Effect of notch position and orientation on flexural behaviour of neat epoxy GFRP laminates

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Abstract. In this work the effect of notch position on the flexural properties of neat epoxy GFRP laminates were assessed. Three different set of samples consisting three specimens were prepared. First batch of samples comprised of specimen without any stress raisers, while other two batches consisted samples with 1mm deep and 1 mm wide groove. Further, the notched samples were tested at two different orientations, making the notch to appear on the top (compressive face) and bottom (tensile face) of the specimens. Testing was conducted at the loading rate of 1mm/min according to ASTM D790-17 standard. Test results revealed that when notch was present on the loading side (compressive face), the ultimate strength increased, as the stress raiser compensated the compressive deformation (fiber crushing) and allowed the laminate to go for higher deformation. Whereas the same notch when appeared on tensile face, strength of material decreased. Average ultimate strength of samples without notch was 234.7 MPa while the same for samples with notch on compressive and tensile face were 240.7 MPa and 194.5 MPa respectively. Average flexure modulus of the samples with notch on the compressive and tensile side was 13.27 GPa and 11.90 GPa respectively as compared to 14.44 GPa of sample without notch.

1. Introduction

The outstanding properties of composite materials such as high strength and stiffness with low weight popularized its application in day-to-day work related to structural application. Tailoring properties of composite materials are the key factor, which enables them to be designed according to the in-service requirements. Polymer matrix when reinforced with fibers results in some single-phase materials that are better representative of certain properties, which could not be attained by two materials. Apart from advantages in terms of strength and stiffness, properties such as corrosion resistance [1], wear resistance [2] and temperature resistance [3], make them suitable for aerospace industries, marine industries, automobile & wind turbine blades [4].

Despite so many advantages of GFRPs, there are certain factors which limit the applications of composite materials. One such factor is the presence of stress concentration around a notch that reduces the mechanical properties of the composite materials. Failure modes due to presence of notch appear in the form of fiber pullout, matrix micro cracking & interface debonding at microscopic level but at the macroscopic level the major failure modes are matrix cracking, fiber breakage & delamination [5].

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Several studies have been done to highlight the effect of stress concentration in such specimen. In this context Soutis et. al. [6] concluded that due to the presence of notch the failure strength of composite laminates reduces to half of that of the unnotched specimen. Riccio and associates [7] studied the shear behaviour of a stiffened composite panel with a notch and numerically simulated it by means of a three-dimensional progressive degradation model. Intra-laminar gradual degradation of composite laminates was taken into account. Riccio et. al. [8] in his other work studied the influence of large notch damage in a stiffened aeronautical panel and performed a progressive failure analysis in order to compare the effects of large notch orientation on the mechanical behaviour. Test showed the large notch orientation influences the maximum sustainable load and damage evolution. William [9] found laminated composite plate has low stress concentration factor than single ply and hence claimed structural performance could be improved by laminate fabrication process. Toubal et. al. [10] used an electronic speckle pattern interferometer (ESPI) technique to calculate the tensile strain field in a composite plate containing circular hole.

The above works established a relation that stress raisers affect the mechanical properties adversely. Thus, the aim of this paper is to study the flexural behaviour of symmetric GFRP laminate with notch. Further notch position related to loading condition was changed and its effect by experimental procedure is studied.

2. Materials, fabrication and processes

GFRP composite laminate was prepared by hand layup technique followed by press molding method. The reinforcement used was glass fiber plain weave fabric of 610 gsm surface weight, manufactured by Vetrotex Ltd. India. Matrix used was Bisphenol-A based thermosetting epoxy, brand name Lapox L-12 (ARL-12) and N-N'-Bis (2-aminoethyl) ethane-1,2-diamine hardener, brand name Lapox K-6 (AH312) matrix. The epoxy and hardener were mixed in the ratio of 10:1 as suggested by the manufacturer.

