Research Article

Influence of Kenaf and GO on interlaminar radial stresses in glass/epoxy L-bend laminates

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Abstract

Laminates of L-bends are inherently weak in the through thickness direction at the region of curvature. To address this behavior, experimental investigations have been made to find the influence of graphene oxide (GO) and Kenaf short fibres on interlaminar radial stress of a unidirectional glass epoxy L-bend composite laminate. Kenaf in the range of 5–10 wt% and GO in the range of 1–2 wt% were loaded at each ply at the curvature of a L-bend and their influence on curved beam strength (CBS) was investigated experimentally as per ASTM D6415. L-bend composite specimens with and without fillers were fabricated with the aid of hand lamination technique. Four point bending fixtures were designed and fabricated to hold the specimen firmly in the uniaxial tension machine. Tests were carried out as per ASTM D6415 and load displacement plots were carefully recorded. Experimental data revealed that the laminate loaded with Kenaf fibres at the curvature radius of L-bend had greater influence on CBS and interlaminar stresses than GO. Further, the delaminated surfaces of L-bend at the curvature region was carefully examined using scanning electron microscope to know the interfacial adhesion mechanism of Kenaf and GO with epoxy and glass fibre.

Keywords Interlaminar radial stress · Kenaf fibers · Graphene oxide · L-bend laminate

1 Introduction

Fibre reinforced polymer composites are the most preferred composites for high structural requirements and have found applications in aircraft, civil structures and also various domestic appliances. High strength, high stiffness, low weight and ease of manufacturing of complex geometry have propelled the usage of composites. Boeing Dreamliner 787 is made up of 50% composites by weight [1]. Composite joints are employed in aircraft structures to transmit loads between two orthogonal components. L bends are commonly used to design joints in the structures. Structural integrity and safety of the structure is greatly affected by the load bearing capability of the joints. Composite joints with complex geometries usually receive high interlaminar stresses which are concentrated around sharp corner radius in L-bend and around deltoid region in T-joints. Interlaminar delamination due to interlaminar stresses is a leading cause for failure of L-bend composites. So it is very crucial to determine the interlaminar radial stresses and investigate the complex failure mechanism of these L-bend composites. Ranz et al. [2] investigated the effect of thickness on interlaminar tensile strength (ILTS) of Carbon/epoxy curved beams using four point bend test. A decrease in ILTS has been observed with increase in thickness of curved beam. Also to improve ILTS, Carbon

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laminates with 4, 8 and 12 laminas are reinforced through the thickness by means of tufting of glass fibre 10 mm and 5 mm stitching densities. Laminates with 4 layers and tufted with glass fibre with 5 mm stitching density exhibited 40% increase in ILTS whereas 12 layers laminates showed a 12% improvement in ILTS. Hao et al. [3] experimentally investigated the effect of varying internal radii on CBS and interlaminar stresses using the digital speckle correlation method (DSCM) and a four-point-bending method. The laminates exhibited an enhancement of CBS and a decline in maximum radial stress with an increase in thickness and R/t (internal radius/thickness) ratio. Arca et al. [4] presented the effect of carbon nanotubes (CNTs) on CBS and maximum failure stress of curved Carbon fibre/epoxy composite using four point bending test. Addition of 3 wt% CNT resulted in 50% decline in CBS and maximum failure stress. Avalon et al. [5] studied the influence of bend radius, laminate thickness and addition of carbon nano fibre on CBS and failure mode of carbon/epoxy composite angle brackets experimentally and compared the results with three-dimensional finite element analysis models. The primary objective was to determine approximate critical normal stress values. The results revealed that critical radial stress values were found to be independent of the beam radius, thickness, and nano-scale additive.

Interlaminar delamination due to interlaminar stresses is a leading cause for failure of L and T shaped composite laminates. So it is very essential to minimize the interlaminar radial stresses and investigate the complex failure mechanism of these L-bend composites. Hence in the present investigations, L-bend laminates have been manufactured using unidirectional (UD) Glass fibre as the primary reinforcement and loaded with secondary reinforcements such as Kenaf short fibres and graphene oxide dispersed at the region of curvature with aid of hand lamination process and is investigated for their interlaminar radial stresses.

