5.1 INTRODUCTION

Characterization of materials is important because it helps to identify parameters that influence the strengths and response of composite materials, as fiber and matrix types and fiber-matrix interface. These data can be used to study the relationship among textile preform architecture, type of matrix, mechanical properties and failure modes [67].

Therefore, property characterization of fabric reinforced hybrid polymer matrix composites is currently the subject of extensive research and development worldwide. Mechanical tests on these fabric-reinforced composites are also required for the following reasons:

- To take up characterization for the purposes of materials development, quality control and comparative studies,
- As a research tool in revealing the underlying mechanisms behind mechanical performance,
- To provide engineering performance-prediction data for engineering applications and component design [166], and
- For structural applications, it is now common practice to design the structural element with computer-aided engineering (CAE) software. These computer codes require mechanical property data to calculate the stiffness and the maximum loading conditions of the structural component [82].

Fiber architecture plays a prime role in determining the mechanical response of textile composite materials. Inhomogeneous local displacement fields develop within the textile laminates, even under uniform axial extension, as a result of the interweaving and interlacing of the yarn bundles. This is not seen in laminates formed of unidirectional tape materials. Therefore the specimen dimensions and testing conditions as provided by ASTM standards were adopted to evaluate both in-plane and out-of-plane properties of the fabric reinforced laminates.
5.2 OBJECTIVES

- Preparation of fabric reinforced hybrid composites to suit ASTM standards.
- To conduct various mechanical tests such as tensile, compressive, flexural, fatigue, impact, etc., on the hybrid composite laminates.
- To study the effect of fiber orientation, fiber content and notches.
- To correlate the notch size, laminate property with the stress concentration.
- To determine the fracture toughness of the laminates.
- To conduct the failure analysis.
- To perform FEM modeling on some laminates to validate the results.
- To estimate the contribution of parameters on the strength using ANOVA.
- To validate the experimental results using regression model.

5.3 PHYSICAL PROPERTIES OF THE LAMINATES

5.3.1 Density Testing

Density of the GSFRP laminates were measured according to the ASTM D792 standards [7]. For density tests, rectangular samples of size 10mm X 10mm X 55mm were made with thickness and width variations of ±0.15mm and ±0.2mm, 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 for each group, a total of thirty specimens such that five from each group were tested.

As expected, GSFRP composite manufactured by hand lay-up method had no significant difference in density with respect to fiber orientation, this may be attributed to the approximately same warp and fill count. However, the experiments show that the density increases with the increase in glass content, this is found to be true because glass being the denser constituent among the selected materials increases the sample density. The rule of mixture [99,138] is used to determine theoretical densities of the laminates, the actual and theoretical density variation is shown in Fig. 5.1. The difference in theoretical and measured densities might be due to the presence of micro-voids in the composite. Hence, it becomes quite essential to quantify the percentage of voids present within the composite laminates prepared.
5.3.2 Void Content

ASTM D2734 standard [7] was used to analyze the void percentage in composite laminates. The densities of the composites were measured and the theoretical density is calculated. Normally, up to one percent of voids indicate a good composite, but practical difficulties increase the percentages of voids. The void content of a composite may 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 voids were calculated based on two assumptions. The first assumption was that the mass of fiber in the composite was known (i.e., there is no fiber loss during manufacture). The second assumption is the gas in any voids has the density of air, $1.29 \times 10^{-3} \text{ g/cm}^3$. The results show that void content varies between 2.6 to 4.8% for laminates with different percentages of reinforcement. The details of the void content and densities are given in Table 5.1.

![Fig. 5.1 Density as a Function of Glass Content for Hybrid Laminates.](image)

Table 5.1 Physical Proportions of the GSFRP Laminates

<table>
<thead>
<tr>
<th>Composite Laminate</th>
<th>Volume Fraction, %</th>
<th>Void Content, %</th>
<th>Density, Kg/m$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Epoxy</td>
<td>Glass</td>
<td>Satin</td>
</tr>
<tr>
<td>Glass 15%</td>
<td>40±1.5</td>
<td>15±1.4</td>
<td>45±0.8</td>
</tr>
<tr>
<td>Glass 30%</td>
<td>40±1.2</td>
<td>30±1.2</td>
<td>30±1.1</td>
</tr>
<tr>
<td>Glass 45%</td>
<td>40±1.6</td>
<td>45±1.1</td>
<td>15±0.9</td>
</tr>
</tbody>
</table>
5.3.3 Fiber Volume Fraction
The fiber content in the composite laminates was analyzed using ASTM D3171 standard [7], 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 of by using the fiber and resin densities. Since in this study two types of reinforcements are used, to validate the above method, a second method was also used to compare the results. In the second method fiber volume fraction of composite specimen is determined using standard method by burning small piece of GSFRP of known weight and weighing the residue in the form of glass fibers [29]. Comparing the results of both the tests, the deviation in volume fraction of five specimens in each case is given in Table 5.1.

5.4 MECHANICAL PROPERTIES OF THE LAMINATES
In order to facilitate the utilization of hybrid woven composites, the industries demand the database for information, to further develop the testing and design standards. Therefore, the primary purpose of any material characterization is to investigate its behaviour under different mechanical loads. Experimentations were conducted to characterize the candidate composite material under different loading conditions and with various specimen configurations, the results and the influence of various parameters on the properties are discussed in the following sections.

5.4.1 Tensile Behaviour of Hybrid Composite Laminates
The tensile tests were carried out in accordance with ASTM D3039 standards [7]. The rectangular specimens with dimensions 250 mm of length X 25 mm of width X 4mm of thickness were cut from the planar of polymeric composites. For the in-plane properties of prepared laminates end-tabs of glass fibers/epoxy were bonded, the very purpose of using end-tabs is to provide proper gripping and to ensure failure in the gauge length (gauge length=127mm). Rectangular specimens are required for the composite material characterization, because the dog-bone type tends to split in the region where the width changes. Still the grips of tension test frame introduce large stress concentration in the specimen. To minimize this effect, tabs with tapered ends were bonded on each side of the specimen, because the tensile test can cause stress concentration with shear load.
The test ready composite laminates were subjected to various loads on a computer controlled Universal Testing Machine. The specimens were clamped and the tests were performed at a constant crosshead velocity of 1.27 mm/min. The tensile strength can be defined in different ways, 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. For laminates, this definition corresponds to the last-ply failure [126]. The tests were conducted at room temperature and closely monitored; the effects of various parameters under study are discussed.

5.4.1.1 Effect of Fiber Content
To analyze the effect of fiber content on the tensile strength, seven specimen configurations with various percentages of glass content were selected. The specimen prepared to suit ASTM standards was subjected to tensile load and the test results are shown in Fig. 5.2.

![Graph showing the influence of glass fiber content on the tensile strength of hybrid composites.](image)

Fig. 5.2 Influence of glass fiber content on the tensile strength of hybrid composites.

The experimental results clearly indicate that the trend of increase in tensile strength for increased percentage of glass content, this is evident since the mechanical properties of the glass fibers are superior to those of the satin cloth and epoxy matrix. At the same time the tensile strength of the composite is influenced by the strength and modulus of fibers [171]. On the other hand variation in displacement due to tensile loading is marginal for laminates with 30% to 45% glass content, whereas it is considerable for laminates with glass fibers less than 30%. These variations notify that the evolution of the composite displacement at break starts when the fibers filling ratio is...
very little, this may be due to the displacement of the fibers and the epoxy resin are too close at break. The increase in glass fiber content at the cost of satin fabric will certainly increase the tensile strength but it was observed that the specimen fail due to the effect of debonding and delamination. These effects may be eliminated to some extent by reinforcing the satin cloth as it improves interlaminar shear strength, hence reduced delamination and debonding. The increase in interlaminar shear strength due to added percentage of satin cloth may be attributed to the greater wetability of satin when immersed in resin bath.

5.4.1.2 Effect of Fiber Orientation

When composite materials are designed, the reinforcements are always oriented in the load direction. However, if the load direction is variable, and not parallel to the fibers, it becomes important to investigate the laminate mechanical behavior. For composite laminates, orientation at 0/90° and ±45° results in highest and lowest tensile strengths respectively [126,134]. Hence, to investigate the effect of fiber orientation, these two different fiber orientations were selected for the study. Specimens with seven volume fractions and with ±45° fiber orientations were prepared with the same process as discussed in the earlier sections and the specimen dimensions were in accordance with ASTM D3039 standards [7]. Results of the tensile tests are shown in Fig. 5.3.

