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

3.1 HYBRID COMPOSITE MATERIALS

In order to improve the properties of existing composites, a newer trend is towards the development of Hybrid Composites. Generally Hybrid applies to advanced composites and refers to use of various combinations of fibers or particulate in either thermoset or thermoplastic matrices. Hybrids have unique feature that can be used to meet the diverse and competing design requirements in a more cost effective way than either advanced or conventional composites.

Hybrid composites are used to serve technical purposes apart from the fact that they are cost effective. Enhancing the impact resistance, with the addition of ductile fibers helps in delay of the damage on impact, allows greater energy absorption and prevents breakage of structural elements. Also by combining high modulus plies with ductile foils or sheets, high modulus lighter hybrid composite results. In some hybrids that need stiffening, aluminium is used. Hybridization provides material designers with an added degree of freedom in tailoring composites to achieve a better balance of stiffness, strength, increased failure strain, better damage tolerances, improved ability to absorb impact energy and possibly a significant reduction in cost. Hence, the behavior of fiber reinforced plastic (FRP) hybrid composites under possible service conditions is a matter of significant practical interest. The mechanical behaviors of FRP composites are dominated by the interfacial adhesion at the fiber-matrix interface [96, 73].
In a review article the author has mentioned that for weight reduction and improved damage tolerance characteristics, which were the prime drivers to develop continuous fiber/epoxy/aluminum hybrid composites for aircraft structures as new family of materials. The combination of metal and polymer composite laminates can create a synergistic effect on many properties. The mechanical properties of fiber/metal laminate (FML) show improvements over the properties of both aluminum alloys and composite materials individually. Due to their excellent properties, FML are being used as fuselage skin structures of the next generation commercial aircrafts. It is also mentioned that one of the advantages of FML when compared with conventional carbon fiber/epoxy composites is the low moisture absorption. Due to this favorable atmosphere, recently big companies such as EMBRAER, Aerospatiale, Boeing, Airbus, and so one, starting to work with this kind of materials as an alternative to save money and to guarantee the security of their aircrafts [38].

Mohan and Kishore have reported that in jute-glass hybrid composites, jute can be used as a reasonable core material. They evaluated flexural properties of jute-glass reinforced epoxy laminates fabricated from filament winding technique. Four different hybrid combinations were studied for different percentage of glass and the results compared with the jute-reinforced plastic. They found substantial increase in flexural properties due to hybridization [86,72].

Mishra et.al. studied the effect of glass fiber addition on tensile and flexural strength and izod impact strength of pineapple leaf fiber along with sisal fiber reinforced polyester composites. John et. al., have studied on sisal-glass polyester hybrid composites with 5% and 8% volume fraction and found a considerable enhancement in flexural, impact, tension, compression properties. The coir/glass polyester hybrid composite was studied for the enhancement of properties by Pavithran et. al., [56,57,71,79].

3.2 STEEL REINFORCED POLYMER COMPOSITES

As current infrastructure ages, and load demand continues to increase, both rehabilitation (restoring to original capacity) and strengthening measures must be
made. Fiber reinforced polymer (FRP) materials have been successfully used for rehabilitation and strengthening efforts for the past two decades. Recently, a new form of FRP: steel fiber reinforced polymer (SFRP), has been introduced as an alternative to more conventional carbon or glass fiber reinforced polymers (C/GFRP). In this section literature review focuses on research investigating the use and performance of SFRP.

Steel fiber reinforced polymer (SFRP) composite materials have recently been introduced as an alternative to glass and carbon fiber reinforced polymer (GFRP and CFRP) composite materials (Hardwire, 2002) [46]. There are many benefits in using SFRP over GFRP or CFRP. Significantly, the steel cords that make up SFRP have some inherent ductility. Also, when cementitious grout is used rather than epoxy as the bonding agent, the SFRG can exhibit excellent fire endurance [25]. Similar to GFRP and CFRP, SFRP has the advantage of being relatively lightweight in comparison to steel plates, making it relatively easy to install.

