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ORIGINAL PAPER

Determination of Strength Parameters of Glass Fibers Reinforced Composites for Engineering Applications

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Abstract

The manufacturing of the composite material has been developed tremendously over the years due to its superior properties like low density, stiffness, lightweight and excellent mechanical as well as physical properties. These exceptional properties of composite materials have found its applications widely in aerospace, automotive, marine and many more engineering areas. The synthesis of the varieties of composites is continuously lookout without compromising its mechanical and physical properties. This paper deals in with synthesis as well as mechanical properties (Tensile Strength, Flexural Properties and Fatigue) of Glass-Epoxy as well as Glass-Vinyl Ester composites. The resins used in combination of composites were epoxy as well as Vinyl Ester while the reinforced material was glass fibers. The ultimate tensile strength in Glass-Epoxy composite was observed from 330 to 370 MPa while it was 270 to 330 MPa for Glass-Vinyl Ester Composites. Glass-Epoxy composites showed a 32% increase in flexural strength due to post-curing strength while it was 16% in case of Glass-Vinyl Ester Composites. The results of the fatigue analysis of composites indicate faster growth of cracks and defects at higher frequencies which results in a rapid drop in stress levels in the test specimen. The statistical analysis was carried out to establish mutual correlation among mechanical as well as physical properties.

Keywords Fiber reinforced composites · Glass-epoxy · Glass-vinyl Ester · Mechanical properties · Statistical analysis

1 Introduction

The application of glass fiber reinforced epoxy composites are rapidly increasing in different fields of engineering including aerospace, marine, automobile, etc. But the development of new composite materials with desired mechanical properties is still the real challenge. The selection of the matrix as well as reinforcing material plays a leading role in the development of composite materials with specific applications. The mechanical, as well as the thermal properties of constituent elements of the composite, govern the long-term performance capabilities [1]. Glass fibers are readily used to develop the fiber-reinforced composite, because of their impact as toughness, medium modulus, high tensile strength, and thermal stability [2, 3]. Several studies have been carried out to determine strength parameters of glass fibers reinforced composite material to achieve the desired mechanical properties [1, 4–8]. An Experimental investigation was carried out to determine the tensile strength of glass fiber reinforcement nylon (PA6) composite at variable weight percentage from 80 to 95% nylon and 5 to 20% glass fibers. The tensile strength of 80% nylon +20% glass fiber composite showed the highest elastic modulus and yield strength as compared to pure nylon. The experimental report revealed that the weight percentage of glass fibers influenced much more in the determination of mechanical properties [9]. Increased tensile and flexural strength from 10 to 25% was reported with the incorporation of 20% (*w*/w) glass fibers in short bamboo–glass fiber reinforced polypropylene hybrid composites

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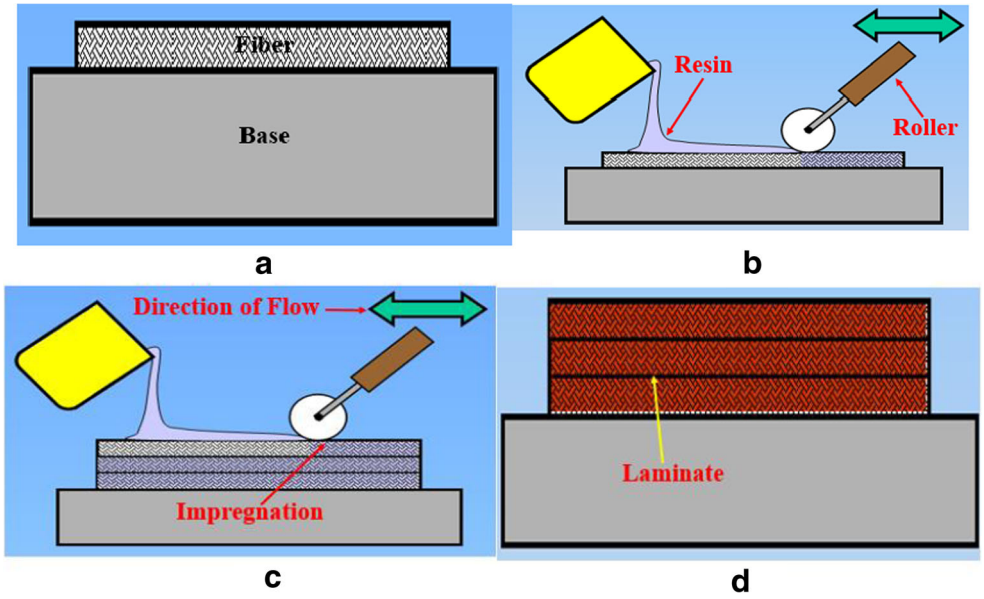

Fig. 1 Hand layup process (**a**) Placing of Fibers on the mold surface (**b**) Resin impregnation of the Fibers with rollers (**c**) Additional layer of Fiber and Resin (Lay-up of layers) (**d**) Room temperature curing of laminates

(BGRP). The inclusion of glass fibers increases the load carrying capacity of the composite, and hence the tensile, as well as flexural strength, increased [10]. The study showed an increase in tensile and flexural properties of glass fiber reinforced epoxy composites along the direction of fiber orientation [11]. The observation on the mechanical behavior of glass fiber reinforced hybrid composites found the significant improvement in tensile properties with the increasing of glass fiber content [12]. Experimentation was carried out on sisal fiber reinforced fibers and observed improved mechanical properties such as low density and high specific strength [13]. The thermal properties of the fiber reinforced composite is another significant parameter to determine the stability of composites at working conditions. The thermal stability of any composites is primarily governed by the matrix functionality and cure temperature. Experimental investigation was carried out with unidirectional glass fiber reinforced polymer (GFRP) at four initial strain rates (25, 50, 100 and 200 s-1) and six temperatures (−25, 0, 25, 50, 75 and 1000C) and observed the increase in tensile strength and toughness by 88.0% and 474.3% from 919 ± 102 MPa and 7.0 ± 1.1 MPa to 1729 ± 67 MPa and 40.2 ± 4.5 MPa respectively. The increase in tensile strength was justified as the friction between adjacent fibers always plays a vital role due to random and misaligned breakage of filaments in the yarn under tension, and the contact force among adjacent filaments increases with increasing strain rate, resulting in the increase of dynamic frictional force (friction coefficient is assumed to be constant) [14]. The increase in tensile strength from 28.25 to 78.83 MPa with the maximum tensile strength being for the composite with 60 wt.% glass

