normalized length along bottom edge of the delamination

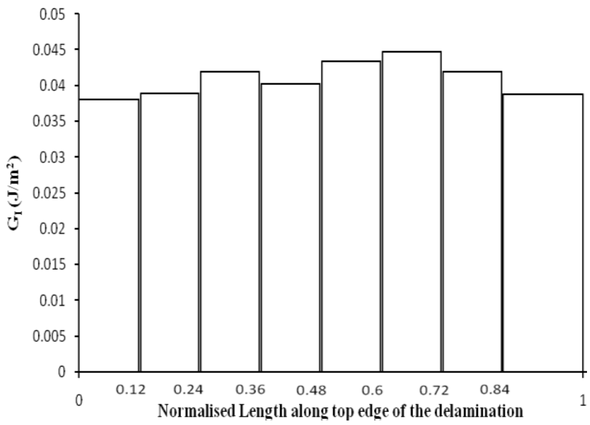

Fig. 4 Variation of 'G_I' with respect to normalized length along top edge of the delamination

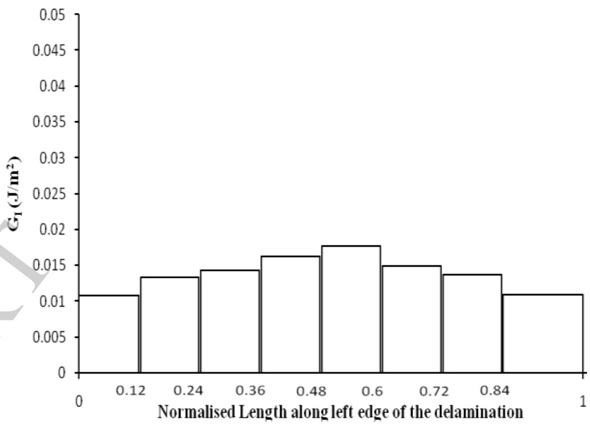

Fig. 5 Variation of 'G_I' with respect to normalized length along left edge of the delamination

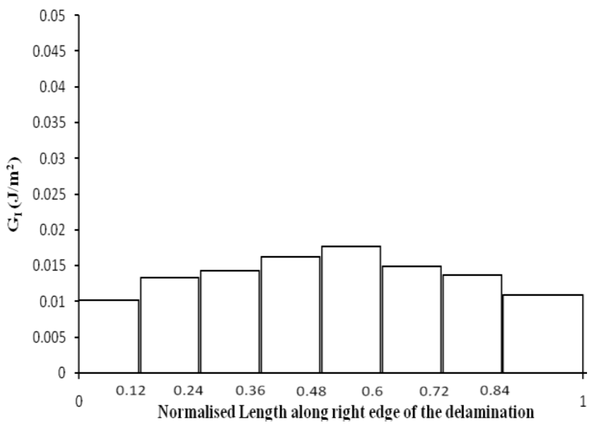

Fig. 6 Variation of 'G_I' with respect to normalized length along right edge of the delamination

The variation of strain energy release rate in sliding mode 'G_{II}' with respect to the normalized length for a delamination length of 25mm along the

ISSN: 2278-0181
Vol. 1 Issue 8, October - 2012

four sides of an embedded delamination in a 4 layered laminate subjected to transverse load is shown in figs. 7 to 10. G_{II} is found to be gradually increased up to the centre and then gradually decreased. A maximum value of 0.056957J/m^2 is found at the 5th normalized location measured from left to right of the top and bottom edges. G_{II} is found to be maximum 0.149215J/m^2 at the 5th normalized location measured form bottom to top of the left and right edges of the embedded delamination.