SFRP materials are composed of ultra high strength steel fibers embedded in a polymeric matrix. The fibers are of a very small diameter so that the steel can have the microstructure of pearlite. The result is a high tensile strength steel, up to eleven times stronger than typical steel plate (Hardwire, 2002). The fibers are similar to the steel cords used as reinforcement in automotive tires. The fields of applications of SFRP mentioned are on double-tee prestressed concrete beams, on Reinforced Concrete Bridge, used in Restoration of Historic Theatre and used in Blast Resistant Design. It is also reported that SFRP can also be used with wood products to protect against impact loading such as that from projectiles in a hurricane or tornado. The U.S. military has interest in using SFRP to armor vehicles and buildings against blasts and small arms fire. Hardwire claims that SFRP is an economical alternative to standard ballistic armor having equal performance. It is also recommended that SFRP is still relatively untested compared with GFRP or CFRP; additional testing over a range of parameters should be conducted to establish more definitive relationships than are possible in the limited study reported here [77].
Yail Kim et al., [112] have reported the test results of an experimental investigation carried out on reinforced concrete beams strengthened in flexure using steel reinforced polymer which is an emerging new composite that offers mechanical properties comparable to those of CFRP at a reduced cost. The study investigates the effect of reinforcement ratios of SRP, in terms of the width of the sheet attached to the tension face of the beam as well as the effect of using SRP U-wraps for the anchorage of longitudinal SRP sheets. This study is also focused on examining the shear stress concentrations near the cut-off points of SRP, as well as evaluating the contribution of SRP U-wraps to flexural stiffness through diagonal crack control and slip control of the longitudinal SRP sheet.

The investigators [112] based on their experimental work have drawn the following conclusions:

1. Significant increase in flexural strength, up to 53%, was achieved in the beams strengthened with SRP sheets. Except for the beam with 100 mm wide SRP sheet, all other beams failed in compression by concrete crushing, followed by the concrete cover delamination induced by high stress concentrations at the cut-off point of the SRP sheet. The beam strengthened with a 60 mm wide SRP sheet achieved 90% of the moment capacity of the beam strengthened with a 100 mm SRP sheet that failed by delamination before concrete crushing.

2. Additional transverse reinforcement such as U-wraps could delay the premature peeling-off failure of the SRP sheet by providing end anchorage and also reduce the downward deflections induced by diagonal cracks. A pseudo-prestressing effect was observed as a result of the confining effect of the U-wraps, which reduced the slip of the longitudinal SRP sheet that resulted from shear deformation of the resin at the interface between the concrete and SRP sheet.

3. The developed theoretical model is simple and has successfully predicted the ultimate loads of the test beams. The shear stress model based on the classical beam theory exhibited good agreement with test results except in the
vicinity of the cut-off points of the sheet where high shear stress concentrations occurred.

John and Venkata Naidu [112], in their investigations have studied the variations of flexural strength and flexural modulus of unsaturated polyester based sisal/glass hybrid composites with fiber content. The hybrid composites showed an increase in flexural properties with glass fiber loading. It is 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. But these hybrid composites showed lower flexural properties than the matrix when the glass fiber content was low. It was also observed that the flexural properties of the sisal fiber-reinforced composite were considerably lower than those observed for the glass fiber-reinforced composite and hence, as the glass fiber is added to the sisal in the composite, a positive hybrid effect has been observed. Further the effects of alkali treatment and silane treatment of fibers on the flexural properties of these sisal/glass hybrid composites have also been studied. No significant effect on the flexural properties has been observed by silane treatment but a small increase in these properties has been observed by alkali treatment.

3.3 CHARACTERIZATION OF MATERIAL BEHAVIOR

The tension and compression tests require only simple specimens, are easy to perform and give accurate and reliable measurements. For these reasons, they are attractive tests to determine as much of the mechanical properties of composite materials as possible. In a tensile test, the ultimate tensile strength of a material can be defined in different ways. Some possible definitions are the onset of plastic yielding (for metals) or the first-ply failure (for laminates). Since it is difficult to detect the first point of damage in laminates, the ultimate tensile strength corresponds to the maximum load a material withstands [44].