2 Materials and processing techniques

The reinforcement used for the present study is UD glass fibre which was supplied by Mark Tech Composites Pvt. Ltd, Bangalore. Epoxy (LAPOX L-12) and polyamine hardener (K-6) were supplied by Atul Ltd., Gujarat, India. Kenaf was processed at University of Agriculture Science, Dharwad, India and GO was synthesized at our laboratory using modified Hummers method [6].

2.1 Preparation of Kenaf and GO

Kenaf (Hibiscus sabdariffa) variety AS73, CD 560 was selected for the study. The fibre extraction was carried out at University of Agricultural Sciences, Dharwad. Mesta stalks harvested between 155 and 160 days of sowing were stacked vertically in the fields for 20 days, where stalks completely dried and the leaves dropped. The dried stalks were sprayed with 2% urea that is proven to aid in microbial growth and speed up the retting process. Bundles of stalks were then dipped in water tanks for retting. Retting is the process of loosening the gum that binds the fibre to the stem. Loosened fibres were beaten to remove all the vegetative matter and fibre extracted was washed thoroughly in clean water and dried under sunlight. Spraying urea reduced the retting time by 4 days [7]. Being a bast fibre the fibre exhibits an uneven diameter, and is coarser at the base and gradually finer towards the tip. However the fibres that are even were obtained from the middle portion (10 mm) of the fibres that were further chopped into 1 mm lengths and used for the dispersion on UD Glass fiber for the present study. Chopped Kenaf fibres were extracted from Kenaf tree using retting process which is shown in Fig. 1.

Graphene was synthesized from natural flake Graphite with Carbon purity more than 85% by the modified Hummer's method [6] with pre-oxidation treatment.

2.1.1 Construction of L-bend specimens

The basic tooling for the fabrication of L-bend composite consists of two inverted V-shaped steel profiles viz. top V-plate and bottom V-plate are shown in Fig. 2. These tool plates were made up of 3 mm thick stainless steel sheet and bottom plate was bolted on wooden flank as shown in Fig. 2. L-bend composite was prepared by hand lamination technique. Initially the releasing agent was applied on both bottom and top tool plates and allowed for drying about 10 min. Then a ply of UD glass fibre was properly positioned on bottom tool plate which was coated with epoxy resin followed by removal of air using roller. Stacking of plies was repeated with the same process till required thickness was achieved. Finally top tool plate was placed on the top ply with the application of additional dead weight on it. Composite was cured under room temperature for about 24 h. After curing, composite was taken out from the mould and finally cut into specimens of size 80 mm × 80 mm × 25 mm × 4 mm. The same process was repeated to obtain the L-bend with Kenaf and GO fillers. As per the Table 1, the amount (wt%) of fillers dispersed using draw down coating [8–10] over the curved region of each ply of L bend before they were placed into mould. L-bend composite laminate which is made up of 18 plies of glass fibre and its graphical representation of Kenaf dispersion on Glass fibres are shown in Fig. 3. For our convenience the laminates are coded according to their compositions and are enlisted in Table 1.

Fig. 1 Process of extracting Kenaf fibres

Fig. 2 Photographs showing bottom V-tool plate (left) and top V-tool plate (right**)**

Table 1 Laminate codes and their compositions

Laminate code	Epoxy (wt%)	Glass fibre (wt%)	Kenaf (wt%)	GO (wt%)
GE	50	50	–	–
GEK 1	50	45	5	–
GEK 2	50	42.5	7.5	–
GEK 3	50	40	10	–
GEGO 1	50	49	–	1
GEGO 2	50	48.5	–	1.5
GEGO 3	50	48	–	2

2.2 Four-point-bending fixture

The fabricated four-point-bending fixture for the present investigations to estimate the interlaminar stresses in L-bend composite is shown in Fig. 4. The fixture was fabricated as per ASTM D 6415 standard [11]. The circular cross section loading bars having diameter of 10 mm and the distance between the centers of the bottom support is 100 mm (l_b) and for the top fixture loading centers are adjustable as per requirement (l_t).

3 Experimental methods

3.1 Four point bending test

The test procedure given in ASTM D6415 [11] was used to determine curved beam strength (CBS) and interlaminar radial stresses of the L-bend composite specimen. An L shaped specimen with internal radius of 6.4 mm used for investigation is shown in Fig. 5.

