The purpose of this literature review is to provide background information on the issues that may be considered in this thesis and to emphasize the relevance of the present study. Limited amount of literature exists on the fabric reinforced hybrid composites, therefore the important literature covering the topics like property characterization, damage characteristics, strength degradation, need for machining and other topics related to the research are reviewed and discussed in the following sections.

3.1 TEXTILE COMPOSITES

Textile composite materials have recently received considerable attention, due to their structural advantages of high specific-strength, high adaptability, high damage tolerance, better out-of-plane stiffness and improved resistance to impact. Compared with unidirectional composites, the interlacing of fiber bundles in textile composites prevents the growth of damage and hence provides an increase in impact toughness. Besides their advantageous mechanical properties, textile composites are easy to handle and have excellent formability and hence are widely employed in many high performance applications [42].

The fibers that are used in fabric laminates are based on specific needs and the geometry of the reinforcement is chosen to reach the requested mechanical properties [27]. The textile preforms are made by weaving, braiding, knitting and stitching [11]. If in practice, all filaments had equal properties, then twisting of strands into yarns would not have any advantages in terms of mechanical properties. However, in a strand consisting of numerous filaments, not all filaments have equal properties. There can also be some broken filaments in a strand. Pre-impregnating the filaments with resin matrix results in to localizing the effect of broken filaments. Twisting the strand also enhances this effect and tends to make the twisted yarn more monolithic. Moreover, in textile preforms, strands are often twisted to avoid damage due to the fabrication process [6].

A textile composite has internal structure on several scales. At the molecular scale, both the polymer matrix and the fibers exhibit structural details that profoundly...
affect strength and stiffness. Matrix properties are determined by chain morphology and cross-linking, among other things. On a coarser scale, for \( \sim 1\text{mm}, 10^3 - 10^4 \) fibers are bundled into yarns or tows. Within the finished composite, each tow behaves as a highly anisotropic solid entity, with far greater stiffness and strength along its axis than in transverse directions. Because tows are rarely packed in straight, parallel arrays, stresses and strains often possess strong variations from tow to tow. Thus composite mechanical properties such as elasticity can only be considered approximately uniform on scales that are even larger still, say \( \sim 10\text{mm} \) or higher, where as the effects of the heterogeneous structure at the tow level are averaged out. Finally, the textile forms part of an engineering structure, perhaps the stiffened skin of a wing or fuselage. Since the engineering structure itself usually has some dimensions as small as \( \sim 10\text{mm} \), the fabrication of the composite material and the fabrication of the engineering structure may no longer be considered distinct operations. To fabricate the textile composite is to fabricate the structure. Fig. 3.1 illustrates steps in the production of a textile composite, the first processing step is the formation of yarns from fibers. In the second step, the yarns are woven into plain-woven cloth. The cloths are then laid up in the shape of the skin and stiffener to create an integral preform. Finally, the composite part is consolidated by the infiltration of resin and curing in a mold.

![Fig. 3.1 Steps in the production of a textile composite.](image)

The fabrication method at Fig. 3.1 also illustrates fairly high utilization of the axial stiffness and strength of the fibers. The fibers are arranged approximately in-plane, straight and with reasonably high volume fraction. High in-plane composite stiffness and strength can therefore be expected. Textile processes have been adapted to handle most of the fibers commonly used in structural composites, like glass, aramid and carbon. The only limitation to fiber selection is that most textile processes subject yarns to bending and abrasion. Machines have been modified to minimize fiber damage, but in many processes, exceptionally brittle or stiff fibers cannot be used [16].
3.2 PROPERTY CHARACTERIZATION

3.2.1 Mechanical Behaviour of Fabric Composites

Fabric reinforced polymeric composites are widely used for manufacturing components in many industries including aeronautical, automotive, sports, navy, home construction, etc. [18,71,148]. The appropriate performance of these composites during use is mainly related to their mechanical properties, as a result adequate combinations of reinforcement, matrix types and processing techniques require in depth investigations [133]. Compared to metals, the polymeric composites have many advantages such as higher fatigue strength, higher corrosion resistance and lower weight [9,133,148]. However, the components fabricated in polymeric composites present tight requirements in service and they can suffer mechanical damages during the utilization. The damages can occur during the fabrication process, handle, transport, storage and maintenance [50]. Despite the several advantages of the polymeric composites over the metallic materials, the former is more susceptible to mechanical damages when they are subjected to great efforts of tension, compression, flexure and impact, which can lead to interlayer delamination [50,119]. With further application of external load, the delamination propagates through the interlayers leading to catastrophic failure of the composite component [93,149].

Damage tolerance of polymeric thermoset composites can be enhanced by improving interlaminar properties by toughening the matrix and/or by using reinforcement with bidirectional arrangement of the tows i.e. fabric. Using fabric reinforcements is to take the advantage of the thickness of arranged fibers for enhancing both interlaminar and compressive strengths and also the toughness. For the purpose of verifying the mechanical performance of polymeric composites different types of mechanical tests like tensile, compressive, flexural, impact, shear, etc. are essential [93].

For composites, the mechanical tests are designed to produce property data for the material specifications, research and development [7]. The tensile tests are used to determine strength, modulus and also to verify technical specifications. The fracture surfaces, resultant of the tests, are used to support the failure mode analysis [7,26]. Compression 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. The presence of local defects, which are often difficult to characterize, also influences the failure in compression. Failure in compression is dependent on the way that the loading is applied. Usually, under axial compression, initially occurs the plastic deformation of the matrix followed by micro-buckling that frequently evolves to kink zones, which can provoke the fiber buckling, and finally the formation of two planes of fracture. Generally this is the way, the composite materials fail under axial compression by macroscopic shear of certain planes [182].