In general, compression testing is difficult because the composite material has high longitudinal strength and low transverse strength. Therefore, direct end loading of samples (ASTM 695) is not possible because the ends of the specimen separate (splitting) and the property measured is the composite
bearing strength rather than the actual compressive strength. This problem also occurs for testing of full-size structural shapes. Many fixtures have been developed to prevent splitting at the ends of the specimen by introducing restrictions to the lateral expansion of the specimen at the ends. In most fixtures this is accomplished by end-tabs, but the use of end-tabs is very time consuming. Since composite materials have high variability in material properties from point to point, a large sample population is needed to obtain good estimates of average, standard deviation, and so on. Therefore it becomes important to reduce the cost and time of specimen preparation, without sacrificing accuracy [17].

Cortes and Cantwell [31] conducted investigation to study the tensile and fatigue properties of a carbon fiber-reinforced PEEK–titanium fiber metal laminate have been investigated. It has been shown that the tensile response of the hybrid systems is dependent on the volume fraction of the composite. In addition, it has been shown that the presence of a notch reduces the tensile strength of the laminates between 46 and 53%. In addition, it has been observed that delamination is more extensive in laminates with thick fiber-reinforced composite layers than in laminates with thin composite layers.

Jane Maria et. al., [52] conducted tensile testing of different carbon fabric reinforced epoxy composites using rectangular specimens in accordance to ASTM D3039 standard using hand lay-up process and analyzed the failure modes of specimens like the type and location of the damage. They also observed that the plain weave fabric (PW) type showed an increase of the tensile strength when compared with the Eight Harness Satin (8HS) type. However, the highest modulus results were determined for the 8HS composite laminates. The correlation of these results emphasized the importance of the adequate combination of the polymeric matrix and the reinforcement arrangement in the structural composite manufacture.
John Nairn et. al., [55] in their investigations on the effects of fiber, matrix and interphase on carbon fiber composite compression strength even though not entirely conclusive, the following dependencies are strongly suggested;

- The failure initiation load increases with decreasing fiber strength.
- The fiber fragmentation rate decreases with decreasing fiber strength.
- The crack density plateau value decreases with decreasing fiber strength.

Unfortunately, composites of this type have relatively poor mechanisms for absorbing energy due to local impact damage where loading is normal to the fiber plane. This is primarily due to the low strain to failure and low transverse shear strength of the graphite fiber and the brittle nature of the epoxy matrix. Since the early 1970's, researchers have been looking for methods to improve impact properties of graphite composites such as fiber and matrix toughening, interface toughening, through-the-thickness reinforcements, and hybridizing [90].

Impact events can be categorized into four velocity ranges; low, high, ballistic, and hypervelocity. Low velocity impact may include situations such as a dropped tool (< 100 ft/sec) whereas high velocity impact might include a bird colliding with an airplane (100 - 800 ft/sec). Ballistic impact events include situations such as a projectile fired from a gun at speeds in excess of 800 ft/sec. Finally, orbital debris traveling in outer-space at velocities up to 50,000 ft/sec are considered to be hypervelocity impact events.

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. This type of damage is most often undetectable by visual surface inspection (Choi and Chang, 1991), and can cause a significant reduction of the compression strength. In previous studies, it has been shown that low energy impacts may significantly reduce the load carrying capability of a composite component by as much as 50%.
The extent of damage imposed by low velocity impact may be affected by the geometry and laminate configuration of the composite. It has been well documented that the principal mechanisms for dissipating low velocity impact is through matrix cracking, delamination, and fiber failure. The three principal damage mechanisms are shown schematically in Fig. 2.1.

Fig. 3.1 Schematic demonstrating the three principal damage mechanisms for low velocity impact (a) matrix cracking, (b) delamination, (c) fiber failure.

The response of a laminated composite to an impact object depends on the impact parameters of the impactor and the material properties of the composites such as stacking sequence, interlaminar shear strength, tensile and flexural properties of the composites. When a foreign object impacted on the laminates, the impact energy was absorbed by the composite and damages such as delaminations, fiber breakage, and matrix cracks occurred in the composite structure [98].

