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RESEARCH PAPER

Effect of Ply Orientation on Residual Stresses and Their Influence on Mode-I Fracture Toughness of Glass-Epoxy Composites With 0°//0° Crack Interface

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Abstract: *The energy release rate for delamination in a laminated composite is supposed to be the material property being considered as independent of non-material property variables. However, Mode I fracture toughness (G_I) is found to vary with lamina arrangement, geometrical dimensions, and process-induced stresses. In this investigation, the influence of lamina stacking arrangement on process-induced stresses and their effects on G_I of laminated composites are studied. Unidirectional (UD) ($[0]_{16}$) and cross-ply ($[90_2/0_6]s$, $[90_4/0_4]s$, and $[90_6/0_2]s$) glass/ epoxy (GE) composites with the delamination plane at 0°//0° were prepared by manual layup method and post-cured at 120°C for 4 hours. G_I of composite laminates were experimentally determined using a double cantilever beam (DCB) specimen as per ASTM D 5528. The slitting method was applied to determine the process-induced stresses in GE laminates. The stacking sequence of laminas was found to have a noticeable effect on the state of residual stresses and GI of GE laminates. Residual stresses do not have much influence on the G_I for delamination initiation, whereas GI for the crack propagation was found to increase with a gradual increase in compressive residual stresses in GE laminates.*

Keywords: *Residual stresses, Mode I interlaminar fracture toughness, slitting method.*

1. INTRODUCTION

Polymer composites reinforced with fibers offer many advantages such as high specific strength, high specific modulus, ease of manufacturing, and tailoring of properties as per the functional requirements which have effectively reduced the weight and improved the reliability of structures. But delamination of laminas remains the most critical failure in these composites, mainly due to their low interlaminar strength. Fracture toughness is an important parameter that characterizes the resistance to the propagation of the interlaminar crack at the interface. The factors that affect the delamination resistance in multidirectional FRP composites are its constituents, lamina arrangement in each arm of DCB (symmetric or asymmetric arms), manufacturing process employed, curved crack front, mode mixing, residual stresses, fiber-matrix bonding, fiber bridging, and breakage of fibers. Process-induced stresses may adversely affect the strength and dimensional stability of composite laminates and could lead to premature failure, delamination, warpage, and matrix cracking. Therefore, the knowledge of the residual stress distribution is essential to predict their impact on the performance of composite laminates. [1-6]
From the earlier works, the influence of cure stresses on the energy release rate of the DCB composite laminates was studied analytically and the errors in actual fracture toughness are large when effects of residual stresses are not considered un-symmetric DCB composite laminate [7]. The impact of residual stresses on GI of different cross-ply [0/90] DCB specimens, having the delamination crack interface occurred at 0°/0° were investigated. The transverse tensile residual stresses resulted in the reduction of G_I and the bend-twist coupling across the arms of the DCB specimen can cause significant alterations in the opening mode fracture toughness [8]. The

influence of layup sequences (unidirectional (UD), quasi-isotropic, and cross-ply laminates) with 0°//0° interface in GE laminates are investigated. The results revealed that the fracture toughness for initiation in UD laminates is much higher than that of multidirectional (MD) laminates and the bending-bending coupling parameter ($D_c = D_{12}^2 / D_{11}D_{22}$) significantly influences the steady-state values of fracture toughness [9]. Opening mode fracture tests were done on carbon/epoxy, GE, and glass/carbon/epoxy (GCE) at 71ºC, 25ºC, and -54ºC. Different temperature ranges had a limited effect on the fracture toughness of symmetric GE and CE composites however fracture toughness of asymmetric GCE composite exhibited a significant temperature dependence [10].

Our earlier work [13] investigated the impact of residual stresses on mode I fracture toughness in carbon epoxy laminates. But our study is limited to uniform ply orientation throughout the laminates. The present work comprises of manufacturing UD GE laminates with different ply orientations and studying the effects of cure-induced stresses on Mode I interlaminar fracture toughness for initiation (G_{IC}) and propagation (G_{IP}). The cure-induced stresses and fracture toughness of UD and cross-ply laminates with 0°//0° interface are found experimentally and the influence of stacking sequence on process-induced stresses and its effects on G_I are studied.

2. EXPERIMENTAL DETAILS

2.1. Materials and Fabrication of composite laminates

The materials used in this work are UD Glass fibers as reinforcements and Epoxy resin cured using Aradur 917 hardener as the matrix. UD GE and cross-ply GE composites were prepared by hand lamination technique and cured at room temperature. Laminates for Mode I testing were prepared by implanting a separation film which acts as a delamination interface for crack propagation. UD GE laminate used to determine the elastic constants of a lamina is shown in Fig. 1 and composite samples for the tensile tests were prepared as per ASTM D 3039 [11]. DCB samples for fracture tests were cut as per ASTM D 5528 [12]. Composite laminates were then post-cured at 120°C for 4 hours. The GE laminates are coded based on their stacking sequence of the laminas and are enlisted in Table 1, '//' indicates the pre-crack interface for crack propagation. The Elastic constants obtained from the tensile test of GE laminates are presented in Table 2. Four UD GE specimens were used to determine elastic constants of GE laminates.