CBS indicates the moment per unit width that needs to be applied to cause a delamination followed by a sudden drop in load applied. L-bend specimen was loaded in a four point bending fixture as shown in Fig. 4 and corresponding displacement of crosshead was measured and recorded. The loaded specimen was under

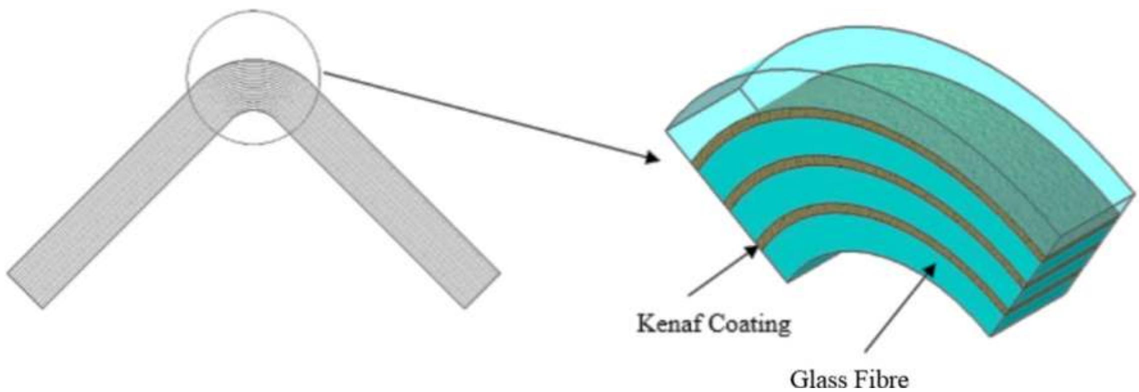

Fig. 3 Graphical representation showing Kenaf dispersion on UD glass fibers

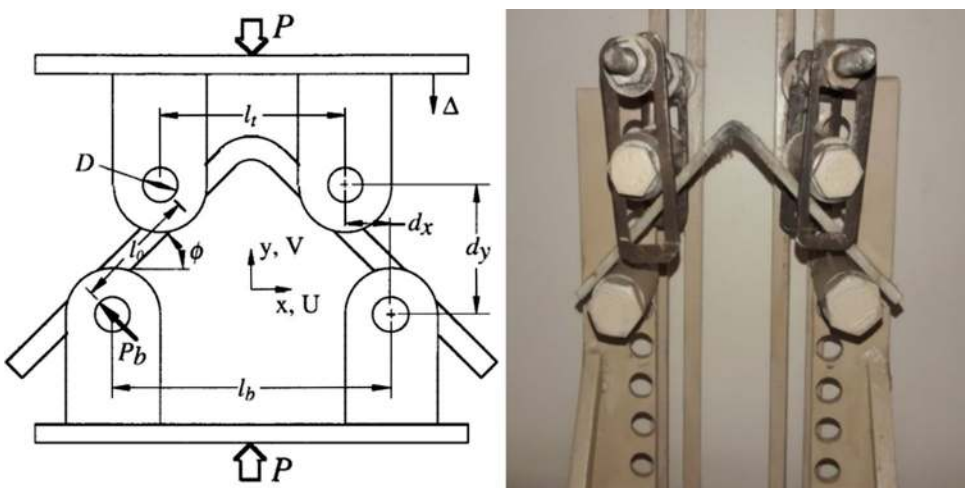

Fig. 4 Schematic representation of four point bending fixture (left) and Fabricated four point bending fixture as per ASTM (right)