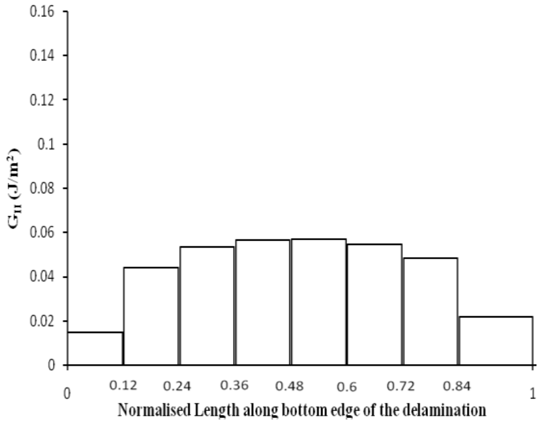

Fig. 7 Variation of 'G_{II}' with respect to normalized length along bottom edge of the delamination

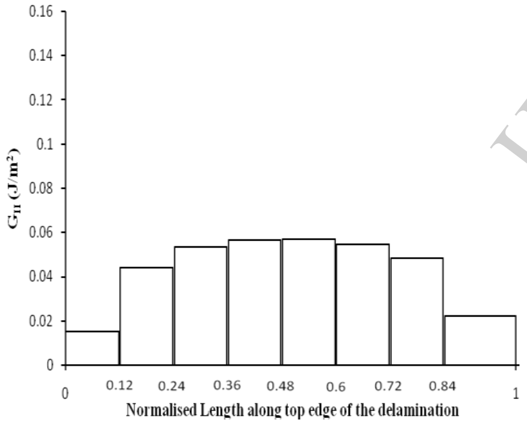

Fig. 8 Variation of 'G_{II}' with respect to normalized length along top edge of the delamination

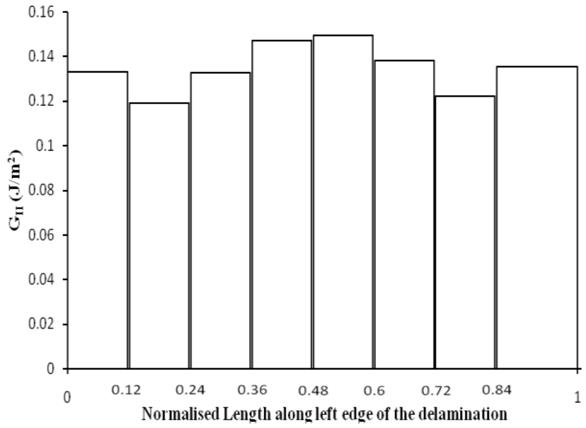

Fig. 9 Variation of 'G_{II}' with respect to normalized length along left edge of the delamination

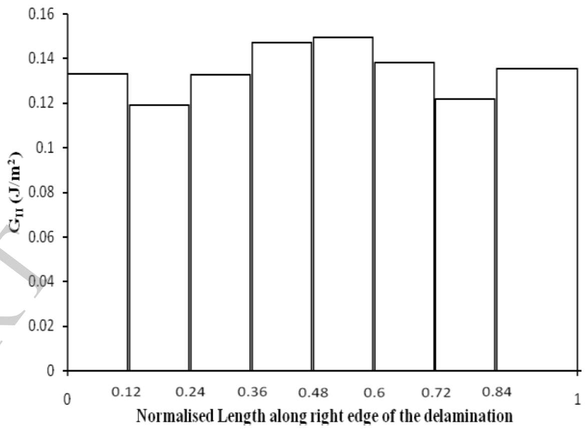

Fig. 10 Variation of 'G_{II}' with respect to normalized length along right edge of the delamination

The variation of strain energy release rate in tearing mode 'G_{III}' with respect to the normalized length for a delamination length of 25mm along the four sides of an embedded delamination in a 4 layered laminate subjected to transverse load is shown in figs. 11 to 14. G_{III} is found to be gradually decreased up to the centre and then gradually increased. A maximum value of 0.003844J/m^2 is found at the 1st normalized location measured from left to right of the top and bottom edges. G_{III} is found to be maximum 0.016223J/m^2 at the 1st normalized location measured form bottom to top of the left and right edges of the embedded delamination.

