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Tensile Response of Epoxy and Glass/Epoxy Composites at Low and Medium Strain rate Regimes

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Abstract

The present research work is to study the effect of low and medium strain rates on tensile behavior of epoxy and glass/epoxy composites. The digital image correlation (DIC) technique is employed for evaluating full-field strain contour plots using high-speed CMOS camera, which captures about 100,000 frames per second. Stress-strain measurements are reported for epoxy and glass/epoxy composites for strain rates ranging from 0.0001 – 450 s^{-1} and the variation of modulus, strength and strain to failure with strain rate is studied. A non-linear regression function is used to predict the tensile properties of epoxy and glass/epoxy composites at both low and medium strain rates regimes. The results reveal that the tensile strength and modulus increases with increase in strain rate for epoxy and glass/epoxy composites. The fracture surfaces of tensile specimens are investigated using scanning electron microscopy (SEM) to understand the influence of strain rate on fracture morphology.

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*Keywords:*Epoxy; glass fibers; strain rate; drop mass test setup; digital image correlation; fractography

1. Introduction

The mechanical properties of most of the polymer and its composites are rate sensitive in nature. For this reason, numerous studies have been carried out to study the variation of strength and stiffness of composites at various strain rates. However, most of the researches have concentrated on the behavior of the polymer matrix composites at

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high strain rates. Split Hopkinson pressure bar (SHPB) technique is widely used to achieve very high strain rate ($>1000\ s^{-1}$) tensile properties. However, the experimental techniques to generate tensile properties in medium strain rates ($1 – 100\ s^{-1}$) are not well established [1]. The high-end servo-hydraulic testing machine and the drop weight impact machine have been widely used to achieve medium strain rates, since the conventional servo-hydraulic machine is restricted to lower strain rates ($<10\ s^{-1}$), due to its inertial effects of the load cell assembly and grips.

Few literatures investigated the effects of strain rate in low and medium strain region for glass/epoxy composites. Saniee et al. [2] investigated the strain rate effect of glass/epoxy composites and observed that the longitudinal strength and modulus has increased to 24.7%, by increasing the strain rate from 0.0001 to 0.1 s^{-1}, respectively. Shokrieh et al. [3] investigated the behavior of unidirectional glass/epoxy composites at quasi-static and intermediate strain rates using servo-hydraulic instrument and found significant increase in tensile properties by increasing the strain rate. The application of drop weight apparatus is introduced by Lifshitz [4] to study the dynamic behavior of angle-ply glass/epoxy composites and it is observed that failure stresses are found to be 20 – 30% higher than the static values; however failure strain and modulus are similar for static and dynamic loadings. Recently, Brown et al. [5] reported the strain rate effects on the tensile, shear and compression behavior of a glass/polypropylene composites over the strain rate range of $10^{-3} – 10^{2}\ s^{-1}$ using an electro-mechanical universal testing machine and a modified instrumented falling weight drop tower with specially designed fixtures. The results showed that the tensile and compression modulus and strength increased with increasing strain rate. Perogamvros et al. [6] developed a tensile testing apparatus using drop tower to study the medium strain rate effects in the regime of $1 – 200\ s^{-1}$and also carried out the parametric FEM study for the validation of experimental results.

This paper discusses the application of a drop mass system and digital image correlation (DIC) technique and investigates the effect of strain rate on tensile properties of epoxy and glass/epoxy composites at both low and medium strain rate regime. Fractographic analysis of tested specimens was carried out using scanning electron microscopy (SEM).

2. Experimental Techniques

2.1. Materials

Matrix - Epoxy, a medium viscous diglycidyl ether bisphenol A resin (DGEBA), and the curing agent, a low viscous aliphatic polyamine (TETA) were procured from Huntsman Ltd, (India) and the reinforcement - glass fiber, 610 GSM woven roving mat (WRM) was procured from M/S Sakthi Fibers, India.

Epoxy specimens were prepared by casting epoxy in the mold. The mold was made from two rectangular glass plates having dimensions of 300 mm × 300 mm. Rubber beadings were used to maintain a 3 mm thickness all around the mold plates. Wax was used as a releasing agent. The curing agent TETA was added and the mixture was gently stirred in order to avoid the formation of bubbles. After degassing, the solution was cast in the mold.

