

EFFECT OF FIBER ORIENTATION ON THE MECHANICAL BEHAVIOR OF E-GLASS FIBRE REINFORCED EPOXY COMPOSITE MATERIALS

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ABSTRACT

This paper deals with the study of the influence of the stacking sequence lay-up configuration on Tensile, Flexural, Compressive and Interlaminar shear properties (ILSS) of glass fiber reinforced epoxy composites. The following laminates were produced by Hand lay-up Technique with vacuum assistance for this study: $[0^{\circ}]_s$, $[90^{\circ}]_s$, $[0^{\circ}/90^{\circ}]_s$ and randomly oriented $[45^{\circ}/45^{\circ}]_s$. The composites, with similar overall fiber volume fraction ($V_f=56.7\%$), were evaluated based on four tests: Tensile, Flexural, Compressive and Interlaminar shear tests. Besides, all these specimens were tested as per ASTM standards in hydraulic servo material Testing machine was measured mechanical properties with an electronic extensometer. The experimental results show that a significant improvement of mechanical properties in the unidirectional at $[0^{\circ}]_s$ laminate presented tensile strength, Flexural strength, compressive strength and interlaminar shear strength almost thrice that of $[90^{\circ}]_s$. whereas the $[45^{\circ}/45^{\circ}]_s$ samples presented higher in-plane shear strength in short beam test used due to its random fiber orientation The shear modulus was higher for the composites $[0^{\circ}]_s$ as expected due to the longitudinally oriented fibers $[0^{\circ}]_s$. High-resolution Scanning Electron Microscope (HR-SEM) study was carried out to analyze the interfacial characteristics of E-glass/epoxy materials internal structure of the fractured surfaces, porosity, fiber damage, matrix crack, bonding/debonding of fiber/matrix and delamination layers of specimens

KEYWORDS: Laminates, Tensile Strength, Flexural Strength, Compressive Strength, ILSS, Failure Mode & HR-SEM

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1. INTRODUCTION

The development and fabrication of composite materials has been a wide domain of research and is well adaptable due to its excellent properties such as light in weight, stiffness, low density and exhibit better mechanical properties. These materials have found to be widely used in various domestic, industrial, defense and medical applications. Briancon. C et al [1] have prepared the unidirectional glass/epoxy composites and observed that when they are subjected to the transverse load, micro-grids are distorted resulting in the brittle failure of the matrix. Benzarti et al [2] Many researchers have studied the effect of glass fiber orientations on the epoxy-based composites. The critical appraisal of the research findings on the said composite as follows. The unidirectional glass fiber-reinforced polymer composites are found to be in industries to a less extent owing to their low stiffness and fatigue strength in the transverse direction. Kies JA [3] have suggested that when unidirectional E-glass fiber reinforced epoxy composites are subjected to the transverse tensile load, the brittleness of composite transverse plies occurs. This is attributed to the insufficient adhesive bonding at fiber/matrix interface and variations in the localized

stress/strain fields in the composite specimen. Cooper GA and Kelly [4] have suggested that the transverse strength of unidirectional E-glass fiber reinforced epoxy composites typically depends on the magnitude of load transferred at the fiber/matrix interface. Asp LE et al. [5] have observed that when unidirectional composite laminates are subjected to tri-axial stress, the brittle fracture of the laminates mainly occurs in the transverse direction. S. Suresh et. al [6] the use of thermosetting polymer-based composite materials are alarming in the current scenario instead of thermoplastic polymer. This is because the thermoplastic polymer possess high melt viscosity causing a major problem during fabrication of the composite. R. Matadi et. al [7] In recent years, there is a great industrial attraction towards epoxy resin amidst thermosetting polymeric resins due to it's remarkable mechanical, thermal, and chemical properties, low shrinkage upon curing, better processing under different working conditions, etc. S. K. Singh[8]. However, currently, glass fiber reinforced thermosetting polymer composites has gained a crucial research and market attention because of its low cost, ease of fabrication, low density, high strength to weight ratio and high heat distortion temperature, and emerging applications. Indicatively such applications include automobiles, defense, marine, power plants, etc. RameshTalRej et. al [9] These materials have replaced the traditional materials like metals, alloys and also natural fiber reinforced composites which are prone to fracture attributed to physic-chemical degradation and micro mechanical damage. Kawata et al. [10] studied a large range of composite materials under tension from 10^{-3} to 2000 s^{-1} strain rates. The materials included glass/polyester, glass/epoxy, and graphite/epoxy composites. They inferred that glass fiber-reinforced plastics have a higher impact absorption capacity than the other fiber-reinforced plastics. Thatiane Brocks et. al[11] have studied the effect of carbon fiber surface characteristics and interfacial adhesion difference on flexural properties of structural composites by using Dynamic analysis Technique. Farid Bajuri et. al [12] have prepared the hybrid kenaf/silica Nanoparticles in Epoxy Composite, silica nanoparticles were introduced as a filler material. Silica nanoparticles with 2% volume have to improve the flexural and compressive properties. Bhoopathia et. al [13] have fabricated the hybrid banana-hemp-glass fiberreinforced in epoxy resin and suggested that improve the mechanical properties such as tensile strength, flexural strength and impact strength. Pietro Russo. et. al [14] have fabricated the thermoplastic polyurethane (TPU) grade and reinforced by woven glass fibers at different fiber volume fractions are equal to 53%, 56% and 48% for plates involving 10, 16 and 22 laminae, respectively prepared by compression molding. Their results showed that the intermediate thickness laminates offer the highest performances, probably for their higher volumetric fraction of reinforcement. H. W. Wang et. al [15]have studied the effect of fiber orientation on Young's modulus for unidirectional E-glass fiber reinforced in epoxy resin. Their results showed that Young's modulus of the composites strongly depends on the fiber orientation angles from 00-900 and also the shear modulus is found to have a significant effect on the composites' Young's modulus, too. Chensong dong et. al [16] has studied the flexural and compressive properties of hybrid glass and carbon fiber reinforced epoxy composites. Their results more dominate failure in compressive than the flexural and also increasing the percentage of fibers then decreasing the flexural modulus. Mansour Rokbi et. al [17] has studied the effect of chemical treatments of fibers by alkalization with NaOH at 1, 5, and 10% for a period of 0, 24, and 48 h to 28 °C on flexural properties of natural fiber reinforced with epoxy matrix. Their experimental results showed that flexural properties of composites decreased after 5% of alkalization treatment with NaOH. P. Russo et. al [18] has studied the Flexural and impact response of woven glass fiber fabric/polypropylene composites. Their experimental results showed in bending tests have shown a clear improvement in the flexural strength for the compatibilized systems, in particular when a high viscosity/high crystallinity polypropylene was used. Thamer Alomayri [19] has the effects of microfiber contents on mechanical properties of fly ash-based geopolymer matrices containing glass microfibers at 0, 1, 2 and 3 mass%. The influence of glass microfibers on the

fracture toughness, compressive strength, Young's modulus and hardness of geopolymer composites are reported, as are the microstructural properties investigated using scanning electron microscopy. Mehdi Kalantari et. al [20] a multi-objective robust optimization (MORO) of carbon and glass fiber-reinforced hybrid composites under flexural loading based on an a posteriori approach has been presented in this paper. The hybrid composite comprised of T700S carbon/epoxy laminate at the tensile side and E glass/epoxy laminate at the compressive side. The conflicting objectives for optimization were to minimize the cost and weight of the composite subject to the constraint of a minimum specified flexural strength. Fiber angles and thicknesses of each lamina were considered as uncertain but bounded variables with the worst-case analyses being performed as a non-probabilistic method and the effect of uncertainties being determined.