Flexural and interlaminar shear strengths of composites are usually performed to characterize composite materials. Gripping, buckling and end tabbing are not the issues for these types of tests [7,26]. In flexural tests, beams with a small span-to-thickness ratio are dominated by shear and beams with long spans fail in tension or compression [26]. Generally the shear failure is affected by the same factors as the transverse tensile strength, because shear stresses and strains become concentrated in the matrix between fibers in a similar manner to that outlined for transverse tensile. However, there is more scope for local matrix deformation to take place, without occurrence of crack. Under shear stress, the local stress concentration is relaxed more readily [77]. The shear tests are also used to evaluate the interfacial fibers-matrix adhesion [185] and the effect of binder on the composite mechanical properties, such as fracture toughness and interlaminar shear strength [165].

Mohan and Kishore [115,136] have carried experimentation on jute-glass hybrid composites and reported that the jute can be used as a reasonable core material. They evaluated flexural properties of jute-glass reinforced epoxy laminates on four different hybrid combinations with different percentages of glass. The authors found substantial increase in flexural properties due to hybridization.

3.2.2 Effect of Fiber Orientation

Under aligned tension, almost all load is borne by the aligned fibers. Their rupture is the primary failure mechanism and determines ultimate strength. However, depending on the fiber architecture, tensile or shear failures of the matrix can cause nonlinearity at much lower loads. Tow rupture strengths in weaves are approximately 30-50% lower than
would be expected from the properties of pristine fiber laminates. When a tensile load is not aligned with a primary group of tows, tow rupture may give way to failure by shear or transverse cracking. For loading at ±45° with respect to two orthogonal sets of tows, the problem reduces to one of deviatoric shear in those tows. Fig. 3.2(a) shows stress-strain curves for a plain weave composite loaded at various orientations. Response in the 0/90° orientation is nearly linear to failure, while considerable plasticity and high strains to failure are exhibited for off-axis loads. Fig. 3.2(b) shows similar trends for open hole specimens [16]. The failure stress for off-axis loads can be higher in the notched than in the un-notched specimen. Naik, et. al., [123] attribute this curious result to plastic tow straightening occurring near the hole.

![Stress-strain curves for Laminates loaded in tension at different angles](image)

Fig. 3.2 Stress-strain curves for Laminates loaded in tension at different angles [16].

As can be seen from the Fig. 3.2, the fabric composite material demonstrate relatively low stiffness and strength under tension at the angle of 45° with respect to the warp or fill directions. The situation is not different for other mechanical properties, hence the Fig. 3.3 below shows the influence of fiber orientation on the mechanical behaviour of fabric laminates [41,61].
3.2.3 Influence of Fiber Content

The increase of the overall fiber content from 0.44 to 0.55 showed an improvement in strength from 0.99 to 1.12 GPa. An increase in the fiber volume fraction, improves the properties but this improvement could be limited by the resin strength [162]. Cortes and Cantwell [40] have investigated the tensile and fatigue properties of a hybrid laminate. The authors have shown that the tensile response of the hybrid systems is dependent on the fiber volume fraction of the composite. In addition, it has been shown that the presence of a notch reduces the tensile strength of the laminates by between 46 to 53%.

The longitudinal modulus and the longitudinal stress increases with the increase in volume fraction of fibers. This is evident since the mechanical properties of the fibers are bigger than those of the matrix material. On the other hand, the strain decreases slightly from 2.7 to 2.3 when the volume fraction of the fibers increases from 0% to 21% and then rises again to reach 3.1 for 44% volume fraction. This evolution of the composite strain at break with the fibers filling ratio is very little since the strain at break of the fibers and the resin are too close. The composite Young modulus increases with the fibers filling ratio and progress from the resin modulus to the fibers one. The relations between the mechanical parameters of the composite and the volume fraction can be described as linear based on at least three points. Therefore the Young’s modulus
and Poisson ratio show the linear relation with respect to the fiber content [146, 183]. Halpin and Tsai [69] describe the behaviour of the Poisson ratio with the fibers fraction as linear when the fibers adhesion with the matrix is perfect.

The increase in fracture toughness with fiber content is consistent with reports of other reinforcing fibers. Fig. 3.4(a) presents a slight difference in fracture toughness between transverse and longitudinal specimens. This slight difference can be attributed to the greater overall fiber alignment across the crack path in the transverse specimens [41]. The variations of flexural strength and flexural modulus of hybrid composites with fiber content have been studied by the authors at reference [84]. The hybrid composites showed an increase in flexural properties with glass fiber loading as shown in Fig. 3.4(b). It was also observed that there has been an enhancement in these flexural properties with increased glass fiber content and the total fiber content in the hybrid composite.

(a) Fracture strength   (b) Flexural Strength

Fig. 3.4 Effect of fiber content on composite laminates [41,84].

3.2.4 Characterization of Interfaces

In most of the long-fiber polymer matrix composites, random fiber fractures accumulate as the applied stress level is raised during axial loading. The extent of interfacial debonding, or local yielding in the interphase, determines the degree to which stress concentrations around fractured fibers become redistributed and hence a catastrophic crack is likely to propagate from such fracture sites. It is therefore desirable for some kind of plastic strain accommodation to occur readily at the interface and in its immediate vicinity. However in general interfaces, PMC’s are required to be relatively strong and also to be chemically stable. For example, it is known that interfacial strength
often dictates the transverse strength of a unidirectional laminate and first ply cracking of an angle-ply laminate. Furthermore, the interface must be resistant to the penetration of water and other solvents. However, the way in which desirable properties are achieved varies with respect to the type of fiber reinforced. It should be noted that very strong interfacial bonding (relative to the strength of the fiber) is often undesirable, since these not only tend to make the region around fractured fibers more prone to crack propagation, but it will also tend to eliminate fiber pull-out, which is an important source of toughening in PMC's. This rather complex set of requirements for the interface in PMC's has led to the evolution of manufacturing procedures that are specific to individual composite systems.

