OPTIMUM NOTCHED STRENGTH EVALUATION OF GLASS-FIBER REINFORCED POLYMERS USING DESIGN OF EXPERIMENTS

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ABSTRACT

Utilization of Glass fiber reinforced polymers has been increased tremendously in many engineering fields like manufacturing, aerospace and naval industry etc. The present work describes the development and notched strength evaluation of new polymer composites consisting of glass fiber reinforcements and epoxy resin. The aim of the present work is to determine the optimum notched strength of FRP composite laminate using DOE. In this study, three parameters viz. volume fractions of fiber, fiber orientation and notch depth with three levels each have been considered. Hence, L9 orthogonal array was selected to conduct the experiment. Laminates were initially treated with basic NaOH solution and fabricated by hand lay-up technique followed by curing under light pressure at room temperature for 24 hrs. The fiber reinforced composite laminates were fabricated and the tensile test has been conducted on the fabricated specimens as per the ASTM D638 standard. The fabrication of composite laminate is justified by conducting standard burn-out test for determining Volume fraction of fiber and tested for void content using ASTM-D2734. The level of importance and percentage contribution of each parameter on the tensile strength was determined by using Analysis of Variance (ANOVA). The optimum material parameter combinations and the corresponding notched strength of composite laminates were obtained using DOE and is found to be at 50% Volume fraction of fiber, 0^0 fiber orientation and 1mm Notch depth with mean ultimate strength of 400.17 MPa. Experimental results are validated using Analysis of Variance (ANOVA) technique and found that the percentage contribution of Fiber orientation is approximately 94.77% with prior importance. Analysis using ANSYS is performed on optimum combination for Maximum stress and deflection and is found to be in good agreement with test result.

Keywords: *Unidirectional E-glass fiber, Epoxy resin, Notched strength, Tensile test, Burn-out test, Void content, Optimization, Design of Experiments (DOE).*

1. INTRODUCTION

The popularity/usage of unidirectional composites has increased recently in the aerospace, automobile and defense industries due to their lower production costs, light weight, higher fracture toughness, low thermal expansion, corrosion resistance and better control over the thermo-mechanical properties. Hinge less and bearing less helicopter rotor hubs that are designed using laminated composite materials experience centrifugal loads as well as bending in the flapping flexure region. The demand for improved performance of these structural materials makes it necessary to evaluate these materials under multi-axial loading. Fiber-reinforced composites show strong orthotropic mechanical behavior due to their fiber orientations. Also, structural members have regions where the state of stress is significantly greater than the theoretical values due to geometric discontinuities. These stress concentrations are highly localized effects which are functions of geometry and loading. Under tensile loading, such discontinuities cause large rise in stress above the nominal stress values which causes sudden failure of composite material with less ductility.

Moreover, fiber orientations cause a variety of failure mechanisms, which are more complex under multi-axial loading conditions. Therefore, continuous effort has been made to make orthotropic composite materials with controlling parameters, such as the Volume fraction of fiber, Fiber orientation and notch depth. Several researchers found that bending strength was greater than tensile strength in polymeric composite materials. Wisnom reported in his review that the ratios between 3-point flexural strength and tensile strength of different composite materials were in the range of 1.3–1.49.The majority of engineering composites materials in demanding applications consists of continuous fibers of glass or carbon reinforcement in thermosetting epoxy polymer.

There has been a tremendous advancement in recent days. Compared to metals, the polymeric composites have many advantages as higher fatigue strength, higher corrosion resistance and lower weight polymeric composites are susceptible to mechanical damages when they are subjected to efforts of tension, flexural, compression which can lead to material failure. The basic concepts of composite materials along with details of earlier works are explained by author at reference. B.S. Hayes, E.N. Gilbert and J.C. Seferis investigated the influence of different sized glass fibers on the mechanical properties of glass fiber epoxy resin composites. S. Deng, L. Ye and Y.W. Mai investigated the compressive experimental study to identify the effects of fiber cross sectional aspect ratio on tensile & flexural properties and failure modes of glass fiber/epoxy composites by using fibers of different cross sectional. K.M. Kaleemulla and B. Siddeswarappa investigated the influence of fiber orientation and fiber content of epoxy resin components on mechanical prosperities. The main aim of the present investigation was to define the optimized parameter for a notched tensile specimen by considering the variable factors, using Design of Experiments.