De Moura, et. al., [34] conducted experiments on carbon/epoxy laminates by low-velocity impact. The internal delaminations can drastically reduce the compressive strength of laminates. In this study, a numerical analysis for predicting the residual compressive strength of delaminated plates was proposed. Due to the complex stress state of the problem, a mixed-mode analysis including the three modes of fracture was considered. Experimental studies were performed on carbon-epoxy [0\degree, 90\degree]_s and [90\degree, 0\degree]_s laminates. They included low-velocity impact tests, followed by X-ray damage characterization and compression tests. Good agreement between experimental and numerical analysis was obtained.
Roy Xu and Ares Rosakis [117] in their systematic experimental investigation have analyzed and documented series of complex failure modes for impact loading. In all cases, inter-layer (interfacial) cracks appeared first. These cracks were shear-dominated and were often intersonic even under moderate impact speeds. The transition from inter-layer crack growth to intra-layer crack formation was also observed. The shear inter-layer cracks kinked into the core layer, propagated as opening-dominated intra-layer cracks and eventually branched as they attained high enough growth speeds causing core fragmentation.

Dhakal, et. al., [35] conducted experiments on the low velocity impact response of non-woven hemp fiber reinforced unsaturated polyester composites. A significant improvement in load bearing capability and impact energy absorption was found following the introduction hemp fiber as reinforcement. The author has indicated a clear correlation between fiber volume fractions, stiffness of the composite laminate, impact load and total absorbed energy. Unreinforced unsaturated polyester specimens exhibited brittle fracture behaviour with a lower peak load, lower impact energy and less time to fail than hemp reinforced unsaturated polyester composites.

3.4 EFFECT OF NOTCHED TESTING
Composites when used in structures need the provision of holes or cutouts to satisfy the structural need. The most common method of assembling composite structure is by the use of mechanical fasteners, even though bolted joints are relatively inefficient. The stress concentration due to the hole will cause substantial reduction in strength and stability of notched composite laminates. The magnitude of this reduction varies considerably with a multitude of factors. All composite materials that exhibit a linear elastic stress-strain relationship to failure will be very sensitive to notches. Unlike metallic materials, the effects of the notch on strength will vary with the size of the notch but are relatively independent of notch geometry. It is generally accepted that flawed structures fail when the flaws grow or coalesce to a critical dimension such that (I) the structure cannot safely perform as designed and qualified or (2) catastrophic fracture is
imminent. This is true for structures either made from traditional homogeneous materials or fiber composites. One difference between fiber composites and traditional materials is that composites have multiple fracture modes that initiate local flaws compared traditional materials which have only few fracture modes [30,26].

Under uniaxial tensile load distribution, stresses occur around the geometrical constraints like holes, reduced cross section, discontinuities, etc. The peak stress reaches to a much larger magnitude than the average stress over the section. The stress is affected by the geometrical shape of the irregularities as well as by the dimensions of the irregularities. The presence of a hole in a specimen under uniaxial load introduces three effects [5].

- There is an increase in concentration of stress at the root of the notch,
- Stress gradient is set up from root of the notch toward the center of the specimen, and
- A triaxial state of stress is produced at the notch root.

The hardness as well as the geometrical shape and dimensions of notch of the specimen affect the stress concentration factor. The factor of the material with higher hardness is larger than that of the material with low hardness [100,109].

The severity of stress concentration initiates propagation of crack, causing the fracture of material. Fracture in all materials, brittle or ductile, homogeneous or composites, is governed more or less by discontinuities and imperfections, such as, cracks, notches, inclusions or dispersed phases. Hence it is necessary to understand the response of composites in presence of notches and holes in establishing a design methodology for a particular composite [54].

The fracture processes in fiber-reinforced composites are the results of a series of microscopic events such as fiber failure, fiber/matrix debonding and fiber/matrix inter-facial friction. 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 neighbors. 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 neighboring 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. In the case of a loose fiber bundle (when no matrix is pre-sent) the surviving fibers most probably share equally all the released stress, a situation that was analyzed. 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.

An analytical model proposed by Zairyo and Kawata [116] included for the first time 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 $V_f$ also appears 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.

### 3.5 STRENGTH DEGRADATION

FRP composites are exposed to temperature extremes as cold as $-53.9^\circ C$ and elevated temperatures up to $250^\circ C$. Strength and stiffness properties are generally unimpaired by cold temperatures and in some instances actually increase. Cold temperatures tend to make the polymers less flexible. On the
other hand high temperatures can cause chemical degrading and almost all chemical reactions are accelerated by an increase in temperature. Further as the temperature of the matrix is elevated, the properties of the composite remain unchanged until the point at which the matrix begins to soften. The matrix will reach the glass transition temperature at some point, during this period it passes from a glass like state to a rubbery state. At this point substantial losses in mechanical properties of the matrix occur.