For glass fiber reinforced plastics, interfacial debonding is generally not observed and matrix yielding is the most probable interfacial event (For high performance polymer fibers, interfacial failure is likely to occur within the fiber, because of their poor transverse properties.). It is perhaps more appropriate to describe the interfacial region as an interphase, which may include material which has penetrated the fiber surface and has different properties from those of the matrix. The nature of the matrix-reinforcement interface within a composite often has a profound effect on its overall properties. In general, interfaces in PMC’s must be relatively strong, to promote good load transfer and ensure that transverse properties are adequate, but not so strong as to create stress concentrations and eliminate fiber pull-out during fracture. In addition, they are often required to be chemically stable, to confer good environmental stability. It is in some cases beneficial to generate an extended interfacial region having a structure and properties different from those of the matrix - the so-called interphase. Optimization of composite toughness comes from retention of as much matrix plasticity as possible. Avoidance of the formation of brittle interfacial reaction zones during processing is often a priority [39].

3.2.5 Stress Concentration

The distribution of elastic stresses across a section of a member may be uniform as in a bar in tension, linear as a beam in bending, or even rapid and curvaceous as in a sharply curved beam. Stress concentration comes from some irregularity, such as tool marks, holes, notches, grooves, material defects, or threads. The nominal stress is said to exist if the member is free of stress raiser. The fracture processes in fiber-reinforced composites
are the results of a series of microscopic and macroscopic events such as fiber failure, fiber/matrix debonding, fiber/matrix inter-facial friction and visible cracks and notches. Consider a tensile stress applied to a unidirectional composite specimen, parallel to the fiber axis. As the load increases, two kinds of fiber fractures may occur. One is caused by the applied stress which exceeds the local strength of a fiber and leads to random breaks along the fiber, starting from the weakest points and progressing to the stronger ones. The other is caused by the redistribution of stress from a failed fiber to its as-yet unfailed adjacent neighbours. Whenever the local stresses in the nearby intact fibers increase to a degree higher than their local strengths, the intact fibers begin to fail. This fracture leads to a further release of stress into the next-nearest neighbouring fibers, within the same cross-section, and to the formation of clusters of breaks that are often observed experimentally. At a high level of applied stress, fiber failures due to stress concentration may dominate the fracture processes and the overall failure pattern is thus a direct function of stress redistribution mode and concentration [57,72,73,126, 171,177].

In the case of a loose fiber bundle (when no matrix is present) the surviving fibers most probably share equally all the released stress, a situation which was analyzed by author of reference [126] in a classical study. However, the presence of the matrix in a fiber-reinforced composite changes the way in which stress is redistributed. It is observed that the surviving fibers closer to the broken fiber bear most of the released load, whereas the more distant fibers bear only a small fraction of the extra load. As a matter of fact, relatively small clusters of breaks are usually observed in fiber-reinforced composites. For a convenient description of the overload in an intact fiber resulting from the load released by a broken fiber, a stress concentration factor (SCF) is defined as the ratio between the local stress in the intact fiber and the applied stress in the fiber far away from a break.

Overloading in an intact fiber was performed by Hedgepeth [73], followed by Hedgepeth and Van Dyke [72], to determine the average SCF in a fiber, resulting from adjacent breaks in a two-dimensional composite material. Hedgepeth's SCF is independent of the inter-fiber distance (or the fiber content), and of the physical properties of the fiber and the matrix. However, overload scale does depend on these quantities, and that affects fiber fracture statistics.
Fukuda and Kawata [63-65] investigated the effect of materials parameters on the SCF, through 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. The effect of the fiber content ($V_f$) was also incorporated in the analysis. The results obtained in the study of Fukuda and Kawata showed that the SCF increases with decreasing inter-fiber distance, with increasing values of the ratio $E_f/E_m$, and with the number of adjacent broken fibers.

Wagner and Eitan [57,177] developed a model for the SCF for two-dimensional composites in which the fibers are aligned parallel to each other. The resulting SCF was an explicit function of the inter-fiber distance, the matrix and fiber properties, the number and position of broken fibers, the position along the fiber away from the fracture site, and the stress-transfer length. The local effect of fiber breaks on nearest neighbours was found to be very mild and negligible.

At macroscopic level, for the cases where changes in sections are present stress-dependent yield criterion is usually used to analyze stress concentrations in plastics. The maximum stress in par with the nominal stress was used to calculate the stress concentration factor and to identify the location that possibly initializes the fracture. In addition to the von Mises stress, the maximum principal stress, which is more suitable for the analysis of brittle materials, was also applied to locate the stress concentration. The finite-element analysis provides results of stress components and the von Mises and principal stress at each node. To estimate the stress concentration factor ($K$), the ratio of maximum to nominal stress was used [116].

### 3.2.6 Failure criteria in composites

Failure criteria used for analysis of composites structures are similar to those in use for isotropic materials, which include maximum stress, maximum strain and quadratic theories. These criteria are empirical methods to predict failure when a laminate is subjected to a state of combined stress. The multiplicity of possible failure modes prohibits the use of a more rigorously derived mathematical formulation. The basic material data required for two-dimensional failure theory is longitudinal and transverse tensile, and compressive as well as longitudinal shear strengths [99,111,148].
Maximum Stress Criteria
Evaluation of laminated structures using these criteria begins with a calculation of the strength/stress ratio for each stress component. This quantity expresses the relationship between the maximum, ultimate or allowable strength, and the applied corresponding stress. The lowest ratio represents the mode that controls ply failure. This criterion ignores the complexities of composites failure mechanisms and the associated interactive nature of the various stress components.

