

Effect of strain rate on flexure properties of GFRP laminates- An experimental and numerical investigation

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Abstract. Eight layered symmetric GFRP laminate was prepared by hand layup followed by press moulding. Samples were prepared according to ASTM D790-17 and were tested at three different strain rates of 1s^{-1} , 10s^{-1} and 100s^{-1} . Flexure properties of the samples being a matrix dominated property were found to be highly strain rate dependent. At the nominal and moderate strain rates of 1s^{-1} and 10s^{-1} samples showed a small variation in flexure strength and flexure modulus. While the same specimen when tested at 100s^{-1} depicted increased strength and modulus, while flexure strain decreased. Further numerical simulation of the test using shell model was carried out on ANSYS and results were found out to be well within experimental results.

1. Introduction

Now-a-days, polymer matrix composite (PMCs) are taken as an alternative to the conventional isotropic materials. These materials offer high strength and stiffness to weight ratio together with corrosion resistance [1]. Woven fiber composites are known for better through thickness stiffness [2] and impact resistance [3]. Tailoring properties and ease of manufacturing in woven fabric composites make them an attractive alternative in structural application. But PMCs are susceptible to damage under static [4] and dynamic [5] loading and generally damages start and propagate from the bulk or matrix material [6], which further fails fibers.

Under service, structural elements are exposed to variable strains. Thus it is highly recommended to study the strain rate dependent mechanical properties of PMCs. In this context; Xin Li et al. [7] studied the effect of strain rate on warp-knitted and plain woven carbon fiber composites under tensile and compressive loadings. The strain rate was kept 0.5s^{-1} for quasi-static and varied from 200s^{-1} to 2300s^{-1} for dynamic testing. The result showed that as strain rate increased for both type of fabric, tensile strength increased whereas negligible effect on compressive strength was observed. Gilat et al. [8] studied the strain rate dependent behavior of IM7/977-2 carbon epoxy matrix composite in tension and tested at different strain rate for various resins and laminate configurations. The quasi-static strain rate was approximately 10s^{-1} and intermediate strain rate was about 1s^{-1} . The results revealed that strain rate had a significant effect on the material response. Amijima and Fuji [9] investigated the effect of strain rate on compressive behavior of glass/polyester composite. The strain rate was varied between 10^{-3} to 10^3s^{-1} and it was observed that compressive strength increased with increasing strain rate. Velmurugan and Gurusideswar [10] studied the strain rate dependent behavior



of glass/nano clay filled epoxy resin composite and observed that longitudinal strength and stiffness increases as strain rate increases. Work by Shokreih and Omid [11] showed that tensile strength increases as the strain rate is increased. Fereshteh-Saniee et al. [12] investigated the strain rate dependency of glass/epoxy composite at low strain rates. The result showed that the longitudinal strength and stiffness increased by 24.7% and 4.2% respectively by increasing the strain rate from 0.0001 to 0.11 s^{-1} . Zebarjad et al. [13] studied the combined effect of nano-sized calcium carbonate and strain rate on the tensile properties of HDPE. They observed that the strain rate dependency of pure HDPE is higher than that of its nanocomposites. Szu-Hui Lim et al. [14] studied the effect of loading rate and temperature on tensile yielding and deformation mechanism of nylon 6-based nanocomposites, with and without POE-g-MA rubber particle. In nylon 6 ternary nanocomposites, the volumetric strain response showed that the nylon 6 nanocomposites enhanced the shear deformation and decreased delamination of the organoclay layers. Bao et al. [15] investigated that flexural properties of polypropylene nanocomposites reinforced with multi-walled carbon nanotube are strain rate and temperature dependent.

From the above references it was observed that strain rate dominates the mechanical properties of polymer matrix composites. Thus the objective of this paper is to study the strain rate dependent flexure properties of a neat epoxy GFRP laminate and compare its results with numerical results obtained by FE analysis.

2. Materials, fabrication and processes

Reinforcement: Plain weave glass fiber fabric with a surface weight of 610GSM. This fabric was manufactured by Vetrotex India Pvt. Ltd. and supplied by MS Industries Kolkata, India.

Matrix: Bisphenol-A based-thermosetting epoxy [brand name: Lapox L-12 (ARL-12)] and Amine based hardener [brand name: Lapox K-6 (AH312)], manufactured by Atul Limited, India, were used in these sets of experiments. Both epoxy and hardener were room curing products.