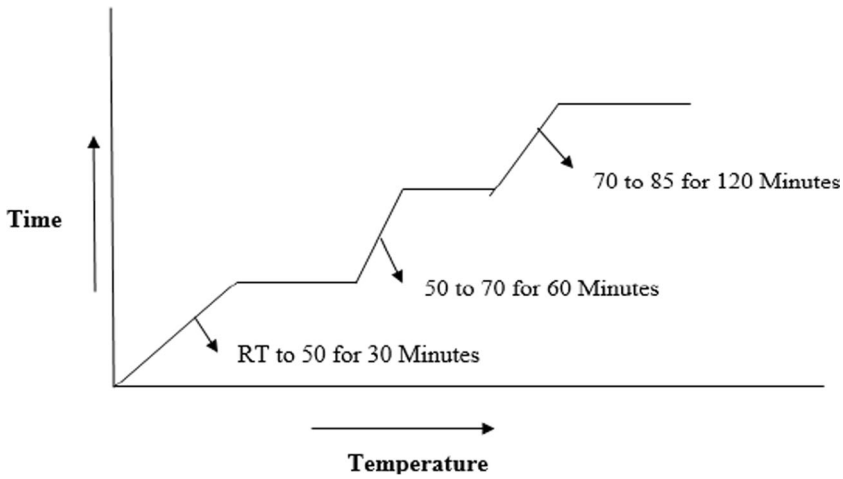

Fig. 2 Post curing schedules for Glass/Epoxy and Vinyl Ester PMC laminates

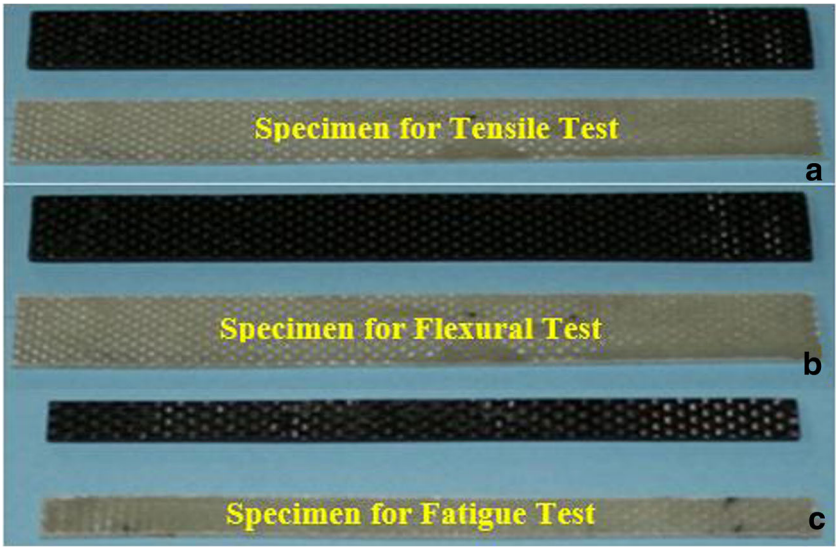

Fig. 3 Standard test specimens of polymer composite (**a**) Sample for tensile test (**b**) Sample for flexural test (**c**) Sample for fatigue test

fiber percentage were observed in the experimental investigation of Glass fiber reinforced polyester composites. It was concluded that the tensile strength of the fabricated composite depends to a large extent on the interfacial bonding strength between the matrix reinforcement and also on the inherent properties of the composite ingredients