![Graph showing the influence of fiber orientation on tensile strength](image)

**Fig. 5.3** Influence of fiber orientation on the tensile strength of hybrid composites.

The experimental results reveal that tensile strengths are affected by the fiber orientation significantly. The tensile strength found to be superior in case of 0/90° oriented specimens as compared to specimens with ±45° orientation. This may be attributed to the reason that, in case of 0/90° orientation the external tensile load is
equally distributed on all the fibers and transmitted along the axis of the fibers. Whereas in case of ±45° orientation, fiber axes is non parallel to load axis, resulting in off-axis pulling of fibers and increased stress concentration causing the premature failure of laminates. Even in case of ±45° orientation the trend of increased tensile strength for increase in glass content were found to be true, but it may be clearly observed that the margin of increase is comparatively less, similar observations were given by author at reference [41]. The displacement due to tensile loads again followed the same trend of increased displacement for increase in glass percentage, this might be due to greater extensibility of glass fibers than other constituent materials [72,73]. But on comparison it is found that the displacement in case of laminates with ±45° fiber orientation is large compared to laminates with 0/90° orientation, this may be again due to off axis loading and large fiber pull outs before fracture.

5.4.2 Compressive Behaviour of Hybrid Composite Laminates
The compressive tests were carried out in accordance with D3410 standards [7]. The rectangular specimens with 6mm thickness were cut to suit the required dimensions from the polymeric composite laminate and the specimens were tested in a universal testing machine at a constant cross-speed.

Normally for composites, the compression tests are designed to produce compressive property data for the material specifications, research and development [42]. 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. These data can be used to study the relationship among textile preform architecture, type of matrix, mechanical properties and failure modes [67]. The presence of local defects, which are often difficult to characterize, also influences the failure in compression. Following discussion outlines the effects of various parameters on compressive strength.

5.4.2.1 Effect Fiber Volume Content and Orientation
The results of the compression tests were used to analyze the effect of fiber content and fiber orientation, experimental results are shown in Fig. 5.4. It is quite evident from the plots 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 $\pm 45^\circ$ fiber
orientations, the compressive strength is comparatively less, this difference in the load
bearing capacity of composites may be due to the initial plastic deformation of matrix
and followed by buckling which provokes the fiber buckling and resulting into uneven
load distribution between the fiber and matrix material [182]. From the Fig. 5.4 it is clear
that as glass fabric increases, compressive strength will also increase and found to be true
upto 30% of glass content. The change in compressive strength is almost negligible from
30-45% of glass content in case of $0/90^\circ$ fiber orientation; this may be due to the fact that
as glass percentage increases specimen starts behaving as brittle material and brittle
materials are poor in compressive loads [26].

![Graph](image)

**Fig. 5.4** Influence of Fiber Content and Orientation on the Compressive Strength of
Hybrid Laminates for (a) $0/90^\circ$ Orientation and (B) $\pm 45^\circ$ Orientation.

### 5.4.3 Open Hole Tension Test

For open hole tension (OHT) test the specimen preparation was in accordance with
ASTM D5766 dimensions, with a notch centrally located in the form of drilled hole. The
$0/90^\circ$ and $\pm 45^\circ$ oriented composite specimens with central holes of different diameters, 2,
4, 6, 8, 10, and 12 mm were drilled in different specimens. The open hole tensile test
specimen with various notch sizes were loaded on a computer controlled Universal
Testing Machine. The specimens were clamped and subjected to monotonic uniaxial
tension at a displacement rate of 1.27 mm/min. The tests were conducted at room
temperature and closely monitored. The load at which the complete fracture of the
specimen occurred has been accepted as the critical load.
5.4.3.1 Effect Fiber Volume Content and Orientation

The effect of percentage of glass fiber content on open hole tensile strength can be easily understood from Fig. 5.5. Certainly, the effect of glass content can be noticed and it may be observed that higher glass fabric will improve even the open hole tensile strength. The open hole tensile strength is not only dependent on fiber content, but it is also dependent on the notch diameters. Further, the specimen with higher glass content has exhibited less tensile strength for larger notch diameters. From the trends available in the Fig. 5.5, it may be observed that the notch size is inversely related, while the glass content is directly related to the OHT strength. In addition the dependence of OHT strength on the fiber orientation can also be observed.

![Graph showing the influence of fiber content and orientation on OHT strength](image)

Fig. 5.5 Influence of fiber content and orientation on the OHT strength of hybrid laminates for (a) $0^\circ/90^\circ$ Orientation and (b) $\pm45^\circ$ orientation.
5.4.3.2 Finite Width Correction Factor

The notched laminates carry much less load than the un-notched laminates. The stress at the edge of an open hole in an anisotropic sheet of finite width was normalized by tensile strength and plotted against the ratio of laminate width to notch diameter (W/d) as shown in Fig. 5.6. Marginal variations in OHT strength was recorded for W/d ratios upto 2.5, thereafter the variations in OHT strength are considerable and even the trends indicate the linear behaviour. This response draws a line at 40%, means specimen with hole diameters consuming material more than 40% reduce the tensile strength severely. At the same time the strength is dependent on the percentage of glass fabric; higher the percentage of glass fabric, the more will be the tensile strength. In addition when the OHT strengths are compared with respect to fiber orientation, it was observed that the effect of notch has indicated the similar behaviour in case of ±45° fiber orientations.

![Graphs showing influence of hole size on OHT strength of laminates with different glass percentages for (a) 0°/90° orientation and (b) ±45° orientation.](image)

Fig. 5.6 Influence of Hole Size on the OHT Strength of Laminates with different Glass Percentages for (a) 0°/90° Orientation and (b) ±45° Orientation.
5.4.3.3 Effect of Glass Content on Fracture Toughness

With regard to the effect of notch size, it can be seen from the Fig. 5.7 and Fig. 5.8 that the fracture toughness (K_i) of the notched specimen increases for the range 0.1 < d/W < 0.5 and for d/W > 0.5 fracture toughness start reducing. This nature of the hybrid specimen may be due to the fact that as glass percentage increases, glass being too brittle among the constituents, the fracture toughness of the composite is affected. Upto 10 mm of notch diameter, fracture toughness increases, but the margin of increase found to be too meager and hence may be stated that the effect of notch size has marginal influence on fracture toughness. Notch diameter with 10mm may be treated as a critical notch size because the toughness starts reducing once notch size exceeds 10 mm. From Fig. 5.7(a), the increase in the fracture toughness for the range 15 ≤ V_f ≤ 45 could be attributed to the fact that fabric hinders crack propagation, compelling the crack to follow fabric matrix interfaces and/or to branch and circumvent the fabric [114].

![Fig. 5.7 Influence of Hole Size on Fracture Toughness of Laminates under Tension with various Glass Percentages for (a) 0°/90° Orientation and (b) ±45° Orientation.](image)
If the interfacial fracture toughness is better than half that of the matrix, the apparent fracture toughness of the composite will be higher [106]. Observations are made regarding monotonic increase in fracture toughness with small volume fractions of fabric in epoxy. In addition, observations reveal that the critical volume fraction of glass is 25%, because the increase in fracture toughness was found to be marginal after 25% of glass content for all the notch configurations. Further, the fracture toughness observed to be superior for 10 mm of notch diameter, indicating 10mm as the threshold notch diameter. Considering fiber orientation as a parameter for comparison, observations reveal that reduced toughness levels for laminates with ±45° fiber orientation, otherwise the behaviour is same as seen in 0/90° laminates. However d/W ratio with a value of 0.3 may be treated as the threshold ratio for ±45° laminates.