Maximum Strain Criteria
The maximum strain criteria follow the logic of the maximum stress criteria. The maximum strain associated with each applied stress field is calculated by dividing strengths by moduli of elasticity, when this is known for each ply. The dominating failure mode is that which produces the highest strain level. Simply stated, failure is controlled by the ply that first reaches its elastic limit. This concept is important to consider when designing hybrid laminates that contain low strain materials, such as carbon fiber. Both the maximum stress and maximum strain criteria can be visualized in two-dimensional space as a box with absolute positive and negative values for longitudinal and transverse axes. This failure envelope implies no interaction between the stress fields and material response. Structural design considerations will dictate whether a stress or strain criterion is more appropriate.

Quadratic Criteria for Stress and Strain Space
One way to include the coupling effects in failure criteria is to use a theory based on distortional energy. The resultant failure envelope is an ellipse which is very oblong. A constant, called the normalized empirical constant, which relates the coupling of strength factors.

First- and Last-Ply to Failure Criteria
These criteria are probably more relevant with aerospace structures where laminates may consist of many plies. The theory of first-ply failure suggests an envelope that describes the failure of the first ply. Analysis of the laminate continues with the contribution from that and successive plies removed. With the last ply to failure theory, the envelope is developed that corresponds to failure of the final ply in what is considered analogous to ultimate failure.
3.2.7 Failure prediction of Textile Structural Composites

Ko and Pastore [95] used the yarn orientations to first estimate the strength of the fabric preform and then computed composite strength using a simple rule of mixture. Dow and Ramnath [54] modeled woven fabric composites using a simple geometry model that assumed a linear undulation path for the fill and warp yarns. They computed constituent fiber and matrix stresses from local stresses which were calculated using an iso-strain assumption and predicted failure based on the average stresses in the fiber and the matrix along with a maximum stress criterion. An important characteristic of textile composites is that they also exhibit non-linear shear behaviour. The earlier analysis techniques to model damage propagation and strength of textile composites often made simplifying assumptions regarding the fabric architecture and did not account for both geometric and material nonlinearities. R.A. Naik [160] developed a general-purpose analysis technique for the prediction of failure initiation, damage progression and strength of 2D woven and braided composite materials, including the effects of non linear shear response and nonlinear material response. R.A. Naik predicted failure within the representative unit cell (RUC) by discretizing the yarns into slices, averaging the stresses over the volume of the RUC to get the overall stiffness matrix and using the cumulative stresses in each yarn slice, together with appropriate failure criteria, to predict failure at each step of the incremental analysis. He further developed a progressive damage model by using either a stress reduction scheme or a cracked yarn bending model to account for the change in yarn compliance.

3.3 CHARACTERIZATION OF DAMAGE

3.3.1 Damage in Composite Structures

When selecting composites for different products, there is often a need to consider their susceptibility to impact damage. This can be as to the extent of through thickness damage produced by minor impacts to full penetration damage. Composites are often used in applications that are at risk of impact damage and their impact performance extensively is a requirement [46, 140].

Due to completely different material specifications between metals and composites, the impact behaviour of structures made by these materials differs inherently. Metals show visible damage caused by impact mainly on the surface of...
structures, while damage is hidden inside composite structure especially when subjected to low velocity impact. This invisible form may cause serious decrease in material strength [137], which can be created during production, repair, maintenance and small particle crashes to the composite body [127].

Ross and Sierakowski [142] studied the effects of impacts exerted by conical head impactors and observed delamination in glass epoxy plates. Clark [37] developed a model for delamination of different fiber reinforced plates and showed that the delamination is in the form of stretched or almond shape. Evans and Masters [60] showed how toughened matrix could develop impact characteristics of epoxy composites while Zhou and Greaves [186] studied damage resistance and tolerance of glass fiber reinforced plates with different thickness.

3.3.2 Effective Stress Concept

Since damage is not a quantity that can be measured, to develop a damage theory, the first thing is to define a damage variable and one of the ways of describing damage is by using effective stress concept. Lemaitre [101] defined effective stress as a damaged volume of material under the applied stress shows the same strain response as the undamaged one submitted to the effective stress. In an energy sense, this definition can be explained as the energy stored in the damaged material is equivalent to the energy in a fictitious undamaged material. The damage variable can be measured through the overall section area of a material element and the effective area after damage occurred. Different values of the damage variable correspond to different states of the material element, as damage variable lies between zero to unity; zero corresponds to undamaged state while unity corresponds to the fully-damaged state.

Roberto and Marvin [139] extended his investigation on unidirectional laminate strengths of notched and un-notched quasi-isotropic laminates and also on compression-after-impact strengths of five carbon fiber/toughened matrix composites. The compression-after-impact (CAI) strengths were determined primarily by impacting laminates and the author made clear that damage variable could also be measured in terms of residual compressive strengths of laminates after impact damage. Few CAI tests were also made using a drop-weight impactor with a given impact energy and concluded that the compression-after-impact strengths are dependent of impactor velocity.
3.3.3 Low Velocity Impact of Composites
Considerable attention in the composite community has been given towards the effects of low velocity non-penetrating impact similar to that of a dropped tool, careless handling, or runway debris. Choi and Chang [33] in their study showed that these types of damages are most often undetectable by visual surface inspection and can cause a significant reduction of the compression strength. The studies have already shown that low energy impacts may significantly reduce the load carrying capability of a composite component by as much as 50% [21, 51].

3.3.4 Low Velocity Damage Mechanisms
When traditional engineering materials such as steel and aluminum experience low velocity impact, the energy is typically absorbed through plastic deformation. Although this deformation is permanent, it usually does not significantly reduce the load carrying capability of the structure. Composites however experience very little or no plastic deformation during low velocity impact because of the low strain to failure of the fiber and brittle nature of the epoxy matrix. Therefore, the impact energy is absorbed through various fracture processes. It has been well documented that the principal mechanisms for dissipating low velocity impact is through matrix cracking, delamination, and fiber failure [20,33].

