Chapter 2

LITERATURE SURVEY

2.0 Introduction

Textiles are primarily a part of the basic need of human beings i.e. clothing. It has entered every part of our lifestyle encompassing home furnishing, automobiles, medical use, filters etc. It has extended its annexes in diversified field like ballistic protection, marines, aeronautical, space research, energy storage and has encompassed in technical fields including chemical, mechanical and electrical engineering. The emergence of composites in textile field has helped in broadening of these applications. Composite constitute of two or more materials having extensively varied physical or chemical properties combined to formulate a material, having noticeable different properties than individual components. Composites consists of two main components: reinforcement and matrix material. In textiles, the term composite is coined as textile composite wherein materials like fibre, yarn and fabrics are used as reinforcement for diversified application with matrix polymer.

Textile composites are anisotropic, due to use of fibres in bundles or layers, exhibit different properties along different axes. Whereas, metals are homogenous and isotropic in nature viz.; all parameters are equal in all directions and at all points. In textile composites the different parameters can be varied in different directions. This provides flexibility in designing of composites which provide high strength, light weight, long life, etc give preference to textile composite over metals. The amazing part of composites exists in its continuous renovation and innovation process.

2.1 Historical importance of composites

In nature, there is amalgamation of different materials having distinctively varied properties to satisfy a prerequisite objective for the final product aimed. Mankind has been using knowingly and unknowingly many composite materials available in nature. For example, in the wood there is a union of cellulose (providing the ability to bend) implanted in lignin (providing stiffness). Human body is a combination of bones which provides strong framework for basic structure and muscles providing the required flexibility. The use of natural fibres in composite construction can be traced back many centuries. The conception of ‘composite’ in construction of building have existed since ancient times [10-11].

The history of composites follows from 1500 B.C when Egyptians and Mesopotamian immigrants used a mixture of mud and straw to construct strong and durable buildings. In 1200 AD composite Mongolian bows made from combination of wood, bone and ‘animal glue” were powerful weapon in use [11]. Israelites using bricks made of clay and reinforced with straw are an early examples of application of composites [12].

Along 1870’s to 1890’s, development of composite was changed by the chemical revolution. The process of polymerisation transformed early synthetic resins like bakelite, melamine and celluloid from a liquid to solid state in a cross-linked molecular structure [13]. It also reported that the most important era for the composite industry is considered as 1930s, wherein development of resin took place. Higher performance resin systems like epoxies became accessible by 1938.

Fibre reinforced polymer industry was commenced by Owens Corning in 1935 with the introduction of first glass fibre whereas in 1961, first carbon fibre was patented [14-15]. In the late 1950s polyacrylonitrile (PAN) carbon-fibre, a material consisting of extremely thin acrylic fibres mostly made out of carbon atoms, was developed at Japan’s former Government Industrial Research Institute. As per claimed by Dupont company, Stephanie Kwolek, a DuPont chemist invented Kevlar, a para-aramid fibre, in 1966 [16-17].

2.2 Market scenario for Textile Composite

Composite is young, fast growing and technologically evolving market. The growing demand for specific product material in various fields like high flame-retardant materials in electrical and electronics industry, corrosion and chemical resistance in construction, electrical resistivity, lightweight materials in the aerospace & defence and automotive industry are the foremost drivers for the growth of this market.

The global composite materials market is expected to reach an estimated $40.2 billion by 2024 and it is forecasted to grow at a CAGR of 3.3% from 2019 to 2024. The global composites end product market is expected to reach an estimated $114.7 billion by 2024 as forecasted by Lucintel [18]. It was analysed by Lucintel that cost of raw material used in composite textiles is largely dependent on the fibre cost which is quite high, in carbon fibre the cost of precursor is more than 80% of the total cost whereas in glass 50% to 70% is attributed to borax cost. Again, this also includes the volatile cost of the fuel. Reuters has reported Global Hybrid Composites Market was valued at USD 436 Mn in 2017 and is expected to reach US$ 1288 Mn by 2026, at a CAGR of 14.50 % [19].

As presented at ICERP 2019 (Mumbai), Indian composites industry is poised to provide a lucrative opportunity to the International Composites Community, and the still untapped markets will provide a platform for investments, both FII & DII [20]. Hand lay-up process is still the first choice among the composite fabricators due to its low operating cost and easy to handle. It covered around 40% of market distribution by manufacturing processes in 2018. In the last five years, the Indian composites industry has witnessed the increased use of mechanized processes. Also, among the widely preferred manufacturing processes filament winding (15%) and injection moulding (13%) are considered. The government of India has stated in regulation acts to outsource (30%) components locally in the aerospace industry.

The Indian textile composite industry has shown strong growth during the last decade even with the problems of deficient of fibre producers in India, lack of automated process and import limitations as reported by Marketsandmarkets, market research firm [21].

The increasing penetration of hybrid composites in market growth is forecasted to be 15% from USD 436 million to USD 876 million. Carbon/glass and glass/carbon hybrid fibre composites are expected to drive the market during the forecast period. Thermoset resin dominates the hybrid composite market owing to its wide-scale applications in various end-use industries including automotive & transportation, aerospace & defence, wind energy, and marine as reported by Marketsandmarkets [21].

2.3 Textile Composite

A composite is a unique combination of two or more materials at macroscopic level with characteristically different individual properties that results in a material with unique properties than those of the material used alone [22-24]. The progression of technology lead to need for adaptable product development. A single material cannot placate this demand, so existence of composites became probable.

There are several types of natural and synthetic composites available. The different types of synthetic composites are stated as Metal-metal, Ceramic-ceramic, Polymer-polymer, Metal-ceramic, Metal-polymer, Ceramic-polymer as cited by Ahmad et al. and Bannister [25-26].

The positive characteristics of composite like its efficacy, properties, flexibility, adaptability and applications of composites make them the most sought materials as stated by researchers [27-29]. Composites material had been efficaciously used for decades and have replaced the metal parts due their inherent high stiffness– weight ratios, high strength to weight ratio, fatigue and corrosion resistance, excellent chemical resistance, superior electrical and thermal conductivity and many other properties according to assessed from Wikipedia. These varied potentials gave them the ability to produce components with significant weight and performance advantages.

Many researchers [1,27-30] have stated that the basic two components of composite are reinforcement material and matrix.

Encyclopedia of Polymer Science and Technology states that textile composite is made of a textile reinforcement phase and a matrix phase [24]. According to Kanitkar et al. The reinforcement material provides the strength to the material while the matrix binds the fibrous material together and protect them from outside effects [31]. The matrix also transports the forces and stresses acting on the boundary of the composite to fibre. Textile structures have long been known as prime reinforcement for fibre reinforced composite applications due to their unique properties, such as easy handling, shapeability, adaptability and structural complexity. Textile structure composites have higher strength to weight ratio. High tensile strength and stiffness as well as high fatigue life, low weight and excellent chemical resistance are certain major attributes of fibre reinforced composites, which make them highly an attractive material for distinctive and relinquished applications. Textile composite can be flexible or rigid.