Eight layers of glass fiber woven mat was cut in which four layers had fiber orientation (0°/90°) and other four were of (+45°/-45°) fiber direction. Plies were stacked in the order of [(90°/0°), (+45°/-45°), (-45°/+45°), (0°/90°)] $_{2S}$, (figure 1) with each ply amply wetted with the liquid matrix. After placing the plies in the prescribed stacking order, a mild steel roller was rolled over the glass fibers to remove any trapped air as well as the excess polymer present. Figure 2 shows a sample being pressed under molding machine. The curing was done at room temperature for a period of 24 hours, under the pressure of 25 MPa.

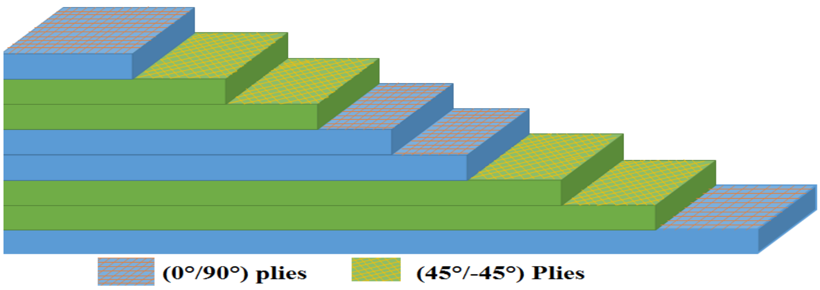

Figure 1. Ply stacking sequence of the laminate.

After the curing process was completed, samples for flexure test were taken out from the prepared laminates. Nine specimens for flexure test and one for fiber volume test were prepared. Further, nine samples for flexure test were subdivided into three categories, each one containing three specimens.

Stress raisers were created along the width by a computer controlled diamond tipped cutting wheel with a feed rate of 1mm/min. Samples without and with the asperities can be seen in figure 3(a and b).

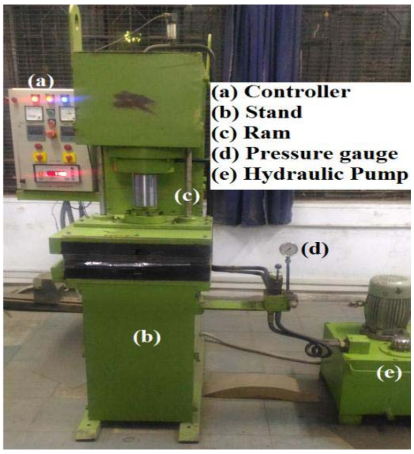

Figure 2. A press moulding machine.

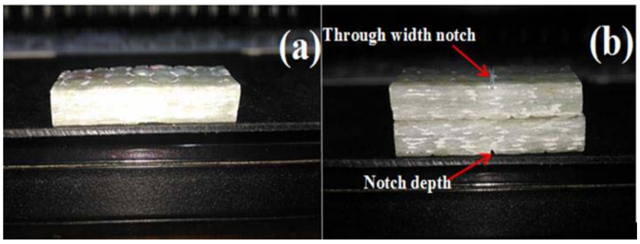

Figure 3. Specimen (a) without notch; and (b) with top and bottom notch.

3. Testing

Fiber volume fraction of the laminate was measured according to ASTM D2584-11 [11] standard specification. Flexure test of the samples were performed at the loading rate of 1mm/min on a Hounsfield H50KS universal testing machine having a load cell of 50 KN. A total of three samples from each set were tested according to ASTM D790-17 [12] standard. The position of the notch on the samples varied according to the loading direction (i.e. compressive and tensile face). Picture of the samples undergoing test is shown in figure 4.

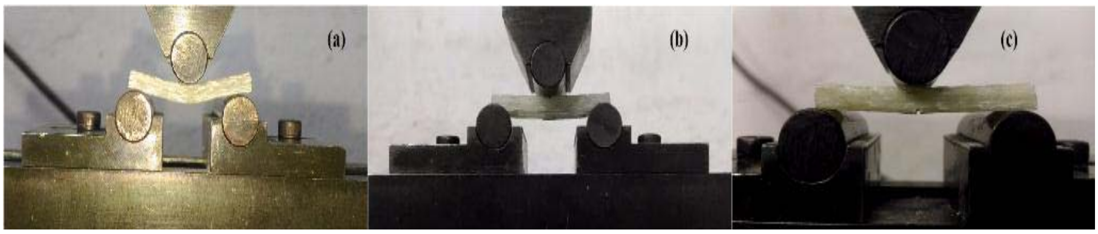

Figure 4: Samples undergoing flexure test (a) without notch; (b) with notch on top face; and (c) notch at bottom surface.