In the present paper, E-glass fiber reinforced epoxy composites are synthesized respectively using a vacuum bagging technique. The epoxy is chosen as the polymer matrix amidst other matrices because of its good mechanical strength, chemical resistance and service temperature requirements. Then the synthesized composites are subjected to tensile, compressive, flexural and interlaminar shear strength (ILSS) characterization of fabricated different fiber orientations of (0°), (90°), (0°/90°) and 45°/45°E-glass/epoxy composite was carried out as per ASTM standards.

2. EXPERIMENTAL

2.1. Fiber materials

In this experiment, for fabricating the composites specimen with four different fiber orientations of E-Glass fibers are used. The raw E-glass fibers are collected in the form of woven type unidirectional (0°) glass fiber, Transverse directional glass fiber (90°) bidirectional glass fiber (0°/90°) and 45°/45° glass fiber purchased from Arun fabrics, Bangalore, India. The epoxy resin used in the present study was Araldite® LY 5052 with a curing agent Aradur® HY5052 supplied by M/s. Tirven industries Ltd., Hyderabad, India. The Glass-Fiber of unidirectional, Transverse directional bi-directional and 45°/45° glass fiber mat type with 200gsm is used for the fabrication of specimen. The physical properties of the E-glass fibers are presented in Table 1

Table 1

Sample	Number of Plies	Density (G/cm ³)	Fibre Volume (V _f %)	Tensile Strength(Mpa)	Flexural Strength(Mpa)	Compressive Strength(Mpa)
[0]s	10	2.54	56	2700-3500	4000-5000	4000-5000
[90]s	10	2.54	56	2700-3500	4000-5000	4000-5000
[0°/90°]s	14	2.62	57	3100-3800	4450-5250	4400-5300
[45°/45°]s	14	2.62	57	3100-3800	4450-5250	4400-5300

2.2. Fabrication of Composite Laminates

E-Glass fabric areal densities 200 GSM were used as reinforcement. Epoxy resin Araldite® LY5052 premixed and homogenized with hardener Aradur® LY 5052 in the ratio of 10:1 by volume was used as matrix materials and preparation of test specimen's unidirectional glass fibre (0°), directional glass fibre (90°) bidirectional woven fabric (0°/90°) and 45°/45° glass fabric-reinforced epoxy was studied in this paper. For the present investigation, layer sequences were considered as shown in Figure.1. Dedicated 10 layered unidirectional glass fabric laminate (0°), Transverse directional glass fabric laminate(90°), dedicated 14 layered bidirectional woven fabric laminate (0°/90°) and +45° fiber of glass/for the same 14 layered arrangements were fabricated.

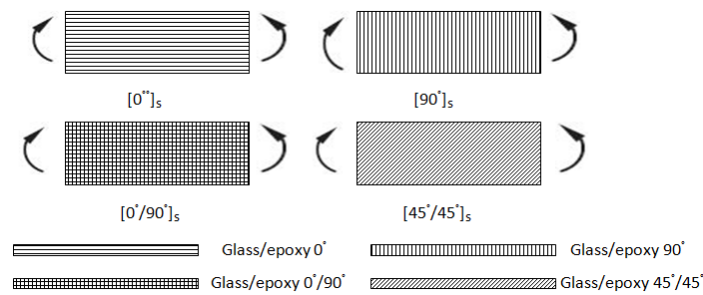


Figure 1: Stacking Configurations of Glass Fibre Plies

All, four different fiber orientation types of composite laminates considered for investigation were fabricated by vacuum bagging layup technique as shown in Figure.2. A uniform fiber weight fraction (W_f) of 56.7% was controlled for all three types of laminates in fabrication. This approximates to an overall fibre volume fraction (V_f) of 57%, considering the fiber density as 2.55 g/cc and the matrix density as 1.17 g/cc. Then the vacuum bagging is applied to the mold with a vacuum pressure of 2.525 MPa for uniform distribution of resin and also to remove the entrapped air. The composite is cured at room temperature and the post-curing was done at 80 °C for 4hours[21]. By using the diamond cutter or hex saw the specimens were cut from the plates and was polished with the help of the polishing machine. The fiber reinforced PMCs is mainly used due to easy availability of glass fibers and economic processing technique adopted for producing the fiber-reinforced PMCs.

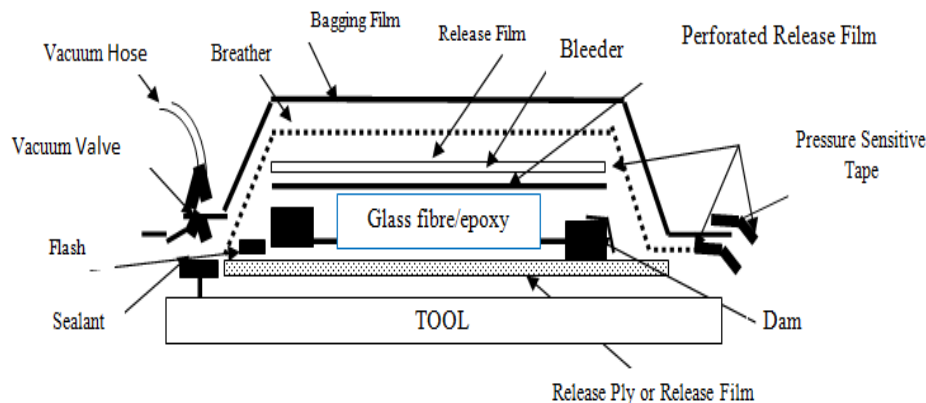


Figure 2: Schematic View of the Vacuum in Mould Curing Process

3. EXPERIMENTAL ANALYSIS

3. 1. Tensile Testing of the Composite

Tensile tests were conducted for the composite specimen using the electronic tensometer setup to obtain the tensile properties. The flat specimens of the composites were prepared according to the ASTM D 638[22] standards. The specimens were machined to a standard size of the specimen for unidirectional laminate(0°) is $250 \times 15 \times 3 \text{ mm}^3$, for transverse directional laminates(90°) is $175 \times 25 \times 3 \text{ mm}^3$, bidirectional woven fabric specimen size($0^\circ/90^\circ$) is $250 \times 25 \times 3 \text{ mm}^3$ and $45^\circ/45^\circ$ laminate specimen size is $250 \times 25 \times 3 \text{ mm}^3$ for a gauge length of 50 mm. For this testing, the load cell of 100KN was utilized in the tensometer with the same crosshead speed of 1.5 mm/min[6,7]. Five identical test specimens were used for each fiber orientation of glass/epoxy laminates testing and numbered in series as 0° , 90° , $0^\circ/90^\circ$, and $45^\circ/45^\circ$. Properties such as tensile strength, tensile (elastic) modulus, tensile load, and elongation at break of the composites were

measured from the experimentation. During tensile testing, the specimens were broken in between the gauge length of the specimen and the corresponding image was shown in Figure. 3.