2. EXPERIMENTATION

Glass fiber reinforced polymer composites are widely used now-a-days in various structural applications such as Wind turbine blades, chemical pressure vessels, fiber gratings, subsea installations protection covers etc. The present investigation is carried out using two basic materials: Unidirectional E-glass fiber and Epoxy resin. The matrix material was medium viscosity epoxy resin (LY556) with a room temperature curing hardener (HY951).The Unidirectional E-glass fiber is the reinforcement, with thickness of each ply about 0.6 mm.

2.1 Basic NaOH treatment

The fiber material is initially treated with basic NaOH solution to improve the surface roughness for better interaction between fiber and matrix, thus improving the strength property to some extent and remove dirt. This is the basic type of treatment carried out on fibers. NaOH treatment usually increases the strength of the fiber by 4%. NaOH was mixed at 40 grams per liter of water. The quantity of NaOH (40 gm/lit) taken is due to the reason that the molar mass of NaOH being 40 g/mol. The fiber is then soaked in the NaOH solution for about 1 hour. Then, the fiber is dried in open atmosphere for time period of 24 hours.

2.2 Parameters and their levels

Variable parameter that affect the tensile strength properties of the composite laminate are Volume fraction of the fiber, Fiber orientation and Notch depth. A total of 3 parameters are taken with three levels each, which is as shown in Table.1

Table 1: Process parameters for Notched Tensile response

Notation	Parameter	Level 1	Level 2	Level 3
V.F	Volume fraction, in %	40	45	50
F.O	Fiber orientation, in degrees	0	45	90
N.D	Notch depth, in mm	1	2	3

2.3 Selection of Orthogonal Array

Orthogonal Array is a statistical method used to define parameters that convert test areas into factors and levels. From the Orthogonal array selector, based on 3 factors and 3 levels, L9 series is selected thus reducing full factorial design to nine required subset of combinations with 27 runs, without compromising the test coverage and is shown in Table2. Once the parameters affecting a process that can be controlled have been determined, the levels at which these parameters should be varied must be determined. Also, the total degree of freedom is calculated and is found to be 6.

Table 2: Reduced full factorial design using L9 Orthogonal array

Test case	V.F	F.O	N.D
1	40	0	3
2	40	45	2
3	40	90	1
4	45	0	2
5	45	45	1
6	45	90	3
7	50	0	1
8	50	45	3
9	50	90	2

2.4 Specimen Configuration

The Unidirectional glass fiber-epoxy composite specimen is fabricated at room temperature and under constant pressure in the form of a rectangular plate by hand lay-up technique. Ample precautions were taken to minimize voids in the material. Specimen preparation includes three levels of volume fractions of fiber of 40-50% in steps of 5%. The specimen preparation is in accordance with ASTM D638 dimensions, with a V-notch located centrally as shown in Figure 1. This standard test method is used for testing materials with minimum of 1 mm in thickness and up to 14 mm. Specimen configuration also includes selection of three fiber orientations i.e. 0°, 45°and 90° and three notch depths of 1, 2 and 3mm were cut centrally.

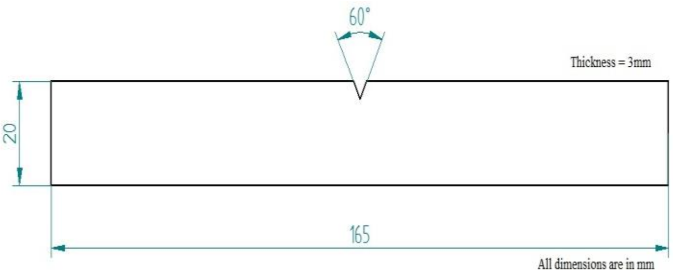


Figure 1: Dimensions of tensile specimen (as per ASTM D638 standards)

3. RESULTS AND DISCUSSIONS

3.1 Density

Density of the composite is measured experimentally using ASTM D2734 standard. It is observed that the density of the composite has no significant change with respect to fiber orientation but changes with increase in Glass content because glass being denser. Figure 2 shows the comparison of densities computed both experimentally and theoretically. It is ensured that the density obtained experimentally is less than the theoretical density and is compared.