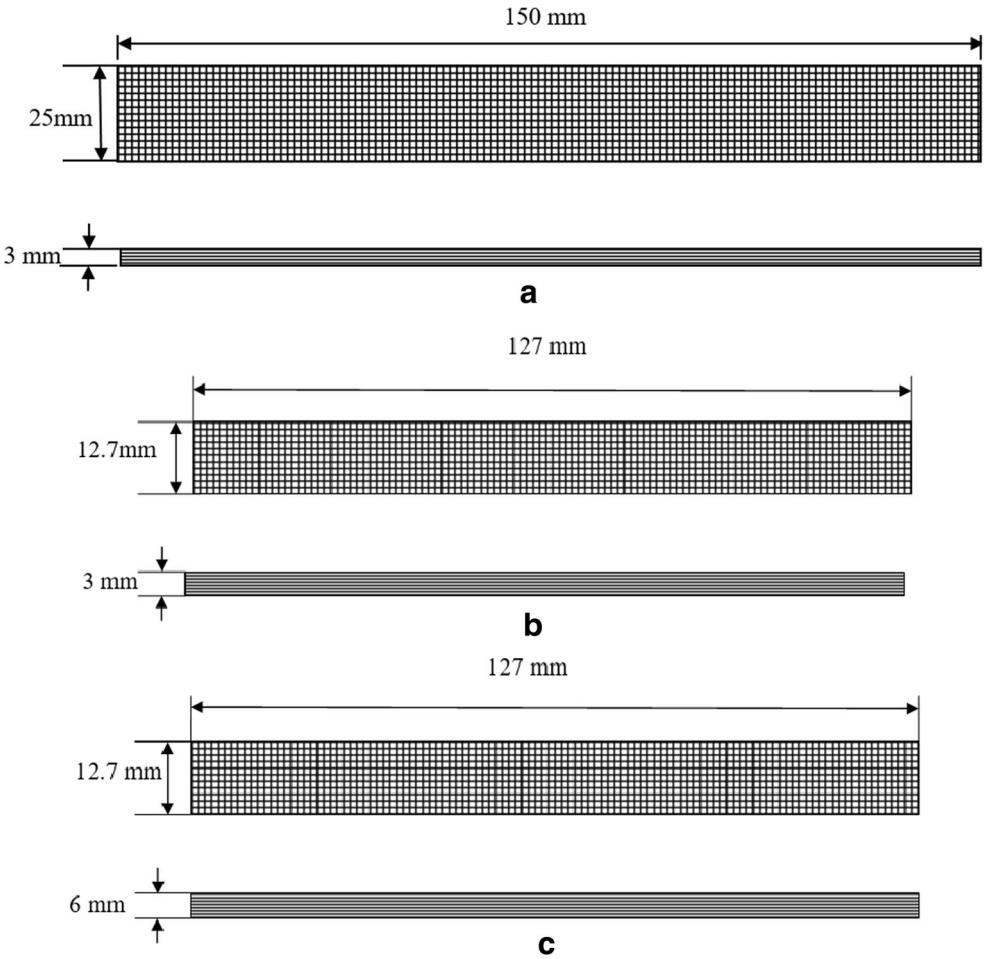

Fig. 4 Dimensions of standard test specimens (**a**) Sample for tensile test (**b**) Sample for flexural test (**c**) Sample for fatigue test

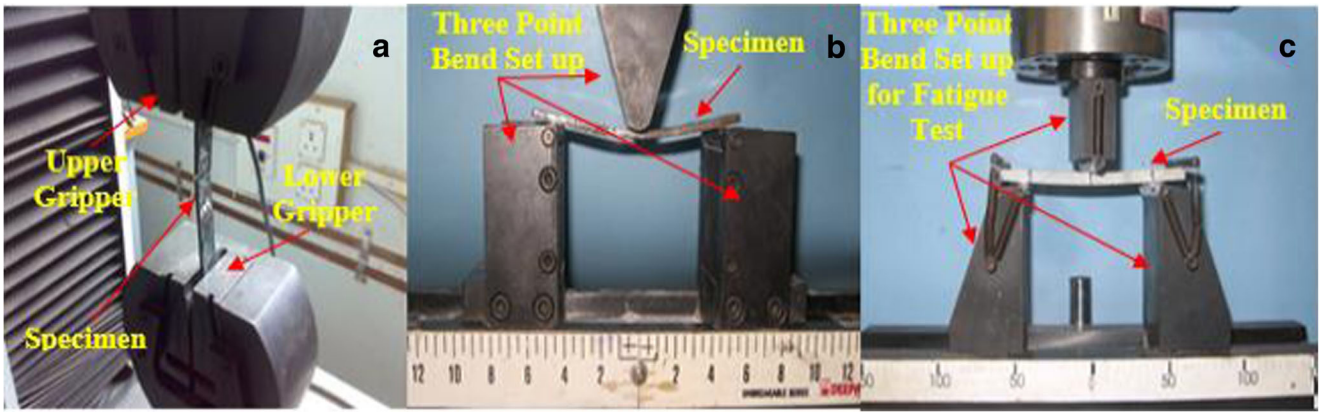

Fig. 5 Set up for testing (**a**) Tensile strength (**b**) Flexural strength (**c**) Fatigue strength

[15]. Experimentation on the tensile strength of GFRP was carried out before and after exposure to heat to understand the variation of tensile strength with curing. The samples at 90 °C show highest tensile strength than at 150 °C. Increase in tensile strength was reported from untreated sample to temperature 90 °C, and gradual decrease in tensile strength was observed with further increase in temperature. The variation is due to the internal phase change during heat treatment [16].

In this paper, the development and determination of mechanical properties of Glass fibers reinforced Epoxy, as well as Vinyl Ester composites at variable curing temperature, have described. The developed specimens were tested to determine the tensile strength, flexural properties, and fatigue behavior to identify the strength of composites. Statistical analysis was carried out on experimentally obtained data to establish the mutual relationship between various mechanical and thermal parameters.

The novelty of the investigation is that the glass-epoxy and glass-vinyl ester composite materials have a wide range of applications specifically glass-epoxy laminates can use in aerospace, automobile, etc. applications and glass-vinyl ester laminates can use in marine applications. In this research work, the composite materials evaluated for mechanical properties, and the glass transition temperature determined which plays a vital role in the enhancement of the composite strength and increases the bonding between the lamina in the fabrication of the composite materials. The properties of the composites are elaborately explained in this paper before and after curing of the fabricated composites.

2 Materials and Methods

The composite developed for the study was based on two resin systems Epoxy as well as Vinyl Ester. The former resin consists of Diglycidyl Ether of Bisphenol A (LY556) with triethylene tetra-amine hardner (HY951) in a stoichiometric ratio of 100:11(*w*/w) while later is Vinyl ester with 2% cobalt as accelerator, Methyl Ethyl Ketone Peroxide (MEKP) as catalyst, Di-Methyl Acetamide as promoter in the ratio of 100:2:2:2(*w*/w). The standard resins were procured from Huntsman Advanced Materials and Suntech Group, Bangalore India. The E-glass fabrics 360 gsm, 0/90 plain weave, was procured from Suntech Group, Bangalore India, and was used as the reinforcement for the composites.

The PMC laminates were fabricated using hand layup process (Fig. 1). The number of fiber layers was derived

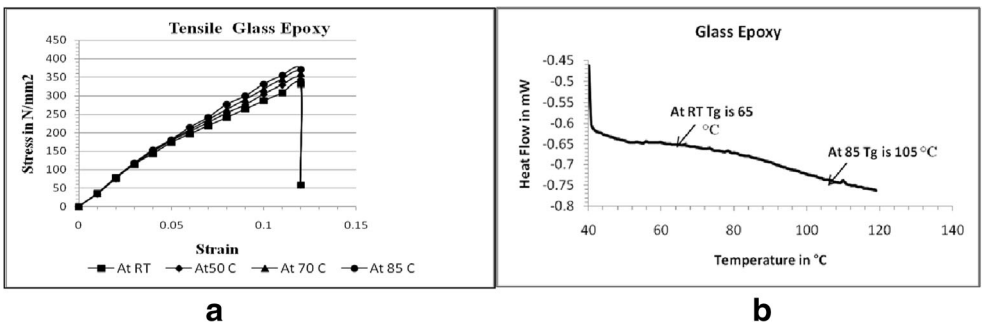

Fig. 6 **a** Stress-strain plot of Glass/Epoxy composites (**b**) DSC plots and the Tg points of the Glass/Epoxy composites before and after curing