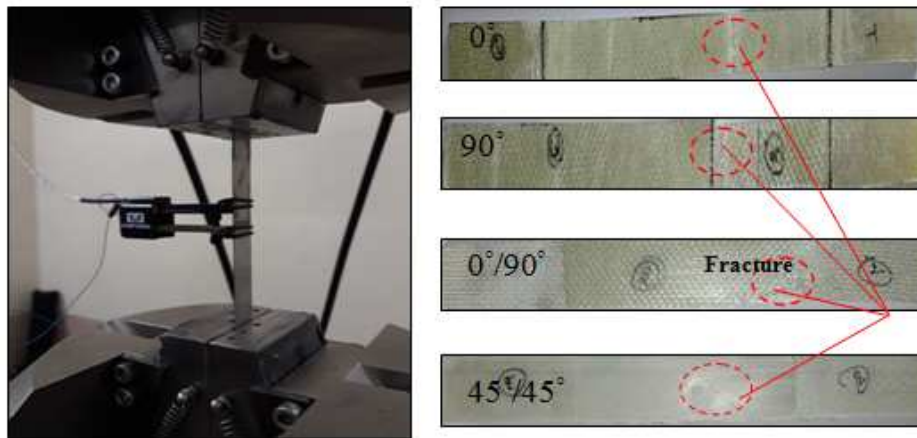


Figure 3: Tensile Tested Specimens

3. 2. Flexural Testing of the Composite

Three-point flexural testing were conducted according to the ASTM D 790 [22] standards using the spring mass - testing machine. The specimens were machined for the dimensions of 64 mm × 16 mm × 6 mm. The span to the depth ratio of the specimens was considered as 16:1. For this testing, the load cell of 100KN was utilized with the crosshead speed of 1.5 mm/min [7]. Five identical test specimens were prepared for each fiber orientation and numbered as 0°, 90°, 0°/90° and 45°/45° for each flexural testing. For a specimen in the three-point bending test, the flexural strength (σ_F), Flexural modulus (E_F) and strain to failure (ϵ_F) are calculated given by Ref. [11]

$$\sigma_F = \left(\frac{3WL}{2bt^2} \right) \left[1 + 6 \left(\frac{d}{L} \right)^2 - 4 \left(\frac{d}{L} \right) \left(\frac{t}{L} \right) \right] \quad (1)$$

$$E_F = mL^3/4bt^3 \quad (2)$$

$$\epsilon_F = \left(\frac{6dt}{L^2} \right) \quad (3)$$

where σ_F is the flexural stress, W is the applied load, L is the support span, b and t are the width and thickness of the sample, d is the displacement, m is the slope of the tangent to the initial straight-line portion of the load-deflection curve, d is the maximum deflection before failure, and ϵ_F is the strain at the centre of the specimen. Deflections of the specimen were measured using the digital dial gauge and the flexural properties like flexural strength, flexural modulus, flexural load and deflection at break of the composites were evaluated. As similar to the tensile testing, the five identical specimens were broken in between the gauge length and the corresponding image was shown in Figure. 4.



Figure 4: Flexural Tested Specimens

3.3. Compressive Testing of Composite

The specimens used for compression test had the same material as those of the flexural test except that these specimens were made of fourteen plies so that the total thickness is 3 mm. Compression specimens were cut in the longitudinal direction (0°) transverse direction (90°), bi-directional ($0^\circ/90^\circ$) and $45^\circ/45^\circ$ E-glass fiber reinforced epoxy composites, for longitudinal compression tests and a fixture is used for the tests according to ASTM D3410[23]. Woven glass/epoxy tabs were locally bonded on each side of the specimens to reduce the gripping effects. Also, a thin Teflon sheet, as a weakly bonded area, was inserted on each of the contacting surfaces between the specimens and the tabs to reduce the gripping effects in fiber compression specimens as shown in Figure 5.

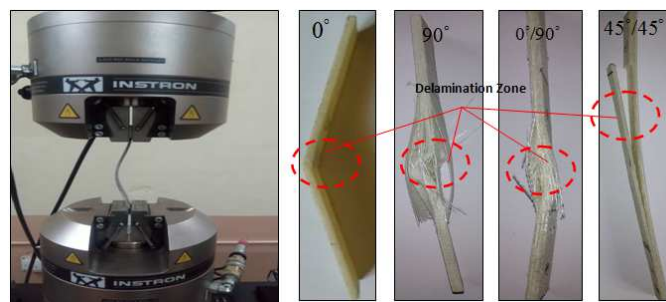


Figure 5: Compression Tested Specimens

3.4 Inter Lamina Shear Stress (ILSS)

To determine the interlaminar shear strength of the composites, short beam shear tests were performed following ASTM D2344[24]. A sliding roller three-point bending fixture, which included a loading pin (diameter 6.4 mm) and two support pins (diameter 3.2 mm), was used for the room temperature short beam shear tests. The test fixture was mounted in a 5-kN capacity, screw-driven load frame. A universal testing machine was used, with a cross-head speed of 1.5 mm/min[6,7], and at least five specimens were tested for each type of sequence layout/fiber orientations. The dimension of specimens was maintained as per ASTM standard for the three-point bend test. The length and width of the test specimens were 26.3mm and 6.4 mm, respectively. The apparent interlaminar shear strength of composites was determined from specimens that were tested with a support span/sample thickness ratio of 5:1. The simply supported specimens allow lateral motion and a line load is applied at the mid-span of the specimens. The apparent shear strength was then calculated as follows:

$$V = 0.75 \left(\frac{P_{\max}}{wt} \right)$$

where V is the apparent shear strength, P_{\max} is the failure load, w and t are the width and thickness of the specimen, respectively.

3. 5. Scanning Electron Microscope

The microstructural failures of the tensile, flexural compressive and ILSS fracture composite were studied and analyzed using the crosssection analyses method through the Scanning Electron Microscope (SEM) of model JEOL JSM-6390. The following specifications were used for scanning the image: (a) Resolution (300 μm (Acc V 20 kV, WD 9.4 mm, and SEI), (b) Magnification (500X (WD 48 mm or less) and (c) Electron gun (Accelerating voltage: 0.5–20 kV and Filament: Pre-Centered tungsten hairpin filament).

