With the rise of huge variety of composites, the experimental determination of the mechanical properties of composite laminates under static loading conditions has always been a key issue in the research of composite materials. Since steel fiber reinforced polymer (SFRP) composite materials have been recently introduced as an alternative to glass and carbon fiber reinforced polymer composite materials the need for an efficient and reliable way of measuring and documenting these properties has become more important. Hence this chapter presents an insight into the characterization of macro mechanical behavior of steel fiber reinforced polymer (SFRP) hybrid composite material.

5.1 INTRODUCTION
Fiber reinforced polymer composites have steadily gained in popularity over the past four decades for use in fields ranging from aerospace to piping to sports equipment. This appeal is primarily due to their high strength-to-weight ratio, tailorable mechanical properties and fatigue resistance. In order to improve the properties of existing composites, a newer trend is towards the development of Hybrid Composites. Generally Hybrid applies to advanced composites and refers to use of various combinations of fibers or particulate in either thermoset or thermoplastic matrices. Hybrids have unique feature that can be used to meet the diverse and competing design requirements in a more cost effective way than either advanced or conventional composites. Traditional unidirectional laminated composites perform very poorly when subjected to transverse loads; in order to properly design the composites, bidirectional and hybrid composites evolved [44]. Therefore, characterization of such new materials is important as it helps to identify parameters that influence the strengths and response of composite materials, as fiber and matrix types and fiber-matrix interface.

Hence the investigations regarding characterization of mechanical behavior of hybrid composites appear quite vital for the purpose of materials development, quality control and comparative studies. For structural applications
it is now a common practice to design the structural element with computer-aided engineering software [53]. These computer codes require mechanical property data to calculate the stiffness and the maximum loading conditions of the structural component. Hence in the present work the preparation of composite specimen & experimentations were carried out as per ASTM standards and the outcome of the results are discussed in the following sections.

5.2 PHYSICAL PROPERTIES OF HYBRID LAMINATES

5.2.1 Density

Density of the laminates was measured according to the ASTM D792 standards [13]. Rectangular samples of size 100mm X 20mm X 10mm were used with thickness and width variations of ±0.25mm and ±0.20mm, respectively. Distilled water at room temperature was used as the immersion fluid and the mass was measured using digital balance with a $10^{-4}$ g resolution. To obtain the mean value of density of each group, a total of fifteen specimens, five from each group were tested.

![Graph showing density as a function of steel content for 0°/90° fiber orientation.](image)

**Fig. 5.1 Density as a Function of Steel Content for 0°/90° Fiber Orientation.**

Rule of mixture [41,66] is used to determine theoretical densities of the laminates; the difference in densities is shown in Fig. 5.1. The difference in theoretical and measured densities is mainly due to the presence of microvoids in
the composite. Hence it becomes quite essential to measure the percentage of voids in the samples prepared.

There is no significant difference in density of laminates with respect to fiber orientation due to approximately same warp and fill count. However, the experiments show that the density increases with the increase in steel content and it is obvious that as steel is the denser constituent among the selected ingredients, the specimen density increases.

5.2.2 Void Content
To analyze the void percentage in the composite laminates, ASTM D2734 standard was used [7]. One percent of the void indicates a good composite, but practical difficulty tends to increase the voids percentage. Since, the void content of a composite significantly affect the mechanical properties, higher percentages of voids usually mean lower fatigue resistance, greater susceptibility to water penetration and weathering and increased variation in strength properties. Knowing the densities of the constituents, the volume fractions of fiber, resin, and void are calculated based on two assumptions. The first assumption is that the mass of fiber in the composite is known (i.e., there is no fiber loss during manufacture). The second assumption is that the gas in any voids has the density of air, $1.29 \times 10^{-3} \text{ g/cm}^3$. The void content varies between 6.6 to 7.2 % for laminates with different percentages of reinforcement and the details are mentioned in Table 5.1.

5.2.3 Fiber Volume Fraction
To estimate the fiber content of the composite laminates ASTM D3171 standards [9] was used. This method consists of dissolving the resin portion of a weighed composite specimen in a hot digestion medium, i.e., Nitric acid. The residue is filtered, dried, and weighed. The weight percent of fiber can be converted to a volume percent by using the fiber and resin densities. The volume fraction of laminates was estimated for four samples in each group and the results are shown in Table 5.1.
Table 5.1 Physical Properties of the Composite Laminates.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Volume Fraction, %</th>
<th>Void Content, %</th>
<th>Density, Kg/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Polyester</td>
<td>Steel</td>
<td>Nylon</td>
</tr>
<tr>
<td>Sample-1</td>
<td>40±0.4</td>
<td>15±1.7</td>
<td>45±1.1</td>
</tr>
<tr>
<td>Sample-2</td>
<td>40±0.6</td>
<td>30±1.2</td>
<td>30±1.0</td>
</tr>
<tr>
<td>Sample-3</td>
<td>40±0.9</td>
<td>45±1.1</td>
<td>15±0.9</td>
</tr>
</tbody>
</table>

5.3 MECHANICAL PROPERTIES OF HYBRID LAMINATES

The primary purpose of any material characterization is to investigate its behavior under different mechanical loads. The results of the experimentation on the steel fiber reinforced composite material under different loading conditions and with various specimen configurations are discussed in the following sections.

5.3.1 Tensile Behavior of Composite Laminates

ASTM D3039 standards [8] were used to investigate tensile behavior of hybrid composite laminates. The rectangular specimen having dimensions 220 mm length (Gauge length 127±2 mm) X 25.4 mm width X 4mm thickness were cut from the planar of polymeric composites. For the in-plane properties of prepared laminates, end-tabs were bonded in order to provide effective gripping and also to ensure that the specimen failure is within the gauge length. The rectangular specimens are required for the composite material characterization, because the dog-bone type tends to split in the region where the width changes. The grips of tension test frame introduce large stress concentration in the specimen, to minimize this effect; tabs with tapered ends were bonded on either ends of the specimen. The test ready laminates were subjected to tensile loads on a computer controlled Universal Testing Machine and the tests were performed at a constant crosshead speed of 1.27 mm/min. In this work the tensile strength is defined as the ultimate strength at which the complete fracture of the specimen occurs and the corresponding load is the critical load or the maximum load a material can withstand and for laminates, this definition corresponds to the last-ply failure [74]. The tests were conducted at room temperature, and closely monitored. Some of the tensile tested specimen are shown in Fig. 5.2 and the
effect of various parameters on the tensile strength is discussed in the following sections.

Fig. 5.2 Tensile strength tested specimen Photograph.