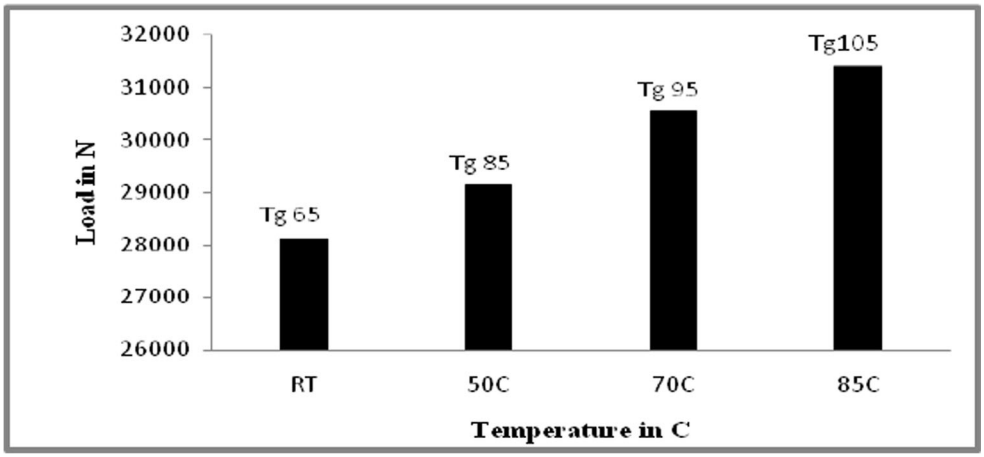

Fig. 7 Effect of post curing on load carrying capacity of the Glass/Epoxy composites

based on the resin: fiber proportion 35: 65 wt% in all the cases. The glass-epoxy composites were cured at 28 °C for 24 h followed by post-curing in a hot air oven. The schedule of curing in glass-epoxy and glass-vinyl ester composites was followed as:

(i) Increase the temperature from 25 to 50 °C at 2 °C/min, followed by soaking at 50 °C for 30 min
(ii) Ramp from 50 °C to 70 °C and soak for 1 h (Ramp from 70 °C to 85 °C and soak at 85 °C for 2 h. The samples were allowed to cool to 28 °C in the oven.
(iii) The glass-vinyl ester composites were also prepared using a similar procedure. The post-curing schedule for glass-vinyl ester was 25 to 80 °C at 2 °C/min, followed by soaking at 80 °C for 2 h.

3 Experimentations

The 62 g of epoxy resin was weighed in a beaker, 6.8 g Amine Hardener HY 951 was added and stirred, the gel time for the reaction was 20 min, and the layup was completed in 20 min. Similarly, 60 g vinyl ester resin, was mixed with 6 g Ecmalon 9911 (2% cobalt accelerator, catalyst 50% Methyl Ethyl Ketone Peroxide (MEKP) in 10% DMA solution, the ratio of resin: accelerator: catalyst: promoter 100:2:2:2). The technique used to prepare the epoxy and vinyl ester composite was 'Wet Hand Lay-Up' process. The procedure of Wet Hand Lay-Up is as shown in Fig. 1a–d:

Figure 1a Placing of Fibers on the Mold Surface, Fig. 1b indicates the additional layer of Fiber and Resin as Lay-up of layers, Fig. 1c is resin impregnation of the fibers with rollers, and Fig. 1d shows the curing of the laminate at room temperature

After preparing the laminates using the hand-layup process, it was allowed to cure for 24 h. The laminates were then post-cured at an elevated temperature using a hot-air oven, as per the process schedule is given in Fig. 2. High-temperature post-curing was employed for the following benefits:

(a) To increases the glass transition temperature
(b) To improves the mechanical properties
(c) To provide dimensional stability to the product at different operating temperatures

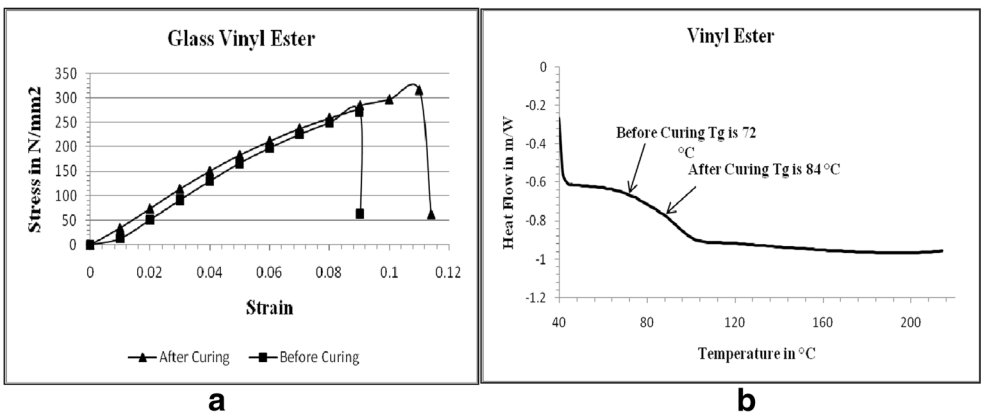

Fig. 8 **a** Stress-strain plot of Glass/Vinyl Ester composites (**b**) DSC Plots and the Tg points of the Glass/Vinyl Ester composites before and after curing