Glass/epoxy composite specimens were prepared by hand layup technique followed by compression molding. After adding the required amount of curing agent, a thin layer of epoxy was applied with a brush on an aluminum plate coated with a releasing agent. Then the epoxy mixture was impregnated into the WRM glass fiber with the assistance of hand roller to ensure that all fibers were uniformly wetted. The laminates were cured at room temperature and kept in the compression molding machine for 24 h for complete curing.

2.2. Quasi-static testing

Tensile modulus, tensile strength, and strain to failure were evaluated for both epoxy and glass fiber/epoxy composites as per ASTM: D638-10 standard using universal testing machine. Epoxy tensile specimens having 3 mm thickness and 50 mm gauge length were cut using water jet cutting machine. Thin laminate composed of glass/epoxy, having a laminate thickness of 1 mm and 12.7 mm width were prepared and glass/epoxy tabs of 2.5 mm thick and 35 mm long with tapered ends were locally bonded to each end of the specimens. These tabs allowed a smooth load transfer from the grip to the specimen. The gauge length of the composite specimens was 12.7 mm. The fiber weight fraction of the composites was 50%.

Tensile tests were conducted at cross-head speeds of 0.5, 5, 50 and 500 mm/min for epoxy and glass/epoxy specimens. These stroke rates resulted in nominal strain rates of 0.0001, 0.001, 0.01, 0.1 s^{-1} and 0.0006, 0.006, 0.06, 0.6 s^{-1} for epoxy and glass/epoxy specimens, respectively. The nominal strain rates were calculated by dividing the stroke rate of the machine cross-head with the gauge length of the specimen.

2.3. Dynamic testing

Dynamic tensile tests were carried out in a drop mass tower using an in-house fabricated specimen fixture assembly. Load was measured using PCB 208C04 Integrated Circuit Piezoelectric (ICP) sensor. A Phantom V611 high-speed camera with 1MP resolution, coupled with a SIGMA 50 mm f/2.8 EX DG Macro lens was used for the dynamic experiments and an aperture of f/2.8 was used. Camera with lens attachment was placed at 15 cm stand-off distance away from the specimen surface. Specimen configuration with smaller region of interest (128 X 128 $pixel^2$) allowed capturing images at a very high frame rate of 100,000 fps.

2.4. Fractography

The failed tensile specimens were investigated using a Hitachi S-4800 Scanning Electron Microscope (SEM) operating at an accelerating voltage of 5 kV. Prior to analysis, specimen surfaces were coated with a thin layer of gold film to increase the conductance of the sample during SEM observation.

3. Results and discussion

3.1. Epoxy

Low strain rate tensile tests were conducted on Instron test frame for epoxy specimens. Fig. 1 shows the stress-strain curves of epoxy system at three different strain rates (0.0001 – 0.01 s^{-1}). The stress–strain response of epoxy system is linearly elastic up to the maximum stress point followed by an abrupt failure at a failure strain of 2.2% under lowest strain rate (0.0001 s^{-1}) and it has slightly increased to 2.5% under highest strain rate (0.1 s^{-1}). Elastic modulus, failure stress, and failure strain extracted from stress-strain curves at various strain rates are summarized in Table 1. The behavior of epoxy is similar to metallic materials, wherein the strength and modulus increased and failure strain decreased with increase in strain rate [7].