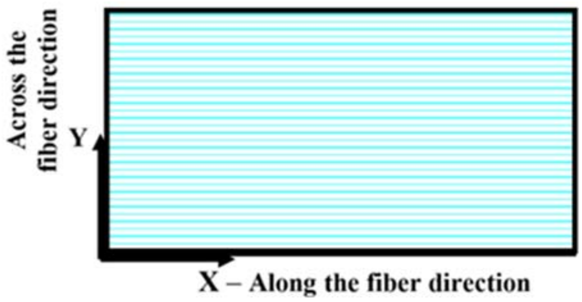


Fig. 1. Glass epoxy laminate

2.2. Mode I Fracture Test

G_I of GE laminates was determined by using a DCB specimen as per ASTM D5528. Fracture tests were conducted with a displacement rate of 2 mm/min using Tinius Olsen UTM having a load cell of 10 kN capacity. Piano hinges were bonded using Araldite at the bottom and top of the DCB specimen to facilitate loading and gripping in UTM. The geometrical dimensions of the DCB specimen are shown in Fig. 2.

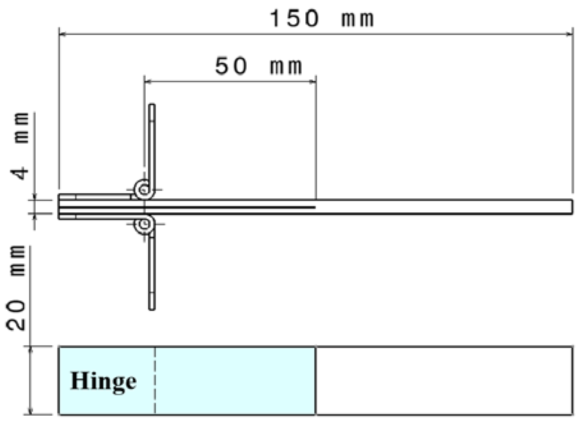


Fig. 2. Geometrical dimensions of DCB specimen

A paper scale is glued on the top of the laminate, white paint was applied across the thickness of DCB laminates to enhance the visualization of delamination crack growth. On the paper scale, vertical lines are marked starting from the crack tip with increments of 1 mm up to 5 mm. The remaining 45 mm is marked with vertical lines for every 5 mm.

Table 1. Stacking sequence and specimen codes of GE laminates

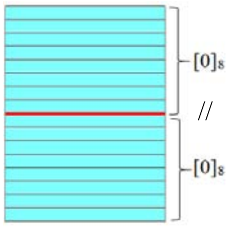
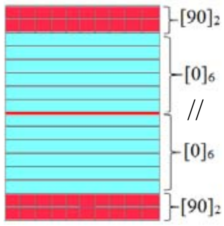
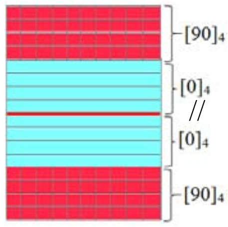
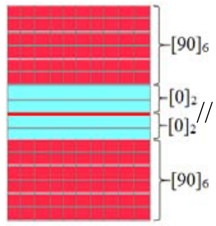
Specimen code	UD GE	GE 1	GE 2	GE 3
Stacking sequence	$[0_8 // 0_8]$	$[90_2/0_6 // 0_6/90_2]$	$[90_4/0_4 // 0_4/90_4]$	$[90_6/0_2 // 0_2/90_6]$
Stacking sequence				

Table 2. Mechanical properties of UD GE Lamina

Elastic Modulus along with fibers 'E_X' (GPa)	Elastic Modulus across fibers 'E_Y' (GPa)	Shear Modulus 'G_{XY}' (GPa)	Poisons ratio 'ν_{XY}'
5.84	2.16	0.94	0.22

The load applied (P), displacement of DCB arms (δ), and delamination length (a) are the three parameters used to estimate strain energy release rate (SERR), should be used in a synchronized manner.

The load applied and the corresponding displacement of arms are recorded in the load-displacement plots. The initiation of the delamination and the crack growth is recorded by the Sony HD video recorder. Critical SERR was evaluated using modified beam theory as per ASTM D5528 using Equation (1).

$$G_I = \frac{3P\delta}{2b(a+|\Delta|)} \quad (1)$$

where 'b' is the sample width; 'a' is the delamination length and 'Δ' is the correction parameter considered to account for the twist of the DCB arms, which is evaluated experimentally as per ASTM D 5528.