4. RESULTS AND DISCUSSIONS

4. 1. Effect of Fibre Orientations on Tensile Behavior of the Composite

Figure.6 shows the tensile stress-strain curves for the various fiber E-glass/epoxy composites with four different fiber orientations. The stress–strain curve for the cure epoxy resin is similar to the brittle materials [19,22]. The maximum ultimate tensile strength of 747.86 ± 10.1 MPa is obtained for $[0^\circ]_s$ fiber orientation length, in the present work as compared to other orientation of fibers i.e $[90^\circ]_s, [0^\circ/90^\circ]_s$ and $[45^\circ/45^\circ]_s$ when the percentage volume fraction is 56.7. The tensile strength is suddenly reduced to 747.86 - 81.84 MPa for various orientations of fibers when the percentage volume fraction is 56.7 as shown in Table 2. From the results, it is inferred that in the case of 0° oriented composite specimen, the external tensile load is equally distributed on all the fibers and transmitted along the fibers axis whereas, in other fiber orientations fibers ($90^\circ, 45^\circ/45^\circ$ and $0^\circ/90^\circ$) axis is not parallel to loading axis resulting in pulling-off of fibers which causes early failure load and also other three important factors considered such as (i) stress transfer between the fiber and the matrix is highly reduced due to the less matrix content in composite which is also the main reason for the reduction in tensile strength. (ii) stacking sequence (iii) the thickness and the interior and exterior disposition of 0° and 90° oriented layers in the laminate. A significant improvement obtained for maximum tensile strength the of the composite lies in between 0° and $0^\circ/90^\circ$ orientation of the fibers. respectively. It is absorbed that the tensile strength of the composite increases with the increase in fiber content. Hence a good load transfer is visible in between the fibers and the matrix. Further increase in the fiber thickness and volume fraction highly reduces the tensile strength and load transfers between the fibers and matrix which cannot be a significant one for any applications[25,26].

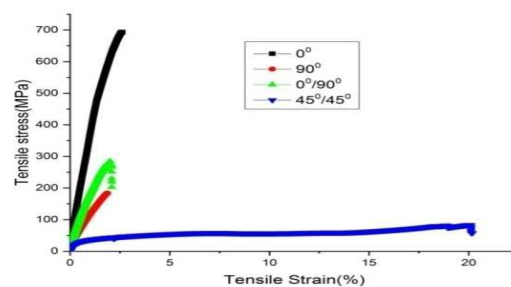


Figure 6: Tensile Stress-Strain curves for Different Fibre Orientations of E-Glass/Epoxy Composite

Table 2 shows the variation in the tensile modulus values over the constant volume fraction for the various orientation of fibers composites. For approximately constant 56.7% V_f , composites have a maximum tensile modulus of 14.23 ± 8.16 GPa when the fiber orientation is 0° and the minimum tensile modulus of 5.53 ± 3.42 GPa for 90° fiber orientation. Similarly, the tensile modulus value gradually decreases when increases the thickness of the laminate and beyond the 56.7 V_f . It is clearly visible that there is a marginal amount of change in tensile modulus value for any constant volume fraction when the fiber orientations altered.. This shows that the orientation of fibers has an influential effect in setting the tensile modulus value of any fiber composites[31].

Table 2: Average Static Tensile Properties of E-Glass/Epoxy Composite Laminates

Sample	Density g/cm ³	Fibre volume (V_f %)	Composite Thickness (mm)	Load at Break (KN)	Ultimate Tensile Strength (MPa)	Tensile Modulus (GPa)	Yield strength (MPa)
[0°] _s	2.54	56.3 ± 2.1	2.97	54.97 ± 5.31	747.86 ± 10.12	14.23 ± 8.16	483.27 ± 6.11
[90°] _s	2.54	56.4 ± 2.3	2.99	8.93 ± 2.33	187.67 ± 6.54	5.53 ± 3.42	91.85 ± 5.23
[$0^\circ/90^\circ$] _s	2.62	57.8 ± 2.3	2.98	14.89 ± 6.11	283.54 ± 8.32	7.17 ± 7.14	183.24 ± 8.01
[$45^\circ/45^\circ$]	2.62	57.6 ± 2.1	2.99	4.07 ± 1.34	81.84 ± 2.31	7.01 ± 2.11	33.79 ± 1.33

4. 2. Effect of Fibre Orientations on Flexural Behavior of the Composite

The flexural property is one of the important parameters in composites mainly useful to quantify in structural applications. Figure 7 shows the variations in the flexural strength (σ_f) values over the constant volume fraction for increase the angle of fiber orientations. It is observed that the flexural strength values are gradually increased up to 1.5% of flexural strain (ϵ_f). Beyond 1.5% of ϵ_f fiber in composite, the flexural strength is suddenly decreased. Then the decreasing curve suddenly changes and the flexural strength gets drastically reduced when volume of fiber (V_f) in composite is 56.7%. During the composite preparation, if the volume of the fiber (V_f) content is more than 56.7%, it leads to insufficient filling of matrix into the surrounding fibers and it is one of the main reason for the incomplete composite. At 56.7% Volume of the fibre (V_f), the orientation of 0° composite have the maximum flexural strength of 129.74 ± 12.2 MPa and it has a more significant change of strength when compared to the other fiber orientations is varied, because the composite specimens are subjected to both tensile and compressive stresses during bending. In addition, that in the three-point test configuration results shows the measurement of the maximum strength carried by at the outermost fibers of the beam specimens and also noted that the maximum flexural strength depends upon the fiber content and the fiber length in the composite, in the present case it lie in between 66 mm and 80 mm for 56.7% V_f . From the extensive experimentation, it is evident that the maximum flexural load is carried by the fiber orientation of 0° than other fibre orientations have load carrying in short fibers side only[27,28].

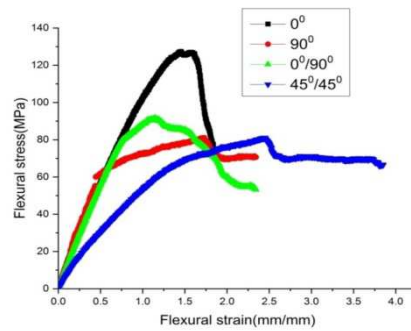


Figure 7: Flexural Stress-Strain Curves for Different Fibre Orientations of E-Glass/Epoxy Composite

Table 3 shows the variation in the flexural modulus values over the constants volume fractions of orienting glass fiber reinforced with epoxy composites. As with inprevious cases, the values of the flexural modulus decreases while - increasing the volume fraction. The minimum flexural modulus continues in to $[90^{\circ}]_s$ of the composite, which have the maximum flexural modulus of 9.62 ± 0.81 GPa when the fiber orientation is $[0^{\circ}]_s$. For aconstant volume fraction when the orientation of fiber content changes, the variations in the flexural modulus is clearly visible from the results.. The observation concludes that the maximum and minimum flexural modulus of the composite isobtained at 56.7% V_f for the fiber orientation of 0° and the 90° orientation had the next highest flexural strength values in $0^{\circ}/90^{\circ}$, and then followed by the $45^{\circ}/45^{\circ}$ fiber orientations respectively[16].