5.3.1.1 Effect of Fiber Content and Orientation

In this section the effect of fiber content and fiber orientation on tensile strength is analyzed for different specimen configurations. The tensile specimen prepared to suit ASTM standards was subjected to tensile load and the test results are shown in Fig. 5.3 (a). The experimental results clearly indicate the increasing trend in tensile strength is due to increased percentage of steel content; this is evident since the mechanical properties of the steel fibers are superior to those of the nylon and polyester matrix [57]. At the same time the tensile strength of the composite is influenced by the strength and modulus of fibers [102]. At the same time the displacement due to tensile loading is marginal for laminates with higher percentage of steel content, whereas it is considerably greater for laminates with steel percentage less than 30%. These variations notify the evolution of the composite displacement at break with little fibers filling ratio because the displacement at break of the fibers and the resin are too close. The increase in steel fiber content at the cost of decrease in nylon fiber leads to increase the tensile strength but the failure of the specimen may be due to the effect of poor interlaminar shear strength. This is presumed to be due to the poor interface resulted between the steel and polyester and hence debonding observed to be more in the laminates with higher steel percentages.
Normally, the composites are designed to load in the direction of the reinforcements. However, in such cases where the load directions is off-axis and not parallel to the fibers, it becomes important to investigate the laminate mechanical behaviour. The authors at reference [74,84] have shown that the composite laminates with 0/90° and ±45° orientations resulted in highest and lowest tensile strengths respectively. Hence, to investigate the effect of fiber orientation, three different orientations namely 0/90°, 30/60° and ±45° were selected in this work. Specimens with different fiber orientations were prepared with the same process as mentioned earlier to suit ASTM D3039 standards [104]. For each of the three fiber orientations, the specimens with three fiber volume fractions were tested and the results indicating the effect of fiber orientation can be seen from the Fig. 5.3 (b).

The experimental results show that the tensile strengths are affected by the fiber orientation significantly. The tensile strength is superior in case of 0/90°
oriented specimens as compared to specimens with 30/60\(^0\) and ±45\(^0\) orientations. This is attributed to be the reason in case of 0\(^0\)/90\(^0\) orientation where the external tensile load is equally distributed on all the fibers and transmitted along the axis of the fibers. Whereas in case of other fiber orientations, fiber axis is non-parallel to load axis, resulting in off-axis, pulling of fibers and increased stress concentration causing the earlier failure of laminates. Even in case of 30/60\(^0\) and ±45\(^0\) orientations, the trend of increased tensile strength for increase in steel content found to be true, but it can be clearly observed that the margin of increase is comparatively less. The displacement due to tensile loads again follow the same trend of increased displacement for increase in nylon percentage, this may be due to greater extensibility of nylon fibers than other constituent materials [48,49]. But on comparison it is found that the displacement in case of laminates with ±45\(^0\) fiber orientation is large compared to laminates with 0/90\(^0\) and 30/60 orientations owing to off-axis loading and significant fiber pull out before fracture.

5.3.1.2 Effect of Notch Size

Tensile tests on notched composite specimens were conducted as per ASTM D3039 standards. The specimens were prepared with a single end notch located centrally on the length side. The specimen configurations include three volume fractions and three orientations as selected earlier with a notch having 2mm width & different depths such as 2, 4, 6 and 8mm, as shown in Fig.5.4. The notched tensile tests were carried on a computer controlled Universal Testing Machine. The specimens were clamped and subjected to monotonic uniaxial tension; the tests were conducted at room temperature and closely monitored. The load at which the complete fracture of the specimen occurred was taken as the critical load. The analysis of results include categorization of specimen with respect to percentage of steel content, hence results of samples with respect to volume of steel is grouped and shown in Fig. 5.5.

![Specimen for Notched Tensile Strength.](image)

Fig. 5.4 Specimen for Notched Tensile Strength.
Again the effect of steel content can be observed from the results where in the strength increases with the increase in steel percentage. The notched tensile strength assumed to be dependent not only on fiber content, but also dependent on the notch depth. Even the specimen with higher steel content has exhibited less tensile strength for larger notch depths.

![Graphs showing influence of fiber orientation and notch depth on tensile strength for different steel contents.](image)

**Fig. 5.5** Influence of Fiber Orientation and notch depth on the tensile Strength for (a) 15% steel (b) 30% steel and (c) 45% steel.
From the Fig. 5.5 it can be seen that the laminates have shown that effect of orientation is highly significant, however the influence of notch size and steel content for a given fiber orientation reduces the strength considerably. Comparing the strengths, it can be observed that the margin of reduction in tensile strength is quite less after 4mm of notch depth for laminates with 15% and 30% of steel content. However in case of 45% steel laminates such a behavior is not observed and this may be attributed to the poor interfacial bonding between steel and polyester.

5.3.1.3 Notch to width ratio
The tensile laminates with notches carry much less load than that of the unnotched laminates. The stress at the edge of the notch was normalized by tensile strength and the plots drawn against the ratio of laminate width to notch depth are shown in Fig. 5.6. Both 15% and 30% steel content laminates show approximately linear relation with respect to the width to notch ratio indicating a proportionate strength reduction, while the same relation in case of laminates with 45% steel content seems to be not linear, this might be because the laminates are rich in steel content and hence exhibit the properties of steel.

Though the trends show linear relation for 15% and 30% steel laminates, these composite laminates are non-linear in nature because the composite combinations fall in the category of brittle materials. The increased stress accumulation at the notches reduce the tensile strength of the specimens and it can be seen that the reduced width ratio is responsible for reduction in tensile strength. Hence, for safe structural design, larger width factors are preferred. Normally the specimen with smaller width factor introduces higher stress concentration and hence smaller width factors are not preferred. The effect of fiber orientation on tensile strength for various notch sizes can also be seen from the Fig. 5.6. It can be observed from the figure that hybrid laminated composite specimens with 0/90° orientation show higher load bearing capacity compared to 30/60° and ±45° degree orientation irrespective of notch sizes. This may be due to the fact that 0/90° oriented fibers are coaxial with external load and hence loading is uniform and stress concentration is less. Whereas with ±45° orientation
due to aligned fibers and the loading axis, the effect of stress concentration is higher and hence the laminates fail early.

Fig. 5.6 Effect of width ratio on the tensile Strength of Laminates with different orientations for (a) 15% Steel, (b) 30% steel and (b) 45% steel.