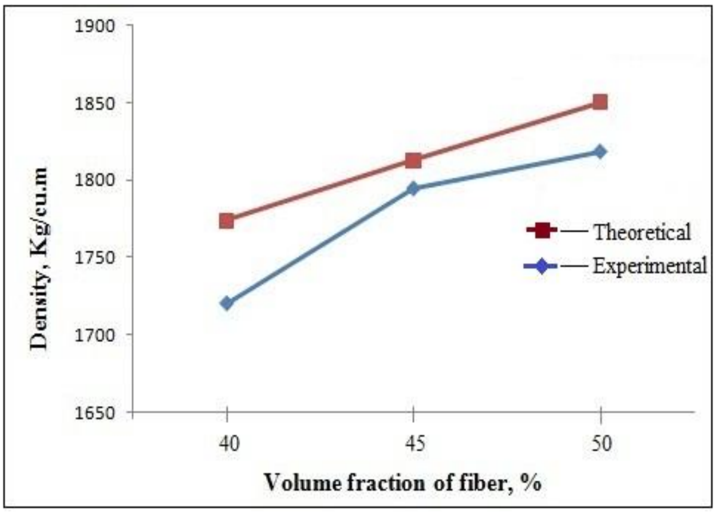


Figure 2: Graphical representations of Actual and Theoretical densities at different Volume fractions of fiber

3.2 Void Percentage

Void percentage in the treated composite specimen is computed using experimental and theoretical values of density from Table 4.1 and found to be well below the maximum value of 8%. Figure 3 shows the graph for void fractions at different volume fractions of fiber. From the observations, the fabricated composite specimen can be considered as good sample.

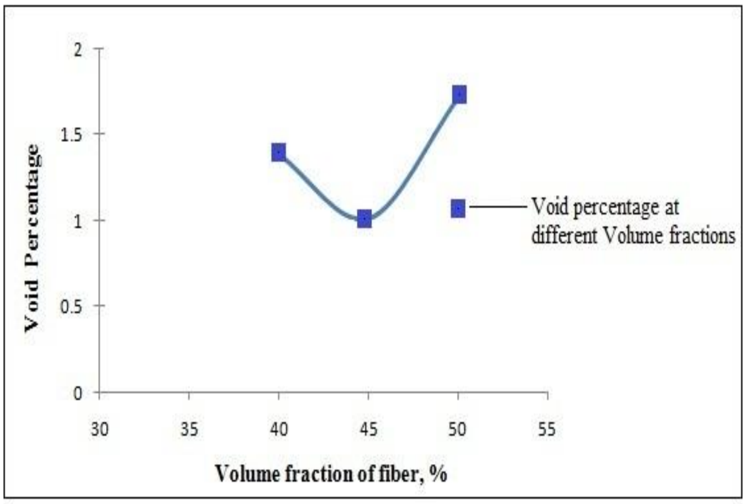


Figure 3: Void percentages at different Volume fractions of fiber

3.3 Fiber content

Fiber content in the fabricated composite material is ensured by conducting burnout tests. Weight of the composite specimen is measured before conducting burn-off test. Then the specimen is exposed to heat until the matrix gets evaporated entirely. Weight of the fiber after the test is taken. The difference in weights before and after the test is the weight of the matrix. Volume fraction of the fiber is then calculated by substituting the weights to Rule of mixtures equation. Figure 4 shows the percentage error in Volume fractions of the composite material found both theoretically and experimentally.

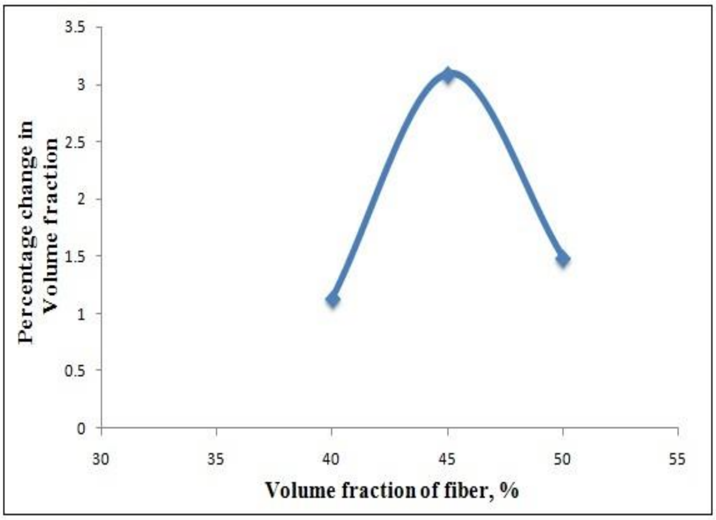


Figure 4: Percentage change for different Volume fractions of fiber

3.4 Experimental setup

The fabricated composite samples according to ASTM D638 standard are tested by applying tensile load using Universal Testing Machine (UTM). Figure 5 shows the tensile test specimens with different fiber orientation (0^0, 90^0, 45^0). The machine used for tensile testing of specimens can be used to apply a maximum load of 40KN. The specimen size is 165mm X 20mm X 3mm.