4. Results and discussion

Load vs. Displacement graphs generated for the tested samples are shown in figure 5 (a, b & c), whereas table 1 shows the individual and average flexure properties of the samples. A large scattering of data can be seen in samples with notch in terms of linearity and peak load. Whereas, unnotched specimens showed lesser deviation from the average results in terms of CV and SD. Burn residual testing showed the laminates contained 48% of fibers, thus formation of matrix rich region was inevitable. Table 2 shows standard deviation and coefficient of variation in the results for all the three batches.

Results showed that delamination was the major form of failure in all the samples, which was incited by matrix cracking, intra-ply crack saturation, fiber-matrix crushing and tensile failure. Although in samples without notch these phenomenon took place gradually in absence of any stress raisers. Samples tested with notch up showed increased flexure strain and strength. Since the notch was present on compressive face, its deformation compensated for the arc formation and delayed fiber-crushing phenomenon. Whereas samples with notch down did not compensated for crushing but also increased the tensile deformation within the samples. After peak load was attained, a sudden drop in load vs. deflection curve was observed. This was due to the propagation of simultaneous intralaminar and interlaminar cracks, which damaged the fiber-matrix interface [13] and failed the specimen.

Table 1. Flexure properties of the tested specimen.

Set Number and Name	No. of samples	Flexure strength (in MPa)	Average flexure strength (in MPa)	Flexure Strain	Average flexure strain	Flexure Modulus (in GPa)	Average flexure modulus (in GPa)
1	1	225.8		0.016		15.1	
(Without	2	241.1	234.7	0.017	0.018	15.13	14.44
notch)	3	237.4		0.020		13.1	
2	1	246.2		0.044		12.53	
(notch	2	235.3	240.7	0.019	0.036	12.6	13.27
up)	3	240.6		0.047		14.7	
3	1	221.6		0.024		11.67	
(Notch	2	196.4	194.5	0.020	0.02	11.72	11.9
below)	3	166.5		0.016		12.33	