Further it can also be observed from the Fig. 5.6 that, for 45% steel content specimen having a notch size of 8 mm, the tensile strength is 66.5 MPa for 0/90° orientation and in case of laminates with ±45°orientation tensile strength is 49.85 MPa (i.e., a reduction in tensile strength by about 28%). The influence of
notch size is greater for laminates for 45% steel content compared to 30% & 15% steel content laminates and which is found to be true irrespective of fiber orientation. Similarly the margin of reduction in tensile strength observed to be very high in case of 45% steel content laminates compared to 15% & 30% steel content laminates. This variation in behavior assumed to be due to the reason that steel is highly sensitive to external loading and crack propagation.

5.3.1.4 Finite element analysis

Typically, the behavior of reinforced composites is studied by full-scale experimental investigations. Finite element analysis can be used to model the behavior numerically, as well as to provide a valuable supplement to the laboratory investigations, particularly in parametric studies. Finite element analysis, as used in structural engineering, determines the overall behavior of a structure by dividing it into a number of simple elements, each of which has well-defined mechanical and physical properties.

The hybrid composite tensile test specimen was modeled using linear shell 99 elements for the configurations shown in Table 5.2. This element allows up to 250 different material layers with different orientations in each layer. The input data needed for the analysis such as number of layers, thickness of each layer, orientation of the fiber for each layer, elastic modulus & Poisson’s ratio of both the reinforcements were mentioned. The coordinate system was defined such that the x-direction was same as the fiber direction, while the y and z-directions were perpendicular to the x-direction. The analysis was carried out for various mesh densities in order to achieve the convergence of results.

The finite element results agree quite well with the experimental data with the error percentage ranging from 2.5 to 7.49% and hence the validity of the results. However, the stresses obtained in the FEM analysis were slightly higher than those from the experimental results at the same load. This difference may be due to some of the assumptions being used in the modeling such as linear elastic properties, the existence of perfect bond between materials and the exclusion of micro cracks in the model. The Von-Mises stress contours for specimen configurations mentioned in Table 5.2 are shown in Figs.5.7 to 5.12.
Table 5.2 Comparison of Experimental and FEM Results.

<table>
<thead>
<tr>
<th>Specimen configuration</th>
<th>Experimental Results in MPa</th>
<th>Fem Results in MPa</th>
<th>Error, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>45%, 0/90°, Unnotched</td>
<td>81.33</td>
<td>86.76</td>
<td>6.67</td>
</tr>
<tr>
<td>45%, 30/60°, Unnotched</td>
<td>74.36</td>
<td>77.75</td>
<td>4.56</td>
</tr>
<tr>
<td>45%, ±45°, Unnotched</td>
<td>65.30</td>
<td>68.22</td>
<td>4.47</td>
</tr>
<tr>
<td>45%, 0/90°, 4mm Notch</td>
<td>69.80</td>
<td>75.03</td>
<td>7.49</td>
</tr>
<tr>
<td>45%, 30/60°, 4mm Notch</td>
<td>59.82</td>
<td>61.32</td>
<td>2.50</td>
</tr>
<tr>
<td>45%, ±45°, 4mm Notch</td>
<td>54.12</td>
<td>57.79</td>
<td>6.78</td>
</tr>
</tbody>
</table>

Fig.5.7 Von-Mises Stress Contour for 0/90° Orientation (Un-Notched)
Fig. 5.8 Von-Mises Stress Contour for 30/60° Orientation (Un-Notched).
Fig. 5.9 Von-Mises Stress Contour for ±45° Orientation (Un-Notched)
Fig. 5.10 Von-Mises Stress Contour for 0/90° Orientation (4mm Notch).
Fig. 5.11 Von-Mises Stress Contour for 30/60° Orientation (4mm Notch).
Fig. 5.12 Von-Mises Stress Contour for ±45° Orientation (4mm Notch).
5.3.2 Compressive Behavior of Composite Laminates

The ASTM D3410 standards (Width 38.1±0.1, length 60±0.2 mm and thickness 6.4 to 8.0mm) were adopted for the study of compressive behavior [10], the rectangular specimens with 6mm thickness were cut to suit required dimensions from the polymeric composite laminates. The rectangular specimens were tested in a Universal Testing Machine at a constant cross-speed. To minimize the effect of stress concentration, tabs with tapered ends were bonded on each side of the specimen. All the specimens were tested at room temperature; the photographs of the compression-tested samples are shown in Fig. 5.13. This test is important because it helps to identify parameters that influence the compressive response of composite materials, as fiber and matrix types and fiber-matrix interface. Following discussion outlines the effects of various parameters on compressive strength.

Fig. 5.13 Compression strength tested specimen Photograph.

5.3.2.1 Effect of Fiber Content and Orientation

The results of the compression test are shown in Fig. 5.14, to analyze the effect of fiber content and fiber orientation. Again it is quite evident from the results that the compressive strength is superior for 0/90° bidirectional fiber orientation, which may be due to the reason that the longitudinal fibers directly absorb, transfer and
distribute the load uniformly throughout the cross-section. Whereas in case of other fiber orientations, the compressive strength is comparatively lesser, this difference in the load bearing capacity of composites might be due to the fibers start slipping as they are subjected to the load. Also from the Fig. 5.14 it is evident that as steel fiber percentage increases, compressive strength will also increase and is true up to 30% of steel content. The change in compressive strength is quite marginal from 30-45% of steel content; this may be due to the percentage increase of steel fibers where the laminates experience poor interfacial bonding and hence resulting into large buckling, delaminations and failure of the laminates.

![Graph showing Influence of Fiber Content and Orientation on Compressive Strength](image)

**Fig. 5.14** Influence of Fiber Content and Orientation on the Compressive.

### 5.3.2.2 Effect of Notch Size

Compression failure may occur in several modes ranging from buckling of the whole composite specimen to actual material compression at the microstructural level depending on material properties and loading scheme. Effect of notches on the compressive strength of laminates was carried out in accordance with ASTM D3410 standards [10], with a single ended notch centrally located along the length side. The laminates with notch depths 1, 2, 3, and 4mm were cut on all specimen configurations. The compression test specimen with three fiber orientations and volume fractions with various notch sizes were loaded on a computer controlled Universal Testing Machine. The experimental setup and testing conditions were same as that of the usual compression test.
The results of the experimentation are shown in the Fig. 5.15, the trends clearly indicate that more the percentage of steel, superior will be the notched compressive strength and at the same time the greater the notch depth, lesser will be the compressive strength and this behavior is found to be true irrespective of fiber orientation. It is also observed that the notched compressive strength is less in case of ±45° orientation specimens compared to other orientations. The effect of notch is less severe for notch depths between 2-4mm, because the
margin of reduction in compressive strength is less for depths greater than 2mm. This may be due to increased stress concentration at the notch root and smaller cross sectional area of resisting material.