2.3. Residual stress determination using Slitting Method

The slitting method [13-24] is one of the most commonly employed semi-destructive methods for residual stress measurement. The procedure of stress determination using the slitting method can be explained with a typical specimen shown in Fig. 3. This method involves machining a thin slit through a stressed specimen and the relaxed strains due to machining are read by a bonded strain gauge across the adjacent material. This method can estimate residual stresses perpendicular to the direction of the incremental slit.

An incremental slit is cut starting from the front face along the X-direction, the strains relaxed due to incremental cuts are recorded by strain gauges bonded to specimen as shown in Fig. 3. Recorded strains are utilized to determine the residual stresses in each lamina.

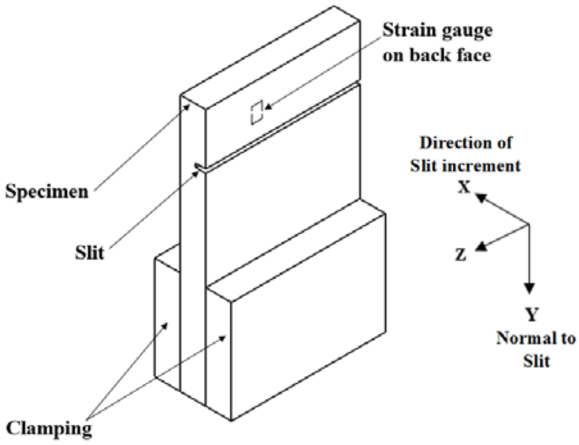


Fig. 3. Details of Slitting Specimen

The mathematical correlation between relaxed strains and residual stresses is of integral form and is given by Equation (2).

$$\varepsilon_{yy}(a_i) = \int_0^{a_i} C(x, a_i)\, \sigma_{yy}(x) \quad (2)$$

Where, '$\varepsilon_{yy}(a_i)$' are the recorded strains when the slit depth is 'a_i', 'σ_{yy}' are residual stresses to be determined, and '$C(x, a_i)$' is kernel function which is equal to strains measured when unit stress is applied at depth 'x' within a slit of depth 'a_i'.

To obtain a solution to equation (2), it is required to assume the profile of the residual stresses to be determined. The residual stresses estimated depend on the assumed profile, which defines how these stresses vary across the chosen material.

In laminated composites, the profile of stress is not continuous because of discontinuity in the material properties along the lamina boundaries. Therefore, evaluation of the stress profile in these composites is carried out by applying the Pulse method. The main benefit of this approximation is that it does not requires the condition of continuity of the residual stress profile and thus can be applied for laminated composites. This method can be described with the help of Fig. 4.

Consider a residual stress profile acting across the faces of a slit of increasing depth as shown in Fig. 4(a). In this method, the stress profile is determined by a sequence of strip or pulse loads over each increment of the slit, as shown in Fig. 4(b). Stresses are considered to be constant over each incremental cut and the residual stresses can be given by Equation (3)

$$\sigma(x_j) = \sum_{j=1}^{n} \sigma_j \, U_j(x) \tag{3}$$

Where 'σ_j' implies the stress in 'j^{th}' incremental cut when the 'total number of incremental cuts is 'n'.

The pulse functions [$U_j(x)$] can defined as

$$U_j(x) = \begin{cases} 1 & a_{j-1} \le x \le a_j \\ 0 & x < a_{j-1}, x > a_j \end{cases} \tag{4}$$

The measured strains and the residual stresses to be determined for each incremental cut can be expressed in matrix form as

$$[C]\{\sigma\} = \{\varepsilon\} \tag{5}$$

Where [C] is compliance matrix, {σ} is Residual stress vector and {ε} – Recorded strain vector To find the residual stresses, the compliance matrix has to be determined by using Finite Element Analysis. The particular element of the compliance matrix C_{ij} specifies the strains measured at the strain gauge for a slit of depth a_i when normal stress of unit load is applied in the domain $a_{j-1} \leqslant x \leqslant a_j$.

$C_{ij} = \varepsilon\ (a = a_i, \sigma(x) = U_j(x))$

Compliance coefficients were determined by simulating the Slitting method using ANSYS software. The test specimen was modeled using PLANE142 2D elements with experimentally determined elastic constants of a lamina. The elements around the slit were refined to accurately capture the strains across the strain gauge during the Finite Element simulation of the slitting technique. To replicate the experimental boundary conditions during simulation, one end of the model is completely constrained and in the other end, an incremental slit is introduced. Each cut of the incremental slitting experiment was simulated; first by removing the elements forming the slit then by applying unit stress along the border of the slit and corresponding strains across the strain gauge are measured. These compliance coefficients are utilized to estimate the process-induced stresses using the recorded strains. The compliance coefficient matrices of all GE laminates are determined using finite element simulation.