Depending on the dimensions of the test specimen, such as in long thin beams, a portion of the impact energy can also be absorbed through global bending of the composite [21]. The extent of damage imposed by low velocity impact may be affected by the geometry and laminate configuration of the composite. Cantwell and Morton [20] found a top surface contact initial failure in short thick composites and a lower surface flexural initial failure in long thin laminates. Wide varieties of test methods for low velocity impact of composites have been used in the literature. The test methods most widely used include the Charpy pendulum, the Izod pendulum, the drop-weight and the hydraulic test machine.

3.3.5 Impact Induced Delamination in Laminated Composites
Impacts on the surface of laminates can represent a major source of failure for layered composite structures. The final rupture mechanism can be linked to nonlinear irreversible
phenomena inside each lamina as well as to the nucleation and propagation of cracks inside the resin-enriched interlaminar phases. This latter phenomenon is commonly termed as delamination [160]. Crack formation between two adjacent plies, or delamination, is a damage mechanism of composite laminates that can form during any moment of the life of the structure: manufacturing, transport, mounting and service [128].

Delamination in laminated fiber reinforced composites is due to their relatively weak interlaminar strengths. Delamination may arise under various circumstances, such as in the case of transverse concentrated loads caused by low velocity impacts. Structural collapse in a composite structure is often caused by the evolution of different types of damages created in a local zone of the structure. The particular damage modes depend upon loading, lay-up and stacking sequence. Delamination is often a significant contributor to the collapse of a structure [3].

Impact is an important source of delamination in composite structures. Interlaminar cracks can be originated by internal damage in the interface between adjacent plies as a consequence of an impact in the laminate, due to drop of a tool during production, mounting or repair, or ballistic impacts in military planes or structures. Location of delamination has an important effect on the growth of delamination, according to Bolotin [15] two types of delaminations can be considered; internal delamination and near-surface delamination. Internal delaminations originate in the inner ply interfaces of the laminate and reduce the load capacity of composite elements. In particular, when compression loads are applied, the overall flexural behaviour of the laminate is significantly affected. Although the delamination separates the laminate into two parts, but still there is an interaction between the deformation of both the parts. Due to this interaction, both the parts of the laminate deflect in the similar way. Near surface delaminations, as its name indicates, originate near the surface of the laminate and represent more complex scenario than internal delaminations. This is due to the deformation of the delaminated part which is less influenced by the deformation of the rest of the laminate. After initiation, both types of delaminations can propagate under loads. In both the cases, reduction in strength and stability of the composite is considerable.
Albert et al. [3] justified the need to account delamination from the point of view of fracture mechanics, the energy release rates necessary for failure of a composite part from intralaminar and interlaminar damage were computed and the results showed that the lowest energy release rate obtained was for delamination.

3.3.6 Improving Low Velocity Impact Damage Resistance
Researchers have been looking at various methods for improving the low velocity impact response of composites. Opplinger and Slepetz [129] in their study concluded that any attempt to improve impact behaviour must confront the low strain capability of composites. Either fibers with higher strain to fracture must be developed, or ways to reduce the local strain under the impacting object must be contrived. The methods of improving the damage resistance of composites due to low velocity impact can be divided into five major areas; fiber toughening, matrix toughening, interface toughening, through-the-thickness reinforcements, and hybridizing.

Fiber toughening involves the use of fibers developed with a higher strain to failure. The impact performance of this type of fiber has been evaluated with moderate success. Several different approaches have been taken to toughen the matrix material. Although the stiffness of the composite is slightly reduced, one method of toughening the epoxy matrix is through the addition of rubber or thermoplastic compounds. Impact induced delamination occurs due to low interlaminar strength, interface toughening through the use of adhesive layers has found success, but this additional adhesive layers may cause a great weight penalty. Another method for decreasing the amount of damage due to delamination caused by low velocity impact is through-the-thickness reinforcements such as braiding, three dimensional weaving and stitching. Although significant delamination reductions are achieved, these techniques are costly and degrade the in-plane properties due to fiber impalement [10,21,22].

Hybridizing composites with additional high strain energy fibers have been shown to improve the damage tolerance due to low velocity impact. The high strain capabilities of these fibers allow the impact energy to be spread over a wider area allowing the load to be shared by a greater volume of material. However in most of the cases, the improved impact damage resistance is achieved at the expense of a reduction in the intended load bearing ability of the composite [178].
3.3.7 Calculation of Energy Absorption Values

The impact performance of target specimens can be characterized by calculating the loss of kinetic energy of the impact mass during impact penetration resistance. By measuring striking velocity and residual velocity, the energy absorption by the impacted specimens can be analyzed using the following formula:

\[ E = \frac{1}{2} m_i \left( v_i^2 - v_r^2 \right) \]  

(3.1)

Where \( E \) is the energy dissipated by the target during impact, \( m_i \) the mass of the impactor, \( v_i \) the incident impactor velocity and \( v_r \) is the residual velocity after rebound or perforation. \( v_i \) and \( v_r \) can also be considered as initial and final velocity, respectively. If final velocity is less than the initial velocity, then acceleration will be negative and can be termed as deceleration [49,141].

3.3.8 Damage Resistance of Laminated Composites

Damage resistance of a material is commonly considered to be the resistance of the material to impact damage, impacts may arise due to several reasons. Impact testing is commonly used to screen materials for damage resistance and tolerance and as a part of larger sub-element and element tests performed. Simulation of all these conditions may require testing at differing energy levels, velocities, impactor geometries, and support conditions. The most common method for investigating impact resistance is the falling weight test. This type of impact is included as a portion of the Compression after Impact testing.