![Graph](image)

**Fig. 5.8** Width Effect on Fracture Toughness of Laminates under Tension with various Glass Percentages for (a) 0°/90° Orientation and (b) ±45° Orientation.
5.4.4 Open Hole Compression Test

Open hole compression (OHC) strength is a good measure of consolidation quality, matrix properties and interface strength. 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. Open hole compression test of the composite specimen was carried in accordance with ASTM D6484 standards [7], with a notch centrally located in the form of drilled hole. Composite specimens with central holes of different diameters ranging between 2mm to 10mm in steps of 2mm were drilled on different specimens. The OHC test specimen with two fiber orientations (0/90° and ±45°) and 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 investigation are discussed in the following sections;

5.4.4.1 Effect Fiber Volume Content and Orientation

In this section the analysis of composites is made for OHC strength of laminates with different percentages of glass, orientations and hole diameters, the results of the experimentation is presented in Fig. 5.9.

![Graphs showing OHC strength vs hole diameter for different fiber orientations and glass contents.](image)

Fig. 5.9 Effect of Hole Size and Glass Percentage on the OHC Strength of Hybrid Laminates for (a) 0/90° Orientation and (b) ±45° orientation.

Trends indicate that more the percentage of glass, superior will be the OHC strength and at the same time the greater the hole diameter, lesser will be OHC strength. This behaviour is true irrespective of fiber orientation, however OHC strength observed
to be less in case of ±45° orientation specimens compared to 0/90° orientation specimens due to the reasons stated in the earlier discussions. The highest OHC strength obtained is 85 MPa and 106 MPa respectively for ±45° and 0/90° orientations, both in case of laminates with 45% glass content. For both the types of orientations, the severity tends to increase as hole diameter crosses 4 mm, this is probably due to increased stress concentration and smaller cross sectional load bearing area.

5.4.4.2 Finite Width Correction Factor

OHC strength of all the laminates is plotted against width correction factor (W/d) as shown in Fig. 5.10 for all the samples with different glass contents and orientations. From the plots, the significance of width factor may be observed, the laminates sustain higher compressive loads for width factor greater than ten. This might be attributed to the fact that as width factor reduces, the load bearing material will also reduce and hence resulting in to smaller OHC strengths. In case of width factor values less than ten, the OHC strengths found to be quite less because the holes in the form of notches consumes more than 10% of the load bearing material.

![Fig. 5.10 Width Correction Factor of OHC Laminates with different Glass Percentages for (a) 0/90° Orientation and (b) ±45° Orientation.](image)

Laminates were severely affected for ratios upto W/d=10 and thereafter its severity has reduced, this behaviour of the laminates reveal the fact that composites with load bearing material less than 90% exhibit higher stress concentration. The failure of these laminates may not only be due to reduced load bearing area but also may be due to
the difference in the Poisson’s ratio of the matrix and fiber materials. Longitudinal compressive loading produces transverse tensile stresses within the matrix. These transverse tensile stresses may result in longitudinal cracks developing parallel to the fibers within a weak matrix [115]. In addition, a weak interface may also fail under these transverse tensile stresses. Voids within the matrix or at the interface tends act as stress raisers and increase the chance of longitudinal cracking. Upon further loading, these cracks grow and result in transverse rupture of the composite [182].

5.4.4.3 Effect of Glass Content on Fracture Toughness

The results of the OHC tests are used to evaluate the fracture toughness of the composite laminates under compression, the results are shown in Fig. 5.11. Again as stated earlier, superior fracture toughness for laminates with higher percentages of glass content were found to be true irrespective of fiber orientation. The effect of hole diameter on fracture toughness is quite significant, it may be clearly observed that there is a reduction in toughness as hole diameter increases from 4mm for laminates with 15% glass content in $0/90^\circ$ orientation.

![Fig. 5.11 Effect of Hole Size on Fracture Toughness of Laminates under Compression for various Glass Percentages for (a) $0/90^\circ$ Orientation and (b) $\pm45^\circ$ Orientation.](image)

Similar observations were also made in case of specimen with 30% glass, but the margin of reduction observed is quite small. However, for laminates with 45% glass content the fracture toughness has never reduced, such a type of behaviour is may be due
to that glass is more tougher material among the other two constituent materials. In case of ±45° oriented laminates the toughness has reduced for samples with hole diameter equal to 6mm, though the fracture toughness values show increasing trend even at 8mm notch diameter, but still these values are comparatively less than 0/90° specimens for a given notch size and glass percentage. This behaviour may be due to off-axis loading, which results in shorter fiber length and reduced interface.

During longitudinal compressive loading, the fibers desire to buckle is resisted by the surrounding matrix; either the matrix must deform and/or the interface fail to allow buckling. Failure in strong glass-fiber reinforced composites initiates by micro-buckling of fibers that have the least lateral support due to free boundaries, voids, stress concentrations, or locally weak matrix. Micro-buckling may progress into many different failure modes depending on the matrix and interface properties. The matrix and interface may be strong enough to withstand the Poisson’s ratio induced transverse tensile stresses, but as fiber micro-buckling begins, shear stresses are created at the interface. The interfaces may begin to fail in shear and lead to ultimate composite failure. Two modes of failure were visible in the tested specimens. Diagonal cracks in case of ±45° Orientation and transverse cracks for 0/90° oriented laminates. On close observation there was no evidence of longitudinal cracks, but there exists damage in the form of delamination. The extent of delamination on laminates is not that severe, because the delamination is not propagated largely. The fractured specimen show cracks both transverse and diagonal pass through the drilled hole with angles approximately equal to the fiber orientation angles.

5.4.5 Stress Concentration

As mentioned in the literature review, Hedgepeth [72,73] determined average stress concentration factor by overloading the fibers, while Fukuda [63-65] estimated the SCF by considering the Young’s modulus ratio of fiber to matrix. Keeping these investigations in view, the SCF of OHT specimen were estimated by considering both overloading and Young’s modulus ratio. The ratio $E_f/E_m$, where E is Young's modulus, and the subscripts f and m designate the fiber and the matrix, respectively were calculated for all the laminates with different glass percentages. By doing so the effect of the fiber content can also be incorporated in the analysis. The SCF of notched laminates was estimated by considering the ratio of maximum stress to the nominal stress. The
results obtained for all the notch diameters in case of 0/90° orientation laminates are shown in Fig. 5.12.

![Stress Concentration Factor vs. E/E_m Ratio](image)

**Fig. 5.12** Effect of E/E_m ratio on the SCF of Laminates under Tension.

From the observations it is clear that for notch diameters up to 8mm the SCF has no significant variation with respect to the volume fraction of the material, however it is found that there is an increase in SCF for Ø10 and Ø12mm notches up to E/E_m=18 (i.e. up to 25% glass content). In addition, the above trends reveal the fact that SCF increases as the notch diameter increases, the maximum SCF obtained was 3.5 for laminates with 15% glass content having a central notch with 12mm diameter.

### 5.4.6 In-Plane Shear Properties of Laminates

The off-axis tensile tests to determine the In-plane shear properties of the laminates, require specimens with off-axis angle of 45°, that can be achieved by fabricating the specimens with ±45° fiber orientation. Specimen dimensions and test setup is in accordance with ASTM D3518 standards [7]. Testing conditions and rate of loading was same as that for tension test. This test method involves the measurement 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 [25]. The experimental mean values of in-plane shear stress are shown in Fig. 5.13.
Fig. 5.13 In-Plane Shear Stress of laminates for various glass percentages.

The experimental results show that shear stress ranges between \(\approx 42\) to \(52\) MPa for the variation in percentage of glass content for the range 15\% to 45\%. During loading up to the break, the individual structures differ substantially in their deformation behaviour but initially all structures show a similar deformation behaviour up to \(\approx 20\) MPa. As expected, the laminate with the highest percent of glass, has the largest tensile stress with 104 MPa and its respective shear stress with 52 MPa. The margin of increase in shear stress found to be quite meager for considerable increase in glass content, this may be due to that the shear stress is not only dependent on fiber strength but also on the contact areas. Since in this work the reinforcement fabrics used have finest layer thickness which will enhance the shear properties and also take care of smallest strain inhomogeneity [97]. Therefore the contact area of the fabrics used is more or less same for all the specimen combinations, hence the variation in shear stress may be attributed to the percentage of glass and satin fabric and not to the contact area. The results of the in-plane shear stress indicate that the satin fabric as a reinforcement material has provided the shear strength approximately same as that of the glass fabric with marginal variations.