Textile reinforcement structure can be made of fibre, yarns or fabrics (woven, braided, knitted or non-woven) and are generally flexible. Textile reinforced composite has provided a path to amalgamate highly tailored material with improved approach attributable to the application of traditional textile technology to organize high performance fibres for composite material applications [31].

As per described by Adanur, textile composite is made up of textile reinforcement structure and a matrix [1]. The reinforcing materials can consist of fibres, yarns or fabrics (woven, braided, knit or nonwoven). The fibre encompasses a wide variation consisting of natural fibres like Jute, hemp, flax; synthetic organic fibres like Carbon, aramid; synthetic inorganic fibres like Glass, silicon carbide and lastly fillers like Calcium carbonate. The matrix is of thermosetting polymers, thermoplastic polymers, ceramics and metal. One of the most widely known composite fibreglass wherein glass fibres are embedded in polymer material to produce a relatively strong and stiff material. There is an interface zone across which the matrix and reinforcement interact physically, chemically and mechanically.

Special fillers and additives can influence mechanical properties, especially for improvement in dimensional stability, but they are mainly used to confer specific properties, such as flame retardancy, ultraviolet (UV) stability or electrical conductivity. The cured thermoset resin can be recycled and used as fillers in new laminates by breaking down and grounding them into fine particles.

Textile reinforced structure can be classified as (1) Dimension (2D and 3D) (2) Method of manufacturing (woven, knit, braid and non-woven) (13) (3) Linearity of reinforcement (linear or nonlinear) (4) Direction of reinforcement (1,2,3 or multi) (5) Integration (Laminated or integrated) [32].

2.4 Reinforcement

Reinforcement fibre is having the primary purpose of improving the strength and stiffness properties of the system. It is largely responsible for determining key structural properties, such as tensile strength and stiffness in the fibre direction as described by Kaw [12]. These are the basic load-carrying components of the composite. Being immensely important for the final product selection of reinforcement becomes a very important task.

A broad spectrum of reinforcements for composite laminates like glass fibres, carbon fibres, aramid fibre and other fibres including high-density polyethylene (HDPE), poly-benzoxazole (PBO), boron, polyester, and nylon is available. For obtaining a material possessing desired engineering properties, selection of an appropriate type and form of reinforcement is prominent. With the diverse array of reinforcement fibres and fabrics available today, selection of an optimal reinforcement is a challenging task.

High performance fibres used as reinforced fibres are specific fibres which have exceptional stiffness, strength, higher tenacity, higher modulus, heat resistance and chemical resistance. The demand of today’s market is not only quantitative but qualitative aspect of the production of the fibres. The process has seen a shift of mindset wherein the industrial nations are moving in lower volume but higher worth products for various industrial demands.

Far-reaching developments have taken place in the growth of high-performance fibres through technological innovations [33]. High performance fibres having well-oriented rigid chains based on aromatic structures, give fibres in which both mechanical properties are excellent. In case of carbon fibres, the planar graphitic structures with excellent mechanical properties. One of the high-performance applications is their use as reinforcements for composite materials.

It should be noted that in first category of fibres viz. average mechanical strength comes the standard textile fibres. These fibres are generally used as non-woven in industrial sectors. A bulk of fibres belongs to this category as it covers all standard textile uses.

In second category of fibres viz. above average mechanical strength comes industrial fibres like tyre cords. These fibres generally have a high degree of toughness. In the third category of fibres viz. superior mechanical strength comes the industrial fibres whose development is a way to bridge the gap between the category second and fourth.

In the fourth category comes the high-performance fibres which can be metallic or inorganic. In this group are included high performance fibres like carbon fibres, aramid, glass fibres, boron fibre, ceramics fibres like silicon carbide and alumina fibres and metallic fibres etc.

2.4.1. Carbon fibre

Carbon fibre is defined as a fibre containing at least 92 wt. % carbon, while the fibre containing at least 99 wt. % carbon is usually called a graphite fibre researchers [27,34-39] have mentioned in their research that carbon fibre have undergone tremendous progress in scientific approach and practical application since its first application as a filament of light bulb developed by Thomas Edison in 1879.

Carbon fibres have very high strength to weight ratio, excellent chemical resistance, and superior electrical and thermal conductivity [40].

Carbon fibre is composed of carbon atoms bonded together to form a long chain. Carbon fibres are manufactured basically by three different precursors i.e.: polyacrylonitrile (PAN), pitch rayon. Typical sequence used to form carbon fibres from polyacrylonitrile involves spinning, stabilizing, carbonizing, treating the surface and sizing. In 1971, Toray began manufacturing its PAN high-strength carbon fibre TORAYCA® yawn T300 [22]. In the U.S., Union Carbide sold their T300 counterpart, Thonel300. In 1982, Boeing 757, 767 and Airbus A310 planes used carbon fibre for making its parts.

Each carbon filament is produced from a polymer such as poly-acrylonitrile (PAN), rayon, or petroleum pitch, known as a precursor. For synthetic polymers such as PAN or rayon, the precursor is first spun into filament yarns, using chemical and mechanical processes to initially align the polymer atoms in a way to enhance the final physical properties of the completed carbon fibre. Precursor compositions and mechanical processes used during spinning filament yarns may vary among manufacturers. After drawing or spinning, the polymer filament yarns are then heated to drive off non-carbon atoms (carbonization), producing the final carbon fibre.

The precursor is drawn into long strands or fibres and then heated to a very high temperature with-out allowing it to come in contact with oxygen. Without oxygen, the fibre cannot burn. Instead, the high temperature causes the atoms in the fibre to vibrate violently until most of the non-carbon atoms are expelled. This process is called carbonization and leaves a fibre composed of long, tightly inter-locked chains of carbon atoms with only a few non-carbon atoms remaining. After carbonizing the fibre surface does not bond well with epoxies so surface treatment is given which is basically addition of oxygen atom to the surface to provide better bonding properties. The carbon fibres filament yarns may be further treated to improve handling qualities, then wound on to bobbins. The procedure is described schematically in Figure 2.1.

Each carbon fibre is a long thin strand made up of thousands of carbon filaments. Each fibre is about 5-10 μm in diameter and composed mostly of carbon. Microscopic crystals in the carbon bond together in a structure that is more or less aligned parallel to the long axis of the fibre. It is this alignment of crystals that make the fibres so strong.