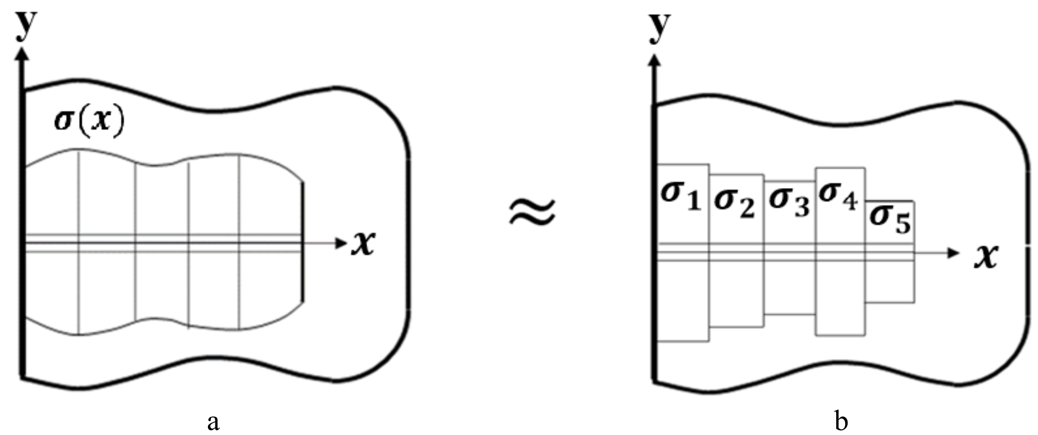


Fig. 4. (a) An unknown residual stress profile on slit faces; (b) A series of uniform strip loads are used to approximate the Unknown residual stress.

2.4. Experimentations with Test results

Insights of the slitting and Mode I fracture test experiments are discussed in the following sections.

2.4.1. Specimen preparation for Strain Gage bonding

The geometric dimensions of the composite specimen used for the slitting experiment are provided in Table 3. The specimen is thoroughly cleaned with acetone and a strain gauge of 1 mm gauge length is bonded on the specimen at a distance of 15 mm from the top face as shown in Fig. 5 (c).

Table 3. Dimensions of slitting specimen

Length in mm	Width in mm	Thickness in mm
75	20	4.0

2.4.2. Slitting experiment

The machining of a slit in incremental cuts on composite laminate was accomplished using a CNC machine, with laminate being clamped at one end and free at the other end to the cut the slit as shown in Fig. 5(c). Utmost care is taken to machine the slit in-line with bonded strain gauge starting from the other face of the specimen (front face) in incremental cuts. The slit is cut using a circular saw blade of diameter 20 mm and thickness 0.3 mm, with a spindle speed of 2000 rpm and a feed of 180 mm/min.

Each incremental depth of cut is equal to the thickness of each lamina of a composite laminate. For UD laminate the slit is machined through the entire thickness and for cross-ply laminates, the slit was machined to half of the laminate thickness due to their symmetry.