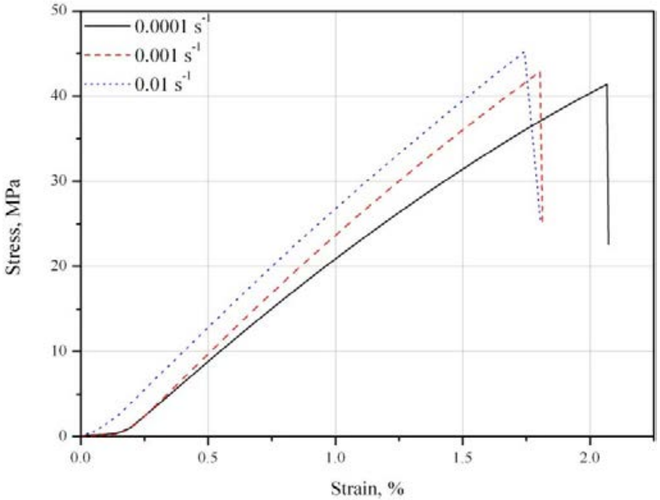

Fig. 1. Stress-strain curves of epoxy system at various strain rates

High strain rate tensile tests were conducted on the drop mass tower using an impactor mass of 0.5 kg at heights of 0.5, 0.75 and 1 m corresponding to velocities of 188, 230 and 266 m/min, respectively. The nominal strain rates are 315, 385 and 445 s^{-1}, which is calculated by dividing the drop mass velocity with the gauge length of the specimen.

Table 1.Tensile properties of epoxy system at low and medium strain rates

Cross-head speed (m/min)	Tensile modulus (GPa)	Tensile strength (MPa)	Tensile strain (%)	Strain rate (s^{-1})
0.0005	2.57 ± 0.13	41.39 ± 5.91	2.23 ± 0.27	0.0001
0.005	2.76 ± 0.17	44.49 ± 1.56	2.08 ± 0.1	0.001
0.05	2.82 ± 0.13	48.98 ± 4.39	1.91 ± 0.12	0.01
0.5	2.96 ± 0.08	56.51 ± 1.91	2.54 ± 0.06	0.1
188	5.18 ± 0.15	42.5 ± 3.15	0.974 ± 0.008	315
230	5.64 ± 0.33	51.47 ± 2.32	0.928 ± 0.009	385
266	6.25 ± 0.35	56.24 ± 2.32	0.852 ± 0.021	445

Specimen strain versus time curves (Fig. 2) were used to determine the actual strain rate. It is observed that the initial portion of the strain–time curve was not a true indication of the effective strain rate experienced by the specimen, and hence actual strain rates were thus determined by differentiating the strain histories [5], [8]. The actual strain rate derived from the gradient of the strain-time data during the tests at various velocities of 188, 230 and 266 m/min were 21, 44 and 52 s^{-1}, respectively. However, the actual strain rates are used in practice for analysis.

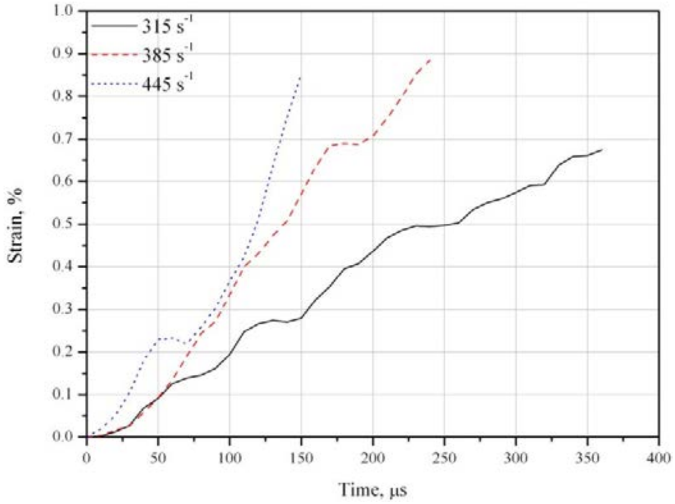

Fig. 2. Strain histories of epoxy system at various strain rates

From Table 1, an increment of 143% in modulus and 36% in strength is observed for neat epoxy system at the strain rate of 445 s^{-1} in contrast to quasi-static strain rate (0.0001 s^{-1}). It is inferred that the stiffness of epoxy system is more sensitive to strain rates when compared to tensile strength. In addition, decrease in failure strain is observed as strain rate is increased for epoxy system. Increasing strain rate will decrease the molecular mobility of the polymer chains, consequently leading to a stiffer and more brittle material [9].

3.2. Glass/Epoxy

Tensile test on glass/epoxy specimens were conducted at cross-head speed of 0.5, 5, 50 and 500 mm/min, respectively. Fig. 3 shows the stress–strain curves at various strain rates (0.0006 – 0.06 s^{-1}) for glass/epoxy composites. The stress-strain responses are similar to epoxy and the behavior is consistent at various strain rates. The stress–strain response is linearly elastic up to the maximum stress point followed by abrupt failure at a strain of 10.5% under lowest strain rate (0.0006 s^{-1}) and it is increased to 13% under highest strain rate (0.6 s^{-1}).