5.3.2.3 Notch to width Ratio
The notched compressive strength of the laminates is plotted against width ratio as shown in Fig. 5.16. The significance of width to depth ratio can be clearly seen from the figure, the laminates sustain higher compressive loads for higher width ratios. This is attributed to the fact that as width ratio reduces; the load bearing material reduces and hence smaller notched compressive strengths.

For width ratios less than twenty, the load bearing material is less resulting in to smaller notch compressive strengths. This behavior of the laminates reveal the fact that the composites with smaller load bearing material exhibit higher stress concentration, resulting into the failure of earlier laminates. The failure of these laminates is not only due to reduced load bearing area but may also be due to the difference in Poisson’s ratio between the matrix and fiber. This difference in Poisson’s ratio increases the internal stresses at the interfaces causing elevated stress concentration and finally the failure of the laminates. Again at the same time longitudinal compressive loading produces transverse tensile stresses within the matrix. These transverse tensile stresses can result in longitudinal cracks developing parallel to the fibers within a weak matrix. In addition, a weak interface may also fail under these transverse tensile stresses. The voids within the matrix or at the interface will act as stress concentrations and increase the chance of longitudinal cracking. Upon further loading, these cracks will grow and result in transverse rupture of the composite.
Fig. 5.16 Width ratio for the notched compressive strength of Laminates for different orientations and notch depths (a) 15% steel, (b) 30% steel and (b) 45% steel.

5.3.3 In-Plane Shear Properties of Laminates

To determine the in-plane shear properties of the laminates, off-axis tensile tests were carried in a Universal Testing Machine. The specimens prepared from the laminate with an off-axis angle of 45° such that the bidirectional fiber orientation is ±45°. The specimen dimensions and test setup was in accordance with ASTM D3518 standard [11] (Width 25.4±0.1, Gauge length 127±2mm and thickness 3.25mm). For gripping and uniform load transfer the laminates were bonded with
end tabs. Testing conditions and rate of loading was same as that of the tension test. This test method involves the measure of the axial load applied to a ±45° symmetric laminate and from these experimental data the in-plane shear stress referred to the material principal coordinate system, can be obtained as proposed by Rosen [23]. The experimental results of the In-plane shear stress are shown in Fig. 5.17.

![Fig. 5.17 In-Plane Shear Stress of laminates for various steel percentages.](image)

Again as expected, the laminate with the highest percent of steel has the largest tensile strength of 65.3 MPa and its respective shear stress with 32.65 MPa. The marginal increase in shear stress is obtained for considerable increase in steel content, this is mainly due to the shear stress is dependent not only on fiber strength but also on the contact areas [64]. Since in this work the contact area is more or less the same for all the specimen combinations, the variation in shear stress may be mainly due to the steel percentage and not to the contact area. The experimental results show that shear stress ranges between ≈10 to 33 MPa for variation in percentage of steel content between 15 to 45%.

### 5.3.4 Flexural Behavior of Composite Laminates

To investigate the flexural behavior of laminates ASTM D790 standards (Width 13±0.1, Gauge length 130±2 and thickness 6.4 to 10 mm) were used [12]. Specimens were loaded in three point bending arrangement with a recommended span to depth ratio of 16:1. The load was applied at a constant cross head speed at room temperature and the failure load for flexural strength is
obtained. The flexural test samples are shown in Fig 5.18 and the results of the experimentation are shown in Fig. 5.19.

![Fig. 5.18](image)

**Fig. 5.18** Flexural test samples with various steel percentages.

![Fig. 5.19](image)

**Fig. 5.19** Flexural Strength of laminates for various steel percentages and orientation.

From the above figure the variation in flexural strength of the samples with respect to steel fiber content clearly indicate that greater the percentage of steel, higher will be the flexural strength [56]. The results also indicate that the flexural strength of the samples is also an indicative of the relation between the flexural strength and fiber orientation. It is observed that the flexural properties of these hybrid fiber-reinforced composites were significantly less for fiber orientations other than 0/90°, this might be because of the reason that the straight continous fibers in case of 0/90° distribute load uniformly with reduced stress concentration [93]. As the steel fiber is added to the hybrid composite, a positive hybrid effect has been observed, while decrease in flexural strength of the reinforced samples
was recorded with increased percentage of nylon reinforcement. This may be due to the lower strength of the nylon reinforcement. Almost all the specimens fractured with the fracture occurring under the loading nose. These specimens appeared to have failed in tension since a much greater amount of damage is evident on the tension side of the specimens. The crack at the fractured location appeared to be propagated from the tensile surface to compression surface. In addition, at the fracture, the compression side of the specimen showed much greater deformation than the tension surface. The cracks appeared to have propagated away from the loading nose resulting in delamination of laminate. The direction of crack propagation and delamination is same for the entire sample irrespective of percentage of steel content and it lies on the tension side. However, the severity of delamination is more for samples with higher steel percentage and at the same time the tensile surface of the laminates showed no visible signs of damage. Comparing the laminates with respect to fiber orientation, the laminates with 0/90° fiber orientation have showed failure with transverse cracks formation on laminates before failure, whereas for laminates with 30/60° and ±45° fiber orientations diagonal cracks aligned approximately at an angle equal to the fiber orientation angle were observed.

5.3.5 Impact Behavior of Composite Laminates

The machines with their pendulum-type hammers have been standardized including a fixed mass of the hammer and height of hammer fall, which results in a substantially fixed velocity of the hammer at the moment of impact. The striking edge of the pendulum in Charpy test, is tapered with an included angle of 45° with a radius of 3.17mm and with an angle of fall being 141.45°. According to the ASTM D256 standard [6] impact tests were carried on laminates. The fracture specimen geometry used in this study is the standard Charpy V-notch specimen (45° angle), with a length of 55 mm and a cross section of 10 mm X 10 mm, with a notch at mid length having 0.25 mm root radius and 2 mm deep. A tri-axial state of stress is developed at the root of notch and hence notched specimens are used in these tests. The specimen preparation includes the selection of different fiber orientations and volume fractions as mentioned earlier. Some of the impact-tested samples are shown in Fig. 5.20.
The specimen was clamped into pendulum impact test fixture with the notched side facing the striking edge of the pendulum. The pendulum was released and allowed to strike through the specimen, the standards used for the investigation define test conditions in order to decrease dynamic effects so that a quasi static loading situation may be assumed [88].