Fig 5 Fiber Orientations (0^0, 90^0, 45^0

3.5 Tensile Test Results

Tensile test has been carried out on composite specimens using UTM having specimen dimensions according to ASTM D638 standards. The results obtained are as follows and is shown in Table 3. S/N ratio is calculated using the relation

$$S/N \text{ ratio} = -10 \log (1/y^2) \qquad \text{-----} (1)$$

Where y = value of Mean Ultimate stress, MPa

Table 3: Tensile Test result

Test case	Subset	Trail 1	Trail 2	Mean stress, MPa	S/N Ratio
		Ultimate stress, σ_1	Ultimate stress, σ_2		
1	40,0,3	272	277.33	274.7	48.78
2	40,45,2	86.67	82	84.34	38.52
3	40,90,1	59.33	80.67	70	36.9
4	45,0,2	337.67	294.67	316.2	50
5	45,45,1	101.33	113.33	107.3	40.61
6	45,90,3	53.67	67.33	60.5	35.64
7	50,0,1	381	419.33	400.2	52.04
8	50,45,3	107.67	130.67	119.2	41.52
9	50,90,2	68.67	81	74.83	37.48

Based on the experimental results obtained by tensile test, means for S/N ratio and Ultimate strengths are calculated and are shown in table 4 and 5. Using this data, graph for ain effects plots for S/N ratios and means are shown in Figures 6 and 7. From the means and S/N plots, Volume fraction of Level 3, Fiber orientation of Level 1 and notch depth of Level 1, has the optimum parameter. From the observations, it is evident that Fiber orientation plays a major role in obtaining maximum Ultimate strength followed by Volume fraction of fiber and Notch depth.

Table 4: Analysis of Mean table for S/N ratio

Para meter	Level 1	Level 2	Level 3	Max-Min	Rank
V.F	41.4	42.08	43.68	2.27	2
F.O	50.27	40.21	36.67	13.6	1
N.D	43.18	42	41.98	1.2	3

Table 5: Analysis of Mean table for Ultimate tensile strength

Para meter	Level 1	Level 2	Level 3	Max-Min	Rank
V.F	143	161.33	198.06	55.06	2
F.O	363.67	103.61	68.44	295.23	1
N.D	192.5	158.45	151.45	41.05	3