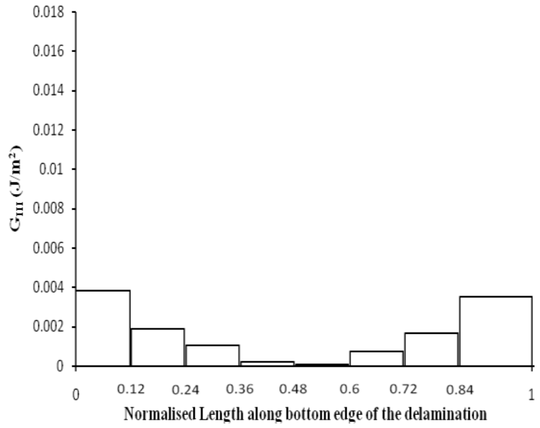

Fig. 11 Variation of 'G_{III}' with respect to normalized length along bottom edge of the delamination

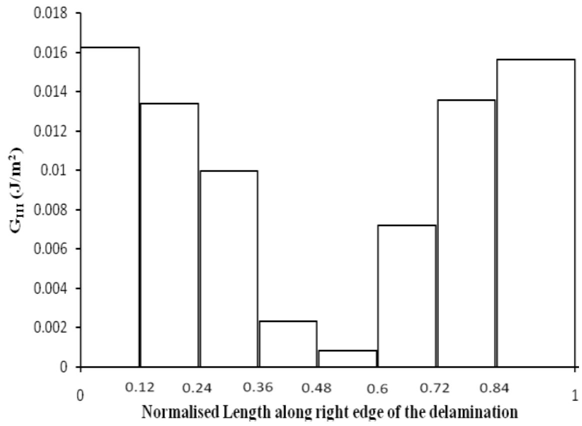

Fig. 12 Variation of 'G_{III}' with respect to normalized length along top edge of the delamination

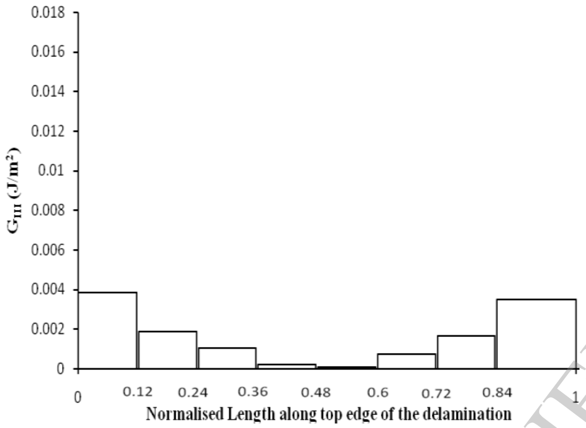

Fig. 13 Variation of 'G_{III}' with respect to normalized length along left edge of the delamination

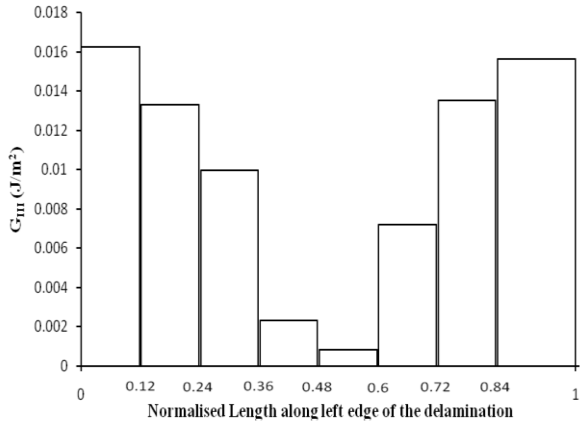

Fig. 14 Variation of 'G_{III}' with respect to normalized length along right edge of the delamination

4. Conclusions

Fracture analysis of a 4 layered FRP cross ply laminate with embedded delamination at the centre of the plate subjected to transverse load is carried out and the following conclusions are drawn:

- G_I is maximum along the top and bottom edges of the embedded delamination.
- G_{II} and G_{III} are maximum along the left and right edges of the embedded delamination.
- G_{II} is found to be the dominating mode with a maximum value of 0.149215J/m^2.

5. References

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