The graphite is word used for a very specific structure wherein the adjacent aromatic sheets overlap with one carbon atom at the centre of each hexagon. In carbon fibres, the structure basically consists of large aromatic sheets which are randomly oriented to each other. The arrangement of this kind is usually known as Turbostratic and such carbon fibres tend to have high tensile strength. The carbon ribbons described above are oriented parallel to the fibre axis. Carbon fibres achieve their exceptional strength due to the interlocking and folding of these ribbons. The structure of carbon is shown in the Figure 2.2

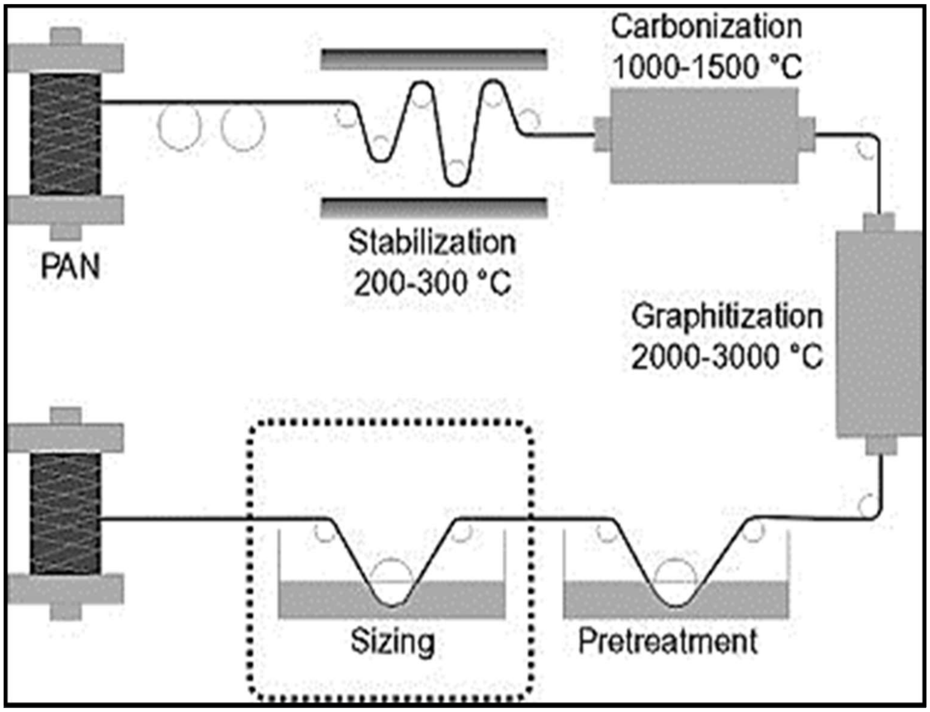

Figure 2.1: Schematic illustration of the carbon fibre production process out of polyacrylonitrile (Precursor) [41]

The PAN-based conversion process quickly became the primary method for producing carbon fibre. Ninety percent of carbon fibres today are made from polyacrylonitrile a synthetic, semi-crystalline organic polymer resin. The remaining 10% are made from rayon or petroleum pitch. Fibres made from PAN are extremely strong and light. These fibres are bound by thermoset or thermoplastic polymers such as polyester, vinyl ester or nylon to make carbon fibre reinforced plastic, or carbon FRP [43,44]. Carbon are obtained in form of "tows". Theses tows consist of no of filaments and so the nomenclature goes as: 24K (K=1000) filaments, 12K,6K and 3K. These are supplied on spools without applying any twist or crimp.

Carbon fibres offer excellent long-term performance in combination of high strength and stiffness, and low weight. Carbon fibres have been used as material

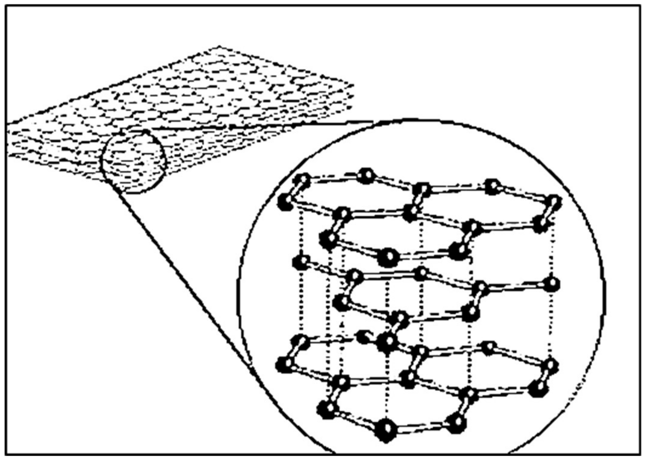

Figure 2.2: Structure of Carbon fibre [42]

of significant interest in various engineering applications. The performance of a carbon fibre is determined by the precursor fibre used to produce it; process parameters used. The successful adhesion between a carbon fibre and the polymer matrix material is critical in obtaining high-performance laminates [45].

2.4.2 Aramid Fibres

In 1971 DuPont introduced the world to Kevlar ™ commercially (polyparaphenylene terephthalamide), a fibre based on an aramid compound developed by Stephanie Kwolek back in 1964. Kevlar is the registered trademark for a para-aramid synthetic fibre related to other aramids such as Nomex and Technora as stated by Du Pont ,2016 [17].

Aramid belong to the nylon family of polymers. Their key structural features are aromatic rings (basically benzene rings) linked by amide groups [44] as depicted in Figure 2.3. Kevlar fibres have extended chains, are highly oriented and are almost completely crystalline, the ordered structure along the fibre axis is in the form of a highly ordered fibrillar structure. According to researcher [46], Kevlar fibre has crystalline structure which is orderly, untangled arrangement of molecules. He also states that this crystallinity is obtained by spinning process which involves the extrusion of molten polymer solution through small holes. In case Kevlar 49 fibre when studied by optical and electron microscopy, it is observed that there are pleats of around 500nm with the adjacent components of pleats being at approximately equal but opposite angles of 170 degree Celsius. Kevlar is produced in two grades 29 and 49 which are running successfully for last many years. It has found its place in as textile reinforcing material. Later the range was also further led to 149 and 981. Other range also included Twaron™ Akzo, Holland and Technora™ from Teijin Co., Japan [33]. Kevlar 49 has its applications in fields of textile processing, plastic reinforcement, ropes, fibre optics, marine sporting goods and aerospace applications.

Kevlar-49 fibre has a tensile strength comparable with that of carbon fibre, a modulus between those of glass and carbon fibres and a lower density but Kevlar fibre reinforced composites show poor interfacial adhesion between fibre and the thermoplastic matrix resin due to low surface energy and chemically inert surface of the fibre [47]. In order to improve the interfacial adhesion, extensive studies have been performed than both.