Table 3: Average Static Flexural Properties of E-Glass/Epoxy Composite Laminates

Sample	Density g/cm^3	Fibre Content (Vol %)	Composite Thickness (mm)	Max Flexural Load (kN)	Flexural Strength (MPa)	Flexural Modulus (GPa)
$[0^{\circ}]_s$	2.54	56.3 ± 2.1	6.01	0.84 ± 0.15	129.74 ± 12.2	9.62 ± 0.81
$[90^{\circ}]_s$	2.54	56.4 ± 2.3	6.02	0.27 ± 0.01	64.82 ± 2.65	4.71 ± 0.56
$[0^{\circ}/90^{\circ}]_s$	2.62	57.8 ± 2.2	6.02	0.43 ± 0.04	84.25 ± 8.12	8.43 ± 0.72
$[45^{\circ}/45^{\circ}]_s$	2.62	57.6 ± 2.1	6.03	0.36 ± 0.02	79.65 ± 4.02	6.02 ± 0.24

4. 3. Effect of Fibre Orientations on Compressive Behavior of the Composite

As shown in Figure 8. stress strain relations are slightly non-linear and final failure occurs catastrophically in all cases. The main specific property of unidirectional fiber orientation (0°) is maximum compressive stress-strain curve against other non-linear stress-strain curves of transverse direction(90°), bi-directional ($0^{\circ}/90^{\circ}$) and $45^{\circ}/45^{\circ}$ fiber directions. This may be due to the interface bonding between matrix and fibres. Imperfect fiber-matrix bonding is a manufacturing defect that is created during a curing process. This defect influences the role of the matrix that supports the fibers when the composite is under compression. From stress-strain curves, it seems that by increasing compression in unidirectional fiber orientation(0°), this bonding becomes greater and the role of matrix against microbuckling of fibres is more highlighted. As shown in the figure, significant nonlinear deformation was often observed before the maximum load, and this behavior was associated to the plastic deformation of the polymeric matrix[23,29].

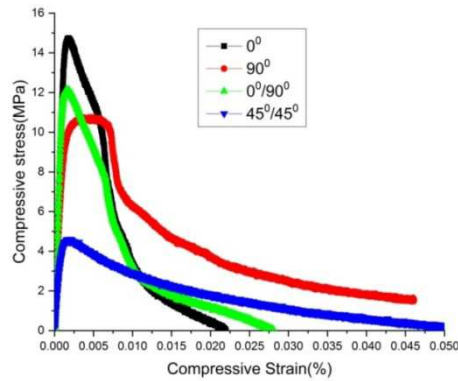


Figure 8: Compressive Stress-Strain Curves for Different Fibre Orientations of E-Glass/Epoxy Composite

Table 4. shows the variation of compressive modulus over the constants volume fractions of orienting glass fiber reinforced with epoxy composites. As like in previous cases, it is observed that the maximum compressive modulus of sample $[0^\circ]_s$ is the highest, $(15.27 \pm 0.41 \text{ GPa})$, followed by bi-directional woven e-glass fiber $[0^\circ/90^\circ]$, Transverse fiber orientation $[90^\circ]_s$, and $[45^\circ/45^\circ]_s$ epoxy composite respectively. Multiple factors can influence the compressive strength and modulus of composites. One factor might be the interfacial bonding between the fibers and epoxy matrix that facilitates load transfer. Fibre volume fraction and fiber orientation were determined as important factors in the mechanical properties of the composites. Increase the angle of fiber orientation has also a negative effect on the compressive modulus and strength of the composites [30].

Table 4: Average Static Compressive Properties of E-glass/epoxy composites

Sample	Density (g/cm ³)	Fibre Volume (%)	Composite Thickness (Mm)	Max Compressive Load (KN)	Compressive Strength (Mpa)	Compressive Modulus (Gpa)
$[0^\circ]_s$	2.54	56.3 ± 2.1	3.01	0.96 ± 0.05	14.65 ± 5.12	15.27 ± 0.41
$[90^\circ]_s$	2.54	56.3 ± 2.3	3.02	0.63 ± 0.03	10.32 ± 3.34	6.87 ± 0.32
$[0^\circ/90^\circ]_s$	2.62	57.8 ± 2.2	3.02	0.93 ± 0.04	12.45 ± 4.02	9.16 ± 0.71
$[45^\circ/45^\circ]_s$	2.62	57.6 ± 2.3	3.03	0.27 ± 0.07	4.64 ± 2.13	6.65 ± 0.23

4. 4. Effect of fibre Orientations on Interlaminar Shear Strength (ILSS) Behavior of the Composite

Figure 9 shows typical load Vs displacement curves obtained for short beam shear testing. The $[0^\circ]_s$ glass/epoxy specimen supported higher load than the other samples, which is a strong evidence of the effect of fiber alignment on this test. The $[0^\circ/90^\circ]_s$ glass/epoxy specimens produced similar maximum load and curve profile, and the abrupt drop noticed for the $[90^\circ]_s$ specimen may be an indication that bending and compressive loads are relatively less important in this case, and the lack of fibers along the 0° promotes sudden failure. Indeed, the $[0^\circ]_s$ laminate supported the highest load but did not display sudden failure. In short beam testing, the shear response is strongly dependent on fiber orientation and it decreases from 0° (test direction) to 90° (transversely to the loading), and not so with the fiber content [23].

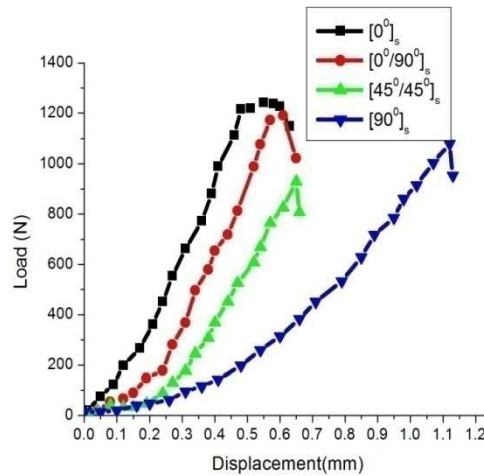


Figure 9: Typical load Vs Displacement Curves for Short Beam Shear Test Specimens

Table 5 shows the variation of short beam shear strength over the constants volume fractions of orienting glass fiber reinforced with epoxy composites. The $[0^\circ]_s$ orientation of composite presented the highest strength, around value of 15.62 ± 3.11 MPa, whereas the transverse orientation of the laminate $[90^\circ]_s$, bi-directional woven symmetrical laminate $[0^\circ/90^\circ]_s$ and the randomly oriented $[45^\circ/45^\circ]_s$ specimens presented similar strength. Considering the low deviation in the values, there is evidence of the orthotropy effect on shear strength. These results show the same trend observed by Selmy et al. [17], who reported that unidirectional glass/epoxy ($\%V_f = 35\%$) composites achieved higher (c. a. 50%) Short beam shear strength than randomly oriented specimens.