Moisture is constantly present in the operational environment in which a composite is manufactured and throughout its useful life. From the studies it is observed that moisture has a potentially degrading effect by lowering the glass transition temperature. The end result is that as the amount of moisture increases, the mechanical properties of the composites are reduced [43].

While the aerospace industry has been traditionally the major driver for the advancement of composite materials, current trends find these materials used in a wider variety of applications. Among those industries leading research efforts related to the expanded utilization of composites are the infrastructure industry, marine industry, and the offshore oil industry- all of which require composite materials to endure harsh moisture and temperature environments. The potential effects of each condition are very similar in nature; interfacial degradation, matrix property degradation, build up of residual intralaminar stresses due to expansion and swelling, and changes in fracture toughness and ductility and other properties.

But unfortunately, polymeric composites are susceptible to heat and moisture when operating in changing environmental conditions. They absorb moisture in humid environments and undergo dilatational expansion. The presence of moisture and the stresses associated with moisture-induced expansion may cause lowered damage tolerance and structural durability. The structural integrity and lifetime performance of fibrous polymeric composites are strongly dependent on the stability of the fiber/polymer interfacial region [87].

Moisture absorption in polymer composites lead to changes in the thermophysical, mechanical and chemical characteristics of polymer matrix by
plasticization and hydrolysis. The amount of moisture absorbed by the matrix resin is significantly different than that by the reinforcement fiber. This result in a significant mismatch in moisture induced volumetric expansion between the matrix and the fibers, and thus leads to the evolution of localized stress and strain fields in fibrous composites. Also 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 introduce dilatational stresses. During moisture absorption, the outside ply of a composite laminate is under compression [73].

Sneha Patel Davison [97], conducted experiments on Enviro-mechanical durability of graphite/epoxy composite materials and found that tensile strength increased with temperature for the thin laminates, but decreased slightly for the thicker laminates. Also the author has lamented that in the toughened epoxy composite system the crack density decreased with temperature while the first crack strain increased with temperature. Delamination at the fiber/matrix interface was also observed in this system due to fiber/matrix interfacial debonding. However, the amount of delamination decreased with temperature, while the delamination onset strain increased with temperature. The amount and rate of delamination also increased with thicker 90° layers. Further, in the author's analysis, failure surfaces indicated that little or no additional interfacial debonding took place at elevated temperature than at room temperature.

Roger Vodicka [91] conducted experiments on environmental exposure of boron-epoxy composite material at two tropical exposure sites within Australia for a period of about 3.5 years to evaluate the effects of outdoor exposure on mechanical properties. Mechanical tests were then performed in ±45° in-plane shear at both room temperature and 60°C to assess the effects of moisture on the matrix. The chord shear modulus was also determined in some cases. The results indicated that no significant changes in shear strength occurred at room temperature or 60°C due to outdoor exposure. The peak shear stress was about 15% lower when tested at 60°C compared to those tested at room temperature. This study found no evidence that absorbed moisture is likely to degrade the
strength of boron-epoxy repair patches used on RAAF aircraft when tested at room temperature and 60°C.

Dash and Chatterjee [109] had 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 has been established. The fracture toughness has been found to decrease continuously with increased duration of environmental exposure, whereas the fracture toughness has been 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.

3.6 DELAMINATION

Delamination is one of the predominant forms of failure in laminated composites due to the lack of reinforcement in the thickness direction. The presence of delaminations may cause complete fracture, but even partial delaminations will cause at least a loss of stiffness. Delamination as a result of impact or a manufacturing defect can cause a significant reduction in the compressive load-carrying capacity of a structure. The stress gradients that occur near geometric discontinuities such as ply drop-offs, stiffener terminations, skin-stiffener flange interfaces, bonded and bolted joints, and access holes promote delamination initiation, trigger intraply damage mechanisms, and can result in a significant loss of structural integrity. The fracture process of high performance composite
laminates is quite complex, involving both intralaminar damage mechanisms (e.g. matrix cracking, fiber fracture) and interlaminar damage (delamination) [80, 20].