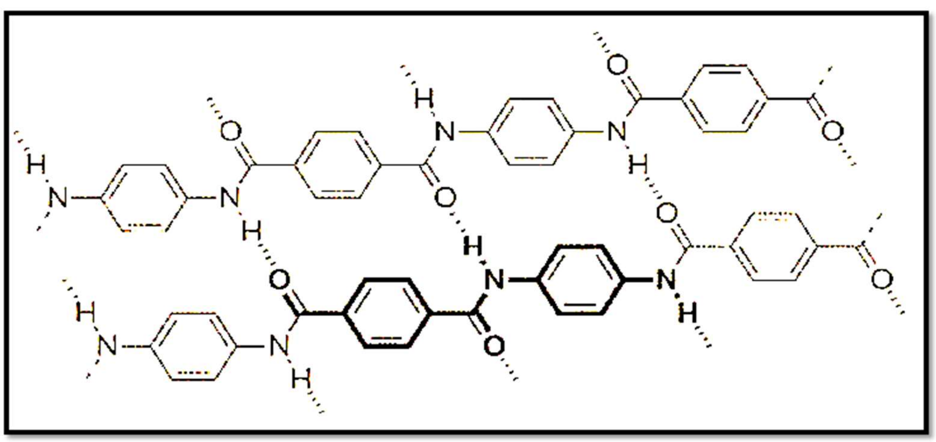

Figure 2.3: A single rod- like fibre structure of Kevlar [48]

2.4.3 HDPE

High-density polyethylene (HDPE) or polyethylene high-density (PEHD) is polyethylene thermoplastic made from petroleum. HDPE is defined by density of greater or equal to 0.941 g/cm^3 [49]. HDPE has little branching as shown in figure 2.4, giving it stronger intermolecular forces and tensile strength than

LDPE [50]. Its speciality lies in its light weight yet strong quality. It's low cost, light in weight, flexible, strong impact resistance, long lasting, weatherproof, good chemical resistance, resists mold, dew, rotting and insects. Some of the important properties of this fibre is high tenacity, high specific modulus, low elongation, low fibre density (lighter than water). In addition to high tenacity, HDPE fibres have very good abrasion resistance and excellent chemical and electrical resistance [51]. It also stated that HDPE fibres have very good abrasion resistance and excellent chemical and electrical resistance. This fibre has been used for protective clothing, ropes, cordage and reinforcement for impact-resistant composites as mentioned in Handbook of technical textiles by Horrocks [52].

These fibres have found their varied applications in chemical drums, jerricans, carboys, toys, picnic ware, household and kitchenware, cable insulation, carrier bags, food wrapping material as well as soft and semi-rigid body armour and in cut resistant materials such as gloves.

According to Sudarshan et al. HDPE fibres enables to produce a hardened concrete which has improved surface quality, greater impact resistance, increased damage resistance [53].

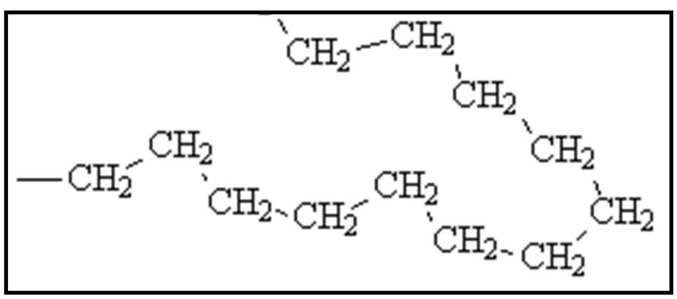

Figure 2.4: Strucutre of HDPE [50]

2.5 Matrix/Resin material

Resin is a generic term used to designate the polymer, polymer precursor material, and/or mixture or formulation thereof with various additives or chemically reactive components. Matrix is used to bind the reinforcement material [54]. The choice of matrix system depends on what final properties are aimed at. The properties aimed can be multiple for a single matrix system also. These include the properties like adhesive, mechanical, flexural, cracking resistance, degradation etc. According to researcher Vicario [55] resins are used to attach(stick) the fibres together. The basic functions of resins include to keep the fibres in the proper position, to distribute loads, to protect the filaments from abrasion, and provides interlaminar shear strength. The resin also provides a uniform external surface for bonding of external hardware to the structure. The different groups of resins include polyesters, epoxies, phenolics, bismaleimides, and polyimides. Widely used resin systems are Polyester resin, Vinyl ester resins and Epoxy resins and phenolics. He also claimed in his work that formulation of resin has been done to enhance various parameters like improved fracture toughness, adjust moisture absorption characteristics, provide high-temperature capabilities, tailor pot life, viscosity, and strength.

2.5.1 Types of Matrix

Matrix material can be thermoplastic or thermoset polymers. Certain resins involve elevated temperature for the chemical reaction while for highly viscous resin entails pressure for resin to flow into the fibres and bind them. The chemical reaction of resin forming cross linking is called curing. The time required to complete the curing is called the cure cycle according to Nptel website. In the case of thermoset or thermoplastic prepregs, the resin is present within the reinforcement during the forming stage, but exists in a weak state. In thermoset prepregs because the resin is not yet polymerized, and in thermoplastic prepregs it is because the process is performed at a high temperature. As claimed by Boisse et al., the resin is not hardened and the forming is mainly led by the reinforcement [56].

2.5.1.1 Thermoset resin

The International Union of Pure and Applied Chemistry (IUPAC) defines a thermosetting resin as a petrochemical in an indulgent solid or viscous state that changes irreversibly into an infusible, insoluble polymer network by curing [57].

Thermoset resin has gained their popularity due to their subsistence in liquid state at room temperature and when not cured. They're converted from a liquid to solid through polymerisation. That is during the curing these resins undergo a molecular cross-linking process which is irreversible and cannot be melted again. These are cured by using catalyst, heat or a combination of both. Thermoset materials are generally stronger than thermoplastic materials due to their cross-linking network of bonds These distinguishing features of thermoset are responsible for high thermal stability, good rigidity, hardness and resistance to creep as cited by Materialstoday [58]. The uncured liquid state property of thermoset aids in suitable impregnation of high-performance fibres like Kevlar, carbon and fibreglass.

Researcher Khalil et al., have confirmed that thermoset resins have attained excellence in field of advanced composites due to its resistance to solvents and corrosives, resistance to heat and high temperature, excellent finishing, fatigue strength, excellent adhesion, tailored elasticity, simple application process and reduced cost [59]. The most frequently used thermosetting resins are polyester, epoxy, phenolic, vinyl ester, polyurethane, silicone and polyamide and polyamide-imide. Thermoset resins are substituting the use of expensive steels and alloys in the field of advanced composites because of their characteristics such as resistance to erosion, high strength, simple application process, and reduced cost. These special characteristics have made thermoset resins such as epoxy resin feasible in the composite process as supported by Materialstoday website [58].

2.5.1.1.1 Epoxy resin

Epoxy resin is one of the most widely used thermoset resins. It is being used in wide range of composite structure and concrete work. Epoxy resins can also be formulated with different materials or blended with other epoxy resins to achieve precise performance features. A proper formulation can be prepared by using specific hardeners or catalyst system to acquire the required process necessities.

Epoxy resins are characterized by the presence of a three-membered ring containing two carbons and an oxygen (epoxy group or epoxide or oxirane ring). The curing of epoxy resins is associated with a change in state from a low molecular weight resin to a highly cross-linked network. Many commercial hardeners suitable as curing agents have been used for epoxy resins. The most common types of curing agents are (1) primary, secondary polyamines and their adducts, (2) anhydrides, (3) polyamides, and (4) catalytic types etc.