Table 5: Average Shear Strength Properties of E-Glass/Epoxy Composites

Sample	Density g/cm ³	Fibre Volume (V _f %)	Composite Thickness (mm)	Shear Load (KN)	Shear Strength (MPa)	Max Displacement (mm)	Shear Modulus (GPa)
$[0^\circ]_s$	2.54	56.3 ± 2.1	6.43	12.38 ± 2.31	15.62 ± 3.11	1.99 ± 0.06	7.97 ± 0.01
$[90^\circ]_s$	2.54	56.4 ± 2.3	6.41	10.75 ± 1.03	11.35 ± 1.64	3.03 ± 0.12	3.01 ± 0.13
$[0^\circ/90^\circ]_s$	2.62	57.8 ± 2.3	6.51	11.27 ± 2.11	14.88 ± 1.43	3.97 ± 0.04	6.94 ± 0.02
$[45^\circ/45^\circ]_s$	2.62	57.6 ± 2.1	6.59	9.25 ± 0.34	10.15 ± 1.21	2.41 ± 0.13	4.19 ± 0.04

5. SEM Micrograph Analysis of Tensile Fractured Specimens

Figure 10a–d shows the SEM micrographs of the composite fracture surface obtained from tensile tests at volume fraction $V_f = 56.7\%$. As can be seen in Figure. 10(a), shows Interfacial delamination of the interphase is found to be much lower than the other stacking sequence lay-up configuration. A significant improvement tensile strength values have confirmed that the adhesion between the fiber and matrix is good and the fiber pull-out is not so predominant. Strength at the interphase of the fiber and matrix is found to be higher due to the breakage of the individual fiber to the vicinity of the interphase at the loading region. Due to the strong interphase, glass/epoxy laminates have undergone individual fiber breakage appreciably. At this volume fraction, intra fiber delamination is not as frequent as the fiber breakage which is found to be dominant. Figure. 10(b) it was found that the surfaces of as-received fibers were smooth and clean and the fibers were pulled out from epoxy matrix. There is no evidence or traces of matrix resin adhering to the fiber. Indeed, the fiber surfaces seem to be clean and free from any adhering polymer. It is clear that the interfacial adhesion between the

fibers and the matrix is poor. This observation suggests an adhesive failure in the interface. Therefore, the fracture mode of the as-received fiber reinforced composite is at the interface of the fiber/matrix and the interface structure cannot transfer stress effectively. Figure 10(c). Fiber wetting at this volume fraction is higher when compared to the $[0^{\circ}]_s$ glass/epoxy composite and $[90^{\circ}]_s$ glass/epoxy composite which leads to the fiber breakage and also the intra fiber delamination. The effective stress transfer between the fiber and matrix is provided due to the higher stress values. Figure.10(d) it was found that surface of the fibers were roughness, fibers pull out and poor inter fiber delamination due to the tensile load axis was applied at an angle of randomly oriented $[45^{\circ}/45^{\circ}]_s$ glass/epoxy composite[28].

Altogether, the optimized strength values of $[0^{\circ}]_s$ glass/epoxy composite have very good interfacial properties, higher wetting, lesser fiber pull-out and poor intra fiber delamination as compared to the other stacking sequence lay-up configurations respectively

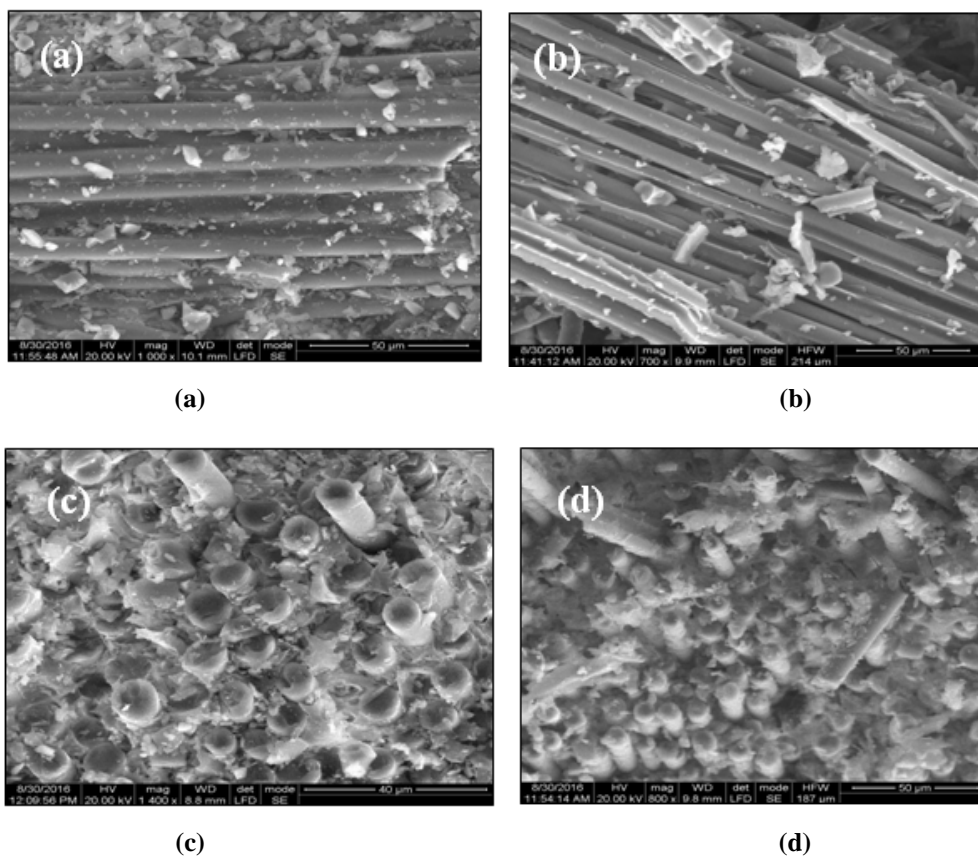


Figure 10: Representative SEM Images of the Breakage Region for
(a) As-Received $[0^{\circ}]_s$ Glass/Epoxy Composite
(b) $[90^{\circ}]_s$ Glass/Epoxy Composite
(c) $[00/90^{\circ}]_s$ Glass/Epoxy Composite
(d) $[45^{\circ}/45^{\circ}]_s$ Glass/Epoxy Composite that were
Tensile-Tested in Machine Direction