To identify the evolution of failure modes for different loading regimes, it is convenient to first classify these modes based on the material constitutions of layered/reinforced structures. As shown schematically in Fig.3.2, there are two major categories of failure observed in post-mortem studies. The first major failure category is decohesion (or cracking) between bonded layers at an interface. This is often referred to as delamination in composite laminates or interfacial debonding in thin films or sandwich structures. It is also called inter-layer failure. Generally, two distinct inter-layer failure modes are observed. The first one involves opening-dominated inter-layer cracking or delamination. The second one involves shear-dominated inter-layer cracks or shear delaminations, and often occurs in layered materials subjected to out-of-plane impact [117].

![Fig. 3.2 Possible failure modes for layered materials.](image)

The second major category is referred to as intra-layer failure. There are three possible intra-layer failure modes depending on the material constitution. The first one is called intra-layer cracking or matrix cracking. This type of cracking often occurs inside the matrix of fiber-reinforced composites or within the soft core of sandwich structures. It is also found in the form of tunneling cracks in thin film/substrate. Another possible intra-layer failure is the failure of reinforcements such as fiber breakage and fiber kinking within a layer. The fifth possible intra-layer failure mode is interfacial debonding between the matrix material and the reinforcement such as debonding between particle/fiber and matrix occurring within a constituent layer.
Lorriot, et. al., [114], in their investigation have stated that identification of the interlaminar tensile parameters based on test results on [+152/90/-152]S laminates fits reasonably with the thickness effect. But unfortunately, the onset of delamination was not accurately detected. Finally the tests performed in order to study the influence of the tensile term in the proposed stress criterion do not allow reliable investigations. No damage or interlaminar cracks are required to study onset delamination with this approach.

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 and impact, which can lead to interlayer delamination. With further application of external load, the delamination propagates through the interlayers leading to catastrophic failure of the composite structure [42].

Ross and Sierakowski [61] studied the effects of impacts and observed delamination in glass epoxy plates. Clark [115] developed a model for delamination of different fiber reinforced plates and showed that the delamination due to impact is in the form of stretched or almond shape.

3.7 MACHINING OF FIBER REINFORCED COMPOSITES
Machining of fiber-reinforced composites is significantly different in many aspects compared to metals & their alloys. In the machining of fiber reinforced composites, the material behavior is not only homogeneous but also depends on diverse fiber and matrix properties, fiber orientation, and the relative volume fraction of matrix and fibers. The tool encounters continuously alternate matrix and fiber materials, whose response to machining can be entirely different. It is this diverse requirement of a cutting tool that makes composites somewhat unique & at the same time difficult to machine. Therefore, machining of fiber-reinforced composites impose special demands on the geometry and abrasion resistance of the tool materials [85].

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The earliest of the reported work in machining of Fiber Reinforced Plastics (FRPs) composites were due to Koplev et. al., [65]. The machining characteristics of parallel (0°-fiber orientation) and perpendicular (90°-fiber orientation) were only presented with regard to chip size, cutting and thrust force variations with rake and relief angles. In general a reduced cutting force for increasing rake and a reduced thrust force for increasing relief were reported.

Takeyama et. al., [99] have presented results of machining forces and surface roughness for different fiber orientation, especially for a so-called negative fiber orientation. Wang et. al., [4] have presented in their investigation about the mechanism of orthogonal cutting and resulting chip formation for different fiber orientations and tool geometries. They have tried to co-relate the chip size with degree of principal force fluctuation [106].

Abdul Budan [1] has conducted an experimental investigation and observed that the fiber proportion also influences the machining performance. The results revealed that the increase of fiber content increases the cutting and feed force values, which were in agreement with FEA results. The results of the variation of cutting and feed force values with depth of cut & rake angle were also reported.

Caprino et. al., [22] have reported the effect of depth of cut (often termed as the size effect) on the unit cutting force. Higher cutting forces were recorded for increasing depth of cut (especially at 30° rake); but reported a decreased pattern with increased depth of cut for higher rake angle. The rake angle was found to have significant effect on cutting force whereas relief angle had little influence. Contrary to the belief, it was reported that the value of unit cutting force is independent on depth of cut. Wang and Zhang [107] have presented result of orthogonal machining of UD-CFRP for wide range of depths of cut. The results of the variation of cutting forces with some rake angles were also reported.