The mechanical properties are summarized in Table 2. It is observed that tensile strength and modulus increased with increase in strain rate. An increment of 380% in modulus and 67% in strength is observed for glass/epoxy composites at a strain rate of 445 s^{-1} in contrast to quasi-static strain rate (0.0006 s^{-1}).

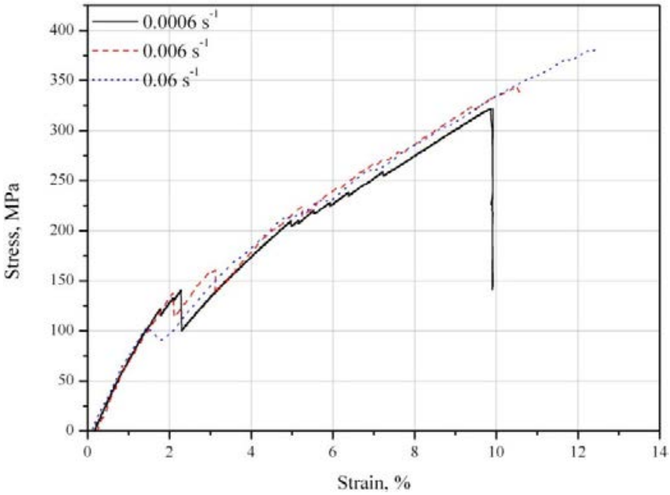

Fig. 3. Stress-strain curves of glass/epoxy composite at various strain rates

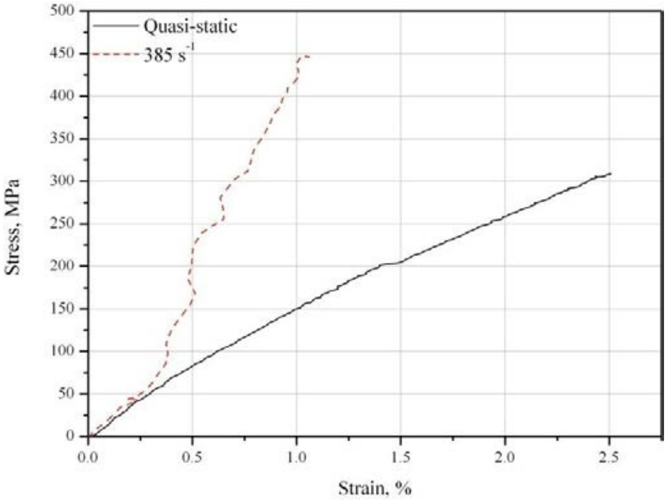

Fig. 4. Stress-strain curves of glass/epoxy composite at quasi-static and medium strain rate

Fig. 4 shows the comparison of stress-strain response at medium strain rate regime (385 s^{-1}) in contrast to quasi-static testing using DIC technique. A clear increment in strength and slope is observed with the increase in strain rate. The rate sensitivity of the tensile strength is due to the rate dependence of the glass fibers in fiber dominated loading mode, as reported by Okoli [10].

Table 2.Tensile properties of glass/epoxy composite at low and medium strain rates

Cross-head speed (m/min)	Tensile modulus (GPa)	Tensile strength (MPa)	Tensile strain (%)	Strain rate (s^{-1})
0.0005	7.79 ± 0.55	315.1 ± 11.4	10.52 ± 0.92	0.0006
0.005	8.35 ± 0.15	331.4 ± 10.2	10.62 ± 0.14	0.006
0.05	8.83 ± 0.08	351.5 ± 7.05	12.3 ± 0.31	0.06
0.5	9.11 ± 0.55	392.3 ± 21.5	12.94 ± 0.89	0.6
188	28.58 ± 1.36	421.7 ± 10.1	2.27 ± 0.21	315
230	34.81 ± 3.13	476.9 ± 20.2	1.94 ± 0.23	385
266	37.31 ± 2.06	526.1 ± 15.8	1.8 ± 0.02	445

3.3. Effect of strain rate on tensile properties

A non-linear regression function [3] is employed to predict the tensile properties of epoxy and glass/epoxy composites at various strain rates. The equations 1 and 2 are given below for predicting modulus and strength, respectively.

$$\dot{E} = a + b\dot{\varepsilon}^{c} \tag{1}$$

$$\dot{\sigma} = a + b\dot{\varepsilon}^{c} \tag{2}$$

where a, b and c are regression constants, $\dot{\varepsilon}$ is strain rate.