The CAI test is an empirical evaluation of the degradation of laminate compressive strength due to out-of-plane impact. Investigators use different impact and damage tolerance tests depending on material form, application and expected damage. The CAI tests were developed by the airframe industry for determining the damage tolerance of composite materials and they may be generally applicable to other industries as well. Since the impact is with relatively low velocity, the test is not commonly used to assess ballistic damage tolerance. The impact level for CAI test is generally selected to cause visual damage to the laminate, but such that the damage is localized at the center of the plate [110].
3.4 ENVIRONMENTAL EFFECTS ON COMPOSITES

In many cases, polymer composites are used in harsh environments because of their chemical and moisture resistance properties. When evaluating the utility of a composite material for a potential practical application, the behaviour of the composite under the intended service conditions must be considered [157].

Femand and Christof [62] carried experimental investigations to study the effects of immersion in distilled water, temperature (ambient and 90°C) and cyclic loading on the mechanical behaviour of glass fiber reinforced epoxy matrix composite laminates. Following immersion for long durations, a steady state moisture uptake was reached for the ambient temperature specimens while no such state of saturation was observed for those immersed at 90°C temperature. Immersion in 90°C temperature results in excessive swelling and cracking, and considerable reduction in the fatigue resistance. The interrelation among accumulated creep strain due to cyclic loading, crack density variation and stiffness reduction were also discussed. In addition the effect of moisture absorption on the mechanical properties of polymeric composites was studied extensively.

Kotsikos, et. al., [98] investigated combined effect of pre-exposure in an aqueous (marine) environment and flexural cyclic load. They observed that the exposure to a marine environment altered damaged progression mechanism in a glass/polyester cross-ply laminate from matrix cracking in unexposed samples, to matrix cracking (with increased density) plus debonding and delamination.

Ellyin, et. al., [58] investigated the effect of aqueous environment and temperature on glass fiber reinforced epoxy matrix composites under monotonic (quasi-static) loading up to failure. It was reported that the degree of damage strongly depended on the immersion temperature. The effect of immersion in aqueous environment, temperature and cyclic loading was investigated separately and also in combination. In this manner, the interaction between different environments and cyclic loading was studied. The investigators concluded that the Glass-fiber/epoxy resin composite laminates immersed in distilled water absorb moisture and swell, the amount of moisture absorption depends on the temperature of the immersed water. The strength of specimens immersed in water at room temperature is slightly below that of the dry specimens, this situation the authors have attributed to crack (defect) closure resulting from swelling of
the epoxy-resin. In all environments and for all laminate geometries a crack saturation state was reported at a relatively early life.

Dash and Chatterjee [43] have conducted experimental investigation on the fracture toughness of woven carbon fiber reinforced composite after exposing to various adverse environments, like, water, saline water, acidic water, organic fuel, ice temperature and hot air, for different durations using single edge notched (SEN) specimens. A relationship between fracture toughness and duration of exposure under these adverse environments was established. The investigators have reported that the fracture toughness has decreased continuously with increased duration of environmental exposure, whereas the fracture toughness was found to be independent of pre-crack length. The author has reported that debonding and delamination occurred in initial phase of fracture toughness testing. This phenomenon has been predominant in all the cases prior to complete failure of the specimen. At the same time the temperature has significant influence over matrix debonding and reduced the original strength in greater margin. In case of liquid environment, the density of the medium has significant influence over the rate of diffusion of moisture into material. It depends on the constituent particles of the liquid, osmotic pressure and number of voids in material.

3.5 MOISTURE ABSORPTION IN COMPOSITE LAMINATES

The mechanical behaviour of FRP composites are dominated by the interfacial adhesion at the fiber-matrix interface. The presence of moisture at the interface can modify the interfacial adhesion thereby affecting the mechanical performance of the FRP composites. Moisture absorption in the composites introduces dilatational stresses. During moisture absorption, the outside ply of a composite laminate is in compression. This results from the outer ply trying to swell, but being restrained by the dry inner plies. Similarly, on desorption, the outer plies try to shrink, but are restrained by the wet swollen inner plies resulting into the tensile stresses in the outer plies. Consequently the mechanical properties and long term durability show a marked deterioration. Hence an environment comprising of high humidity fluctuations, where moisture absorption occurs in the high humidity regime and desorption occurs in the low humidity regime, can have highly deleterious effects on the mechanical behaviour and long term durability of the composites [122].
Shen and Springer [150] found moisture related degradations in tensile strength and stiffness of 0° and 45° carbon/epoxy composites to be independent of temperature. On the other hand, tensile properties of 90° laminates were significantly affected by moisture and temperature. Browning, et. al., [17] also found significant degradation in transverse strength of a carbon/epoxy composite with moisture and temperature.

Karasek, et. al., [90,91] performed a study on the influence of moisture and temperature on the impact resistance of epoxy composites. They found that damage initiation energy decreased with temperature due to reduced matrix properties with temperature. Also, while moisture individually was found to have no effect on damage initiation energy or subsequent energy absorption at ambient temperatures, the influence of moisture at elevated temperatures was significant and dependent on the matrix behaviour and wet glass transition temperature of the matrix. The damage initiation energy of a composite consisting of unmodified epoxy increased with moisture at elevated temperature, while that of toughened epoxy decreased with moisture at elevated temperature.

3.6 PREDICTION OF STRENGTH RETENTION

It is practically not feasible to expose the bars in real environmental conditions for its service life in years. So the service life is predicted using the data available from accelerated ageing conditions for shorter time periods.

According to Phifer and Lesko [132], using Fickian diffusion for the resin and the pultruded laminates, the moisture - temperature curves were generated. They also showed that a linear relationship exists when tensile strength versus moisture content was plotted. Therefore, a method is required to predict moisture uptake with time and temperature for GFRP bars so as to relate the moisture content with the strength degradation.