The experimental results for the standard specimen are shown in Fig. 5.21, from which it can be clearly seen that the steel content plays vital role in the impact strength of laminates. Hence, it can be said that more the steel percentage more will be the impact toughness and it can also be observed that the impact strength has increased significantly for an increase in steel percentage; this trend is true irrespective of fiber orientation. The margin of
increase in impact toughness for increased steel percentage is approximately same for all the orientations. However, the laminates with 30/60° and ±45° orientations have indicated reduced impact strength compared to 0/90° fiber orientation, this may be due to uniformity in fiber lengths and stress distribution in 0/90° oriented specimen.

5.3.6 Fracture Toughness
The fracture toughness of any composite material is dependent on the type of loading, the material composition, fiber orientation and also the fiber percentage. Hence to analyze the effect of these factors, the discussion is grouped into three sections based on the type of loading.

5.3.6.1 Fracture Toughness under tensile loading
The fracture toughness of the laminates due to tensile load is shown in Fig. 5.22; the trends reveal that the fracture toughness is directly influenced by fiber percentage and orientation. The results show that as fiber percentage increase fracture toughness will also increase and it is comparatively greater for 0/90° fiber orientation. However, it is mainly dependent on the notch depth. From the figure it is revealed that as the notch depth increases, the fracture toughness also increases.

This does not mean that the toughness will increase as depth increases, but it means that the resistance offered by the available material exposed to external load is more compared to the material with small notch depths. It can also be observed from the Fig.5.23 that, there is no such significant difference in fracture toughness for increase in steel fiber content ranging from 15 to 30%. But fracture toughness has increased significantly for 45% steel content and this increase may be due to the fact that steel has superior fracture toughness as compared to all the constituents of the composite and hence at 45% steel level the component starts exhibiting the properties of steel, which acts as a dominant reinforcement.
Fig. 5.22 Influence of notch depth on Fracture Toughness of Laminates under Tension for (a) 15% steel, (b) 30% steel and (b) 45% steel.

Also from Fig. 5.22, it can be noted that the fracture toughness is more for laminates with 0/90° orientation in comparison to ±45° and 30/60° oriented laminates. The fracture toughness for a 45% steel content specimen with 8mm notch is 17.55 MPa.√m for 0/90° fiber orientation, whereas for the same combination it is approximately 12.68 MPa.√m for ±45° oriented specimens. And
also this trend found to be true for all specimens irrespective of steel percentage and notch depths.

**Fig. 5.23** Influence of notch depth on Fracture Toughness of Laminates under Tension for (a) 0/90° Orientation (b) 30/60° orientation and (c) ±45° Orientation.
Fig. 5.24 Effect of Width to Notch ratio on Fracture Toughness of Laminates under Tension with various Steel Percentages of (a) 0/90° Orientation, (b) 30/60° orientation and (c) ±45° Orientation.

The influence of fiber orientation can be assessed by analyzing Fig. 5.23, there is significant variation in fracture toughness with respect to orientation angle for a given notch depth and steel percentage. The percentage of steel
influences directly the fracture toughness, at the same time for a given notch depth the C/W ratio is also same, but the laminates indicate reduction in fracture toughness with respect to fiber orientation. This is because the fracture toughness has been estimated using tensile test specimen, and the tensile strength of the laminates is mainly dependent on fiber orientation.

During tensile test the load axis is coaxial with specimen axis, if the fibers are arranged such that they are parallel to load axis then, load carrying capacity of laminates increase, otherwise it reduces. In case of 0/90° orientation laminates the fibers are parallel and hence load carrying capacity of these laminates is higher, whereas ±45° oriented laminates have fibers inclined at 45° degree angles and hence load axis and fiber axis does not match resulting in increased stress concentration and uneven load distribution among fibers causing early failure. Compared to the failure of ±45° and 0/90° specimens, the 0/90° oriented specimen fail completely and fibers break resulting into a brittle failure whereas in case of ±45°oriented specimen fibers slip, initiate delamination and partial failures with fibers pulling out of matrix.

The basic parameter to compare the notched specimen is by using the width to notch ratio, which is essential to bring all the results on a common scale for comparison. From the Fig. 5.24 it can be seen that greater the width ratio lesser will be the fracture toughness, and it is true for all laminates irrespective of steel percentage and fiber orientation. This behavior reveals that the gain in fracture toughness for deep-notched laminates is very high for marginal reduction in width ratios. This behavior is mainly due to greater resistance offered by the laminates before failure. Hence, due to this, the fracture toughness will increase drastically, and it can be clearly seen in laminates with deep notches.

5.3.6.2 Fracture Toughness under compressive loading
The notched compressive strengths are used to evaluate the fracture toughness of composite laminates under compression and the results are shown in Fig. 5.25. The results indicate superior fracture toughness for laminates with higher percentages of steel content and this trend found to be true in majority of cases irrespective of fiber orientation and notch depths.
Fig. 5.25 Effect of notch depth on Fracture Toughness of Laminates under Compression for various fiber orientations for (a) 15% steel (B) 30% steel and (b) 45% steel.
The effect of notch depth on fracture toughness is quite significant in 30 and 45% steel laminates indicating increase in fracture toughness with respect to notch depth for all the orientations. While the laminates with 15% steel content have exhibited marginal change in fracture toughness for change in notch depth and it is found to be true for all the fiber orientations. This behavior of laminates may be due to nylon fibers, which are poor in compressive strength. Comparing laminates with respect to the fiber orientation; it was observed that the laminates with 0/90° fiber orientation have superior toughness, this behavior of laminates may be attributed to the reason that the fiber and load axis are co-axial which is already discussed in the earlier sections.

Comparing the laminates based on percentage of steel content; the trends indicate increase in fracture toughness for increased percentage of steel content. However, for laminates with 45% steel content, the fracture of laminates was found to be due to delamination, whereas in other cases the failure of laminates were indicative of buckling. The lower fracture toughness of laminates with ±45° fiber orientation may be attributed to the off-axis loading, which results in to shorter fiber length and reduced interface. The effect of width to notch ratio can be depicted from the Fig. 5.26, the results of the analysis indicate lower fracture toughness for specimens with 15% steel content and it is found to be valid for all the fiber orientations. While the laminates with 0/90° and 30/60° fiber orientation resulted into greater toughness for increased notch depths, upto the toughness threshold. The SFRP laminates indicate a threshold value of 20 for the ratio (W/C), this threshold value is same for all the samples with different orientation and fiber percentages.
Fig. 5.26 Effect of Width to Notch ratio on Fracture Toughness of Laminates under Compression with various Steel Percentages of (a) 0/90° Orientation, (b) 30/60° orientation and (c) ±45° Orientation.
5.3.6.3 Fracture Toughness under Impact

The results of the impact test in terms of the energy are used to determine the fracture toughness of all the laminates and are shown in Fig. 5.27. From the results the effect of steel percentage and orientation on fracture toughness can be analyzed. It is observed that the fracture toughness of individual laminate under impact is largely dependent on the percentage of steel content and less dependent on fiber orientation.