Curing may be achieved by reacting an epoxy with itself (homo-polymerisation) or by forming a copolymer with polyfunctional curatives or hardeners. In principle, any molecule containing reactive group may react with the epoxide groups of the epoxy resin. In theory, if epoxy is made of a stoechiometric mixture of epoxide + hardener, curing agent group, a fully cured epoxy should not remain any uncured groups. Practically, small amount of uncured epoxy and unreacted groups are presence in the final product. Therefore, post curing need to be taken sometime. When the epoxy reached the high level of cure (network), at the very end of reaction, the movement of the molecules become more difficult. In addition, due to topological features of the stoechiometric ratio, and curing conditions the curing level of epoxy may vary. However, the cured stage should typically attain the glass transition temperature (T_g) of the fully cured network in order to achieve maximum properties.

Since the amine molecules 'co-react' with the epoxy molecules in a fixed ratio, it is essential that the correct mix ratio is obtained between resin and hardener to ensure that a complete reaction takes place. If amine and epoxy are not mixed in the correct ratios, unreacted resin or hardener will remain within the matrix which will affect the final properties after cure. To assist with the accurate mixing of the resin and hardener, manufacturers usually formulate the components to give a simple mix ratio which is easily achieved by measuring out by weight or volume [60].

It consists of many excellent such mechanical strength, resistance to heat, resistance to chemicals, adhesive strength, low curing contractions. Epoxy resins are used with a number of fibrous reinforcing materials, including glass, carbon and aramid. Epoxies are used mostly for fabricating high-performance composites with excellent mechanical properties, excellent electrical properties, good performance at elevated temperatures resistance to corrosive liquids and environments, good adhesion to a substrate or a combination of these benefits. Epoxy resins do not however, have particularly good UV resistance [10].

2.5.1.2 Thermoplastic resin

A thermoplastic, is a plastic material, a polymer that becomes mold-able above a specific temperature and solidifies upon cooling [61]. It is commodity thermoplastic and engineering thermoplastic. The examples of commodity thermoplastic are polystyrene, polyvinylchloride, polypropylene and polyethylene. The examples of engineering thermoplastic resins are PPS (polyphenylene sulphide), PEEK (poly ether ether ketone) and PEI (polyetherimide).

2.6 Laminates

Laminae or ply is a single layer of woven fabric or unidirectional layer embedded in a matrix [53]. Laminates could be prepared by the assistance of two or more laminae, using no of plies laid at different orientations angles and stacking sequences to achieve the desired outcome in terms of thickness and stiffness as observed by researcher Nermin [64].

Types of Laminates. Depending upon the type of fibre and type of sequence the laminates are classified as depicted below:

I. **Homogenous laminates**: Homogenous laminates are defined as laminates containing only one type of fibre for all the laminae.

II. **Hybrid laminate:** Hybrid laminates are defined as laminates containing more than one type of fibre. Depending on the geometrical pattern of fibre/yarn/ply, hybrid composites can be classified as interply (interlaminated) and interply (intermingled).

1. Interply hybrid laminate consist of different fibre plies bonded together in a matrix. Laminate made up of plies of Glass/Epoxy, Carbon/Epoxy

& Aramid/Epoxy. Here, two or more homogenous reinforcements are staked.

2. In intraply hybrid laminates, each fabric consists of two or more kinds of constituent fibre tow mixed in same layer.
3. In intra-interply laminates is a combination of interply and intraply laminates.
4. Intimately mixed (intermingled) hybrids where the constituent fibres are mixed as randomly as possible so that no concentrations of either type are present in the material
5. Selective placement in which reinforcements are placed where additional strength is needed, over the base reinforcing laminate layer
6. Super-hybrid composites which are composed of metal foils or metal composite plies stacked in a specified orientation and sequence

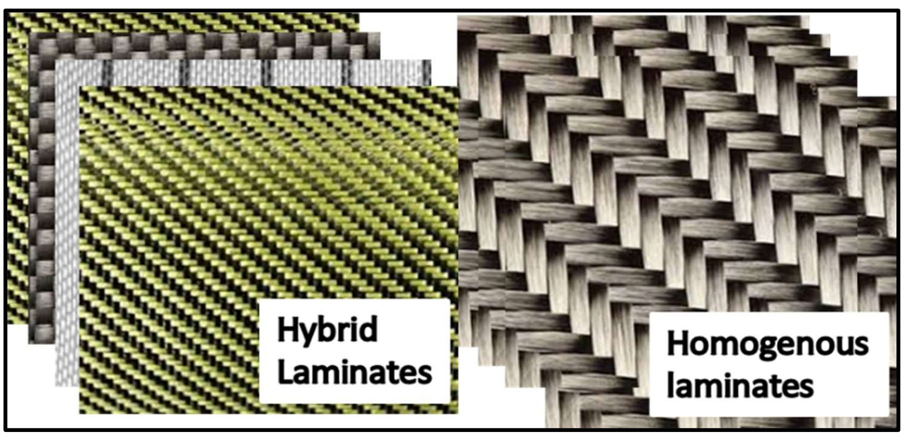

Figure 2.5: Pictorial representation of hybrid and homogenous laminates

2.6.1 Types of Lay-up sequence

The multilayer sequencing depends on the arrangements of the layers along the mid-surface. The stacking sequence can be set in two layer and multi-layer arrangement of layers as shown in Figure 2.6. The multilayer is bifurcated in different system of arrangements of laminates. It can be parallel-ply and cross-ply.

I) Multilayer parallel-ply: In case of parallel-ply all the layers are laid parallel. In case of unidirectional all the layers of laminates are in one single directions (0/0/0/0) or (90/90/90/90).

II) In case of Multi-layer cross-ply arrangement, there can be symmetric and asymmetric stacking.

1. Symmetric laminates: A symmetric laminate has both geometric and material symmetry with respect to the mid-surface. For e.g. all plies oriented at either 0 °or 90 °and arranged symmetrically about the midplane.

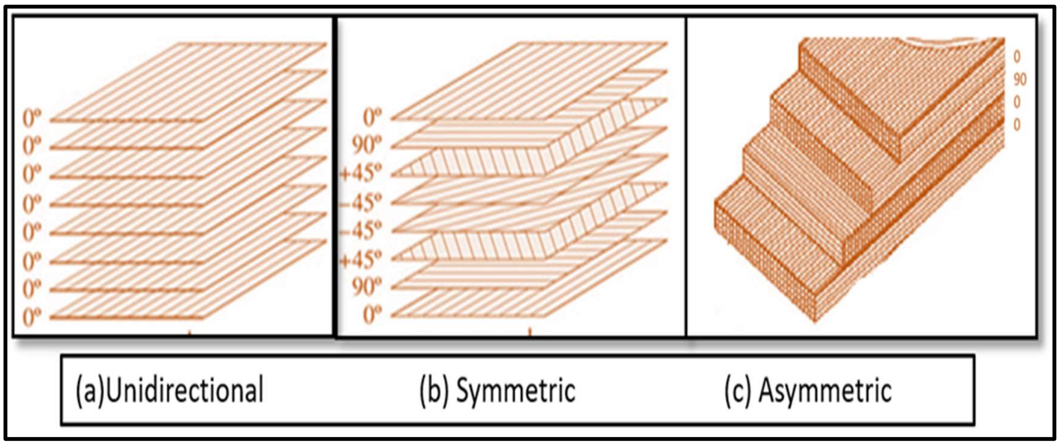

Figure 2.6: Different laminates sequence lay-up with varied angle ply

2. Asymmetric Laminates: This laminate is characterized by having its layers arranged in an asymmetric fashion with respect to the mid-surface.