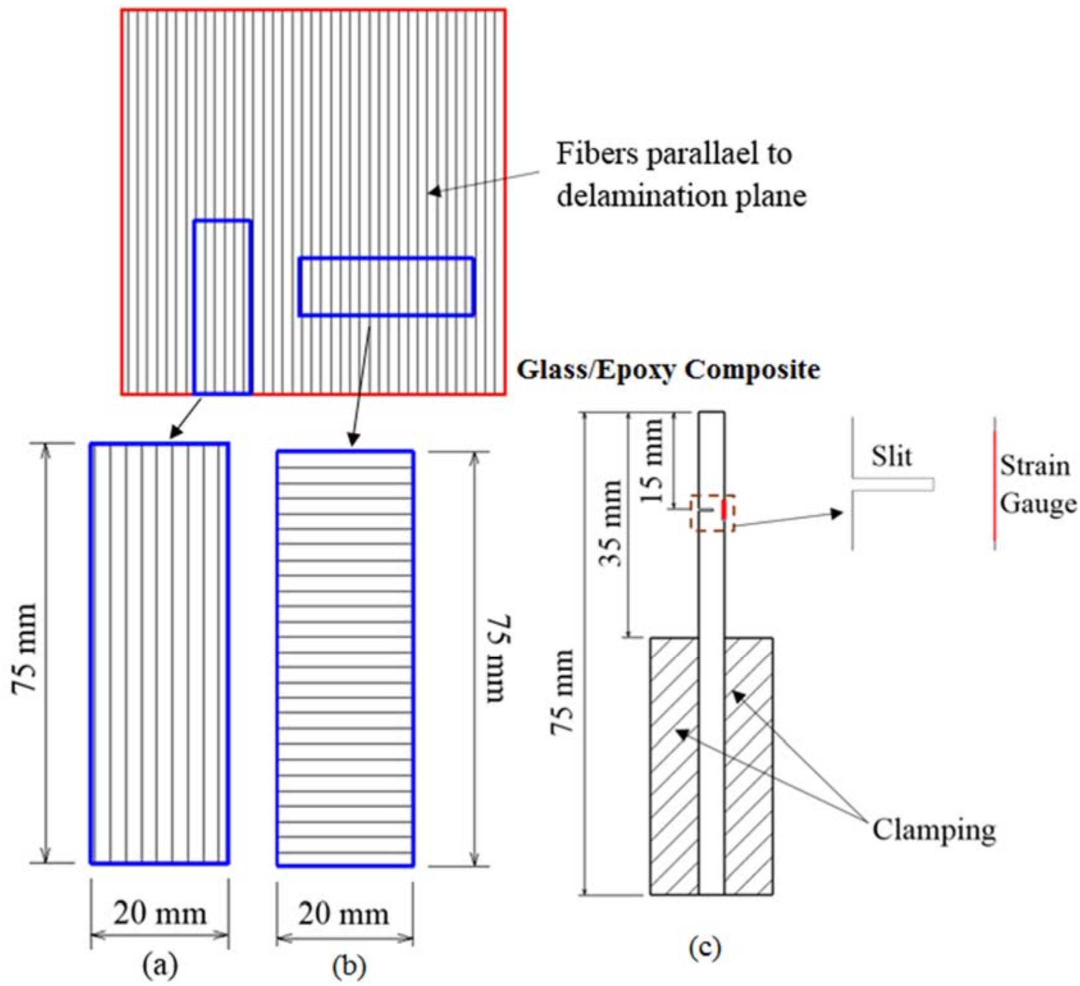


Fig. 5. (a) Slitting specimen used to determine longitudinal residual stresses in composite laminate (b) Slitting specimen used to determine transverse residual stresses in composite laminate (c) Slitting specimen with a bonded strain gauge.

After each incremental cut, the cutter is stopped and withdrawn from the laminate. The strains relaxed due to the slitting process were measured by the digital strain indicator and are recorded, once stabilization in readings was achieved. The slitting was carried out along and across the fiber directions (parallel and perpendicular to crack propagation) to determine the residual stresses in longitudinal and transverse directions, respectively. The specimens used to determine the longitudinal and transverse residual stresses are shown in Fig. 5(a) and Fig. 5(b), respectively.

3. RESULTS AND DISCUSSIONS

3.1. Residual stresses evaluated using strains recorded during the Slitting experiment

The longitudinal and transverse relaxed strains measured during the slitting of GE laminates in incremental cuts along its depth are displayed in Fig. 6(a) and Fig. 6(b), respectively. The longitudinal and transverse residual stresses in each lamina of GE laminates estimated using the recorded strains and compliance coefficients are plotted in Fig. 7 and Fig. 8, respectively. The overall transverse and longitudinal stresses in UD GE and cross-ply GE laminates are summarized in Table 4.

3.2. Mode I test results

Load-displacement plots of UD GE and cross-ply GE laminates obtained from the opening mode fracture test using DCB specimens are shown in Fig. 9. G_{IC} and G_{IP} of UD and cross-ply GE laminates are plotted in Fig. 10. Three specimens from each configuration of GE laminates were tested. Load-displacement plots of UD and cross-ply GE laminates do not show sudden load drops, indicating stable delamination of laminates with no 'Stick-Slip' phenomenon. It can also be observed that GE 1 laminates exhibit higher loads for delamination initiation compared to other GE laminates. Load required for crack initiation in UD GE, GE 2, and GE 3 are almost the same. DCB arms displacement for delamination of the same interface length is much higher in cross-ply laminates compared to that in UD GE laminate. G_{IC} and G_{IP} for GE 1 laminates are higher in comparison with other GE laminates. To study the effects of residual stresses on G_{IC} and G_{IP} in GE laminates, the transverse stresses enlisted in Table 4 are considered

Table 4. Transverse and longitudinal residual stresses in GE laminates

GE laminates	Transverse residual stress (MPa)	Longitudinal residual stress (MPa)
UD GE	-0.39	-1.52
GE 1	-14.00	2.20
GE 2	-9.50	1.33
GE 3	-4.50	2.20