5.4.7 Flexural Behaviour of Hybrid Composite Laminates

The flexural tests were carried out in accordance with ASTM D790 [7], 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 under room temperature and the flexural strength at the load to failure is obtained, the results of the experimentation is shown in Fig. 5.14.
Fig. 5.14 Flexural Strength of Laminates for various Glass Percentages and Orientation.

Above figure shows the variations in flexural strength of the samples with respect to the variations in glass fiber content and fiber orientations. Trends reveal that more the percentage of glass fabric higher will be the flexural strength. The results also indicate that the flexural strength of the samples has directly related with the glass volume fraction. It may be observed that the flexural properties of these hybrid fiber-reinforced composites were considerably lower than those observed with the glass fiber-reinforced composite alone based on the details available at reference [89]. Hence, it may be stated that as the glass fiber is added to the hybrid composite, a positive hybrid effect on the flexural strength has been observed. The decrease in flexural strength of the reinforced samples with increased percentage of satin reinforcement may be due to the lower strength of the satin fabric. At the same time it may also be noticed that the margin of increase in flexural strength is quite significant with respect to the fiber orientation. This difference may be due to the fact that ±45° oriented laminates experiences reduced deflection before failure and hence 0/90° laminates showed superior flexural strengths.

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 surface of the specimens. The crack at the fractured location appeared to have 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 all the samples irrespective of percentage of
glass content and it lies in tension surface. However, the severity of delamination observed to be more for samples with lesser glass percentage and at the same time the compression surface of the laminates showed no visible signs of delamination. If the comparison of laminates with respect to fiber orientation is made then the fracture pattern is same but the laminates with $0/90^\circ$ fiber orientation have showed catastrophic failure with transverse cracks formation on laminates before breaking into two pieces. Whereas for laminates with $\pm45^\circ$ fiber orientation diagonal cracks with large fiber pull-outs may be responsible for the failure of laminates.

5.4.8 Impact Behaviour of Hybrid 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, was tapered with an including angle of $45^\circ$ with a radius of 3.17 mm and with an angle of fall being $141.45^\circ$. According to the ASTM D256 standard [7] impact tests were carried on laminates, the fracture specimen geometry used in this study was the standard Charpy V-notch specimen ($45^\circ$ angle), at mid length, a 0.25 mm root radius, 2 mm deep notch was made. To develop a triaxial state of stress at the root of notch, notched impact specimens are used in these tests. The samples preparation include selection of different fiber orientations and volume fraction. The specimen was clamped into pendulum impact test fixture and 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 [138]. The experimental results for the standard specimen are shown in Fig. 5.15 and from the trends, it may be clearly seen that the glass fabric content plays vital role in the impact strength of laminates.

Therefore it is clear that more the glass fabric percentage, more will be the impact toughness and it may be observed that the impact strength has increased significantly for the increase in glass percentage and this trend found to be true irrespective of fiber orientation. The maximum impact toughness for 45% glass content obtained is 0.71 J/mm$^2$ and 0.89 J/mm$^2$ for laminates with $0/90^\circ$ and $\pm45^\circ$ orientation respectively. The margin of increase in impact toughness for increased glass percentage is approximately same for both the orientations. However the laminates with $\pm45^\circ$ orientation have
indicated greater impact strength compared to 0/90° fiber orientation. This may be due to increased number of load bearing fibers at the fracture plane compared to laminates with 0/90° orientation. When there are more number of fibers along the fracture plane then naturally laminates provide superior strengths, because the fibrous reinforcements have high strength.

![Graph showing impact strength versus volume fraction of glass and fiber orientation.](image)

**Fig. 5.15** Impact Strength of laminates for various glass percentages and Orientations.

### 5.4.7.1 Effect of Notch Size on Impact Strength

To analyze the effect of notch size on the impact strength, hybrid composite laminates with different notch depths; 1, 2, 3, 4, and 5 mm were prepared. The specimens with various notches and volume fractions in different orientations were subjected to impact loads and the results are shown in **Fig. 5.16**.

![Graph showing impact strength versus notch size and fiber orientation.](image)

**Fig. 5.16** Effect of Notch Size on Impact Strength of Composite Laminates with various Glass Percentages for (a) 0/90° Orientation and (b) ±45° Orientation.

The trends of reduction in impact strength for reduced glass percentage were found to be true for all the laminates, irrespective of orientation and notch size. The
higher notch depths have made the specimen to sustain lesser impact strength; this may be clearly seen from Fig. 5.16 (a) and (b), that impact toughness is large when notch depth is less and poor when depth is high. From the plots it may be seen that the effect of notch is not that severe for 0/90° laminates with 45% glass content. Whereas the laminates with 15% glass content exhibits quite a small toughness this might be attributed to the lower strength of satin fabric. This severity of notch depth may be quite easily understandable, because as the resisting material cross sectional area reduces load bearing capacity will also reduce and hence the reduction in impact toughness. The effect of notch estimated approximately to be 10% per mm upto 3mm depth and about 40% strength deterioration was reported for notch sizes above 3mm.

5.4.7.2 Effect of Notch Size on Fracture Toughness

The results of the impact test are used to determine the fracture toughness of all the composite laminates, Fig. 5.17 is presented to study the effect of the notch size, glass percentage and fiber orientation on fracture toughness. From the figure, it is evident that the fracture toughness has reduced with respect to notch depth, while it has increased with respect to increase in glass percentage. In addition the laminates with ±45° fiber orientation have indicated greater toughness against their counterparts with 0/90° fiber orientations.

![Fig. 5.17 Effect of Notch Size and Fiber Orientation on Fracture Toughness of Composite Laminates with various Glass Percentages.](image)

The results indicate that the effect of notch depth is not that severe as compared to the effect of glass content and fiber orientation. For example for a given laminate, the
approximate variation in fracture toughness with respect to notch size found to be 10% in comparison to \(\approx 75\%\) variation with respect to glass content and \(\approx 30\%\) variation based on fiber orientation. The analysis of fractured specimens reveals the catastrophic failure for all the samples, irrespective of orientation and glass content. Laminates have broken into two pieces along the notch section and in some samples the delamination due to impact was observed, such effects are comparatively more in case of laminates with lesser glass percentage.

### 5.4.9 Hardness of Hybrid Composite Laminates

ASTM D785 standard was used to estimate the hardness properties of the laminates. The steel ball with a round pointer act as indenter and the diameter of the ball used was 1.5 mm. The minor load applied was 10 kg, while the major load was 100 kg. The major load was applied by moving the lever in the horizontal direction. The time of indentation was 30 seconds. The experimental results of the Rockwell-B type hardness tester are shown in Fig. 5.18. From the results it may be observed that, the hardness of laminated composites increases with increase in glass volume, maximum Rockwell hardness number was found to be 60 RHN. The increase in hardness with respect to increase in glass percentage might be directly linked to the hardness properties of glass, since glass is the hardest material among the constituents selected for laminate preparation.

![Fig. 5.18 Rockwell Hardness Number for the Laminates with various Glass Percentages.](image)

### 5.4.10 Failure Analysis

The fracture behaviour of fabric reinforced laminates depends on many parameters such as material properties of the constituents, type, size and fraction of reinforcement, lay-up sequence, fabrication method, interlaminar strength and other mechanical properties also. When a composite is subjected to mechanical testing, the energy gets absorbed due to
damages such as delaminations, fiber breakage, and matrix cracks and also due to the deformations. In order to analyze the fracture behaviour under different loading conditions, photographs of some typical fractured specimen samples have taken and discussed.

The specimens fractured due to tensile loading has indicated two types of fractures; transverse and crossed. In case of transverse fracture, the fibers are straight and co-axial to the axis of load with a minimal fiber pullouts, such failures were recorded in the case of laminates having $0/90^0$ fiber orientation. The second type, with crossed fracture, it is an indication of oriented fibers where the fiber orientation is $\pm 45^0$ and the load axis is not parallel to fibers, fracture represents fiber pullouts and V-shaped fracture surface. Transverse pattern is shown in Fig. 5.19(a) and (b) while the crossed type is indicated in Fig. 5.19(c) and (d). Similar fracture appearance was recorded in all the laminates irrespective of percentage of glass content. Further on close observation at the fractured area it was found that the tensile laminates with lesser glass percentages have witnessed the matrix cracks and fiber debonding, typical case is shown in Fig. 5.20. The fractured surface also provided the evidence of fiber pull-outs from the matrix and also the crack path followed the path in a plane parallel to reinforced layers indicating interlayer delamination. Even in case of the open hole tensile tests similar failures were observed, but the fracture plane always has bisected the notch into two portions. Few fractured laminates indicating both the failure patterns are shown in Fig. 5.21.