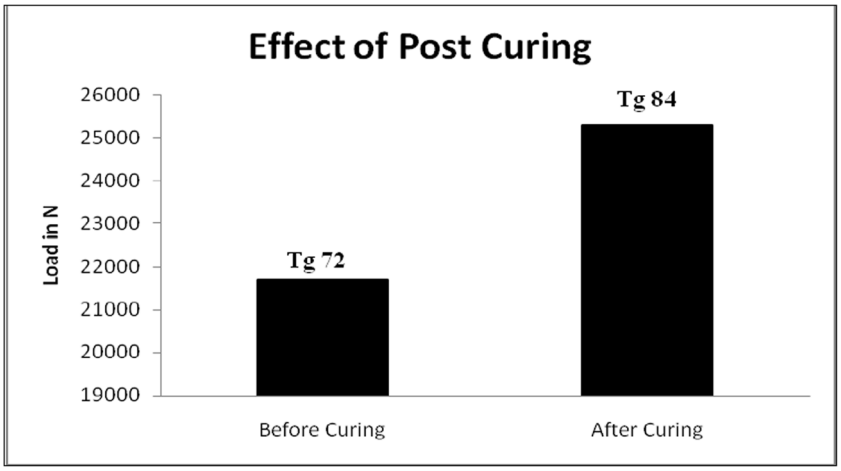

Fig. 9 Effect of post curing on load carrying capacity of the Glass/Vinyl Ester composites

The specimen of Polymer matrix composite (PMC) laminates for determination of mechanical properties as tensile, flexural and fatigue tests were prepared as per the ASTM standard D3039 and D790. The dimension of specimens was 150 × 25 × 3 mm for tensile test, 127 × 12.7 × 3 mm for flexural test and 127 × 12.7 × 6 mm for fatigue test respectively (Figs. 3 and 4). Each experiment was repeated for three times to obtain the higher accuracy of the results. The average of all three replicated data was used for the mathematical calculations and establishment of the relationship in a statistical method.

3.1 Tensile Test

ASTM 3039 standard test method was considered for tensile properties of polymers matrix composites material. The test specimen geometry for balance symmetric glass fiber (0/90) is shown in Fig. 4a. The test setup for tensile strength testing is shown in Fig. 5a. Tensile testing was carried out using a 10-ton capacity UTM, supplied by Kalpak Instruments and Controls, Pune, INDIA. The rate of loading was maintained at 0.5 mm/min. The distance between the two grippers was maintained at 50 mm.

The ultimate tensile strength (σ) is calculated using the formula:

$$\sigma = P/bd \quad N/mm^2 \tag{1}$$

Where, P = Maximum Load in Newton; b = width in mm: d = thickness in mm.

Strain (ε) is calculated as:

$$\text{Change in length}/\text{Original length} \tag{2}$$

Young's Modulus (E) is calculated as:

$$E = \sigma/\varepsilon \quad N/mm^2 \tag{3}$$

3.2 Flexural Test

ASTM D 790 standard test method was considered for flexural properties of the polymer matrix composite material. The

Table 1 Consolidated results of tensile test

360 gsm, plain weave 0/90 – E-glass woven glass fibers						
Material	Ultimate load in N	Maximum deflection in mm	Ultimate stress in N/mm^2	Strain	Young's modulus N/mm^2	Glass transition temperature in ^0C
Glass epoxy at RT	28,114	6	330	0.10	3294	65
Glass epoxy at 50 °C	29,161	6	343	0.09	3515	85
Glass epoxy at 70 °C	30,564	6	359	0.09	3696	95
Glass epoxy at 85 °C	31,416	6	370	0.09	3834	105
Glass Vinyl Ester before curing	21,700	4.5	271	0.11	2319	72
Glass Vinyl Ester after curing	25,308	5.5	316	0.10	2907	84

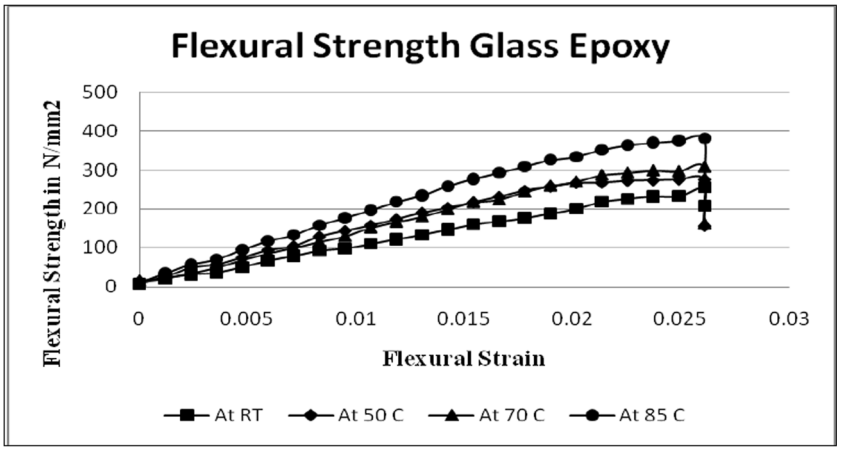

Fig. 10 Flexural strength versus flexural strain of Glass/Epoxy composites

test specimen geometry for balance symmetric glass fiber (0/90) is shown in Fig. 4b. The test setup is shown in Fig. 5b. The flexural test was done using a three-point bend setup with a 10-ton capacity UTM, supplied by Kalpak Instruments and Controls, Pune, INDIA. The rate of loading was maintained at 0.5 mm/min. The distance between the two supports was maintained at 90 mm.

The Ultimate Flexural Stress (σf) is calculated using the formula:

$$\sigma_f = 3PL/(2bd^2) \quad N/mm^2 \tag{4}$$

Strain (ε_f) is calculated as:

$$6Dd/L^2 \tag{5}$$

Modulus of Elasticity (E) is calculated as:

$$E = \sigma_f/\varepsilon_f \quad N/mm^2 \tag{6}$$

Where, P = Maximum Load in N; L = Support Span Length in mm; b = width in mm; d = thickness in mm; D = Deflection from No load condition in mm.