Table 3.Regression constants and correlation coefficients of epoxy and glass/epoxy composites

Material	Regression constants	a	b	c	R^2
Epoxy	Modulus	2.615	0.855	0.353	0.993
	Strength	51.469	0.393	0.359	0.932
Glass/Epoxy	Modulus	7.738	5.619	0.429	0.999
	Strength	289.627	115.389	0.14	0.897

Table 3 illustrates the regression constants and correlation coefficients (R^2) of both epoxy and glass/epoxy composites. Fig. 5 illustrates the effect of strain rate on the tensile modulus for epoxy and glass/epoxy composites. An increment of 15% in tensile modulus is observed for both epoxy and glass/epoxy composites on low strain rate regime, whereas an increment of 77% and 107% in tensile strength is observed at medium strain rate regime for epoxy and glass/epoxy composite, respectively. From Fig. 5, it is observed that glass/epoxy composite is more rate sensitive than epoxy system at medium strain rate regime. The predicted values are in good agreement with experimental values for both epoxy and glass/epoxy composites at both low and medium strain rate regime.

Fig.6 illustrates the effect of strain rate on the tensile strength for both epoxy and glass/epoxy composites. The glass/epoxy is relatively more sensitive to strain rates than epoxy system. An increment of 36% in tensile strength is observed for epoxy at both low and medium strain rate regime, whereas 34% and 66% increase is observed for glass/epoxy at low and medium strain rate regime, respectively. A monotonic increase in tensile strength with increase in strain rate is in agreement with findings of Okoli and Smith [10]. The predicted values show good agreement with experimental values at low strain rate regime for both epoxy and glass/epoxy composites. From the results, it is observed that the stiffness of glass/epoxy composites is more sensitive to strain rates compared to tensile strength. The increase in tensile strength and modulus is attributed to the visco-elastic nature of matrix, fiber-matrix interfacial properties, woven type and geometry of the composites [5].

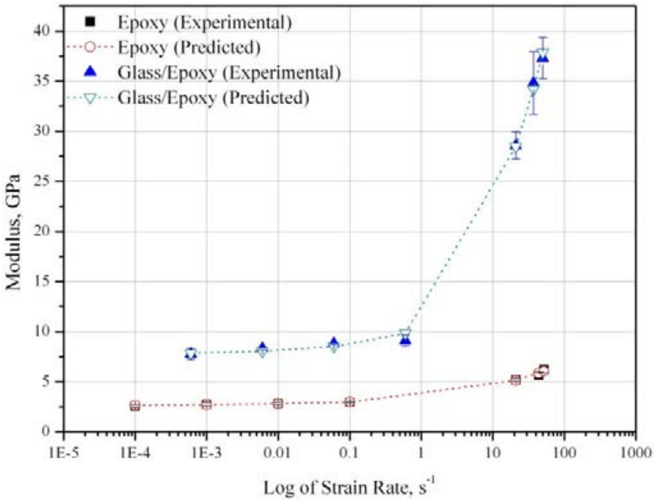

Fig. 5. Effect of strain rate on tensile modulus for epoxy and glass/epoxy composites