![Fig. 5.19 Appearance of fractured specimen under tensile loading.](image)
During the compression tests, fracture was not complete and has not resulted into two separate pieces. However, failed laminates show formation of cracks, both transverse and crossed crack patterns, further in some cases swelling and delamination was also recorded. Typical failure patterns are shown in Fig. 5.22, transverse failure was observed in the laminates with 0/90° fiber orientation as in Fig. 5.22(c) while crossed failures which resembled a shear-like failure at 45° was characteristics for the laminates with ±45° fiber orientations shown in Fig. 5.22(b). In case of compression, some of the
samples have also indicated failures due to swelling, delamination and buckling. Fig. 5.22(a) shows a typical swelling of laminate due to compression, the probable cause of such outer surface swelling is delamination due to interlaminar failures. The fractured surfaces indicate presence of significant delamination between glass and satin layers as shown in Fig. 5.23(c), while almost all laminates buckled before failure, but the margin of buckling may be controlled by the percentage of glass content, more the glass content-smaller will be the buckling and vice versa. Fig. 5.23(a) shows the buckling of laminate with smaller percentage of glass content while Fig. 5.23(b) shows buckling of glass rich laminate. In order to pinpoint the failure initiation, the crack formation was recorded at about 90-95% of the failure load. Localized compressive cracks were observed which periodically propagated along the fiber direction. The open hole compression samples too have exhibited similar patterns, the typical patterns are shown in Fig. 5.24.

**Fig. 5.22.** Appearance of fractured specimens under compressive loading.

**Fig. 5.23.** Types of failures under compression.
In the case of flexural loading almost all the failed laminates exhibited presence of delamination, the failure initiated in the tension surface. The severity of delamination was reportedly large in case of laminates with small glass percentage and the laminates with $0/90^0$ fiber orientation have indicated complete failure into two pieces, while the $\pm 45^0$ fiber oriented laminates experienced fracture at an angle approximately equal to the angle of fiber and also the failure has not resulted into two pieces. The delamination patterns and the clean fibers observed during flexural loading which is as shown in Fig. 5.25. Outer fabric layers in tension region are completely deformed and broken and found that the failure was dominated by interfacial debonding between fabric layer and matrix. The delamination propagation was observed between fabric layer where thin resin layer separated fabric layer, this mechanism can be observed in the Fig. 5.25(a) where the fabric gets delaminated and crack propagates along the mid plane.
The fracture due to impact loads depicts two types of fractures. In the first case laminate failed completely into two pieces, the fibers are straight indicating minimal fiber pullouts, such failure were recorded in the case of laminates with 0/90° fiber orientation as shown in Fig. 5.26. The second type where the fiber orientation is ±45°, fracture represents fiber pullouts and laminate indicated no failure in the last few plies, typical sample is shown in Fig. 5.27. The fracture appearance is same for all the laminates irrespective of percentage of glass content. Little delamination and deformation was found at the fracture in the laminates with 15% glass content, but the principle damage is apparently fiber failure, as a substantial fabric layer has been detached from the matrix and pushed along the direction of the striker motion. The shape of the damaged region depends upon the fabric orientation and lay-up of the specimen.
Fig. 5.26 Fractured surfaces of impacted Laminates with $0/90^0$ fiber orientation.

Fig. 5.27 Fractured surfaces of Composite Laminates with $\pm 45^0$ fiber orientation.
5.5 FEM MODELING

Finite element modeling was used to validate the experimental results of hybrid composites. For modeling purpose ANSYS software with linear shell 99 element was used, because this element allows upto 250 different material layers with different orientations and material properties in each layer. The input data in the form of number of layers, layer thickness, fiber orientation, elastic modulus & poison’s ratio were specified. Modeling was done only for the laminates with 45% glass content under tensile load, the analysis was carried out for three different meshes ranging from course to fine mesh so that results achieve convergence. The results of the analysis were validated against the experimental results with an variation between 3-10%, this variation may be due to the assumptions being made such as the existence of perfect bond & the exclusion of microcracks. Since the margin of variation is quite small indicating the validity of the experimental results with reasonable degree of approximation. The validation results of the composite laminates under tensile test modeling is presented below in the Table 5.2.

<table>
<thead>
<tr>
<th>Laminate Configuration</th>
<th>Tensile Strength, MPa</th>
<th>Error, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass=45%, 0/90°, Un-notched</td>
<td>Experimental: 147.34</td>
<td>Fem: 155.88</td>
</tr>
<tr>
<td>Glass=45%, ±45°, Un-notched</td>
<td>104.12</td>
<td>109.18</td>
</tr>
<tr>
<td>Glass=45%, 0/90°, Φ8mm Notch</td>
<td>78.75</td>
<td>81.49</td>
</tr>
<tr>
<td>Glass=45%, ±45°, Φ8mm Notch</td>
<td>65.32</td>
<td>71.99</td>
</tr>
</tbody>
</table>

The ANSYS generated stress contours are obtained and presented. The stress plots indicate the uniform stress contours in case of 0/90° fiber oriented laminates, the stress plots for these specimens is shown in Fig. 5.28. The Fig.5.28(b) illustrates clearly the way the stress distribution occurred in each layer. The blue coloured stress contour indicate the region of lowest stress, while the stress with red colour is indicative of high stress region. The stress plots shown in Fig. 5.29 represent the laminates with ±45° fiber orientation. The stress distribution pattern is different from the earlier case, criticality of stresses may be seen in the form of V-shape, this shape being the characteristic failure pattern of these laminates. Similarly the layer wise stress plots can be seen in Fig. 5.29(b), these indicate the stress pattern same as what was observed in case of 0/90° fiber orientated laminates.
Fig. 5.28 Stress Contour for Composite with 45% Glass and $0/90^0$ Fiber Orientation (a) Complete Laminate and (b) Layer wise Stress Contour.

Fig. 5.29 Stress Contour for Composite with 45% Glass and $\pm45^0$ Fiber Orientation (a) Complete Laminate and (b) Layer wise Stress Contour.
The stress contours in case of notched laminates represented severity of stress concentration at the notch vicinity. From the Fig 5.30(a) it might be seen that the stress concentration is large in the transverse direction representing the typical failure of laminates. From the Fig. 5.30(b) the layer wise stress distribution can be seen, in addition the stress concentration is severe at two diagonally opposite points on the notch along the transverse direction, while along the longitudinal direction the minimum stress concentration may be observed. Similar observation can be drawn in case of laminates with ±45° fiber orientation, except that the stress pattern resembles X-shape, as shown in Fig. 5.31. Due to these reasons the aligned fracture in the direction of fiber orientation was recorded. The ANSYS stress plots approximately matched the direction and also the location of fracture, for example comparing the fracture predicted by the ANSYS based
on stress accumulation and the actual fracture of $0/90^0$ fiber oriented laminates are illustrated in Fig. 5.32.

**Fig.5.31** Stress Contour for Notched Composite with 45% Glass, $\pm 45^0$ Fiber Orientation and 8mm notch (a) Complete Laminate and (b) Layer wise Stress Contour at the Notch Vicinity.

**Fig.5.32** Comparison of Predicted and Actual Tensile Fracture.
5.6 MODELING OF MECHANICAL PROPERTIES

Traditional method is to evaluate only one variable at a time, all of the variables are held constant during test runs except the one being studied. The experiment reveals the effect of the chosen factor under set conditions and does not show what would happen if the other variables also changed. As the properties of composites depend on several parameters, it appears difficult to study, analyze and quantify the influence of test parameters by investigating separately the various variables involved. The modeling through design of experiment (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 (it exists an optimal experimental distribution of tests which minimizes the variance of the responses), more factors and the interactions among them can be studied with less runs. Thus with a reduced number of tests, DOE allows the experimenter to;

- Study simultaneously the main and interaction effects of many factors on several responses,
- Assess the most important parameters,
- Quantify with empirical polynomials the response changes as a function of the considered variables in the investigated experimental domain.