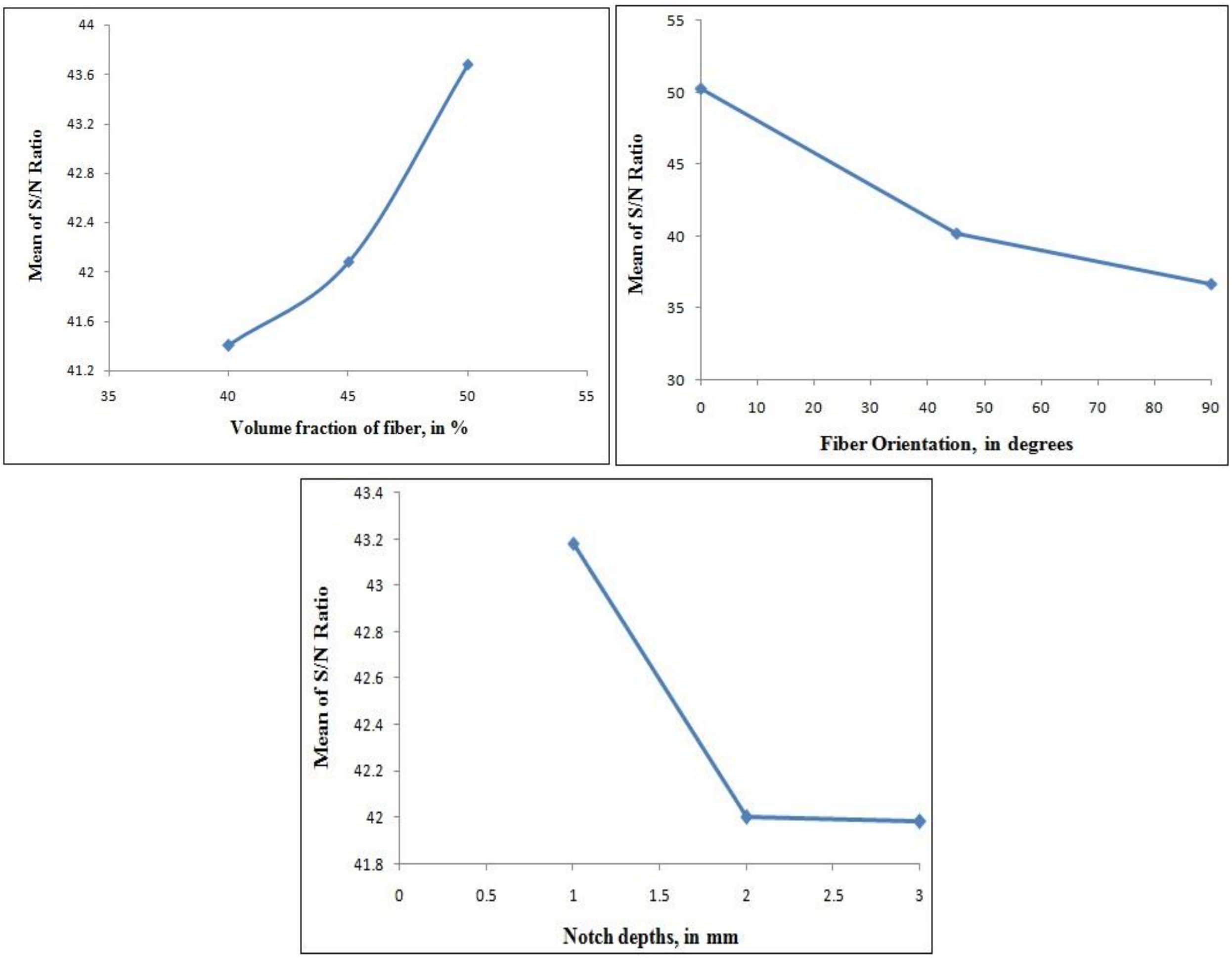
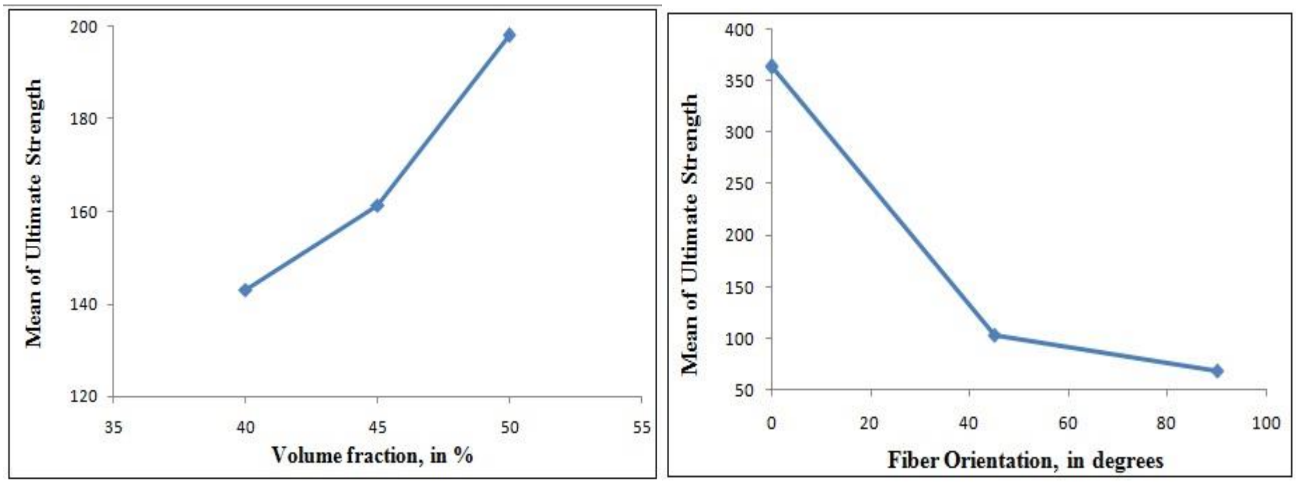