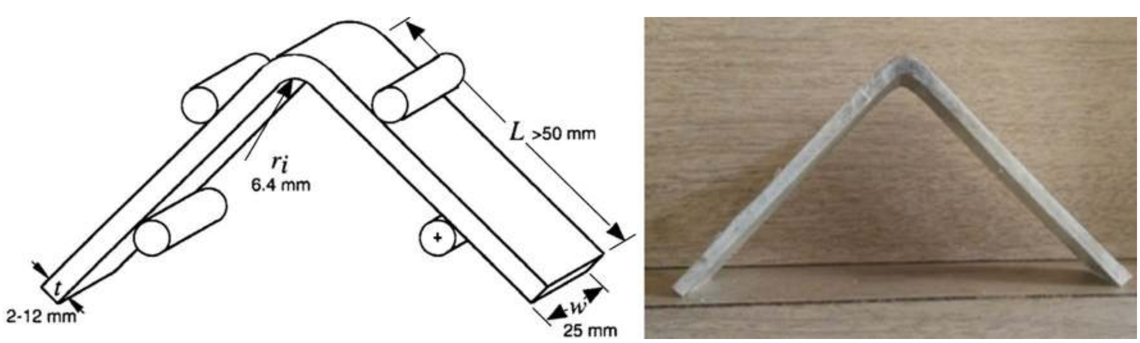

Fig. 5 Test specimen as per ASTM 6415 (left) and Fabricated test specimen (right)

constant bending moment throughout the curved portion of specimen. Tests had conducted using a servo-hydraulic UTM with crosshead rate of 5 mm/min.

CBS from total load at the first load drop (corresponding to the initial delamination) is given by Eq. 1.

$$CBS = \frac{M}{w} = \left(\frac{P}{2w\cos\emptyset}\right)\left(\left(\frac{d_x}{\cos\emptyset}\right) + (D+t)\tan\emptyset\right) \tag{1}$$

The interlaminar radial stress for a curved beam developed by Lekhnitskii [12] under pure bending is given by

$$\sigma_r = -\left(\frac{CBS}{r_0^2 g}\right)\left[1 - \frac{(1-\rho^{k+1})}{(1-\rho^{2k})}\left(\frac{r_m}{r_0}\right)^{k-1} - \frac{(1-\rho^{k-1})}{(1-\rho^{2k})}\rho^{k+1}\left(\frac{r_0}{r_m}\right)^{k+1}\right] \tag{2}$$

where,

$$\rho = \frac{r_i}{r_0} \tag{3}$$

$$k = \sqrt{\frac{E_\theta}{E_r}} \tag{4}$$

$$g = \frac{1-\rho^2}{2} - \frac{k}{k+1}\frac{\left(1-\rho^{k+1}\right)^2}{1-\rho^{2k}} + \frac{k\rho^2}{k-1}\frac{\left(1-\rho^{k-1}\right)^2}{1-\rho^{2k}} \tag{5}$$

$$r_m = \left[\frac{(1-\rho^{k-1})(k+1)\left(\rho r_o\right)^{k+1}}{(1-\rho^{k+1})(k-1)\left(r_o\right)^{-(k-1)}}\right]^{\frac{1}{2k}} \tag{6}$$

where M = applied moment, w = width of specimen, P = load, D = diameter of the cylindrical loading bars on the 4-point bending fixture, t = thickness of the specimen, d_x, d_y = horizontal and vertical distance between two adjacent top and bottom loading bar respectively, Ø = Angle from horizontal of the specimen legs in degrees, r_i, r_o = inner and outer radii of curved segment respectively, r_m = radial position of the maximum inter laminar (radial) tensile stress, k, ρ, g = Parameter used in strength calculations and σ_r = interlaminar radial stress in curved segment, E_θ = modulus in the radial direction, and E_r = modulus in tangential direction. The values of modulus in tangential direction E_θ and radial direction E_r for all the laminates were found using by conducting tensile test as per ASTM D3039. Results of tensile test have been provided as supplementary information 1.

3.2 SEM analysis

Delaminated fracture surfaces at the curvature region of the composite L bend laminates were analyzed using JEOL machine operated at 20 keV with the Microscope Control (SED) software. The laminates were coated with gold by a sputter coater machine, and then cut to a size of 10 mm × 10 mm in accordance with the vacuum chamber of scanning electron microscopy (SEM) and fixed on the special stand using double-sided adhesive tape.