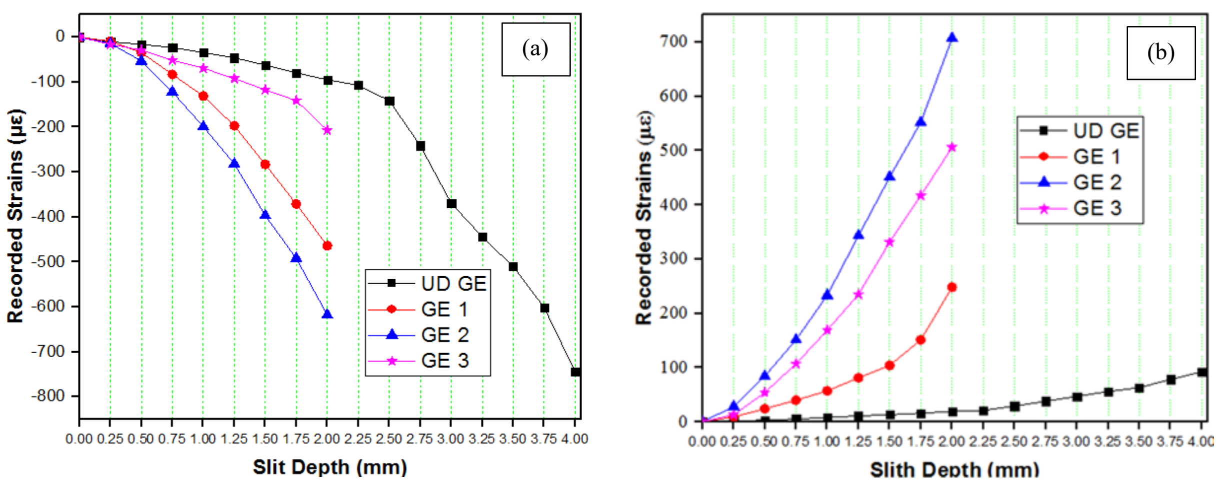


Fig. 6. (a) Strains recorded along with the laminate depth during slitting of all GE longitudinal specimens. (b) Strains recorded along with the laminate depth during slitting of all GE transverse specimens.

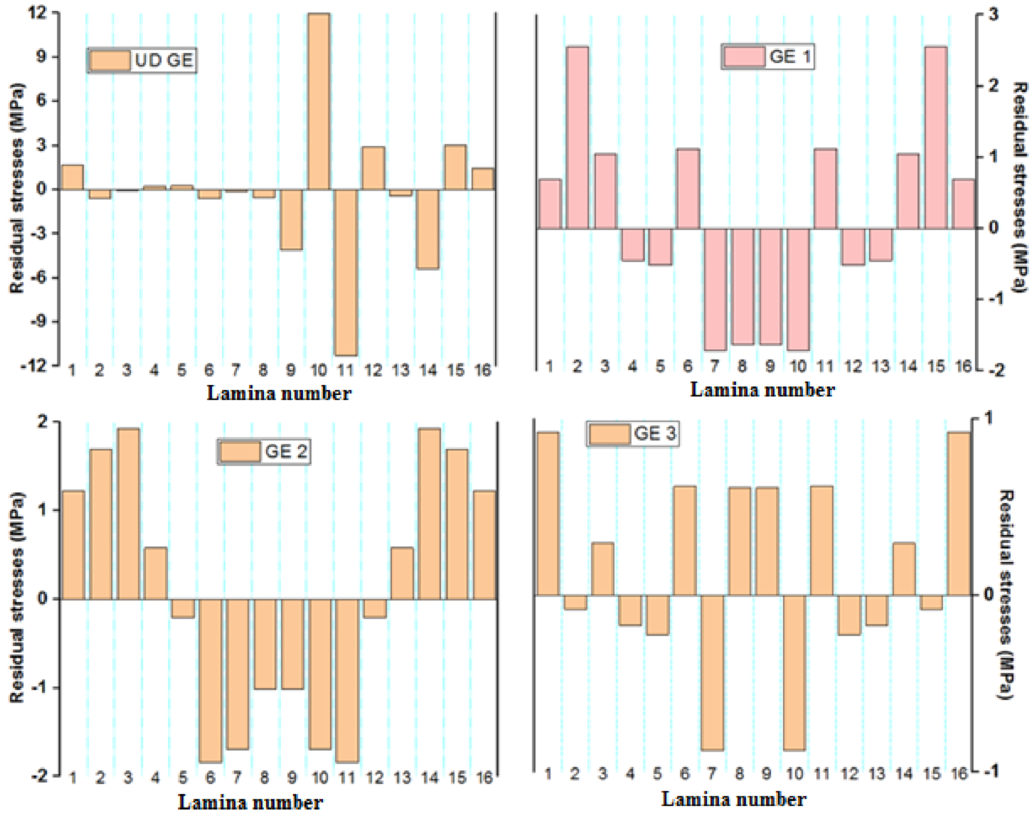


Fig. 7. Longitudinal residual stress in each lamina of GE laminates.