2.6.2 Importance of angle of lay-up (skew angle) in laying sequence of textile composite

Woven fabric composites have advantages like excellent integrity, conformability and balanced properties within the fabric plane due to which it is more widespread in structural applications such as automobile, aircraft, marine and civil structures as described by researcher Murugan et al.,[65].

According to author Boisse [56] the orientation of fibres in a deformed shape is vital for predicting the mechanical behaviour of the final part. Authors such as

Campbell and Adanur [66,1] have stated that the physical behaviour of composite material is quite different from that of most common engineering materials that are homogeneous and isotropic. Metals will generally have similar composition regardless of where or in what orientation a sample is taken. On the other hand, the makeup and physical properties of composites will vary with location and orientation of the principal axes. These materials are termed anisotropic, which means they exhibit different properties when tested in different directions. The angle of the fibres with respect to principal axes is known as skew angle. It can also be referred as skew angle.

The geometric and structural aspects of anisotropy of textile fibres result in extraordinary mechanical properties. It is being observed that fibres used for composite applications have high strength and stiffness in fibre direction, while they are weak and flexible perpendicular to it. Also, other physical properties, like electrical or thermal conductivity may be totally different when measured along or perpendicular to a fibre. When embedded into a matrix, these anisotropic properties can also be transferred to the fibre reinforced composite. In this case, the mechanical and other physical properties can be tailored in the composite part depending on the placement of fibres. For designing composites with tailored properties, it is essential to understand how differently these reinforced materials can be can be laid in it [67].

One of the methods of laying the reinforcement is considering different angle of orientation in composites. However, in case of carbon woven fabric layers, if more numbers of layers are required to achieve a particular requirement, it increase its cost. In the present work an attempt is made to improve the cost effectiveness of fabric laminate without much increase in thickness of the laminate by inter-plying carbon fabrics in fabrication.

Researchers have confirmed that cost effectiveness of the composites can be improved by proper selection of reinforcing fibres to be used for hybridization [65,68-69]. They also added that hybridization process is effective method for designing tailormade hybrid composite which can be suited for various requirements. Hybrid composites give better results when longitudinal as well as lateral performances are needed or when combined effect of the properties of different types of fibres is needed [70-71].

Previous literature survey shows that researchers have studied hybrid composites made of basalt and different fibres for various mechanical properties like Tensile, Flexural and Izod impact properties. Many researchers [72-75] have studied the pure and hybrid composites of basalt and nylon with different volume percentage of nylon to obtain superior characteristics from the composites.

Tensile, flexural and Impact behaviour of composite materials is affected by various factors of hybridization. To improve the impact tolerating rate and tensile strength of these composites, hybrid composites [68, 76-78] are prepared. Mechanical properties including low velocity impact properties of a hybrid composite have not been studied extensively.

Hybridization is also affected by angle of laying the different layers in the composite. Glass fibre reinforced composites were prepared with fibre orientations of 0°, 45° and 90° and other different arrangement for various tensile properties as investigated by researchers such as Alok Hegde et al., 2015 and Khalil et al., 2009 [79,59]. Mechanical properties are affected by the orientation of fibres in the laminate as observed by Rajanish [5]. Weaving construction were used as basis for carbon and carbon-aramid woven fabrics to understand the tensile loading, it was found by Karahan [8] that Young's modulus and the tensile strength declined approximately 34–39% and 24–27% respectively.

The formation of the fabric structure may affect the tensile strength when it is in composite form as researched by Saiman [9]. Various parameters influencing the mechanical properties of fabric, weave structure is identified as one of the main factors influencing the mechanical performance for high strength application. It was claimed by Sevkat [7] hybrid composite can achieve results equivalent to high performance fibre if cautious assortment of the stacking sequence is done.

Only limited studies are available on woven fabric composites. Studies have been done on the tensile behaviour of carbon–glass/epoxy hybrid composites and jute-glass/polyester hybrid composites. In these studies, there was no good match between the classical lamination theory predictions and the experimental observations [81-82]. It has been described that in recent years the use of woven composites in structural applications has increased rapidly due to the advantages it offers in terms of functional properties such as easy handling, dimensional stability, deep drawing shape-ability, enhanced toughness, lower production costs, better drapability, good resistance to fracture and transverse rupture due to weaving resistance and increased impact resistance [71,4]. The development of carbon fabrics and aramid fabrics has also increased the widespread use of woven fabrics in primary aerospace structure [82,84].

2.7 Method of preparation of Textile Composite

Composites manufacturing is done by using matrix and reinforcement. The type of matrix, type of reinforcement fibre, behaviour of matrix w.r.t temperature and curing, geometry of product and cost effectiveness decides the choice of manufacturing technique to be used as there are plenty of methods available some simple or complex, single or multiple. Each method has its own merits and limitations.

The different methods used are as stated: 1) Hand Lay-up 2) Spray-up moulding

3) Vacuum bag moulding 4) Injection moulding 5) Autoclave 6) Pultrusion 7) Compression moulding [1,25]

2.7.1 Hand lay-up technique

Hand lay-up is a simplest and oldest method for composite production. It is a low volume, labour intensive method. The process consists of constructing up or placing layers of composite fibre in a sequenced layup using a matrix mix of resin and hardener.

A thin layer of resin is applied over the surface to wet it with brush. It may also be lightly rolled with roller to remove the air bubbles. For a high-quality part surface, a gel coat is first applied to the mold surface. The fibres are first put in place in piles manually. The fibres can be in the form of woven, knitted, stitched or bonded fabrics. Then the resin is poured and impregnated. The impregnation of resin is done by using rollers, brushes or a nip-roller type impregnator. The impregnation helps in forcing the resin inside the fabric. Entrapped air is removed manually with squeegees or rollers to complete the laminates structure. Room temperature curing polyesters and epoxies are the most commonly used matrix resins. The laminates fabricated by this process as shown in Figure 2.7 are then cured under standard atmospheric conditions [85-86] One can use combination of resins like epoxy, polyester, vinyl ester, phenolic and any fibre material.

The lamination should satisfy the following requirements: a) The fibre layers should be uniformly placed and they should fit correctly into the contour of the product. b) The fibre should not be damaged during lay-up c) The fibre to resin ratio should be correctly maintained.