Laminate preparation: Symmetric [16] 8 plied laminate with stacking sequence as $[(0^\circ, 90^\circ)/(+45^\circ, -45^\circ)/(+45^\circ, -45^\circ)/(90^\circ, 0^\circ)]_2S$ were prepared. Where number in parenthesis shows warp and weft direction of fibers in laminate. Plies were wetted by the epoxy resin using a soft brush, were stacked according to the layup and excess of the resin was squeezed out by a mild steel roller. Later, stacked and squeezed plies were sealed in a polythene bag and were pressed under a press molding machine. Pressure of 25MPa was applied on the laminate. Further, laminate was cured under the same pressure for 24 hours at room temperature. Figure 1 shows schematic of laminate preparation in a flow diagram.

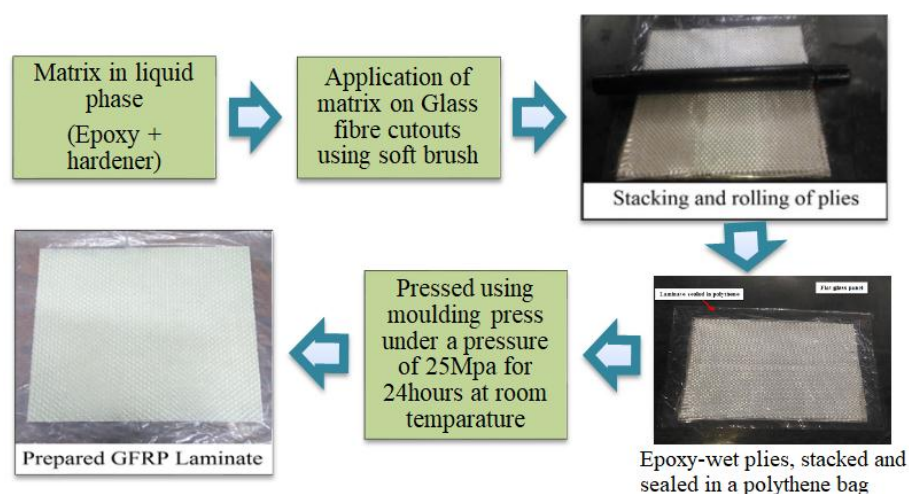


Figure 1. Schematic of laminate preparation technique

3. Testing

Samples were prepared according to ASTM D790-17 [17] flexure testing specifications and tests were conducted on Hounsfield H50KS, a computer controlled universal testing machine (UTM) with the maximum loading capacity of 50KN. Figure 2 shows the schematic of flexure test. Tests were carried out at three different loading rates of 1mm/min, 10mm/min and 100mm/min, which presented us the strain rates of $1s^{-1}$, $10s^{-1}$ and $100s^{-1}$ respectively. Ultimate flexure strength, flexural strain and flexure modulus of the samples were calculated by formulae (1), (2) and (3)

$$\sigma = \frac{3PL}{2bt^2} \quad (1)$$

$$\varepsilon = \frac{6Dd}{L^2} \quad (2)$$

$$E = \frac{mL^3}{4bt^3} \quad (3)$$

Where; σ is flexural stress, ε is flexural strain and E is flexural modulus respectively. P is the peak load, L is span length, b is breadth and t is thickness of the specimen. D stands for deflection in the beam at the peak load and m is initial slope of the load-deflection curve.

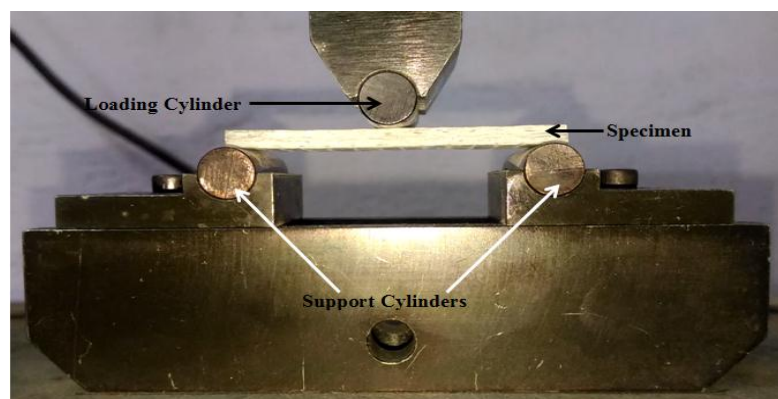


Figure 2. Schematic of flexure test

4. Results and discussion

Figure 3 shows the load vs. deflection graph of the samples tested at three different strain rates. Each batch of samples contained three specimens. Thus a total of 9 samples were tested and their graph are depicted in a comparative manner. Table 1 and table 2 gives the flexure properties of the samples and coefficient of variation (CV) and standard deviation (SD) associated with the testing.