Dewimille and Bunsell [48] studied the diffusion of water in a unidirectional glass fiber reinforced epoxy resin. The objective was to determine the water diffusion into the composites followed Fickian behaviour at temperatures ranging from 22°C to 100°C. Authors found that the rate of moisture diffusion was much faster at higher temperatures than simple Fickian diffusion could predict. These authors suggest that this
was caused by matrix-fiber interfacial micro-damage of the composite at elevated temperatures. This interfacial micro-damage leads to an increased number of possible pathways available for moisture ingress. It is also observed that the composite samples that were cut parallel to the fiber direction absorbed more water and at a faster rate, than samples that were cut perpendicular to the direction of the fibers. This was also attributed to interfacial effects, which cause a positive deviation from Fickian behaviour. The diffusion constant \( D \) for Fickian moisture absorption is given by the equation;

\[
D = \pi \left( \frac{h}{4 M_\infty} \right)^2 \left( \frac{M_2 - M_1}{\sqrt{t_2} - \sqrt{t_1}} \right)^2
\]

\( M_t \) = Moisture mass uptake at time \( t \)

\( M_\infty \) = Equilibrium moisture mass uptake at time \( \infty \)

\( h \) = Specimen thickness

### 3.7 NEED FOR DRILLING OF FRP COMPOSITES

Although FRP composites can be manufactured to near-net shape, post processing operations such as machining are not entirely avoidable to create some features, especially holes. Indeed, drilling is arguably the most common post-processing operation performed on FRP composites. The principal machining operation performed on any composite structures is drilling as hole making operation is essential for assembly of any structures [59] and it accounts for up to 50% of all machining operations [19]. For example, over 100,000 holes are made for a small single engine aircraft; in a large aircraft transport millions of holes are made, most for fasteners such as rivets, bolts and nuts [12]. In spite of such dramatic statistics, drilling is yet to receive adequate attention of researches with respect to the numerous potential benefits of process control. These benefits include cycle time, tool breakage and cost reduction, in addition to part quality improvements [19]. At the same time about 60% of all part rejections during final assembly are due to drilling associated damages.

Typical damages in drilling of composite include surface delamination, internal delamination, fiber pull out, hole shrinkage, last ply damage, hole surface roughness and higher tool wear due to hard fibers. In order to minimize these machining problems
there is a need for research to select suitable cutting conditions for damage free drilling of composite materials [184].

Shen and Bixla Xue [152] made a study on composite leaf springs for light commercial vehicles, the leaf spring with glass fiber reinforcement weighed 2.5 kg and was fabricated by hand lay-up method. The authors reported that about 50-70% of weight was reduced using composite material. Rajendran and Vijayarangan [135] performed a study on unidirectional GFRP leaf spring and reported that 75% of weight reduction is possible. Similarly, Vijayarangan and Ganesan [174] made an attempt to study on the performance of composite spur gear and helical gear. James and Folwin [79] conducted investigations on manufacturing techniques of composite wheels for automobiles. In the above investigations it is observed that there is a need for some secondary operations like drilling of laminates for fasteners, oil holes, valve holes, machining windows, etc.

3.8 DRILLING OF FRP COMPOSITE LAMINATES

In machining of composites, a finish comparable to metals cannot be achieved due to the inhomogeneity and anisotropy of materials. It is commonly known that many problems still exist in terms of the complete understanding of the drilling process, including those related to form errors, burrs, chatter, tool wear and failure due to delamination. Generally, the cutting forces that depend on tool geometry and machining conditions contain information on the sources of these problems. Therefore, estimating the components of the force system acting on the drill’s cutting edges is necessary in order to find optimized designs for new tool geometries, to improve quality and to increase productivity [70].

Hocheng and Puw [75, 76] performed drilling on CFRP composites using HSS drill by varying feed rates. Authors reported that continuous and curly chips were observed in thermoplastics. However a fracture with discontinuous chips and delamination were observed at the hole exit in thermoset fiber reinforcement. Togliaferri, et. al., [168] has performed drilling on GFRP laminates and reported that the damage extent strictly depends upon the speed to feed ratio. The lower the speed-feed ratio the poorer will be the quality. Caprino and Togliaferri [23] reported that at lower feed rates
the delamination occurred at the sub-laminate, whereas at higher feed rates it occurred at the early stage of the drilling.

Bhattacharya and Harrigan [13] performed drilling on Kevlar reinforced composites using normal and modified tools under cryogenic and ambient conditions. They reported that, by introducing a negative point angle and high clearance angle KFRP could be successfully drilled with HSS bits. Hocheng and Dharan [74] reported that, as the end layers of the laminate has got less resistance to deformation, maximum delamination occurs at the entry and exit side of the hole mainly because of peel-up and push-out action of the tool.

Singh and Khare [156] performed drilling on PVC sheets, they presented a relationship between error in hole diameter and drill speeds at different feed rates. They revealed that very high feed rates resulting large thrust and torque value. Caprino and Togliaferry [23,163] have observed that improper selection of the drilling parameter could lead to unacceptable material degradation, such as fiber pullout, matrix delamination. Authors have correlated the width of the damage zone to the drill speed and feed rate ratio, however for small damage zone widths no correlation seems to exist.

Wen-Chou Chen [180] introduced the concept of delamination factor in his experimental investigation on CFRP material. They reported that delamination free drilling is possible by proper selection of tool geometry and drilling parameters. Nam Jeong Lee, et. al., [125] have reported that the tensile modulus and the failure processes such as de-bonding, fiber pullout and locally plastic deformation increases almost linearly with the increase of fiber percentage.

Joshi, et. al., [144] performed study on the mechanics of machining, the authors considered the volume of reinforcement as one of the dependent parameters, they reported that it is difficult to reveal a definite trend on the influence of fiber volume fraction on the magnitude of cutting forces. However the results reported that, at lower cutting speeds and higher depth of cuts there is an increase in cutting forces with the increase of fiber content.
3.9 MODELING OF LAMINATED COMPOSITES

An experiment is a test or series of tests in which purposeful changes are made to the input variables of a process or system so that we may observe and identify the reasons for changes that may be observed in the output response. The major limitation of experimentation is considering one factor at a time and this fails to consider any possible interaction between the factors. To deal with several factors simultaneously is to conduct factorial experiment, it is an experimental strategy in which factors are varied together, instead of one at a time. It is therefore important to produce and validate experimental results using modeling technique that can predict mechanical behaviour of laminates. The modeling for woven fabric composites available can be grouped into two classes. The models of the first class, that includes statistical methods, these provide a reasonable estimate of the mechanical properties but the evaluation of stress pattern is not possible. The second class is based on finite element models of the laminate. This method can provide adequate estimates of the stress patterns within the laminate [27].