3.3 Fatigue Test

ASTM D 790 standard test method was considered for fatigue properties of the polymer matrix composite material. The test specimen geometry for the fatigue test was similar to the specimen for the flexural analysis. The thickness of the test specimens was maintained at 6 mm for fatigue tests (Fig. 4c). All other dimensions for balance symmetric glass fiber (0/90) shown in Fig. 4c. The fatigue tests were conducted at two different frequencies (6 and 9 Hz) and two different peak loads (60% and 80% of Flexural Peak Load). The set up for fatigue test is shown in Fig. 5c. Fatigue test was carried out using a three-point bend setup using a 5-ton capacity high precision fatigue testing machine, supplied by Kalpak Instruments and

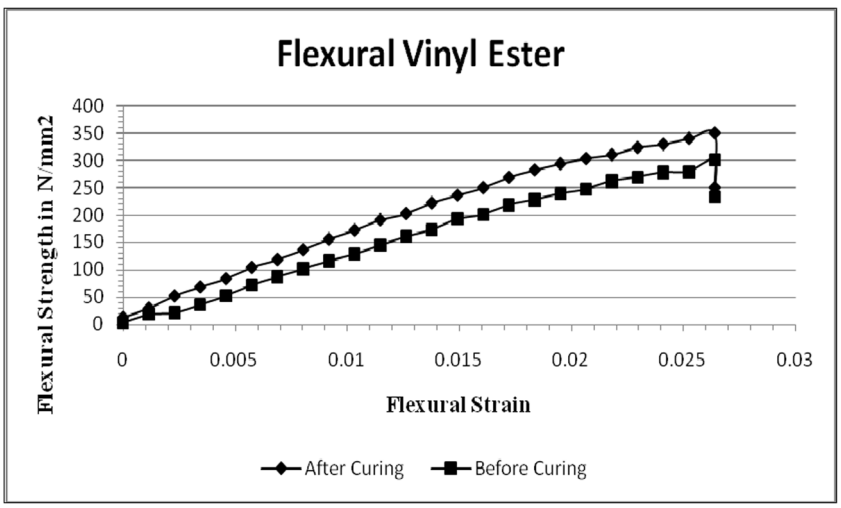

Fig. 11 Flexural strength versus flexural strain of Glass/Vinyl Ester composites

Table 2 Consolidated results of flexural test

360 gsm, plain weave GFRP					
Material	Ultimate load (N)	Maximum deflection (mm)	Flexural strength (N/mm^2)	Flexural strain	Modulus of elasticity (N/mm^2)
Glass Epoxy at RT	245	11.8	255	0.0279	8469
Glass Epoxy at 50 °C	266	9.27	276	0.0219	10,370
Glass Epoxy at 70 °C	296	11.8	307	0.02797	10,627
Glass Epoxy at 85 °C	366	11.1	377	0.02631	14,480
Glass Vinyl Ester before curing	272	12.17	301	0.02794	11,370
Glass Vinyl Ester after curing	314	11.76	348	0.02700	12,455

Controls, Pune, INDIA. The distance between the two supports was maintained at 90 mm.

4 Results and Discussions

The tensile strength of glass-epoxy composites was determined as per the ASTM standard, and the stress-strain plot was drawn as represented in Fig. 6a. The ultimate tensile stress increases by 11% from 330 MPa to 370 MPa due to post-curing. This increase in tensile strength can be attributed to the highly crystalline structure of the post-cured polymer glass-epoxy composites and improved interface bonding between the fiber and epoxy resin. Tensile strength is a fiber dominated property, with the polymer matrix composite test specimens having nearly 65% fibers by weight fraction, post-curing does not significantly increase the tensile strength. The glass-epoxy composite shows two distinct slopes, from 0 to 0.04 and from 0.04 to 0.12. The design of the polymer composite adopts one of the two young's moduli value depending on the level of stress; the structure is expected to withstand under extreme operating conditions. Increased young's modulus by 16% was observed from the tensile testing report, which is again comparable to the increase in tensile strength. The glass-transition temperature increased from 65 °C to 105 °C due to post-curing. The 60% increase in glass-transition temperature was observed, which is due to cross-linking and conversion of epoxy resin to the crystalline structure. Figure 6b shows the Differential Scanning Calorimeter (DSC) plots and the Tg points of the glass-epoxy composites before and after curing. Figure 7 is a bar chart showing the effect of post-curing on load carrying capacity of the glass-epoxy composite. The glass transition temperature increases by 60%, which means that the same glass-epoxy composite can now be used for higher service temperature. The post-curing was observed as the key advantage to improve glass transition temperature. The magnitude of strain in the glass-epoxy composite does not change due to post-curing, which means epoxy resins are highly crystalline or brittle.

Table 3 Experimental plan as per Taguchi's DOE for glass epoxy

Experiment	Response	Load in %		Frequency in Hz
		60	80	6
1	1.6 E+05	1.6 E+05	–	1.6 E+05
2	1.3 E+05	1.3 E+05	–	–
3	1.4 E+05	–	1.4 E+05	1.4 E+05
4	1.1 E+05	–	1.1 E+05	–
Total	5.5 E+05	3.0 E+05	2.5 E+05	3.1 E+05
Average	1.5 E+05	1.5 E+05	1.2 E+05	1.5 E+05
Effect		2.2 E+04		3.1 E+04

The stress-strain plot of glass-vinyl ester composites is given in Fig. 8a. The ultimate tensile stress increases by 18% from 270 MPa to 330 MPa due to post-curing. The maximum strain drops from 0.11 to 0.09. This increase in tensile strength and a decrease in maximum allowable strain can be attributed to amorphous to crystalline transition of glass-vinyl ester composites and to improved interface bonding between the fiber and vinyl ester resin. The glass-transition temperature increases from 72 °C to 84 °C due to post-curing. This is nearly 17%, which is primarily due to cross-linking and conversion of vinyl ester resin to the crystalline structure. Figure 8b shows the DSC plots and the Tg points of the glass-vinyl ester composites before and after curing. Figure 9 is a bar chart showing the effect of post-curing on load carrying capacity of the glass-vinyl ester composite. Tensile strength is a fiber dominated property, with the polymer matrix composite test specimens having nearly 65% fibers by weight fraction, post-curing does not significantly increase the tensile strength. The glass transition temperature increases by 17%, which means that the same glass-epoxy composite can now be