It can be seen from the graphs, as strain rate was increased flexure strength of the laminates increased while flexure strain decreased. For first and second set of experiments the average strength of the laminates were 262.1 and 261.73 MPa respectively, whereas for the third set of tests, average stress increased to 287.43 MPa. On the other hand average flexure strain decreased from 0.022 to 0.020 and 0.018 when laminates were tested at the strain rates of $1s^{-1}$, $10s^{-1}$ and $100s^{-1}$ respectively. Thus the samples moved towards brittle fracture and this changed the stiffness of the laminate by 0.99 and 1.02 times respectively when laminates were tested at moderate and high strain rates. Lower coefficient of Variance in the results ascertained that the specimen were from the same batch.

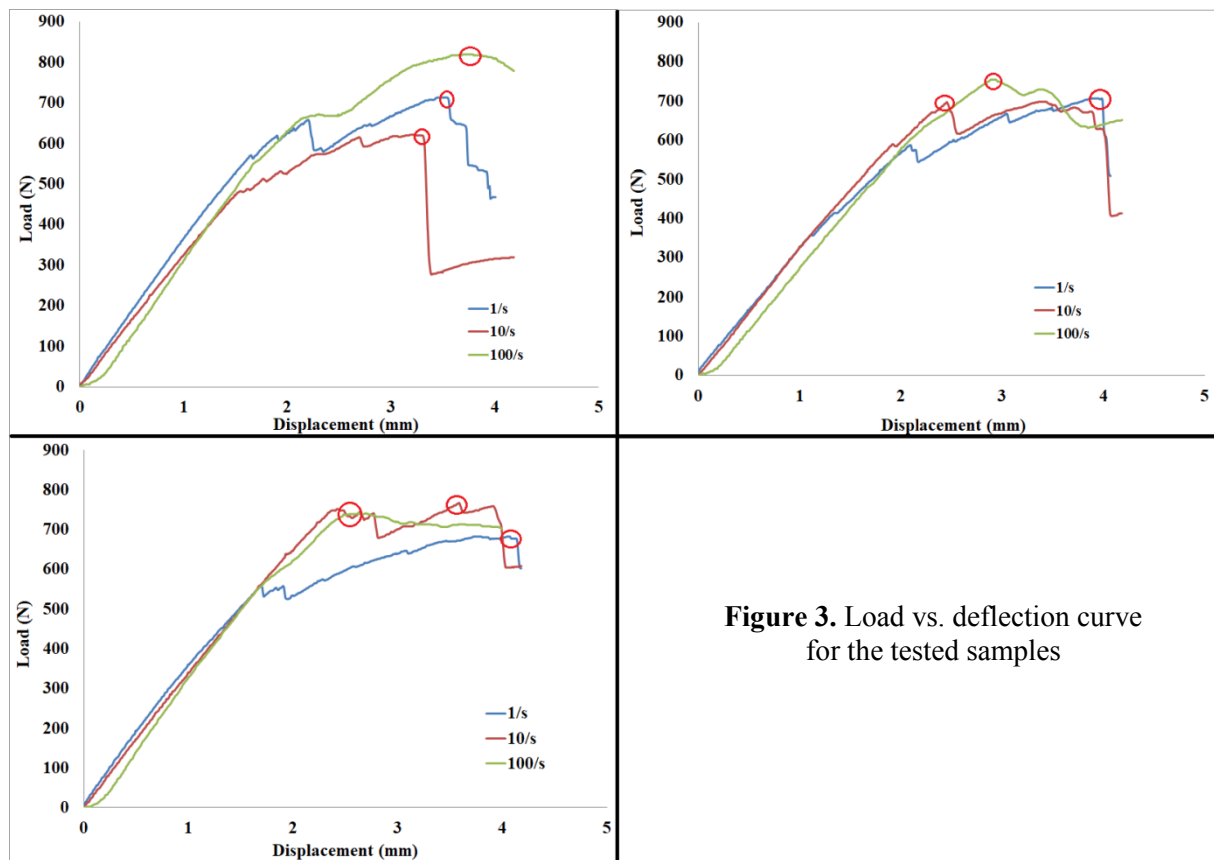


Figure 3. Load vs. deflection curve for the tested samples

Table 1. Flexure properties of the specimen tested at three different strain rates

Set Number	Sample Number	Flexure strength (in MPa)	Average Flexure strength (in MPa)	Flexure strain	Average flexure strain	Flexure Modulus (in GPa)	Average Flexure modulus (in GPa)
1 (1mm/min)	1	267.1	262.1	0.020	0.022	18.823	17.834
	2	264.5		0.024		15.769	
	3	254.7		0.022		18.912	
2 (10mm/min)	1	233.9	261.73	0.019	0.020	18.574	17.724
	2	262.8		0.020		16.025	
	3	288.5		0.021		18.574	
3 (100mm/min)	1	305.1	287.43	0.022	0.018	19.296	18.207
	2	281.1		0.017		16.377	
	3	276.1		0.015		18.949	