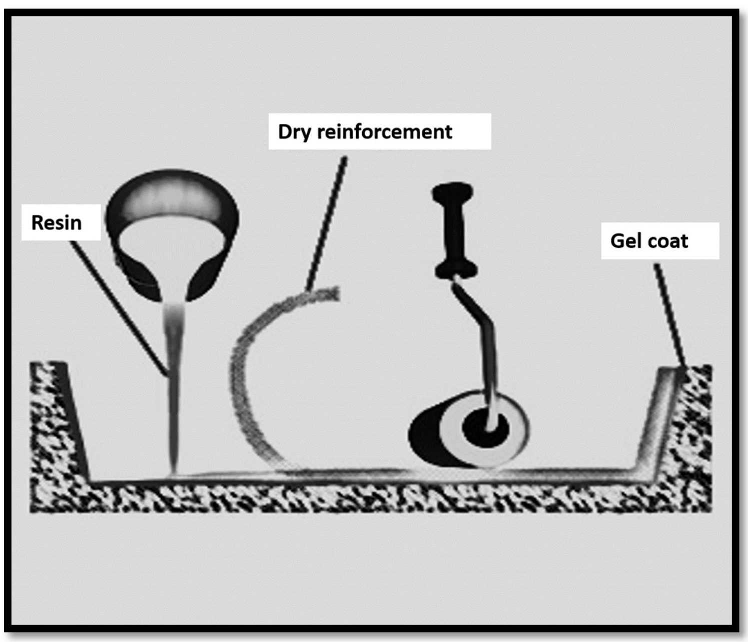

Figure 2.7: Schematic representation of hand lay-up technique.

Tools for Lay-up.

1. Weighing balance - to weigh the chemicals.

2. Brushes - to apply resin for lamination.
3. Rollers - to remove the air bubbles and for applying resin.
4. Mixing container and mixing stick - for making and stirring the resin mix for lay-up.
5. Flat table- for the fabrication process.
6. Release agent (the plastic sheet)
7. Scissors

Solvents. Solvents are required for cleaning the rollers and brushes during or after the lay-up sequence is over. Acetone or toluene can be used as solvents.

Preparation of the Resin Mix. The resin mix can be prepared by using resin, accelerator, fillers, and additives if any. The addition of accelerator to resin will not cause any cross linking until catalyst is added. The mixing can be done by either manually using a paddle or by using an air operated mixer. Vigorous stirring can cause entrapment of air bubbles therefore; mixing should be done at a very low rpm. The container in which resin mix is stored may be closed air tight to minimize the vaporization and loss of styrene.

Lamination procedure. In the process of lamination, a thin layer of resin is applied on the gel coat layer. Then, a chopped strand mat is placed over it. The resin is again applied over the mat by using brush to wet the mat. By using the roller, the air bubbles are removed. After the first layer is laid up, subsequent layers are laid in an analogous manner. More than, 4 layers of resin and glass mat should not be applied without allowing the resin to cure at a time.

Curing of Resin. The curing of resin process depends on the percentage of catalyst and accelerator added. The resin is fully cured when the physical properties of resin are developed. At a fully-cured state, GRP will produce a metallic sound if it tapped with a coin.

Advantages. The process results in low cost tooling with the use of room-temperature cure resins. The process is simple to use. Any combination of fibres and matrix materials are used. Higher fibre contents and longer fibres as compared to other processes.

Disadvantages. Since the process is worked by hands, there are safety and hazard considerations. The resin needs to be less viscous so that it can be easily worked by hands. The quality of the final product is highly skill dependent of the labours. Uniform distribution of resin inside the fabric is not possible. It leads to voids in the laminates. Possibility of diluting the contents. Applications: The process is suitable for the fabrication of wind-turbine blades, boats and architectural mouldings.

2.8 Cutting of the composite samples

The cutting of composite laminates is very difficult as compared to any other metal cutting. The traditionally used cutting tool, if used for high performance fibres like carbon, Kevlar and others, it gets dull due to the abrasive nature of these fibres. The tools also wear out easily so if same tool is used for composite cutting chances of damaging the material is higher. Also, heat generation and overheating are a problem.

Due to overheating resin gets melted and it may damage the tool by clogging it. It can also cause damage to the finish of composite sample. Thus, the structural integrity of sample can be destroyed. Also, while cutting it is possible to delaminate the sample. Delamination can of the range from the smallest edge chipping and final distortion. Thus, it is very necessary to cut the sample with utmost care and efficiency. The commonly used tool for cutting is either basic rotary tools or straight blades [87]. Cutting with straight end blades introduces more damage to the edges of the composite samples due to its to and fro movement for cutting of the samples. Jigsaws and saber saws are used usually. The rotary blades tools are more widely used for cutting composites. These tools are smooth, handy and cause least damage to sample. The cutting of specimens is also done with a help of diamond saw.

2.9 Testing and Analysis

Different characterization techniques are employed in the analysis of physical properties and mechanical properties of the textile composites. These methods make it possible to understand the different relationships exist between the composites and different parameters. The properties of the textile composites depend on their type of reinforcement fibres used, the weave, warp and weft (as woven fabric is considered here), no of fabric layers, angle of layer, cutting of layer, method of preparation and finally resin mix formulation.

The bonding which exists between the reinforcement material and the matrix better known the interface strongly affects the mechanical and physical properties of the composites.

The mechanical properties of textile composites are characterized in accordance with different viewpoints like the tensile strength, flexural strength and impact testing. SEM is one of microscopy techniques used to observe the failure of composites.

2.9.1 Physical properties

The characterization of material includes the basic parameters such as carbon fibre details including yarn denier, no. of filaments, density, fabric weave, thickness, no of stacking used in laminate, Fibre volume ratio, Void content and Coefficient of thermal expansion. The various parameters are measured using standard methods.

2.9.1.1 Fibre volume fraction

Fibre volume fraction is the percentage of fibre volume in the entire volume of a fibre reinforced composite material. When manufacturing polymer composites, fibres are impregnated with resin. The amount of resin to fibre ratio is calculated by the geometric organization of the fibres, which affects the amount of resin that can enter the composite. The impregnation around the fibres is highly dependent on the orientation of the fibres and the architecture of the fibres. The geometric analysis of the composite can be seen in the cross-section of the composite. Voids are often formed in a composite structure throughout the manufacturing process and must be calculated into the total fibre volume fraction of the composite. The fraction of fibre reinforcement is very important in determining the overall mechanical properties of a composite. A higher fibre volume fraction typically results in better mechanical properties of the composite.

Carbon fibre content is one of the most important parameters and controls the mechanical and other properties of fibre/polymer composites such as Brunbauer et al., 2015; Chen et al., 1999 and Yee et al., 1996 [88-90]. Researchers Chen et al., 1999 [89] studied the effect of fibre content on the mechanical properties of composites and found that GIC (critical strain energy release rate under mode I loading condition (J/m^2)) of this material has a decreasing tendency with increasing fibre content in the range of 21%–39%. Brunbauer et al., 2015 [90] investigated the effect of fibre volume content on the mechanical behaviour and damage mechanisms in unidirectional fibre/epoxy laminates and found that higher fibre volume content is beneficial in fatigue tests at angles of 0° and 45°.