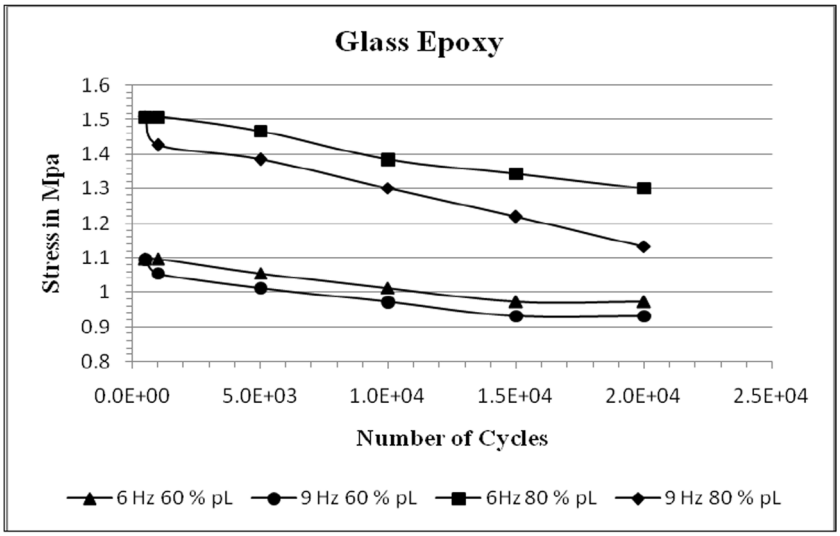

Fig. 12 SN curves for Glass/Epoxy composites

used at marginally higher service temperature. The magnitude of strain in glass-vinyl ester composite reduces by 20% due to post-curing, which means vinyl ester resins show a significant shrinkage, or increase in residual stress. The Young's modulus increases by 25%, which is again comparable to the increase in the tensile strength. The glass-vinyl ester composite shows a uniform slope, which means one single young's modulus value for the entire stress-strain regime. The results of tensile test for glass epoxy as well as vinyl ester have been shown in Table 1.

Flexural strength is critical parameters for applications such as aircraft wings, tail, and stabilizers. Most often these structures are subjected to loads that tend to buckle or deform the structure. The flexural test measures the force required to bend a beam under 3-point loading conditions. The data is often used to select materials for parts that will support loads without flexing. Flexural modulus is used as an indication of a material's stiffness. Figure 10 shows the flexural strength of glass/epoxy composites as a function of post curing.

Similarly, Fig. 11 shows the flexural strength of glass/vinyl ester composites. Glass/Epoxy composites show 32% increase in flexural strength due to post-curing, clearly indicating that flexural strength is a property that depends on both the resin and the fibers, unlike tensile strength which is dominated by the properties of glass. The UTS for Glass Epoxy is 255 MPa at room temperature, 276 MPa after 50 °C for 30 min post-curing, 307 MPa after 70 °C for 60-min post curing and 377 MPa after the final cure temperature of 85 °C for 120 min. The flexural strain remained constant at 0.025 for all the test specimens. In the case of Vinyl Ester / Glass composites the flexural strength increased by 16%, but the ultimate flexural strength was comparable to that of epoxy/glass composite at 350 MPa. The tensile and flexural properties of vinyl ester and epoxy glass composites are similar, but the operating temperatures of vinyl ester are 50 °C less than that of epoxy glass composites. The results of the flexural test for glass epoxy as well as vinyl ester have been shown in Table 2.

The slope of the PMC subjected to 9 Hz is higher than that of 6 Hz for the same peak load, indicating that at higher frequencies the rate of growth of cracks and defects are faster, resulting in the rapid drop in stress levels in the test specimen. Polynomial trend lines were fitted to these plots and extrapolated to determine the number of cycles to failure. These values are recorded in Table 3 as 'Response,' which is a term used in Taguchi's Design of