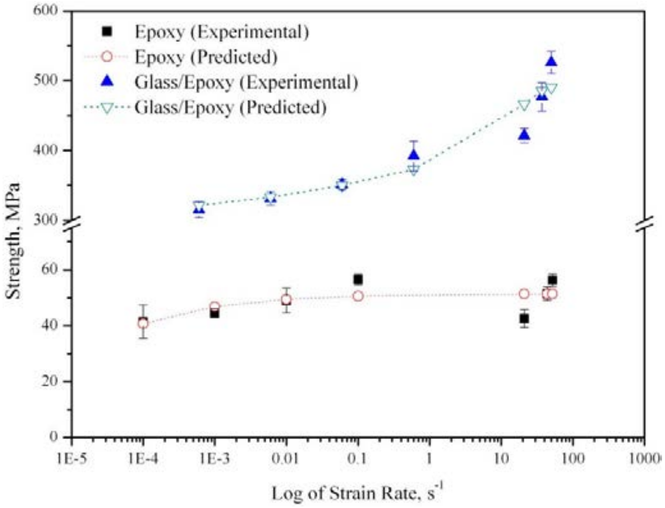

Fig. 6. Effect of strain rate on tensile strength for epoxy and glass/epoxy composites

3.4. Fractography

The SEM micrograph (Fig. 7a) of epoxy system shows a river-like pattern, which exemplifies a typical cleavage type of fracture. It is noted that the roughness of fracture surface increases with strain rate. In the case of glass/epoxy composite, fiber breakage, matrix cracking and debonding are observed at a strain rate of 445 s^{-1} as shown in Fig. 7b. The fiber breakage (brittle failure) and fiber pull-outs are predominantly observed in samples failed at high strain rates. Also the interfacial debonding becomes more severe with increasing strain rate. Similar findings are reported by Shokrieh et al. [3] and Staab and Gilat [11] revealed significant changes in the fracture appearance with increase in strain rate.

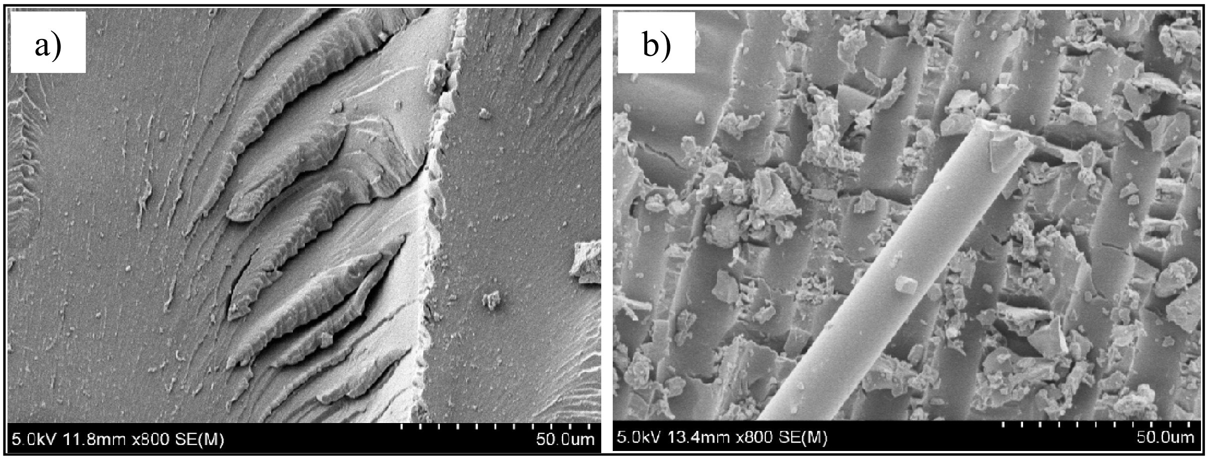

Fig. 7. SEM micrographs of epoxy and glass/epoxy composite at medium strain rate regime

4. Conclusions

In this paper, the effect of strain rate on tensile properties of epoxy system and glass/epoxy composites is studied at both low (0.0001 – 0.1 s^{-1}) and medium (315 – 445 s^{-1}) strain rate regime. It is observed that the tensile properties of epoxy and glass/epoxy composites are rate sensitive, even at low range of strain rate. The dynamic tensile tests are carried out using a drop mass test setup equipped with in-house specimen fixture and high-speed CMOS camera. Significant increase in elastic modulus and tensile strength and a clear reduction in failure strain under dynamic loading are observed. The predicted values of the non-linear regression function show good agreement with the experimental values for both low and medium strain rate regime. SEM observations on the fracture surface show that the surface becomes rougher as the strain rate increases. Fiber pull out, brittle failure of matrix and fiber debonding are the dominant modes of failure at high strain rates.

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