Application of DOE requires several steps such as the choice of the factors to be studied, the levels of the selected factors (values that a factor assumes when used in experiments) and the construction of the test matrix in which the variables are expressed and reduced [53,100]. In this study the concept of DOE is applied to various properties discussed above and to study the effect of different parameters on the strengths.

5.6.1 Modeling of Tensile Strength

It is always better to examine experimental data therefore considering the tensile strengths of composites at each level of glass volume fraction and indicates that tensile strength increases significantly upto 30% of glass content. Beyond 30% of glass content increase in tensile strength found to be marginal. There is no strong evidence to suggest that the variability in tensile strength around the average depends on the glass volume percentage. Therefore to be more specific in analysis of the data, analysis of variance (ANOVA) technique is used.

99
In this case single-factor ANOVA technique is used with seven levels of the factor and four replicates. The 28 run analysis is tested for the equality of means using pair wise comparison, there are 21 possible pairs and they are tested at 95% confidence level. The analysis of variance is summarized in Table 5.3.

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>Sum of Squares</th>
<th>DOF</th>
<th>Mean Square</th>
<th>F₀</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass Volume Percentage</td>
<td>4836.19</td>
<td>3</td>
<td>1612.06</td>
<td>F₀ = 194.75</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Error</td>
<td>198.66</td>
<td>24</td>
<td>8.27</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>5034.85</td>
<td>27</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

From the analysis it is found that the between-treatment mean square (1612.06) is many times larger than the within-treatment or error mean square (8.27). This indicates that it is unlikely that the treatment means are equal. At the same time the F₀ = 194.75, this on comparing with appropriate upper-tail percentage point of the F₃,₂₄ distribution at α=0.05, we get F₀.₉₉₅,₃,₂₄ =3.01. Because F₀=194.75 > 3.01, the null hypothesis is rejected and conclude that the treatment means are different; that is, the glass volume percentages significantly affects the mean tensile strength.

Since the tensile strength of composite laminates evaluated in this investigation is subjected to various parameters, hence using ANOVA technique with only glass percentage as a factor will not give the relation between other parameters. Therefore applying ANOVA technique to check the simultaneous response of all the parameters such as orientation, volume fraction and hole diameter on the tensile strength, and to develop a multiple linear regression model with which the strength can be predicted.

The ANOVA technique was used with the aim of relating all the parameters that control the tensile strength of the composite. The experimental date meets the requirements of standard orthogonal array. The selection of the orthogonal array was 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 [53]. In the present investigation Multilevel Factorial Design was chosen, with three factors and 84 runs. The factors selected to study the response of tensile behaviour are glass volume fraction (VF), fiber orientation (Ori) and open hole diameter (HD). Table 5.4 indicates the factors and their levels used in general linear model having 84 runs in multilevel factorial design. The
tensile strength response was studied with the objective as larger is the better. The experiments were conducted as per the orthogonal array with level of parameters given in each array row. The tensile test results were subject to the analysis of variance. The ANOVA technique was carried out for a level of significance of 5% that is the level of confidence is 95%.

Table 5.4 Process parameters for Tensile Response

<table>
<thead>
<tr>
<th>Factor</th>
<th>Type</th>
<th>Levels</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>VF, %</td>
<td>Fixed</td>
<td>7</td>
<td>15, 20, 25, 30, 35, 40, 45</td>
</tr>
<tr>
<td>Ori, deg</td>
<td>Fixed</td>
<td>2</td>
<td>0, 45</td>
</tr>
<tr>
<td>HD, mm</td>
<td>Fixed</td>
<td>6</td>
<td>0, 2, 4, 6, 8, 10</td>
</tr>
</tbody>
</table>

Since ANOVA is a method of portioning variability into identifiable sources of variation and the associated degrees of freedom in an experiment. In statistics for determining the significant effect of the parameters on the quality characteristics, F-test is used. Table 5.5 shows the result of ANOVA analysis for tensile strength obtained using Minitab software. The table also indicates the percentage contribution of each factor on the total variation indicating the influence on the result.

Table 5.5 Analysis of Variance Results for Tensile Strength

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>$F_{cal}$</th>
<th>$F_{0.05}$</th>
<th>P, %</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>VF</td>
<td>6</td>
<td>8188.8</td>
<td>1364.8</td>
<td>277.46</td>
<td>2.42</td>
<td>12.66</td>
<td>Significant at 95% CL</td>
</tr>
<tr>
<td>Ori</td>
<td>1</td>
<td>10759.9</td>
<td>10759.9</td>
<td>2187.47</td>
<td>4.17</td>
<td>16.63</td>
<td>Significant at 95% CL</td>
</tr>
<tr>
<td>HD</td>
<td>5</td>
<td>42624.1</td>
<td>8524.8</td>
<td>8524.8</td>
<td>2.53</td>
<td>65.88</td>
<td>Significant at 95% CL</td>
</tr>
<tr>
<td>VF*Ori</td>
<td>6</td>
<td>342.3</td>
<td>57.0</td>
<td>11.60</td>
<td>2.42</td>
<td>0.53</td>
<td>Significant at 95% CL</td>
</tr>
<tr>
<td>VF*HD</td>
<td>30</td>
<td>111.2</td>
<td>3.7</td>
<td>0.75</td>
<td>1.84</td>
<td>0.17</td>
<td>Insignificant at 95% CL</td>
</tr>
<tr>
<td>Ori*HD</td>
<td>5</td>
<td>2523.7</td>
<td>504.7</td>
<td>102.61</td>
<td>2.53</td>
<td>3.90</td>
<td>Significant at 95% CL</td>
</tr>
<tr>
<td>Error</td>
<td>30</td>
<td>147.6</td>
<td>4.9</td>
<td></td>
<td></td>
<td>0.23</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>83</td>
<td>64697.5</td>
<td></td>
<td></td>
<td></td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

SS = Sum of squares, DF = Degree of freedom, MS = Mean Square, $F_{cal}$ = F-test calculated, $F_{0.05}$ = F-value at 5% significance level and P = Percentage of contribution.

The ANOVA results in Table 5.5 can be used to investigate the response of factors on tensile strength. It may be observed from the results that the interaction between the above factors does not have significant variation on the tensile strength of the composite. It is clear from the ANOVA table that the glass volume fraction ($p = 12.66$
Fiber orientation (p=16.63 %) and hole diameter (p=65.88 %) have significant influence on the tensile strength. The effect of the volume fraction and orientation is comparatively less, which indicates that hole diameter 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 as it is about 0.23 %. The Regression coefficient ($R^2$) indicates that the predicted model explains 94.37% of variability in the tensile strength. $R^2$ value, which is approximately closer to unity, shows that 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 may be analyzed from the Fig. 5.33, it is found to be clear that the hole diameter has significant influence on tensile strength compared to other factors. For laminates without any drilled hole the tensile strength was higher and at the same time for laminates with increased hole sizes, the tensile strength has decreased. Therefore higher tensile strengths are with laminates having smaller hole diameters. This relation might be used to explain as hole diameter increases the stress concentration increase and also the cross sectional area of the material reduce, resulting in to the failure of laminates for smaller loads.

![Main Effects Plot for Tensile Strength](image)

**Fig. 5.33** Main Effects plot for mean Tensile Strength on all factors.

The above trends may only be used to analyze the overall influence of individual factors, to have the detailed analysis of individual variables of each factor the interaction plots are generated using minitab-15 software. The interaction plots as shown in Fig. 5.34 indicate the relation between the supplement and the cause. The supplement with the highest quality level depends on the variation in the cause. In this study the
supplement being the tensile strength and the cause being the three factors considered. The variation in tensile strength due to variations of factors is better understood by using contour and surface plots, hence to represent the effect of each of the factors at different levels of variation these plots are shown in Fig. 5.35. The contour plots indicate that the highest tensile strength may be obtained when glass levels are high and hole diameter levels are low. This area appears at the lower right corner of the plot. The surface plot also show the same response and in addition it is possible to get a general idea of tensile strength at various levels of the factors.