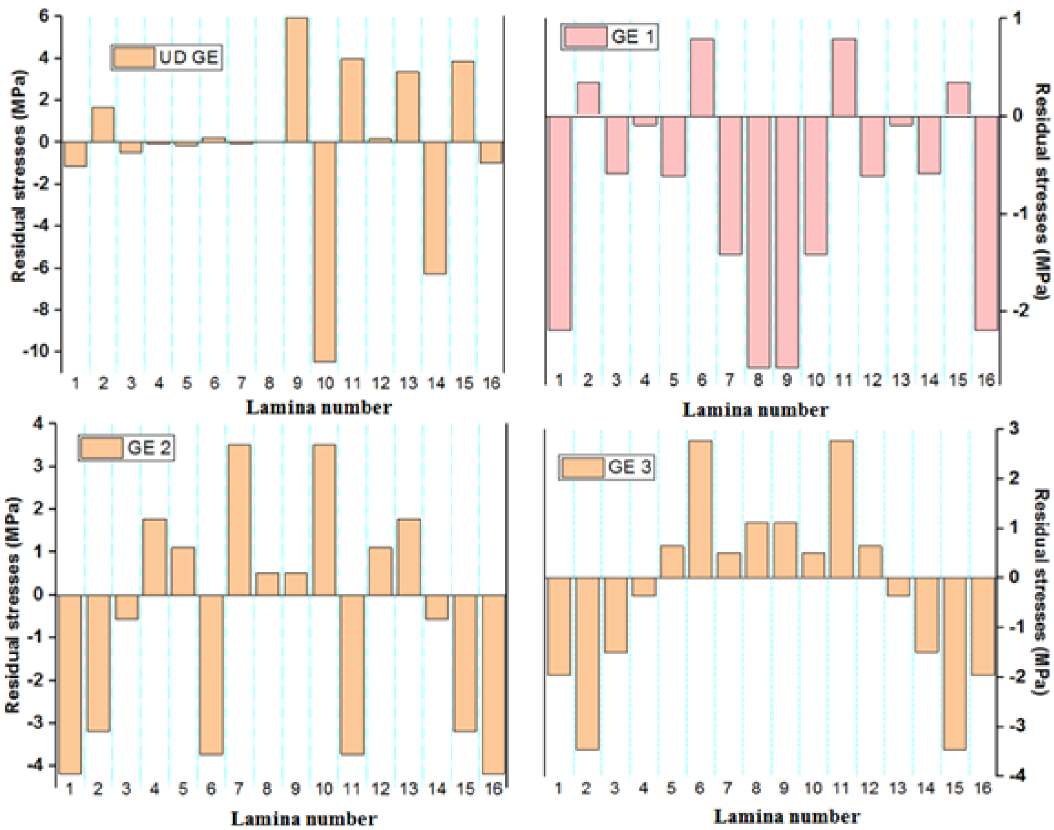


Fig. 8. Transverse residual stress in each ply of GE laminates.