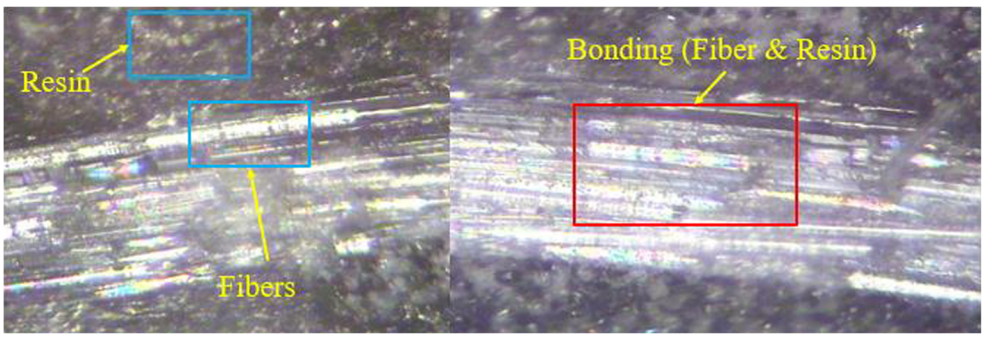

Fig. 13 Microscopic images of Glass/Epoxy composites before fatigue

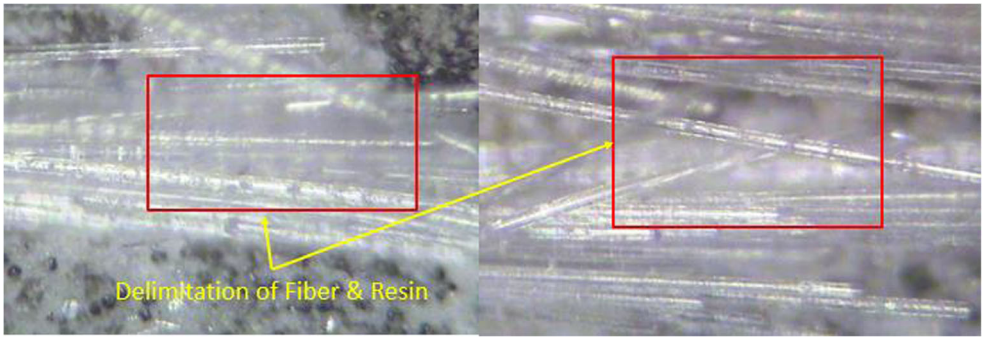

Fig. 14 Microscopic images of Glass/Epoxy composites after fatigue

Experiments approach. The results of the extrapolated trend lines are in-line with the curves in Fig. 12. Statistical analysis was done as per the DOE method, and the percentage effects of peak load and frequency on the number of cycles to failure was calculated. Based on the analysis, the contribution from frequency was 58%, and that of peak load was 42%. The inference that can be drawn from the above study is that frequency has a dominant influence on the fatigue life of PMC compared to the peak load. Figures 13 and 14 shows the microscopic images of glass/epoxy composites before and after failure. The micrographs clearly show that in addition to inter-laminar de-bonding and matrix cracking, there is rupture of glass fibers, which is a sever more of failure in polymer matrix composites. The assignable causes for such a failure could be (a) significantly higher fatigue peak loads (b) weak fiber-matrix interface. Under normal operating conditions, PMC is subjected to 10 to 20% of the peak-load under fatigue loading, in the present test, peak loads of 60 to 80% have been applied to study the response under severe operating conditions. Secondly, the fiber matrix interface can be improved by adopting the vacuum bagging process in place of wet hand-layup technique. Hand-layup technique has inherent limitations, and also, dissolved gases in the resin are another critical factor affecting the fiber-matrix interface.

Figure 15 shows the SN curve for vinyl ester/glass composites. Statistical analysis, similar to that of Glass/Epoxy, was done as per the DOE method and the percentage effects of peak load and frequency on the number of cycles to failure was calculated. Based on the analysis, the contribution from frequency was 47%, and that of peak load was 53%. Table 4 represents the Response of glass vinyl ester in Taguchi's Design of Experiments approach. The inference that can be drawn from the above analysis is that frequency, and peak load has the almost equal effect on the fatigue life of polymer matrix composites. However, glass/epoxy composites had higher fatigue cycles to failure than that of vinyl ester/glass composites.

For example, the projected fatigue life to failure for glass/epoxy composite at 60% PL and 6 Hz were 1,60,000, while that of vinyl ester/glass under the same loading conditions and frequency was 96,000, which is nearly 60% lower. Glass/epoxy and Glass/Vinyl ester composites have the comparable ultimate tensile strength and fatigue strength, but there is a significant reduction in fatigue life. Since most aircraft structures are subjected to fatigue loads; this is a significant parameter.

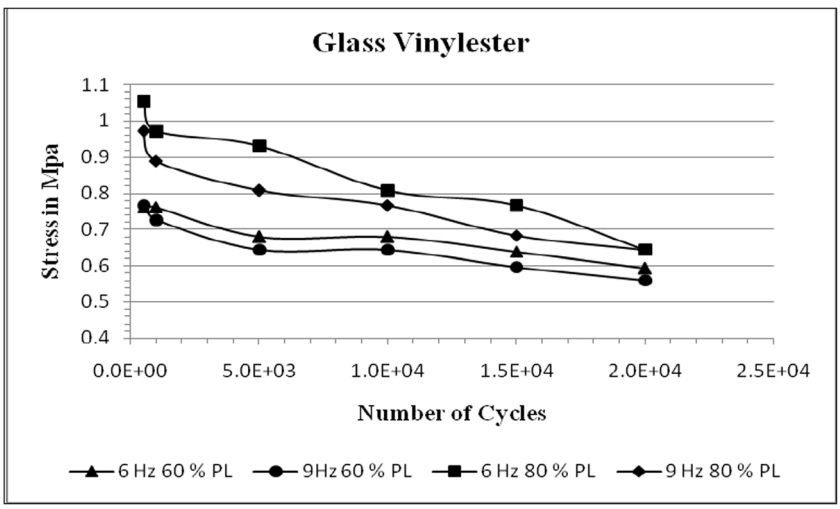

Fig. 15 SN curves for Glass/Vinyl Ester composites

Table 4 Experimental plan as per Taguchi's DOE for Glass/Vinyl Ester

Experiment	Response	Load in %		Frequency in Hz
		60	80	6
1	9.6 E+04	9.6 E+04	–	9.6 E+04
2	8 E+04	8 E+04	–	–
3	7.8 E+04	–	7.8 E+04	7.8 E+04
4	7 E+04	–	7 E+04	–
Total	3.2 E+05	1.7 E+05	1.4 E+05	1.7 E+05
Average	8.1 E+04	8.8 E+04	7.4 E+04	8.7 E+04
Effect		1.4 E+04		1.2 E+04

5 Conclusion

The following conclusion is drawn from the experimental investigations of mechanical properties of glass epoxy as well as glass vinyl ester polymer matrix composites.

- Increase in glass transition temperature of the glass-epoxy composite was observed 60%, which indicates the applicability of the composites at higher service temperature.
- Highly crystalline or brittle nature of epoxy resins was observed.
- The UTS for Glass Epoxy was observed as 255 MPa at room temperature, 276 MPa after 50 °C for 30 min post-curing, 307 MPa after 70 °C for 60 min post-curing and 377 MPa after the final cure temperature of 85 °C for 120 min.
- The 32% increase in flexural strength of Glass/Epoxy composites due to post-curing, indicates the effect of resin and the fibers on flexural strength.
- The increase in Young's modulus was observed by 25%, which is comparable to the increase in tensile strength.
- In the case of Vinyl Ester / Glass composites the flexural strength increased by 16%, but the ultimate flexural strength was comparable to that of epoxy/glass composite at 350 MPa. The tensile and flexural properties of vinyl ester and epoxy glass composites are similar, but the operating temperatures of vinyl ester are 50 °C less than that of epoxy glass composites.
- The frequency was observed as a dominant factor influencing fatigue life of PMC compared to the peak load. The micrographs clearly show that in addition to inter-laminar de-bonding and matrix cracking, there is rupture of glass fibers, which causes failure in polymer matrix composites.

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