![Fracture Toughness Graph](image)

**Fig. 5.27** Effect of Fiber Orientation on Fracture Toughness of Laminates for various Steel Percentages.

The results as indicated by the figure depict that effect of orientation is not that severe as compared to the effect of steel content. For example, for a given laminate the approximate variation in fracture toughness with respect to orientation from 0/90° to ±45° reduced fracture toughness approximately by 50%, while for an increase in steel content from 15% to 45%, corresponding increase in fracture toughness observed to be at 200% approximately. The analysis of fractured specimens reveal the catastrophic failure for all the samples, irrespective of orientation and steel content. However, the laminates with smaller steel percentage have indicated slight delamination due to impact, while the steel rich specimens failed with severe delamination indicating its location near the notch vicinity.
5.3.7 Hardness of Hybrid Composite Laminates

ASTM D785 standard is used to estimate the hardness properties of laminates. The steel ball with a round pointer act as indentor, diameter of the ball used is 1.5 mm. The minor and major load applied was 10 kg and 100 kg respectively. The major load is applied by moving the major load lever in the horizontal direction. The indentation time period was 30 seconds. In Rockwell-B type of hardness test hardness value is read directly from the dial indicator. The experimental results are shown in Fig. 5.28. From the figure it is indicated that the hardness of laminated composites is inconclusive and is ranging between RHN values of 54-60 irrespective of steel percentage. Further it can also be seen that the RHN value is ranging between 43-53 in case of elevated temperatures due to softening of the matrix.

![Fig. 5.28 Rockwell Hardness Number for the Laminates for various Steel Percentages and Temperatures.](image)

5.3.8 Failure Analysis

The laminates subjected to mechanical tests were analysed for the failure type and for the specimen representing typical failures were photographed. Fractured specimens due to tensile loads show three kinds of fractures; straight, aligned and crossed. In case of straight fracture, the fibers are straight and parallel to the axis of load with considerable fiber pullouts. Such failures were recorded in case of laminates having 0/90° fiber orientation and more particularly in 15% steel laminate, a typical fracture is shown in Fig.5.29 (d). The second type, with aligned fracture, indicating oriented fibers where the fiber orientation was 30/60°,
in these cases the crack angle is approximately same as that of the fiber angle, a

typical fracture type is shown in Fig.5.29 (e)

![Fig.5.29](image)

Fig.5.29 Typical failure patterns of notched and un-notched laminates under tension.

The third type being the crossed type, such types of failure are mostly observed in \( \pm 45^\circ \) oriented laminates, these failures can be seen in the Fig. 5.29(f). Similar fracture patterns were also observed for laminates with notches, irrespective of percentage of glass content and notch depth, followed the similar fracture behavior. These patterns can be seen in Fig.5.29 (a) to (c). In addition it was also observed that the fracture pattern along the thickness indicated in almost all the laminates failed with a pattern similar to a lap, however some of the specimens with \( 45^\circ \) fiber orientation have indicated aligned fracture and some with \( 0/90^\circ \) fiber orientation have shown the signs of straight fracture. The fracture surfaces indicated both fiber and matrix failure, but on close observation it can be stated that the matrix cracking initiated first, then propagated into the fibers causing the collapse of structure.

In case of compressive loads, fracture was not partial and has not resulted into two separate pieces. The failed specimen have indicated formation of cracks representing delamination and some have buckled. The buckling was
largely observed in case of laminates with 45% steel content, while the
delamination was largely recorded in case of laminates with 15% steel content.
The delamination length varied between 2-2.5mm for 45° fiber oriented
laminates, and laminates with 30% steel content having 30/60° have indicated
the signs of kinking pattern. Typical failure patterns indicating buckling and
delamination are shown in Fig.5.30.

Two types of fractures were observed in case of impact loading. In the first
case laminate failed completely indicating one or two un-failed extreme layers,
such failures were largely reported in the laminates with 15% steel content, also
these fractures are indicative of less fiber pull outs. The second type where the
steel percentage was 45, fracture represents fiber pullouts and laminate indicated
failures with large delaminations in the plies. The fracture appearance is almost
same for all the laminates irrespective of fiber orientations. Flexural loading
resulted into failed laminates exhibited presence of delamination in almost all the
cases, the failure initiated in the compression region. The severity of
delamination was reportedly large in case of laminates with large steel
percentage measuring upto 17mm of delamination length. It was also observed
that the delamination was minimum in laminates were fibers are aligned,
indicating 0/90° are more prone to delamination. The delamination propagation
was majorly observed between layers of different material, where thin resin layer
separate the layers, indicating largely matrix cracks.
5.4 STATISTICAL ANALYSIS

5.4.1 Modeling of Tensile Strength

Modeling through design of experiments (DOE) is an experimental approach in which more than one factor is changed simultaneously. By systematically varying the levels of the variables and by applying statistics to the experimental process more factors and the interactions among them can be studied. Application of DOE requires several steps such as the choice of the factors to be studied, the levels of the selected factors and the construction of the test matrix in which the variables are expressed and reduced [36].

The experiments were conducted as per the standard orthogonal array. The selection of the orthogonal array is based on the condition that the degrees of freedom for the orthogonal array should be greater than or equal to sum of those tensile parameters [36]. In this investigation Multilevel Factorial Design was chosen, the factors selected to study the response of tensile behavior are steel volume fraction (SVF), fiber orientation (FO) and notch depth (ND). The Table 5.3 indicates the factors and their levels used in general linear model and the tensile strength response was studied with the objective as larger is the better. The experiments were conducted as per the orthogonal array with 45 runs and the level of parameters given in each array. The tensile test results were subject to the analysis of variance. The ANOVA technique was carried out for a level of significance of 5% i.e., the level of confidence is 95%. Table 5.4 shows the results of ANOVA analysis for tensile strength. The table also shows the percentage contribution of each factor on the total variation indicating the influence on the result.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Type</th>
<th>Levels</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>SVF, %</td>
<td>Fixed</td>
<td>3</td>
<td>15, 30, 45</td>
</tr>
<tr>
<td>FO, deg</td>
<td>Fixed</td>
<td>3</td>
<td>0, 30, 45</td>
</tr>
<tr>
<td>ND, mm</td>
<td>Fixed</td>
<td>5</td>
<td>0, 2, 4, 6, 8</td>
</tr>
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</table>
Table 5.4 Analysis of Variance Results for Tensile Response.