Fig. 5.34 Interaction plot for Tensile Strength.

Fig. 5.35 Contour and Surface plots for Tensile Strength.
Minitab-15 generates residual plots that can be used to examine the goodness of model fit. Four types of residual plots are obtained which is shown in Fig. 5.36. The Histogram is an exploratory tool to show general characteristics of the residuals including typical values, spread or variation, shape and also unusual values in the data. Three long tails on one side indicates points of outliers with a standard error of $S=2.21785$, 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 regression line, or the standard deviation of the residuals. In this study, the standard error obtained is not that high indicating model adequacy and 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 two or three points lie far from the majority of points, indicating outliers. The points on either side of the zero line of the residual density is approximately same, it 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.

![Residual Plots for Tensile Strength](image)

**Fig. 5.36** Residual plots for Tensile Strength.
5.6.2 Modeling of Compressive Strength

For modeling of compressive strength the same Multilevel Factorial Design used in the previous section is chosen, with three factors and 36 runs. The factors selected to study the response of Compression strength are glass volume fraction, fiber orientation and open hole diameter. Table 5.6 indicates the factors and their levels used in general linear model having 36 runs in multilevel factorial design. The ANOVA technique was carried out for a level of significance of 5% that is the level of confidence is 95%. For determining the significant effect of the parameters on the quality characteristics, F-test is used. Table 5.7 shows the results of ANOVA analysis for compressive strength.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Type</th>
<th>Levels</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume Fraction, %</td>
<td>Fixed</td>
<td>3</td>
<td>15, 30, 45</td>
</tr>
<tr>
<td>Fiber Orientation, deg</td>
<td>Fixed</td>
<td>2</td>
<td>0, 45</td>
</tr>
<tr>
<td>Hole Diameter, mm</td>
<td>Fixed</td>
<td>6</td>
<td>0, 2, 4, 6, 8, 10</td>
</tr>
</tbody>
</table>

**Table 5.7 Analysis of Variance Results for Compression Test**

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F_cal</th>
<th>F_0.05</th>
<th>P, %</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume Fraction (VF)</td>
<td>2</td>
<td>3156.85</td>
<td>1578.43</td>
<td>368.48</td>
<td>4.10</td>
<td>21.54</td>
<td>Significant at 95% CL</td>
</tr>
<tr>
<td>Fiber Orientation (FO)</td>
<td>1</td>
<td>1123.37</td>
<td>1123.37</td>
<td>262.25</td>
<td>4.96</td>
<td>7.66</td>
<td>Significant at 95% CL</td>
</tr>
<tr>
<td>Hole Diameter (HD)</td>
<td>5</td>
<td>9876.23</td>
<td>1975.25</td>
<td>461.12</td>
<td>3.33</td>
<td>67.39</td>
<td>Significant at 95% CL</td>
</tr>
<tr>
<td>VF*FO</td>
<td>2</td>
<td>228.29</td>
<td>114.15</td>
<td>26.65</td>
<td>4.10</td>
<td>1.56</td>
<td>Significant at 95% CL</td>
</tr>
<tr>
<td>VF*HD</td>
<td>10</td>
<td>75.57</td>
<td>7.56</td>
<td>1.76</td>
<td>2.98</td>
<td>0.52</td>
<td>Insignificant at 95% CL</td>
</tr>
<tr>
<td>FO*HD</td>
<td>5</td>
<td>153.07</td>
<td>30.61</td>
<td>7.15</td>
<td>3.33</td>
<td>1.04</td>
<td>Significant at 95% CL</td>
</tr>
<tr>
<td>Error</td>
<td>10</td>
<td>42.84</td>
<td>4.28</td>
<td>0.29</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>35</td>
<td>14656.22</td>
<td></td>
<td></td>
<td>100</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

SS = Sum of squares, DF = Degree of freedom, MS = Mean Square, F_cal = F-test calculated, F_0.05 = F-value at 5% significance level and P = Percentage of contribution.

Table 5.7 shows the results of ANOVA analysis for compressive strength of laminates. The table also indicates the percentage contribution of each factor on the total variation indicating the influence on the result. It may be observed from the results that the interaction between the above factors does not have significant variation on the compressive strength of the composite laminates. It is clear from the ANOVA table that the glass volume fraction (p = 21.54%), Fiber orientation (p = 7.66%) and hole diameter
have significant influence on the compressive strength. The effect of the volume fraction and orientation is comparatively less, which indicates that hole diameter significantly controls the compressive strength of the composite laminate. However, the interaction between the factors is quite marginal and can be neglected. The error associated in the ANOVA table was almost negligible because it is about 0.29%. The Regression coefficient ($R^2$) indicates that the predicted model explains 98.98% of variability in the compressive strength. The effect of the factors on compressive strength can be analyzed from the Fig. 5.37, it is clear that the hole diameter has significant influence on compressive strength compared to other factors. For laminates without any drilled hole the compressive strength was higher and at the same time for laminates with increased hole sizes, the compressive strength has decreased. This relation may be explained as hole diameter increases the stress concentration increase and also the cross sectional area of the material reduce, resulting in to the failure of laminates at small loads.

![Main Effects Plot for Compression Strength](image)

*Fig. 5.37 Main Effects plot for mean Compressive Strength on all factors.*

To examine the effect of individual factors with all of its levels, the detailed interaction plot for compression strength is given in Fig. 5.38. The variation in compressive strength due to variations of factors is better understood by using contour and surface plots, hence to represent the effect of each of the factors at different levels of variation these plots are shown in Fig. 5.39. The contour plots indicate that the highest compressive strength is obtained when glass levels are high and hole diameter levels are low, this area appears at the lower right corner of the plot.
Fig. 5.38 Interaction plot for Compressive Strength.

Fig. 5.39 Contour and Surface plots for Compressive Strength.

Residual plots that may be used to examine the goodness of model fit, Minitab has generated four types of residual plots as shown in Fig. 5.40. The Histogram shows two long tails indicating points of outliers with a standard error $S=2.206969$. Since the standard error obtained is not that high which indicates 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. The verses fit show a random pattern of residuals, with only two or three points lie far from the majority of points, indicating outliers. The points on either side of the zero line of the residual density is approximately same, indicating the predominance of positive and negative residuals is same.
5.6.3 Modeling of Impact Strength

Similarly modeling of impact strength using the same multilevel factorial design was carried, with three factors and 36 runs. The factors selected to study the response of impact strength are glass volume fraction, fiber orientation and Notch depth. Table 5.8 indicates the factors and their levels and the impact test results were subject to the analysis of variance. The results of the ANOVA technique at a significance of 5% is illustrated in Table 5.9.

### Table 5.8 Process parameters for Impact Response

<table>
<thead>
<tr>
<th>Factor</th>
<th>Type</th>
<th>Levels</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume Fraction, %</td>
<td>Fixed</td>
<td>3</td>
<td>15, 30, 45</td>
</tr>
<tr>
<td>Fiber Orientation, deg</td>
<td>Fixed</td>
<td>2</td>
<td>0, 45</td>
</tr>
<tr>
<td>Notch Depth, mm</td>
<td>Fixed</td>
<td>5</td>
<td>0, 1, 2, 3, 4, 5</td>
</tr>
</tbody>
</table>