5. 1. SEM Micrograph Analysis of Flexural Fractured Specimens

Figure 11(a) shows that the fiber pull-out behavior of the $[0^{\circ}]_s$ glass/epoxy composite occurs rarely when compared to other stacking sequence configurations $[90^{\circ}]_s$, $[0^{\circ}/90^{\circ}]_s$ and $[45^{\circ}/45^{\circ}]_s$ glass/epoxy laminate respectively. This indicates that there is a good interaction between the fiber and matrix at the interphase. Traces of thin layer of resin are found to be coated over the fiber surface which shows the better adhesion between the fiber and the matrix. Less impurities

in the fiber surface, smooth fiber walls are the most probable reasons for the less variation in the mechanical properties. Stress transfer between the reinforcement and the fiber is appreciable which is also evident from the higher flexural strength and modulus values and less agglomeration of fiber in the composite. Fiber breakage occurs very frequently in both tensile and compressive region due to the less fiber pull-out and higher fiber accumulation leads to better adhesion at the interphase region. Figure 11(b) Due to the fiber pull-out at the interphase, holes are created because of the poor interfacial wetting. More fibers pull-out is observed in the compression region due to the higher stress concentration whereas, in the tensile region, it is found to be very less. Figure.11(c) shows that the SEM micrograph of flexural fractured 56.7% V_f specimen. Due to the flexural load, the interphase delamination is found minimum in the cross section of the composite. Due to the uniform compressive force applied during the manufacturing of the composite specimen, the presence of voids in the specimen is found to be very minimal. Fiber pull-out is very low evident in the micrograph, as the bonding between the fiber and the matrix is very strong. Figure 11(d) Crater like structures in the image is found in the micrograph of the specimen which is due to the curing of the matrix under the action of catalyst and accelerator. Due to the minimal fiber pull-out in the composite, the fiber breakage is high and the individual fiber delamination is also predominant due to the same reason[28,32]. Considering all the factors, that the optimized strength values for $[0]_s$ glass fiber/epoxy composites which have good interfacial properties, higher wetting, lesser fiber pull-out and poor intra fiber delamination.

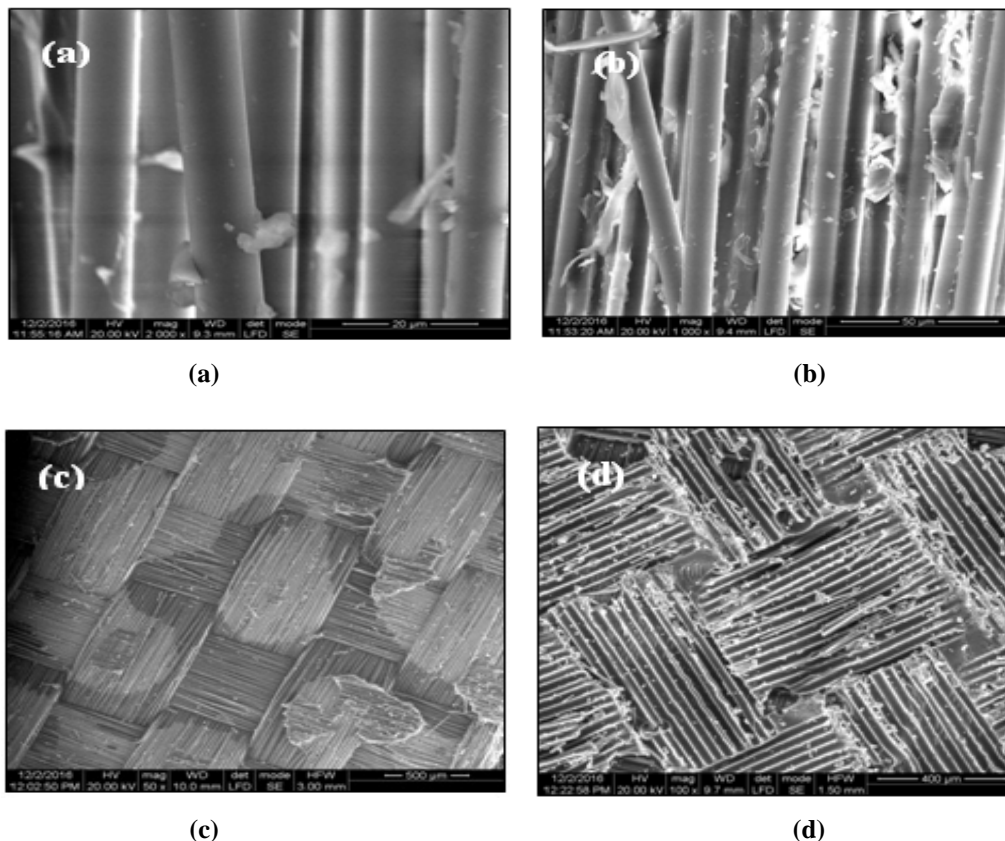


Figure 11: Representative SEM Images of the Breakage Region for
(a) as-Received $[0]_s$ Glass/Epoxy Composite
(b) $[90]_s$ Glass/Epoxy Composite
(c) $[0^\circ/90]_s$ Glass/Epoxy Composite
(d) $[45^\circ/45]_s$ Glass/Epoxy Composite that were
Flexural-Tested in Machine Direction

5. 2. SEM micrograph analysis of compression fractured specimens

To understand the reinforcement mechanisms of various stacking sequence configuration of glass fiber reinforced epoxy composites, the fracture surfaces of compression testing specimens were examined by SEM. Representative fracture surfaces of those composites with $[0^\circ]_s$, $[90^\circ]_s$, $[0^\circ/90^\circ]_s$ and $[45^\circ/45^\circ]_s$ glass /epoxy composites, are shown in Figure. 12(a)–(d). Figure. 12(a) shows the traces of thin layer of resin are found to be coated over the fiber surface which shows the better adhesion between the fiber and the matrix, fibers were smooth and clean, which indicates an accounts for the relatively high amount of energy required to fracture the specimen. Figure. 12(b) it was found that the surfaces of as-received fibers were smooth and clean and the fibers were pulled out from epoxy matrix. In contrast to the, the fracture surfaces of the $[90^\circ]_s$ glass/epoxy composites reveal from different morphologies, these include crack bridging, fiber pullout and fiber fracture, and matrix fracture. Figure. 12(c) clearly indicates that the glass fibers are well embedded into the epoxy resin, which appears to surround and adhere to the fibers. Evident in the matrix near the glass fiber is a large gap, suggesting the occurrence of fiber–matrix debonding which causes losses in strength. Figure 12 (d) shows that glass fibres are perfectly bonded to the epoxy matrix suggest that the presence of fibres may deflect the matrix crack at the interface between fibre and matrix, and thus reduced the crack's growth rate. Additionally, glass fibers could be fractured or pulled from the epoxy matrix when the load is applied[33,34]. Finally, evidence suggests that improvement of mechanical properties mainly depends on the interfacial adhesion is superior in epoxy matrix composites with $[0^\circ]_s$ and $[0^\circ/90^\circ]_s$ stacking sequence of glass fibre content, as opposed to those with $[90^\circ]_s$ and $[45^\circ/45^\circ]_s$ stacking sequence of glass fibre content.