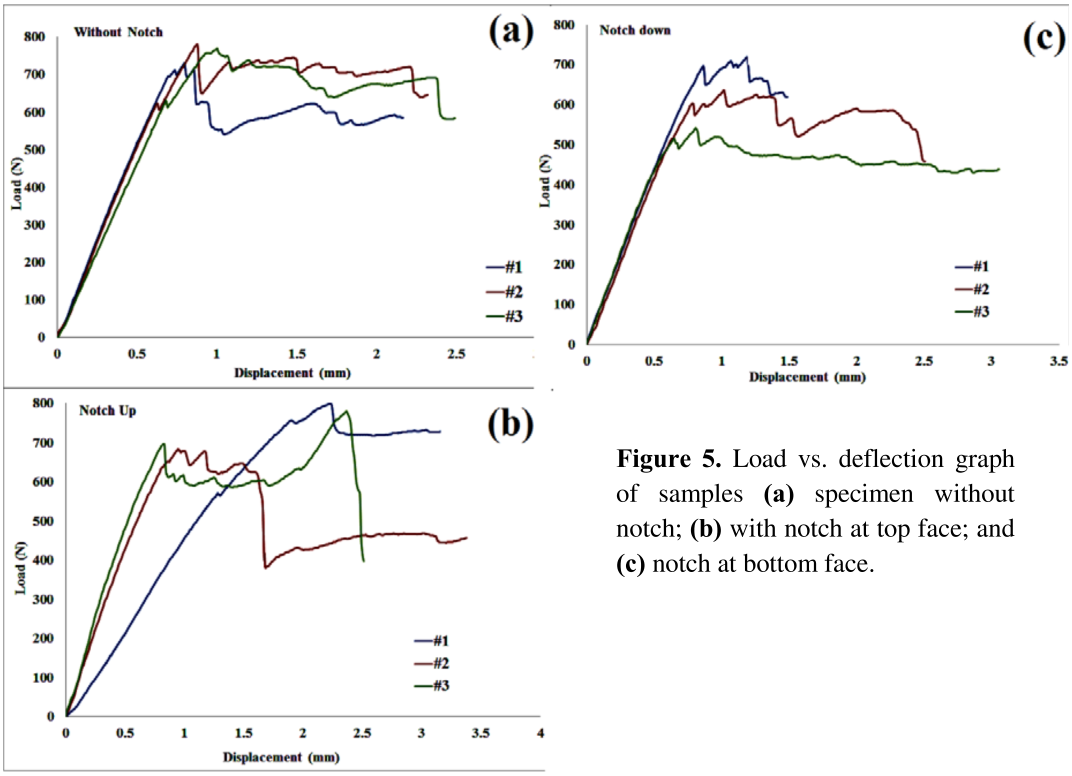

Figure 5. Load vs. deflection graph of samples **(a)** specimen without notch; **(b)** with notch at top face; and **(c)** notch at bottom face.

Table 2. Standard deviation (SD) and coefficient of variation (CV) in flexure results.

Batch no.	Flexure strength		Flexure strain		Flexure modulus	
	SD	CV	SD	CV	SD	CV
1, without notch	10.53	4.48	0.045	25.15	1.22	8.47
2, top notch	5.45	2.26	0.175	48.83	1.33	10.07
3, bottom notch	30.91	15.89	.004	20	.61	5.13

Figure 6 (a, b and c) shows edge of the failed samples. In each case delamination was severe on the bottom ply and originated from the notch edge only in the case of notch down specimen. Since diameter of the loading cylinder was larger than the notch width, samples loaded with notch up direction underwent less fiber crushing, and samples attained higher load and deflection. For notch down specimen delamination started from the notch as fiber crushing and tensile failure in the specimen were dominant. This made the samples attain lower deformation and load.

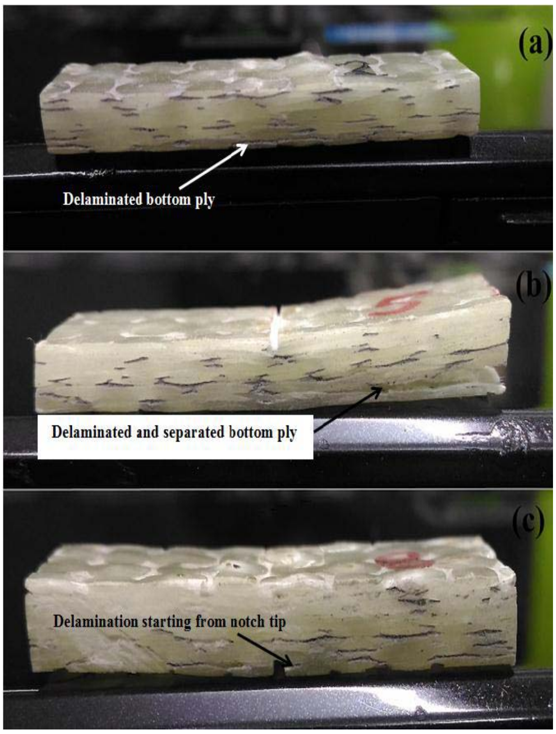

Figure 6. Edge of the failed specimen
(a) Without notch; (b) with notch at top face; and (c) notch at bottom face.

5. Conclusions

Flexure test on samples without notch and with notch on top and bottom face was conducted and the following conclusions can be drawn;

1. Under flexure loading top face fails by crushing, while bottom face fails by tensile deformation.
2. Inter and intraply delamination due to crack propagation is a major form of failure.

3. Stress concentration around a notch lowers the flexure strength, but its orientation about the loading direction decides the amount of reduction.
4. Notch at top face (compression side) led to ductile deformation in the sample, while notch at the bottom face (tensile side) did not alter the strain much.
5. Samples lost about 8% and 18% of average stiffness when notch was present on the top and bottom face of the specimen respectively.
6. Stiffness based modelling gave stress correction factor of 1.08 and 1.21 in case of 1x1mm notch present on top and bottom face of the laminate respectively.

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