4 Results and discussion

4.1 L-bend delamination test

Load versus displacement plots GE and GEK composite L-bend laminate samples obtained by four point bending test are shown in Fig. 6. It is evident that load displacement plots showing almost linear relationship until inception of the delamination followed by an initial sharp drop in the load applied. The GEK 2 and GEK 1 (7.5 wt% and 5 wt% of Kenaf) samples exhibit significant enhancement (79% and 55%) interlaminar radial stresses and CBS values as compared to GE samples. By increasing Kenaf with 10 wt% in GEK 3 gave lower interlaminar stresses but performing still better than GE samples. GEK 1 (5 wt%) and GEK 2 (7.5 wt%) laminates exhibit significant increase in CBS and interlaminar stresses with 101 MPa and 116 MPa respectively. Further, the loading of Kenaf to 10 wt% resulted in the decline of interlaminar stresses from 116 to 84 MPa but, still higher than the GE laminates.

Similarly the investigations were extended to know the influence of GO on interlaminar radial stresses and CBS

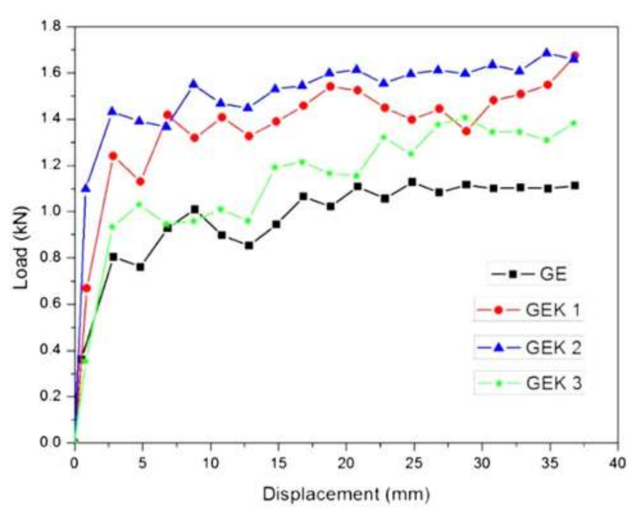

Fig. 6 Load–displacement plots for GE and GEK laminates

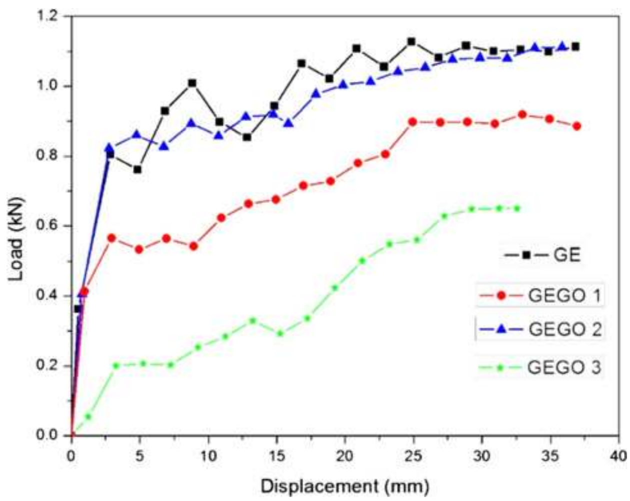

Fig. 7 Load versus displacement plots of GE and GEGO laminates

Table 2 Variation of CBS, interlaminar radial stresses and load at the first load drop (P) for all composite laminates

Laminate codes	Load at the first load drop (P) in N	CBS in (N mm/mm)	Interlaminar radial stress (σ_r) in MPa
GE	801	1388	65
GEK 1	1240	2149	101
GEK 2	1432	2482	116
GEK 3	1031	1787	84
GEGO 1	565	979	46
GEGO 2	860	1490	70
GEGO 3	206	357	17

values of L-bend laminates. Laminates supplemented with GO showing huge deviations in the results with respect GEK samples. GEGO 1 and GEGO 3 samples with 1 wt% GO and 2 wt% GO resulted in reduced interlaminar stresses from 46 MPa to 17 MPa respectively, whereas with 1.5 wt% GO in GEGO 2 samples gave an increased interlaminar stresses by 7% as compared to GE. However, GEK laminates shown in Fig. 6 showing better performance than GEGO and GE laminates (Fig. 7).

For the easy and better understanding of our test results obtained from the experimental investigations, details are listed in Table 2 and are also represented as bar graphs in Fig. 8.