### Table 5.9 Analysis of Variance Results for Impact Test

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>$F_{Cal}$</th>
<th>$F_{0.05}$</th>
<th>P</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume Fraction (VF)</td>
<td>2</td>
<td>1.648760</td>
<td>0.824380</td>
<td>712.20</td>
<td>4.46</td>
<td>80.17</td>
<td>Significant at 95% CL</td>
</tr>
<tr>
<td>Fiber Orientation (FO)</td>
<td>1</td>
<td>0.164428</td>
<td>0.164428</td>
<td>142.05</td>
<td>5.32</td>
<td>7.99</td>
<td>Significant at 95% CL</td>
</tr>
<tr>
<td>Notch Depth (ND)</td>
<td>4</td>
<td>0.169476</td>
<td>0.042369</td>
<td>36.60</td>
<td>3.84</td>
<td>8.24</td>
<td>Significant at 95% CL</td>
</tr>
<tr>
<td>VF*FO</td>
<td>2</td>
<td>0.054121</td>
<td>0.027060</td>
<td>23.38</td>
<td>4.46</td>
<td>2.63</td>
<td>Significant at 95% CL</td>
</tr>
<tr>
<td>VF*ND</td>
<td>8</td>
<td>0.001367</td>
<td>0.000171</td>
<td>0.15</td>
<td>3.44</td>
<td>0.07</td>
<td>Insignificant at 95% CL</td>
</tr>
<tr>
<td>FO*ND</td>
<td>4</td>
<td>0.009224</td>
<td>0.002306</td>
<td>1.99</td>
<td>3.84</td>
<td>0.45</td>
<td>Insignificant at 95% CL</td>
</tr>
<tr>
<td>Error</td>
<td>8</td>
<td>0.009260</td>
<td>0.001158</td>
<td></td>
<td></td>
<td>0.45</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>29</td>
<td>2.056637</td>
<td>0.100</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

SS = Sum of squares, DF = Degree of freedom, MS = Mean Square, $F_{Cal}$ = F-test calculated, $F_{0.05}$ = F-value at 5% significance level and P = Percentage of contribution.
It is clear from the ANOVA table that the glass volume fraction (p= 80.17 %), fiber orientation (p=7.99 %) and hole diameter (p=8.24 %) have significant influence on the impact strength. The effect of the notch depth and orientation is comparatively less, which indicates that glass volume fraction significantly controls the impact 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 as it is found to be about 0.45 %. The predicted model explains 94.4% of variability in the impact strength, as $R^2$ value which is very closer to unity. The main effect of the factors on impact strength can be analyzed from the Fig. 5.41 indicating clearly the dominance of glass fiber on impact strength.

![Main Effects Plot for Impact Strength](image)

**Fig. 5.41** Main Effects plot for mean Impact Strength on all factors.

The detailed interaction plot for impact strength is shown in Fig. 5.42. The variation in impact strength due to variations in the levels of the factors can also be analyzed by using contour and surface plots, hence Fig. 5.43 is also presented. The contour plots indicate that the highest impact strength is obtained when glass levels are high and notch depth levels are low. This area appears at the lower right corner of the plot.
Residual plots are generated for examining the goodness of model fit and shown in Fig. 5.44. The Histogram with two tails indicate points of outliers with a standard error $S=0.034$, since the standard error obtained is very less indicating model adequacy, hence the outlier points have little or no significance. The points in the normal probability plot have approximated a straight line, indicating goodness-of-fit. The verses fit also indicated the predominance of positive and negative residuals as same.
5.6.4 Regression Model

In order to establish the relation between the parameters such as glass volume fraction (V), fiber orientation (F) and notch size (N) on the mechanical properties of the hybrid composite laminate, multiple linear regression model was used to generate the regression equations. The Minitab software generated the following equations for various properties of the laminates.

\[
\text{Tensile Strength, } TS = 93.0 + 0.986 V - 0.503 F - 6.55 N
\]

\[
\text{Compressive Strength, } CS = 77.6 + 0.764 V - 0.248 F - 4.78 N
\]

\[
\text{Impact Strength, } IS = -0.0182 + 0.0191 V + 0.00329 F - 0.0507 N
\]

5.6.5 Model Adequacy

The model adequacy was performed by comparing some of the experimental results with the results from the regression model developed. To check the multiple regression equations derived above correlate with the experimental results of mechanical properties and to determine the percentage of error, confirmation tests were performed and the results are presented in Table 5.10.
Table 5.10 Confirmation tests and their Comparison with Regression Model

<table>
<thead>
<tr>
<th>Test</th>
<th>Specimen Configuration</th>
<th>Experimental Result</th>
<th>Regression Model Result</th>
<th>Percentage Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength,</td>
<td>G45%, 0/90, HD=2mm</td>
<td>139.27</td>
<td>136.06</td>
<td>2.30</td>
</tr>
<tr>
<td>Regression Model Eq. 5.1</td>
<td>G15%, 0/90, HD=2mm</td>
<td>96.03</td>
<td>104.48</td>
<td>8.88</td>
</tr>
<tr>
<td></td>
<td>G45%, 0/90, HD=0mm</td>
<td>147.34</td>
<td>137.37</td>
<td>6.77</td>
</tr>
<tr>
<td></td>
<td>G15%, ±45, HD=0mm</td>
<td>83.50</td>
<td>85.15</td>
<td>1.98</td>
</tr>
<tr>
<td></td>
<td>G45%, ±45, HD=2mm</td>
<td>97.60</td>
<td>103.42</td>
<td>5.96</td>
</tr>
<tr>
<td>Compressive Strength,</td>
<td>G15%, 0/90, HD=8mm</td>
<td>48.01</td>
<td>50.82</td>
<td>5.85</td>
</tr>
<tr>
<td>Regression Model Eq. 5.2</td>
<td>G45%, 0/90, HD=8mm</td>
<td>71.10</td>
<td>73.74</td>
<td>3.71</td>
</tr>
<tr>
<td></td>
<td>G30%, 0/90, HD=2mm</td>
<td>91.20</td>
<td>90.96</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td>G15%, ±45, HD=8mm</td>
<td>42.61</td>
<td>39.66</td>
<td>6.92</td>
</tr>
<tr>
<td></td>
<td>G15%, ±45, HD=4mm</td>
<td>65.60</td>
<td>58.78</td>
<td>10.40</td>
</tr>
<tr>
<td></td>
<td>G30%, ±45, HD=6mm</td>
<td>62.26</td>
<td>60.68</td>
<td>2.54</td>
</tr>
<tr>
<td>Impact Strength,</td>
<td>G15%, 0/90, N=2mm</td>
<td>0.16</td>
<td>0.16</td>
<td>4.31</td>
</tr>
<tr>
<td>Regression Model Eq. 5.3</td>
<td>G45%, 0/90, N=5mm</td>
<td>0.67</td>
<td>0.61</td>
<td>7.76</td>
</tr>
<tr>
<td></td>
<td>G30%, 0/90, N=4mm</td>
<td>0.31</td>
<td>0.33</td>
<td>7.09</td>
</tr>
<tr>
<td></td>
<td>G15%, ±45, N=1mm</td>
<td>0.36</td>
<td>0.36</td>
<td>1.57</td>
</tr>
<tr>
<td></td>
<td>G30%, ±45, N=3mm</td>
<td>0.61</td>
<td>0.57</td>
<td>7.35</td>
</tr>
<tr>
<td></td>
<td>G45%, ±45, N=2mm</td>
<td>0.86</td>
<td>0.88</td>
<td>3.01</td>
</tr>
</tbody>
</table>

From the above analysis the percentage error between the regression model and the experimental results is estimated. The percentage error obtained for all the tests varies between 0.26% to 10.4%, this variation is irrespective of type of strength considered for regression modeling. Therefore the multiple regression equation derived above correlate the evaluation of the strengths of the composite with the reasonable degree of approximation. The graphical comparison for model adequacy for tensile and compression behaviour is also shown in Fig. 5.45, from the plots it is clear that the regression model generates the results nearing to the experimental results hence the model equations can be used for the analysis purpose.

![Graph](image-url)

Fig. 5.45 Model adequacy for the tensile and compressive loads.
5.7 SUMMARY

The mechanical property characterization has been presented with emphasis on fiber orientation, fiber proportion and notch size. The analysis of the results indicate that the tensile strength is orientation dependent, whereas the compressive strength is fiber proportion dependent. However in both the cases the notch size significantly affects the strength. Fracture toughness of the material under tensile and compressive loads is moderately sensitive to percentage of glass content and at the same time it is highly sensitive to the notch size. Impact strength and respective fracture toughness of the composite material also indicate that they are highly dependent on glass fiber percentage and notch size, similarly the hardness of the material is also dependent on glass fiber percentage. The ANOVA results confirmed the material behaviour and the percentage contribution of individual parameters were also estimated, in addition the regression analysis at 95% of confidence level results into a regression model, the model obtained confirms greater degree of accuracy with the experimental results.