Table 2. Coefficient of variation and standard deviation associated with the samples

Set Number	Flexural strength		Flexural strain		Flexural modulus	
	SD	CV	SD	CV	SD	CV
1 (1mm/min)	6.53	2.49	0.0016	7.27	1.85	10.42
2 (10mm/min)	27.36	10.45	0.0013	6.29	1.47	8.33
3(100mm/min)	15.59	5.42	0.0034	18.14	1.60	8.78

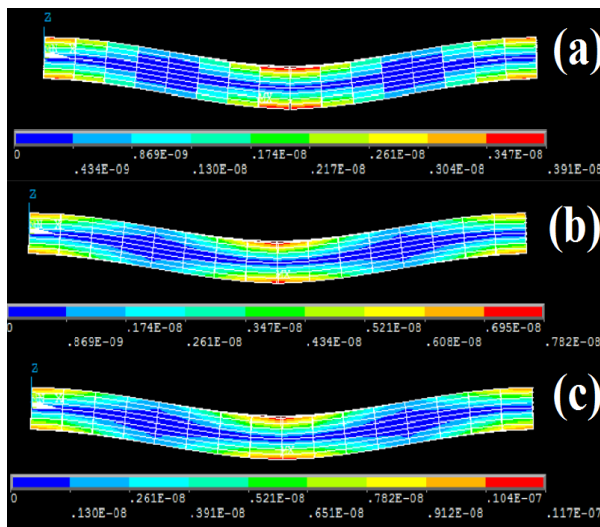


Figure 4. Von-mises strain in laminates at strain rate of (a) 1 s^{-1} (b) 10 s^{-1} ; and (c) 100 s^{-1}

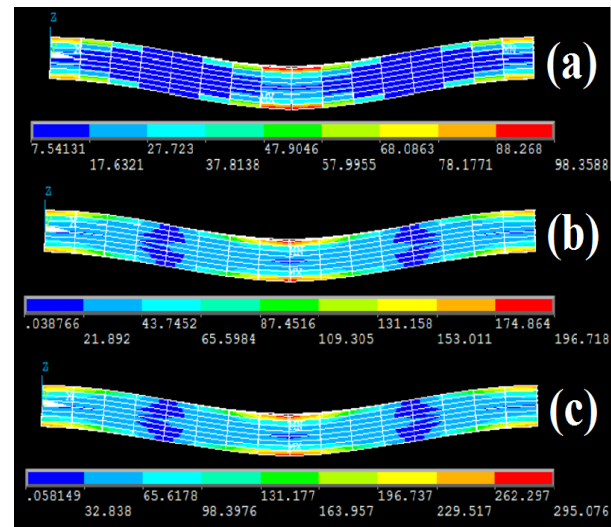


Figure 5. Von-mises stress in laminates at strain rate of (a) 1 s^{-1} (b) 10 s^{-1} ; and (c) 100 s^{-1}

Such discrepancies in the results were due to the strain rate dependent behaviour of the polymers. Epoxies are composed of highly cross linked chains and loading rate dictates the opening of such cross linked polymer chains. At lower strain rate of 1 s^{-1} and 10 s^{-1} laminates had ample time to open their entangled polymer chains and this presented them ductile failure. Whereas at the strain rate of 100 s^{-1} chains failed to open within the stipulated time and their molecular motion was blocked [18]. At higher strain rate most of the strain energy was wasted in plastic deformation and this caused brittle failure of the specimens. Load vs. deformation curve of the samples tested at low and moderate strain rate depicted various stages of damage initiation and propagation like initial matrix cracking, intra-ply delamination, delamination between adjacent plies and fiber failure. Whereas samples tested at high strain rate were unable to depict the similar phenomenon. Curves were smooth which shows simultaneous appearance of damage phenomenon. Figure 4 and 5 shows the Von-mises strain and stress respectively at three different strain rates. Since strain rate varied the results were obtained at $t=2\text{ s}$. Peak stress and strains were observed at the resting and loading point due to compressive and tensile forces acting on the top and bottom face of the laminates. Minimum stress and strains were sensed at the mid plane.

5. Conclusion

Based on the experiments the following conclusions can be drawn;

1. Flexure property of GFRP laminates are matrix dominated and is generally controlled by strain rates.
2. Increasing strain rate increases the ultimate strength while ultimate strain decreases.
3. Inter-ply and intra-ply delamination is a major form of failure.
4. Sample fails by fiber crushing at top face and tensile failure at bottom face.
5. FEA shows mid plane observed minimum deformation and this led to lower stress and strains in the area.

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