<table>
<thead>
<tr>
<th>Source</th>
<th>DOF</th>
<th>Sum of Squares</th>
<th>Mean Square</th>
<th>F-Test $F_{cal}$</th>
<th>F-Test $F_{0.05}$</th>
<th>Contribution, %</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>SVF</td>
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<td>10490</td>
<td>5245</td>
<td>9391.68</td>
<td>3.63</td>
<td>72.87</td>
<td>Significant at 95% CL</td>
</tr>
<tr>
<td>FO</td>
<td>2</td>
<td>2713.4</td>
<td>1356.7</td>
<td>2429.28</td>
<td>3.63</td>
<td>18.85</td>
<td>Significant at 95% CL</td>
</tr>
<tr>
<td>ND</td>
<td>4</td>
<td>1014.87</td>
<td>253.72</td>
<td>454.30</td>
<td>3.01</td>
<td>7.05</td>
<td>Significant at 95% CL</td>
</tr>
<tr>
<td>SVF*FO</td>
<td>4</td>
<td>41.58</td>
<td>10.4</td>
<td>18.61</td>
<td>3.01</td>
<td>0.29</td>
<td>Significant at 95% CL</td>
</tr>
<tr>
<td>SVF*ND</td>
<td>8</td>
<td>107.46</td>
<td>13.43</td>
<td>24.05</td>
<td>2.59</td>
<td>0.75</td>
<td>Significant at 95% CL</td>
</tr>
<tr>
<td>FO*ND</td>
<td>8</td>
<td>20.15</td>
<td>2.52</td>
<td>4.51</td>
<td>2.59</td>
<td>0.14</td>
<td>Significant at 95% CL</td>
</tr>
<tr>
<td>Error</td>
<td>16</td>
<td>8.94</td>
<td>0.56</td>
<td></td>
<td></td>
<td>0.06</td>
<td>Significant at 95% CL</td>
</tr>
<tr>
<td>Total</td>
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<td>14396.46</td>
<td></td>
<td></td>
<td></td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

The ANOVA results in Table 5.4 were obtained by using Minitab software and the results can be used to investigate the response of factors on tensile strength. It is clear from the ANOVA table that the steel volume fraction contributing 72.87%, fiber orientation contributing 18.85% and notch contributing 7.05% towards the tensile property. The effect of the notch and orientation is comparatively less, which indicates that steel percentage significantly controls the tensile strength of the composite laminate. However, the interaction between the factors is quite marginal and can be neglected and also the error associated in the ANOVA table was almost negligible because it is about 0.06%. The Regression coefficient ($R^2$) indicates that the predicted model explains 99.83% of variability indicating the relationship between the tensile strength and other factors are fairly represented by the DOE model considered for design. The effect of the factors on tensile strength can be analyzed from the Fig. 5.31 and it is clear from the figure that steel percent has significant effect on tensile strength compared to other factors. For laminates without notches the tensile strength is higher and at the same time for laminates with increased notch depths, the tensile strength has decreased.
Fig. 5.31 Main Effects plot for mean Tensile Strength on all factors.

To analyze the effect of individual factors in detail the interaction plots are generated and shown in Fig. 5.32. The variation in tensile strength due to variations of factors is better understood by generating surface plot shown in Fig. 5.33.

Fig. 5.32 Interaction plot for Tensile Strength.
Fig. 5.33 Surface plot for Tensile Strength.

Four types of residual plots are obtained which are shown in Fig. 5.34. The Histogram gives only one long tail, indicating the point of outlier. The points in the normal probability plot have approximated a straight line, indicating normal distribution of residuals. Since there is no curvature at the tails, it can be said that the data used for the analysis is sufficient and goodness-of-fit is obtained. The versus fit show a random pattern of residuals on both sides of zero. Only two or three points lie far from the majority of points, indicating outliers. At the points on either side of the zero line, the residual density is approximately same and it is an indication that the predominance of positive residuals is same as that of the negative residuals. The residual versus plot shows random patterns on both sides of zero line; such patterns indicate the relation between the predictor and variables, otherwise indicating incorrect functional form of the model. The standard error from the model obtained is $S=0.7473$, which is a measure of model fit and it is measured in the units of the response variable and represents the standard distance data values fall from the mean regression line, or the standard deviation of the residuals. In this study, the standard error obtained is not that high indicating model adequacy; hence the outlier points have little significance.
The software is also used to obtain a regression equation to establish the relation between parameters and the variables, the equation in terms of steel percentage; fiber orientation and notch depth is used to compare the margin of error between the experimental and equation values. The variations in experimental results are given in Table 5.5, and the results indicate the values which correlate with the experimental results with acceptable degree of accuracy.

Table 5.5 Comparison of experimental values with the regression model

<table>
<thead>
<tr>
<th>Sample</th>
<th>Experimental result</th>
<th>Regression Equation</th>
<th>Error, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>15%, 0/90, 0mm</td>
<td>43.21</td>
<td>39.95</td>
<td>7.54</td>
</tr>
<tr>
<td>15%, 30/60, 2mm</td>
<td>29.4</td>
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<tr>
<td>15%, 45/45, 6mm</td>
<td>13.1</td>
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<tr>
<td>30%, 0/90, 2mm</td>
<td>47.3</td>
<td>50.00</td>
<td>5.70</td>
</tr>
<tr>
<td>30%, 30/60, 4mm</td>
<td>34.3</td>
<td>35.00</td>
<td>2.04</td>
</tr>
<tr>
<td>30%, 45/45, 6mm</td>
<td>24.3</td>
<td>26.00</td>
<td>7.00</td>
</tr>
<tr>
<td>45%, 0/90, 4mm</td>
<td>69.8</td>
<td>70.53</td>
<td>1.05</td>
</tr>
<tr>
<td>45%, 30/60, 6mm</td>
<td>59.8</td>
<td>59.04</td>
<td>1.27</td>
</tr>
<tr>
<td>45%, 45/45, 8mm</td>
<td>46.58</td>
<td>45.775</td>
<td>1.73</td>
</tr>
</tbody>
</table>

5.4.2 Modeling of Compressive Strength

For compressive strength modeling, similar assumptions and parameters were selected and the orthogonal array comprises of three factors and 45 runs. Table 5.6 indicates the factors and their levels used, and the ANOVA technique was
carried out for a level of significance at 5%. Table 5.7 shows the results of ANOVA analysis for compressive strength.