4.2 SEM micro graphs

Figure 9a, shows the morphology of the delaminated composite fracture surface of the neat glass epoxy (GE) after the fracture test, which shows that the fibres are almost smooth, and the interactions between the fibre and matrix indicating fine bonding with little amount of shallow cusps formation along with the significant amount of loosely bonded fibres with matrix.

The introduction of Kenaf short fibres at the interface between epoxy and Glass fibres at the region of curvature of the L-bend fracture sample GEK shown in Fig. 9b indicating dispersion of Kenaf between epoxy and glass fibres is uniform, and the voids are minimal with significant amount of shallow cusps with good bonding, as this seen throughout the length of the fibre. This kind of morphology in our investigations gave better enhancement of interlaminar radial stresses with GEK laminates as compared to GE and GEGO L-bend laminates and corresponding results which are listed in

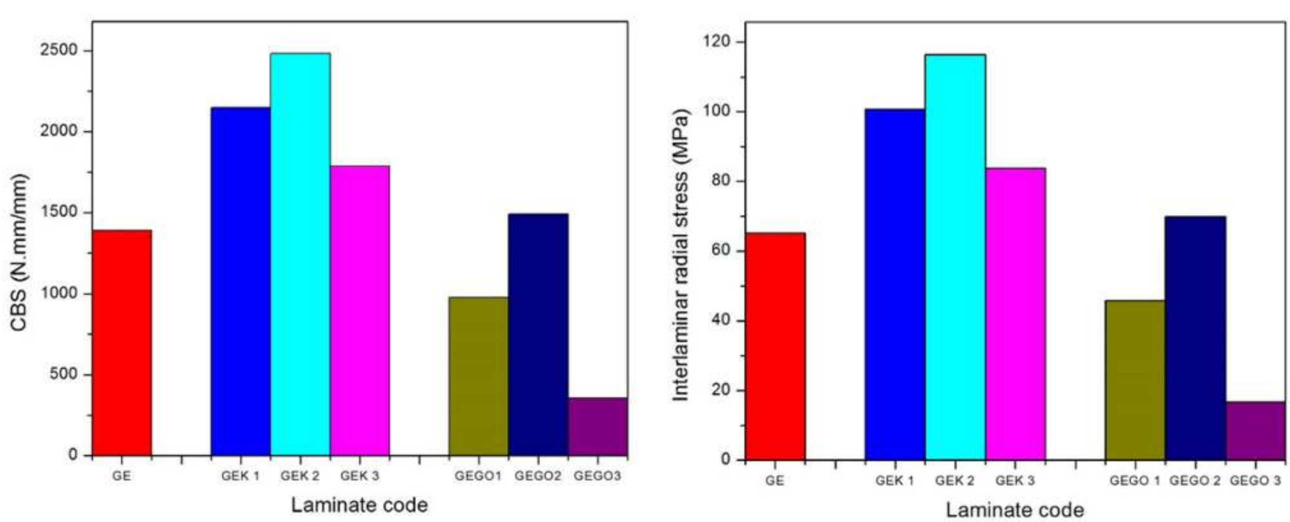

Fig. 8 CBS and interlaminar radial stresses for all composite laminates

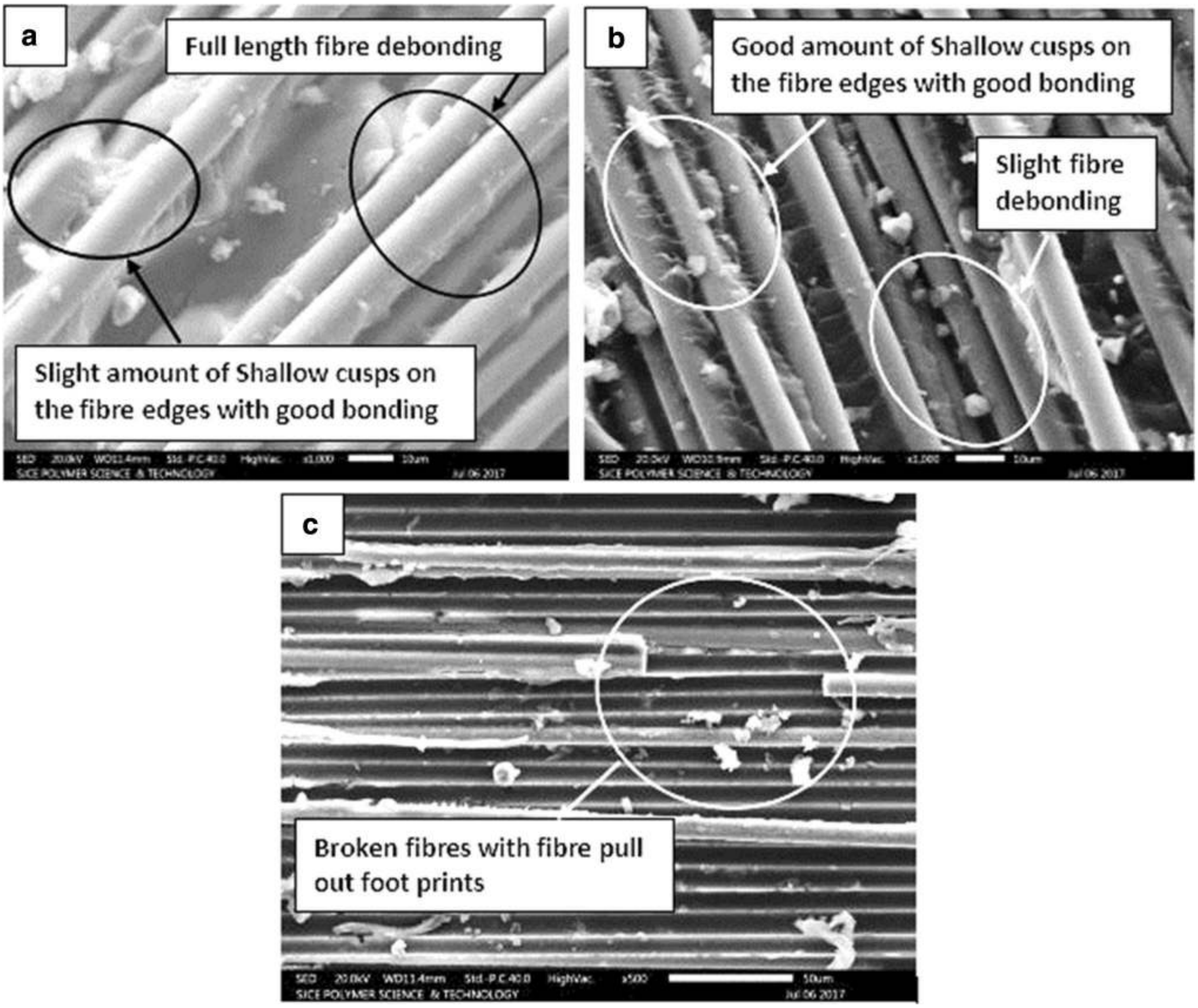

Fig. 9 SEM Images showing delaminated fracture surface at the curvature of L-bend laminate of **a** glass epoxy—GE, **b** glass-Kenaf epoxy—GEK and **c** glass-GO—GEGO samples

Table 2. Similarly, delaminated fracture surface of GEGO Laminates were investigated with SEM and shown in Fig. 9c, which indicates broken fibres with fibre pullout foot prints throughout the length of the fibres. Due to this the performance of GEGO laminates during fracture test gave reduced interlaminar radial stresses with respect to GEK laminates.

5 Conclusions

UD Glass epoxy loaded with Kenaf and GO, L-bend laminates were successfully manufactured using an inverted V shaped open mould hand lamination method. This method is very simple and economical, to produce L-bend composite laminates under the influence of the curing catalysts at room temperature.

Interlaminar radial stresses in L-bend pristine UD Glass epoxy laminate and its hybridization loaded with Kenaf and GO samples were determined and have exhibited a significant enhancement in interlaminar stresses with the value 116 MPa for GEK2 laminates as compared to GE laminates with 65 MPa. It was also observed that further increase in Kenaf to 10 wt% gave a reduced stress values with 84 MPa. Further, L bend laminates (GEGO1, 2 and 3) with GO loading yields decreased interlaminar stresses as compared GEK and GE laminates.

Finally it was concluded that addition of 7.5 wt% Kenaf to UD Glass epoxy was most beneficial and this yields improved interlaminar stresses in L Bend composite laminates.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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