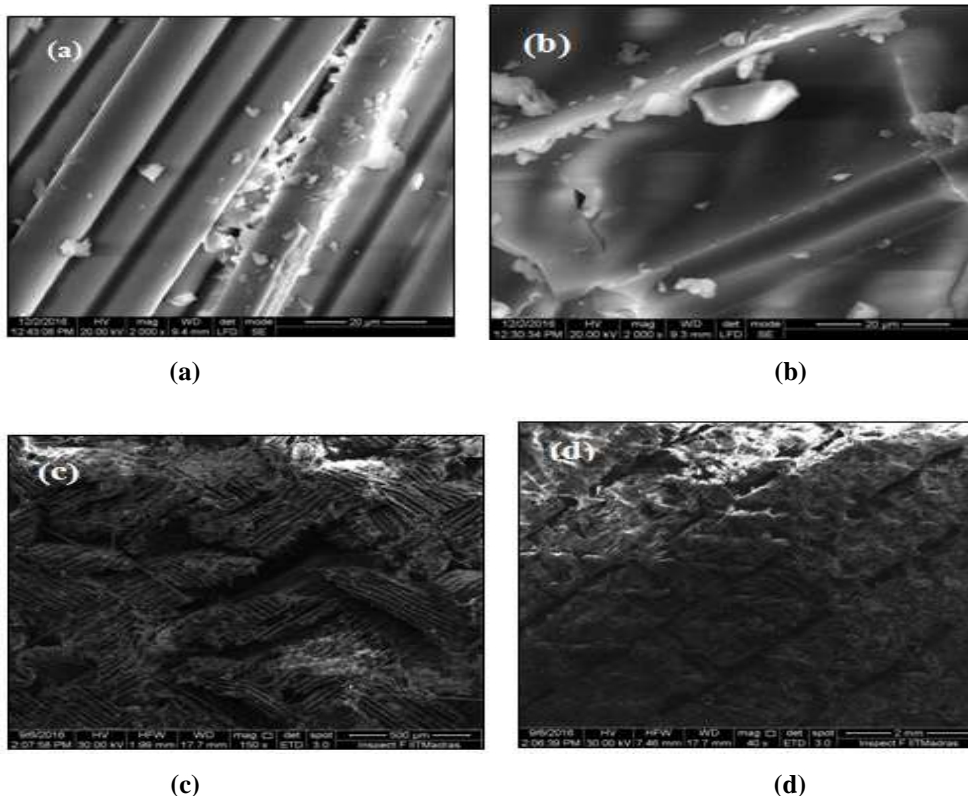


Figure 12: Representative SEM Images of the Breakage Region for
 (a) as-Received $[0^\circ]_s$ Glass/Epoxy Composite
 (b) $[90^\circ]_s$ Glass /Epoxy Composite
 (c) $[0^\circ/90^\circ]_s$ Glass/ Epoxy Composite
 (d) $[45^\circ/45^\circ]_s$ Glass/ Epoxy Composite that were
 Compression-Tested in Machine Direction

CONCLUSIONS

The outcomes of the present work are the effect of glass fiber orientations on the mechanical properties of composites. The effect of glass/epoxy samples (0° , 90° , $0^\circ/90^\circ$ and $45^\circ/45^\circ$) was investigated along with the tensile, flexural, compressive and ILSS performance of the prepared composites. The following conclusions are made based on the extensive experimental study:

- The tensile strength and tensile modulus of the unidirectional glass fiber/epoxy $[0^\circ]_s$ is higher and compared to the other orientation of fibers $[90^\circ]_s$, $[0^\circ/90^\circ]_s$ and $[45^\circ/45^\circ]_s$. The density of the unidirectional glass fiber is very less compared to all other fibers.
- The tensile and flexural properties of with the various orientation of glass fiber epoxy composite are significantly improved the at same fiber volume fraction and for $[0^\circ]_s$, $[90^\circ]_s$, $[0^\circ/90^\circ]_s$ and $[45^\circ/45^\circ]_s$. It is found that the increase in the fiber volume fraction increases the tensile strengths and tensile modulus. The maximum tensile strength and modulus of the fiber $[0^\circ]_s$ glass/epoxy composite is achieved at 56.7% V_f for the unidirectional fiber. In general, the stacking sequence of fibers $[0^\circ]_s$ and $[90^\circ]_s$ were inserted as exterior as well as interior on top and bottom of the layers sequences have higher strength and higher fiber ends which are accumulated in the composite.
- The maximum and minimum flexural strength and modulus of with the various orientation of glass fiber epoxy composite are achieved at same volume fraction 56.7% V_f for unidirectional glass fiber $[0^\circ]_s$ and randomly oriented glass fiber $[45^\circ/45^\circ]_s$ epoxy composites and compared to other orientation of fibers. But the values have significant improvement in unidirectional glass fiber $[0^\circ]_s$.
- The compressive strength of the $[0^\circ]_s$ laminate samples is about 9% higher than that for the $[0^\circ/90^\circ]_s$ fabric - composite, a result of waviness in the bi-directional woven e-glass fiber/epoxy $[0^\circ/90^\circ]_s$. Compression failure modes for the variety of fiber arrangements are different. The experimentally observed shear failure of fiber across the specimen thickness was the failure mechanism of laminate composites. Delamination zone, followed by microbuckling and global buckling is the failure observed in bi-directional woven glass fiber $[0^\circ/90^\circ]_s$ and randomly oriented glass fiber $[45^\circ/45^\circ]_s$ composites.
- The $[0^\circ]_s$ glass epoxy/ composite presented higher interlaminar shear strength (ILSS) and the opposite was observed for the $[90^\circ]_s$ glass-epoxy composite, for short beam test. Short beam test is easier, more practical and cheaper, but experience undesired features during testing, like the influence of compressive loading, crushing and a shear stress in the specimen, easily observed by the delaminated gage area.
- The SEM micrograph of tensile, flexural, compressive and ILSS tested specimens predicts the fiber failure, matrix crack and fibers pull out, bonding/debonding of fiber/matrix during the loading condition at 56.7% V_f of the composite. At higher strength, the volume fraction composite has less fiber pull out due to the more accumulation of fiber being wetted in the matrix and also it transfers higher load.

Overall, it can be concluded that the at the same volume fraction of the various sequence lay-up configuration of, $[0^\circ]_s$ glass fibers/epoxy composite have the maximum mechanical properties. While manufacturing the composite specimens, the fiber stacking sequence plays an important role to enhance the mechanical properties. The glass fibers can be easily available within less cost and the composites can be made by the simply manual method.

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