Table 5.6 Process parameters for Compression Response

<table>
<thead>
<tr>
<th>Factor</th>
<th>Type</th>
<th>Levels</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>SVF, %</td>
<td>Fixed</td>
<td>3</td>
<td>15, 30, 45</td>
</tr>
<tr>
<td>FO, deg</td>
<td>Fixed</td>
<td>3</td>
<td>0, 30, 45</td>
</tr>
<tr>
<td>ND, mm</td>
<td>Fixed</td>
<td>5</td>
<td>0, 1, 2, 3, 4</td>
</tr>
</tbody>
</table>

Table 5.7 Analysis of Variance Results for compression test

<table>
<thead>
<tr>
<th>Source</th>
<th>DOF</th>
<th>Sum of Squares</th>
<th>Mean Square</th>
<th>F-Test F&lt;sub&gt;cal&lt;/sub&gt;</th>
<th>F-Test F&lt;sub&gt;0.05&lt;/sub&gt;</th>
<th>Contribution, %</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
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<td>1824.08</td>
<td>8255.74</td>
<td>3.63</td>
<td>66.47</td>
<td>Significant at 95% CL</td>
</tr>
<tr>
<td>FO</td>
<td>2</td>
<td>965.39</td>
<td>482.69</td>
<td>2184.66</td>
<td>3.63</td>
<td>17.59</td>
<td>Significant at 95% CL</td>
</tr>
<tr>
<td>ND</td>
<td>4</td>
<td>764.24</td>
<td>191.06</td>
<td>864.14</td>
<td>3.01</td>
<td>13.92</td>
<td>Significant at 95% CL</td>
</tr>
<tr>
<td>SVF*FO</td>
<td>4</td>
<td>86.90</td>
<td>21.72</td>
<td>98.32</td>
<td>3.01</td>
<td>1.58</td>
<td>Significant at 95% CL</td>
</tr>
<tr>
<td>SVF*ND</td>
<td>8</td>
<td>10.25</td>
<td>1.28</td>
<td>5.80</td>
<td>2.59</td>
<td>0.19</td>
<td>Significant at 95% CL</td>
</tr>
<tr>
<td>FO*ND</td>
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<td>9.93</td>
<td>1.24</td>
<td>5.62</td>
<td>2.59</td>
<td>0.18</td>
<td>Significant at 95% CL</td>
</tr>
<tr>
<td>Error</td>
<td>16</td>
<td>3.54</td>
<td>0.22</td>
<td></td>
<td></td>
<td>0.06</td>
<td></td>
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<tr>
<td>Total</td>
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<td>5488.40</td>
<td></td>
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<td>100</td>
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</tr>
</tbody>
</table>

The percentage contribution of each factor on the total variation of compressive strength is indicated in the Table 5.7. The results of ANOVA analysis for compressive strength show that the interaction between fiber orientation and notch depth does not have significant effect on the compressive strength of the composite laminates, because the steel percentage alone will contribute 66.47%, while the orientation and notch depth contribute 17 and 14% respectively. At the same time the interaction between the factors is quite marginal and can be neglected and also the error associated in the ANOVA table was almost negligible because it is merely 3.5%. The main effect of the factors on compressive strength can be analyzed from the Fig. 5.35 and it is clearly indicative that the notch depth and orientation have lesser effect when compared to steel percentage.
Fig. 5.35 Main Effects plot for mean Compressive Strength on all factors.

To examine the effect of individual factors, the detailed interaction plot for compression strength is given in Fig. 5.36. The variation in compressive strength due to variations of factors is better understood by using surface plot, hence to represent the effect of each of the factors at different levels of variation this plot is shown in Fig. 5.37.

Fig. 5.36 Interaction plot for Compressive Strength.
To confirm the goodness of model fit, four types of residual plots are shown in Fig. 5.38. The Histogram shows three long tails on one side indicating a skewed distribution; these points may be the outliers. Since the standard error for the model obtained is $S=0.47$, indicating model adequacy, hence the outlier points have little significance. The points in the normal probability plot have approximated a straight line, indicating normal distribution of residuals. Since there is no curvature at the tails, it can be said that the data used for the analysis is sufficient and goodness-of-fit is obtained. The verses fit show a random pattern of residuals on both sides of zero. Only few points lie far from the majority of points, indicating outliers. The points on either side of the zero line the residual density is approximately same; this is an indication that the predominance of positive residuals is same as that of the predominance of negative residuals. The residual verses plot shows random patterns on both sides of zero line; such patterns indicate the relation between the predictor and variables, otherwise indicating incorrect functional form of the model. The regression equation generated by the software is used to find the variation in experimental results and the comparison is shown in Table 5.8. The results show that the values correlate well with the experimental results with acceptable degree of accuracy, indicating an error range between 0.89 to 12%.
Residual Plots for Compressive Strength

Normal Probability Plot

Versus Fits

Versus Order

Fig. 5.38 Residual plots for Compressive Strength.

Table 5.8 Comparison of experimental values with the regression model

<table>
<thead>
<tr>
<th>Sample</th>
<th>Experimental</th>
<th>Regression Equation</th>
<th>Error, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>15%, 0/90, 0mm</td>
<td>21.5</td>
<td>26.66</td>
<td>12.00</td>
</tr>
<tr>
<td>15%, 30/60, 1mm</td>
<td>10.9</td>
<td>16.12</td>
<td>14.00</td>
</tr>
<tr>
<td>15%, 45/45, 4mm</td>
<td>3.91</td>
<td>3.7</td>
<td>5.37</td>
</tr>
<tr>
<td>30%, 0/90, 2mm</td>
<td>31.3</td>
<td>30.41</td>
<td>2.84</td>
</tr>
<tr>
<td>30%, 30/60, 3mm</td>
<td>23.4</td>
<td>19.87</td>
<td>5.00</td>
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<tr>
<td>30%, 45/45, 4mm</td>
<td>17</td>
<td>13.17</td>
<td>2.00</td>
</tr>
<tr>
<td>45%, 0/90, 0mm</td>
<td>46</td>
<td>45.59</td>
<td>0.89</td>
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<td>45%, 30/60, 2mm</td>
<td>30.6</td>
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<td>5.00</td>
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<tr>
<td>45%, 45/45, 4mm</td>
<td>20.5</td>
<td>22.63</td>
<td>3.90</td>
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</table>

5.5 SUMMARY

From the overall discussion on the characterization of macro mechanical properties of SFRP hybrid composites it can be summarized that the strength of the laminates indeed are largely dependent on the percentage of steel fiber content and to some extent on fiber orientation. It can be said that the severity of notch depth is more in case of specimens having greater steel content. The experimental results of both the tensile as well as compressive tests are confirmed using ANOVA results. The ANOVA results indicated clearly that the strength of the laminate is largely dependent on percentage of steel content. Also the results obtained using regression model correlated fairly well with the experimental results.