Figure 6: Main effects plot for S/N ratios



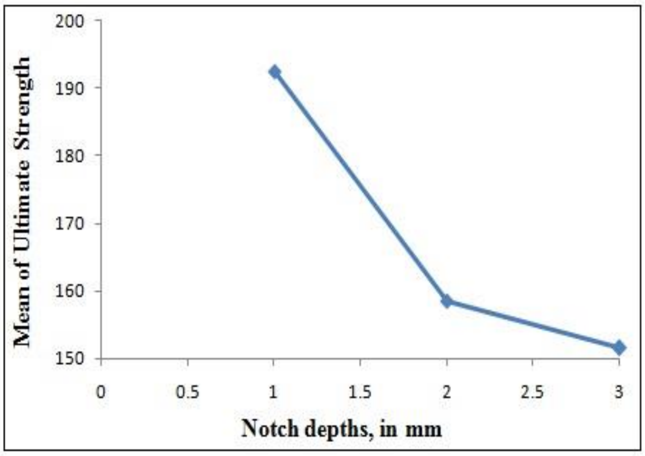


Figure 7: Main effects plot for Means

3.6 Analysis of Variance (ANOVA)

Analysis of variance (ANOVA) is a collection of statistical models used to analyze the differences between group means and their associated procedures (such as "variation" among and between groups). ANOVA is used in the analysis of comparative experiments, those in which only the difference in outcomes is of interest. The statistical significance of the experiment is determined by a ratio of two variances. Variable or Process parameters which affect the Ultimate strength of the composite material are obtained using ANOVA technique. The following formulas are useful for calculating the ANOVA table for S/N ratios and Ultimate strength.

Degrees of Freedom, DOF= No of parameters-1

$$SS_T = \Sigma^n_{i=1} (\beta_i - \beta_m)^2$$

$$F = \frac{Variance\ between\ Variable\ parameter}{Variance\ within\ variable\ parameter}$$

$$F = \frac{Mean\ Square_{parameters}}{Mean\ Square_{error}} = \frac{\frac{SS_{parameter}}{DOF}}{\frac{SS_{error}}{DOF}}$$

$$SS^1 = SS_{parameter} - (MS_{error} - DOF)$$

$$\%\ contribution\ of\ Parameter = \frac{Expected\ Mean\ Square}{Expected\ Mean\ Square\ error}$$

Based on the formulas presented above, analysis of variance table is calculated for S/N ratio and Ultimate strength and the values are shown in Table 6 and 7. Percentage contribution of each variable parameters are shown in Figure 6 and 7 respectively.

Table 6: Analysis of Variance (ANOVA) table for S/N ratio

Parameter	DOF	Sum of Squares	Mean square	F-Ratio	Expected sum of squares	% contribution
Volume fraction	2	8.21	4.105	3.22	5.7	1.85
Fiber orientation	2	295.31	147.66	115.9	292.72	94.85
Notch depth	2	1.98	0.99			
Pooled error	4	5.1	1.274		10.2	3.3
	6	308.62			308.62	100

Table 7: Analysis of Variance (ANOVA) table for Ultimate strength

Parameter	DOF	Sum of Squares	Mean square	F-Ratio	Expected sum of squares	% contribution
Volume fraction	2	4713.34	2356.67	2.48	2809.96	1.41
Fiber orientation	2	190625.74	95312.87	100.2	188722.36	94.77
Notch depth	2	2900.19	1450.1	1.52		
Pooled error	4	3806.77	951.6925		7613.54	3.82
	6	199145.85			199145.85	100

From the values in table 6 and 7, percentage contribution of Fiber orientation in both the cases i.e in S/N ratio and Ultimate strength seems to be same and is significance at 95% confidence level. Therefore from the observations, it is clear that the ultimate strength of the fabricated composite specimen is mainly dependent on fiber orientation which contributes about 94.77% among the parameters considered. Figure 8 and 9 shows the graph for percentage contribution of Volume fraction and Fiber orientation.