Inderdeep Singh et. al., [51] in their concluding remarks have reported that there is an imminent need to develop a Global Damage Criterion and Machinability Index for composite materials. The criterion and the index can aid
the composite's fraternity to select the proper combination of operating variables, tool material, tool point geometry and the material combination (fiber, matrix) depending upon the product specifications.

3.8 NEED OF THIS RESEARCH

Researchers are on a constant look out due to the changes in needs and technology for a worthy and suitable replacement for conventional materials. In order to improve the properties of existing composites, a newer trend is towards the development of Hybrid Composites referred to as advanced composites. Hybrid composites are used to serve technical purposes such as enhancing the impact resistance with the addition of ductile fibers helps in delay of the damage on impact, allows greater energy absorption and prevents breakage of structural elements. Thus hybridization provides materials designers with an added degree of freedom in tailoring composites to achieve a better balance of stiffness, strength, increased failure strain, better damage tolerances, improved ability to absorb impact energy and possibly a significant reduction in cost and so is a matter of significant practical interest. In this direction limited amount of literature exists on the woven steel fabric reinforced hybrid composites [96,73].

Before the material is put to its actual use, it is essential to optimize its composition by studying the effect of various parameters, which influence the mechanical behavior, delamination, strength degradation and also on machining performance. The aim of this work is to create a database giving the details of the properties vis-a-vis its composition. Hence this entire research is devoted to develop steel fiber reinforced polymer hybrid composite as an alternate material for low stress applications. Several experimental investigations have been conducted in this work to achieve the best properties by hybridizing.

3.9 SCOPE OF THE WORK

After an extensive literature survey it was found that limited amount of literature existed on hybrid composites and more particularly on the metal fiber reinforced hybrid composites. Since the hybrid composites are termed as the next generation composites, this research work has been oriented towards hybridizing
a metal fiber with nylon fibers, which possess better toughness at low temperatures and extremely chemically stable. Further steel fiber would be preferred as it possess many advantages such as inherent ductility, apart from not being too sensitive to surface damage also possess high strengths and temperature resistance. Hence in this work it is intended to make a study on the property characterization of SFRP hybrid composites, strength degradation due to varying temperatures, delamination studies and also on the Machinability performance.

3.10 PLAN OF WORK
Experimental characterization refers to the determination of the material properties through tests conducted on suitably designed specimens. The data obtained from the tests are appropriately reduced to evaluate various material properties that can later be used for analysis and design of practical structures. So it is essential to understand the material response over the entire range of loads if advanced design procedures are employed for efficient material utilization. Hence in this research the primary objectives to emphasize the need for experimental and statistical methods for characterizing the macro-mechanical properties of steel fiber reinforced polymer (SFRP) hybrid composite are;

1. Selection of the three ingredients for the preparation of hybrid composite laminated specimens namely; polyester resin, plain weaved steel and nylon fabric mesh.

2. Specimen preparation included the selection of different fiber volume fractions and fiber orientations.

3. Fabrication of laminated specimen using hand lay-up.

4. Conducting experimentation in accordance with ASTM standards.

5. Determination of Physical properties such as density, void content & fiber content of the laminates.

6. Determination of mechanical properties such as, tensile, compressive, impact and flexure strength along with the hardness of the laminates.
7. To analyze the effect of the fiber volume fraction and fiber orientation for the above mentioned mechanical strengths.

8. To analyze the effect of service temperature on the mechanical strengths of SFRP hybrid laminates.

9. To investigate the impact of notch size on the tensile and compressive strengths using single ended notched specimen.

10. To conduct an experimental investigation to study the effect of load type, fiber orientation and temperature on delamination by introducing artificial crack length in the SFRP hybrid composites.

11. To conduct an experimental investigation on the Machinability of orthogonal cutting on SFRP hybrid composite for various cutting speeds, depth of cut, tool materials and angles.

12. To validate the experimental results using statistical package.

Systematic work has been carried out to realize the objectives enumerated above and the details of the work carried out are given in the subsequent chapters.