The design of experiments is a tool with which the interaction between the factors can be established. With any material system, one would like to use the most general information known about the material and be able to predict properties of concern. The author of reference [157] has presented models for design of experiments for the purpose of predicting the elastic properties of woven fabric composites and the author has discussed different models to predict the mechanical properties. Different investigators have studied the drilling behaviour using modeling and experimental techniques in case of composites. Ugo, et. al., [170] have developed an approach of multi-objective criterion to obtain the optimum drilling conditions, Davim, et. al., [130] used different matrix materials and used orthogonal array and analysis of variance (ANOVA) to investigate the cutting characteristics of FRP composite materials.

The author [87] used finite element model for the purpose of the analysis to estimate the effectiveness of the modeling. Carvelli and Poggi [27] have presented a finite element model suitable for the analysis of woven fabric composites, a homogenization process to pass from a micro to a macro scale and to relate the mechanical properties of the macro element to the properties of the single phases, is applied. Unidirectional fiber reinforced composites were considered to determine their
mechanical properties. The numerical results are compared to the experimental values of different laminates in terms of mechanical properties.

David [44] modeled finite element models of simple composite specimens, despite the simplicity of the modeled geometry and loading conditions, the modeling problems are extremely large. Therefore for efficient modeling the composite structures using Ansys, shell elements are often used. The properties of the shell elements allow for arbitrary composite lay-ups and may allow failure and property degradation of each individual ply to be predicted using conventional in-plane failure predictions.

3.10 SCOPE AND OBJECTIVES
Composites can be used to its full advantage only when the behaviour is known, any uncertainty in this regard results in the underutilization of the material properties by the use of unusually large margins of safety in actual design. Also when composites are selected, there is often a need to consider their susceptibility to impact damage. Since the fibrous composites are generally superior to metals with respect to specific strength and modulus. Therefore, thorough understanding of the material properties under varied loading conditions and configurations is crucial for the successful development of components.

From the above literature it is found that hybridizing the composites displays the beneficial characteristics of the separate constituents and serves technical purposes apart from the fact that they are cost effective [122]. The authors of literature [115,136] found substantial increase in mechanical properties due to hybridization. At the same time, hybridization improves the damage tolerance [178] and also damage resistance [129] of composites against low velocity impacts. Hence the major aspects of the above literature reveal the scope for hybrid composites but, there is lack of literature on the systematic investigation and characterization by various techniques including machinability, strength degradation and modeling. An important observation during this literature review is that there are some studies on hybrid composites with glass fibers as one of the constituent materials for reinforcement, while there exists quite a few attempts to prepare hybrid composite laminates using textile fabrics. These studies can be used as a base and reference for considering a new reinforcement material from the textile fabric group.
Textile fabrics such as satin cloth which provide greater tearing and breaking strength at reduced areal density, at the same time they are easily available and cheaper. There is a widespread need for hybrid composite materials data as they show increased damage resistance, hence there is a need for investigation and analysis of these materials properly.

The scope of this thesis is defined to concentrate on damage and environmental effects phenomena. The barely visible damages in composites may be due to low velocity impacts or may be during machining process. At the same time the mechanical properties of the composites degrade when exposed to adverse environments. Hence it is obvious that the definitive solution to damage and degradation problems asks for highly sizable research, hence the following areas are found to be important for the purpose of investigation.

Firstly, mechanical behaviour of hybrid composites is required to generate a database; this requires experimental investigations to characterize the mechanical behaviour of composites. Secondly, influence of parameters on the material is needed to improve the structural integrity and service life of components. Thirdly, investigations on the damage due to low velocity impacts and during drilling of laminates are essential to predict the residual strengths. Finally, strength degradation of composites under strength deteriorating and adverse environments is highly demanding to predict the life of the component. The discussions in this thesis will be limited to the mechanical engineering field, the properties of the hybrid composite structures is studied by means of the combined approach of experimental and modeling techniques.

Hence the main objective of this investigation is to characterize the properties of a new material combination using glass and textile satin fabric as reinforcements in epoxy matrix. Systematic investigations are planned to generate materials data, which will be useful for the materials technologists. The primary objectives of this investigation that addresses the need for experimental and modeling for characterizing the properties of Glass/Satin reinforced epoxy composite (GSFRP) material are;

2. Specimen preparation includes selection of three fiber volume fractions and two fiber orientations using hand layup method.

3. Specimen configurations, dimensions and experimentation are in accordance with ASTM standards.

4. Characterization of Physico-mechanical properties such as density, void content, fiber content, tensile, compressive, impact, flexure, fracture, shear and hardness.

5. Estimation of open hole laminate strength under tensile and compressive loads.

6. Low velocity impact damage characterization for different impact energies and impactor sizes.

7. To analyze the effect of multiple impacts on the laminated composite material.

8. Evaluation of compression after impact (CAI) strength of laminates to analyze the damage tolerance of the material.

9. Study on the moisture absorption property and comparison for Fickian behaviour.

10. To analyze the impact strength degradation of hybrid laminates exposed to various adverse environments for different durations.

11.Characterization of drilling behaviour of composite laminates using HSS drills with different drill diameters, cutting speeds, laminate thicknesses, drill geometries and drill types.

12. Validation of experimental results using modeling techniques and to generate regression equations to relate all the controlling parameters.