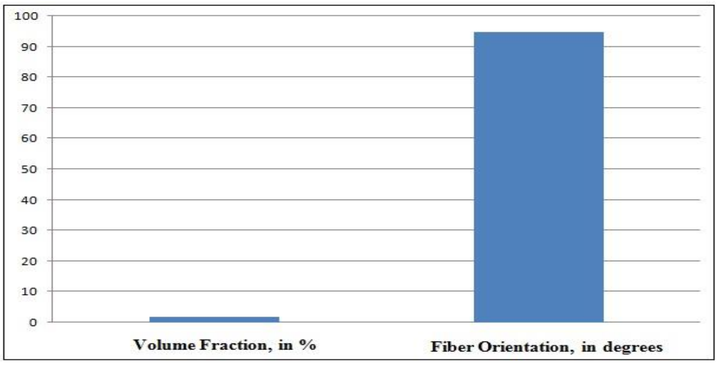


Figure 8: Percentage contribution for S/N ratio

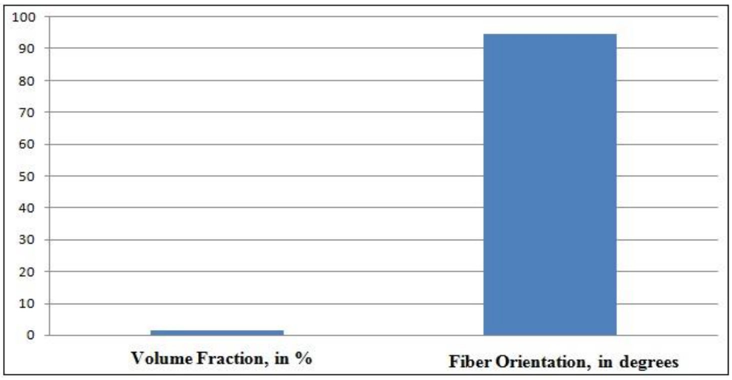


Figure 9: Percentage contribution for Ultimate strength

3.7 FEA ANALYSIS

The fabricated composite specimen is analyzed for Maximum or Ultimate strength using FEA software ANSYS. Analysis at 50% Volume fraction of fiber, 0^0 Fiber orientation and 1 mm notch depth is considered, as this yields the maximum stress value experimentally. 2D-SHELL 99 linear element is considered as element type for analysis with section lay-up given by 3 layers of 1mm each. Modelling is done by using key points and the area is developed by joining the key points using arbitrary KP's. Concentrated key point is generated at the tip of the notch as the stress concentrations accumulate near the notch tip and the part is meshed using fine mesh. Boundary conditions include all degrees of freedom at one end and loading at X-direction at the other end. The model is solved and the results are shown in Figure 10 and Table 8.

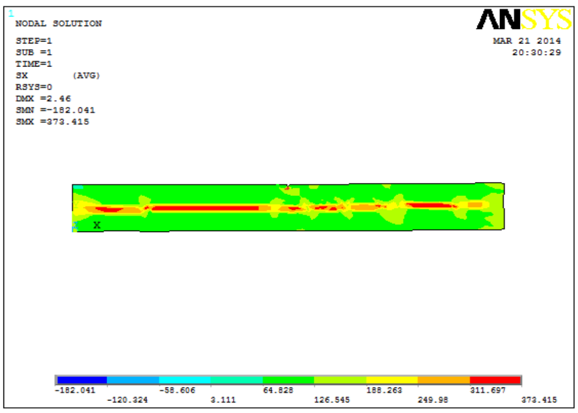


Figure 10: Ultimate strength of the specimen - ANSYS

Table 8: Comparison between experimental and ANSYS result

Parameter	Experimental	ANSYS	% error
Ultimate strength for 50,0,1 combination	400.17 MPa	373.415MPa	6.69

From the table, it is evident that the percentage error is well within the limits and analysis result is found to be in good agreement with experimental result.

4. CONCLUSION

Experimental investigations have shown that the fiber orientation plays a major role in Ultimate strength of the composite material but is less significantly dependent on Volume fraction and Notch depth. Minimum notch depth of 1mm gives maximum tensile strength, as the increase in depth of notch results in increased stress concentrations which reduces its strength and causes sudden failure. It is observed that the failure of the composite specimen takes place along the direction of the fiber in case of 45^0 and 90^0 fiber orientations but ductile failure along 45^0 plane in 0^0 fiber orientation. ANOVA technique is used to validate the discussions and is found that the optimum combination for maximum strength of the composite is at 50% Volume fraction, 0^0 Fiber orientation and 1mm Notch depth. It is also observed that fiber orientation has significant control over the ultimate strength of the composite material with percentage contribution about 94.77% while the Volume fraction and notch depths has less significance in determining the strength of the composite. FEA analysis is done to determine the strength of the composite analytically for the optimum combination and is found to be within the limits which is acceptable.

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