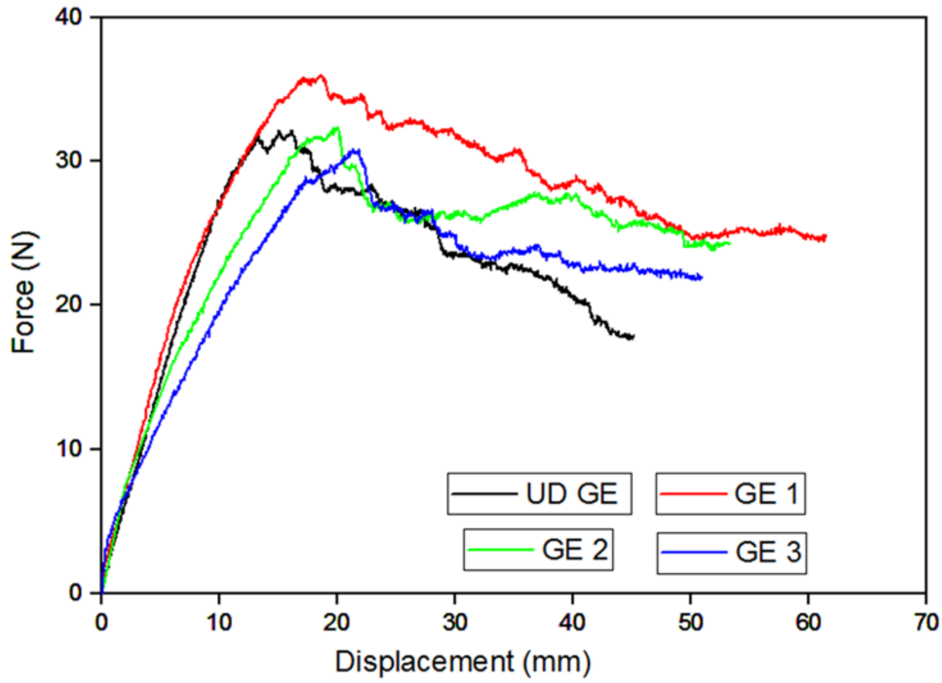


Fig. 9. Load-displacement plots of GE laminates

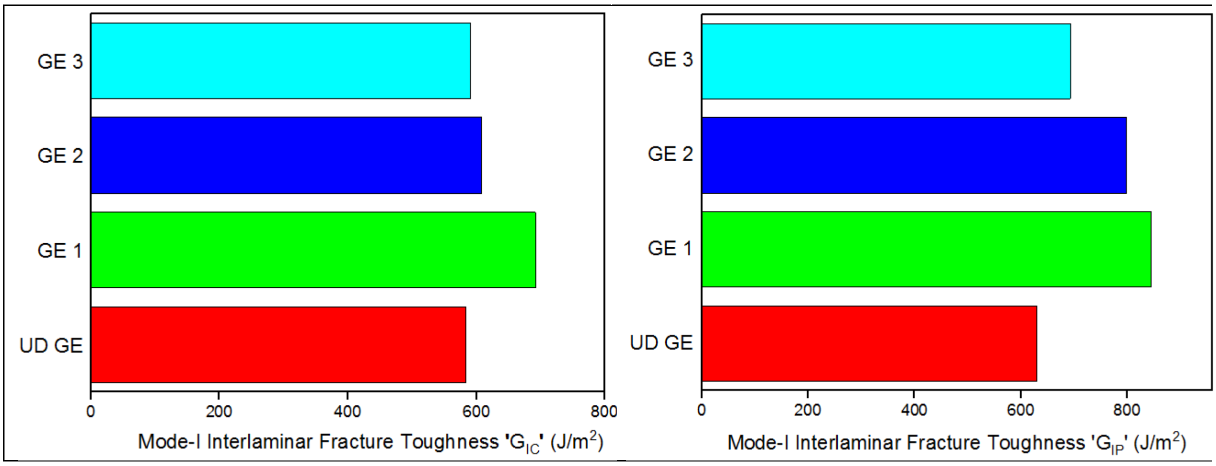


Fig. 10. Mode I interlaminar fracture toughness for initiation 'G_{IC}' (Left) and propagation 'G_{IP}' (Right) of GE laminates

3.3. Impact of residual stresses on G_{IC} and G_{IP} in GE composite laminates

From Table 4 and Fig. 10, it can be seen that G_{IC} for UD GE is 584.07 J/m^2 whereas for cross-ply laminates GE 1, GE 2, and GE 3 G_{IC} being 691.59 J/m^2, 608.39 J/m^2, and 590.36 J/m^2, respectively. Except for GE 1, the variation in GIC for GE 2 and GE 3 with respect to UD GE is around 1% and 4%, respectively. Residual stresses do not have much influence on the G_{IC} of GE laminates. G_{IP} of UD GE laminate being 630.42 J/m^2 and the induced residual stresses being -0.39 MPa. GIP of cross-ply laminates GE 1, GE 2, and GE 3 are 845.40 J/m^2, 798.02 J/m^2, and 692.31 J/m^2 with process-induced stresses being -14.00 MPa, -9.50 MPa, and -4.50, respectively. It can also be observed that as the compressive residual stresses in GE laminates increased, a gradual increase in G_{IP} can be noticed. The increase in the G_{IP} of GE laminates can be attributed to a gradual increase in compressive residual stresses in these laminates.

A surge in the residual stresses in GE laminates from -0.39 MPa to -14 MPa has resulted in an increase of G_{IP} by 34%. Compressive residual stresses have significantly contributed to energy release rate in the form of additional displacement of laminate arms as the crack propagates into the composite laminate.

4. CONCLUSIONS

The effect of residual stresses on mode I interlaminar fracture toughness of glass/epoxy composites was investigated. The GE laminates with remote ply orientation were manufactured with the delamination plane maintained at 0°//0°. The process-induced residual stresses in GE laminates were determined by the aid of the slitting method and the mode I interlaminar fracture toughness for initiation (G_{IC}) and propagation (G_{IP}) has been experimentally determined using DCB specimens. Following are the conclusions that were drawn from the present investigations:

- Load-displacement plots of cross-ply GE laminates do not show sudden load drops, indicating stable delamination with no 'Stick-Slip' and noticeable load drops were observed in UD GE laminate.
- Cross-ply composites exhibit larger displacement in DCB arms compared to UD GE laminates for the delamination of the same crack length.
- Transverse residual stresses in cross-ply laminates are higher than their corresponding longitudinal stresses whereas in UD GE longitudinal stress are larger than transverse stresses.
- Except for GE 1, the variation in G_{IC} for GE 2 and GE 3 in comparison with UD GE are around 1% and 4%, respectively. The residual stresses do not have much influence on the G_{IC} of GE laminates.
- An increase of residual stresses in GE laminates from -0.39 MPa to -14 MPa has resulted in an increase of GIP by 34%. The increase in G_{IP} of cross-ply GE laminates compared to UD GE can directly be related to a gradual increase in compressive residual stresses in these laminates.
- Compressive residual stresses have a significant contribution to energy release rate in the form of additional laminate arms displacement as the crack propagates.

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