Hong et al.,2015 [91] has used Thermogravimetric analysis (TGA) to characterize the fibre volume fraction of the carbon fibre/epoxy composites, using a TGA-92 instrument. Specimens of approximately 5–10 mg from the laminates were cut into small pieces and placed in a platinum crucible and heated. To avoid oxidation of the carbon fibres, a constant nitrogen flow of 45 mL/min was used. The heating temperature ranged from room temperature to 800°C at a heating rate of 10°C/min and then kept at 800°C for 30 min. This heating program is designed to achieve a constant amount of residue while the temperature is not high enough to cause weight loss of the fibres. The mass percentage of matrix X_m was obtained from the TG curves, and then the fibre mass percentage was determined by ($X_f = 1 - X_m$). The fibre volume fraction of the laminates was calculated using:

$$V_f = \frac{m_f \rho_{mf}}{\rho_m m_f + \rho_{f\,(m_c - m_f)}} * 100\% \qquad (2.1)$$

Where,

ρ_m = 1.17 = density of the epoxy matrix, g/cm^3

ρ_f = 1.78 = volume density of the carbon fibre, g/cm^3

m_c = total mass of a sample, g

m_f = fibre mass of a sample, g

$$m_f = m_c X_f = m_c(1 - X_m) \qquad (2.2)$$

In addition, the processing statistical method was also applied to estimate fibre volume fraction. A typical test was carried out as follows: six short laminates were prepared and their lengths and masses were measured precisely. The fibre volume fraction of the laminates was also determined by Equation (2.1). In this method, the fibre mass content can be calculated from the product of the tex number of the carbon fibre and the length of the laminates. V_f was the average of the results from six specimens.

As per ASTM D2584, the fibre volume fraction of the composite samples can be determined by the burn-off method. In this method, the resin is burned and the residue is heated at high temperature at 600°C. The weight of sample before and after burning is noted. The fibre volume fraction was calculated by applying following equation:

$$V_f = \frac{\rho_m w_f}{\rho_f w_m + \rho_m w_f} \qquad (2.3)$$

Where,
V_f = fibre volume fraction,
w_f = weight of fibre, g
w_m = weight of matrix, g
ρ_f = the density of fibre, g/cm^3
m_f = the density of matrix, g/cm^3

According to Broyles et al., 1998 [92] the fibre volume fractions of the composite panels produced in these experiments were calculated by measuring the density of the composite in air and in isopropyl alcohol. A 4 g sample of the composite was dried and weighed. The sample was then immersed in isopropyl alcohol and weighed again. The density of the composite was calculated by Archimedes' principle using the equation 2.4. The fibre volume fraction was then calculated by using the rule of mixtures as in equation 2.5. The fibre volume fractions of the panels ranged from 0.55 to 0.58.

$$\rho_c = \frac{W_{air}}{(W_{air} - W_{IPA})}\rho_{IPA} \qquad (2.4)$$

Where,

ρ_c = density of the composite, g/cm^3

ρ_{IPA} = density of isopropyl alcohol, g/cm^3

W_{AIR} = weight of the sample in air, g

W_{IPA} = weight of the sample in isopropyl alcohol, g

$$v = \frac{(\rho_c - \rho_{resin})}{(\rho_{fibre} - \rho_{resin})} \qquad (2.5)$$

Where,

ν is the fibre volume fraction,

ρ fibre is the density of the carbon fibre = 1.81 g/cc,

ρ_{resin} is the cured resin density =1.162 g/cc,

ρ_c is the composite density.

All above equations are true for single fibre composites, another equation was developed by Karahan [187] where focus was kept on composite consisting number of layers. This equation can be used for various composites by modifying it. Here, the researcher has considered the plate thickness of composite, as given in equation 2.6. It was found by this researcher that the results obtained by equation 2.3 and equation 2.6 were very close to each other.

$$V_f = \frac{n.m}{\rho.h} \qquad (2.6)$$

Where,

n = fabric ply number in the composite,

m =axial density of the fabric (GSM), g/m^2

ρ = density of carbon given by the fibre manufacturer, g/cm^3

h = measured (using a calliper) thickness of the composite, mm.

2.9.2 Mechanical properties

The mechanical behaviour of a composite material is highly dependent on reinforcement material, matrix and interface bonding. These properties are affected by different factors like laying sequence, laying angle, reinforcement yarn and weave structure etc. Mechanical testing of composites includes tensile test, compression test, flexural test, shear test, toughness test and Impact strength.

2.9.2.1 Tensile properties

Tensile test determines the tensile strength and elongation of the composite. Anisotropic composite has different tensile properties in the fibre and traverse directions. Tensile testing of composites is done according to ASTM D 3039. Alok Hegde et al., 2015 [79] tested glass fibre reinforced composites were prepared with fibre orientations of 0°, 45° and 90°for various tensile properties such as Tensile Strength, Tensile Modulus, Specific Tensile Strength and Specific Tensile Modulus. It was found that the fibre reinforced polymer laminates exhibit higher strength and stiffness properties in the longitudinal direction as compared to other directions. The results obtained by Alok Hegde et al.,[79] have been tabulated in Table 2.1.

Rajanish. M et al., 2014 [5] has described that greater understanding of the role of variation in tensile properties with orientation of fibres in the laminate was acquired through the experiments. In the work, epoxy matrix and unidirectional glass fabric was used to reinforce with the polymer matrix by hand layup and vacuum bagging process. In the work of Khalil et al.,2009 [59] the mechanical properties of the vinyl ester reinforced with oil palm of empty fruit bunch fibres (EFB) laminated at different layer arrangements with glass fibre (CSM) composites were investigated. While comparing the layers of orientation of hybrid composites, the results of the tensile and flexural tests showed that composites with glass fibre at the outer layer showed higher tensile and flexural properties than the others. The impact test and the composites with natural fibres in the outer layer showed the highest results as compared to other layer laminations.

Karahan et al.,2014 [8] investigated the mechanical properties of carbon and carbon-aramid hybrid woven composite materials in different constructions with the same yarn and under the same production conditions. The mechanical properties of the composite materials were investigated under uniaxial tensile loading. Based on the weaving construction, Young's modulus and the tensile strength declined approximately 34–39% and 24–27% respectively.

Table 2.1: Tensile test results for glass fibre reinforced composites (Alok Hegde et al., 2015)

Orientation (Degrees)	Specimen Number	Tensile Strength (MPa)	Tensile Modulus (GPa)	Specific Tensile Strength (MPa-m^3/kg)	Specific Tensile Modulus (GPa-m^3/kg)
0	1	324.42	10.07	5.529	0.171
	2	326.92	10.07	5.572	0.171
45	1	47.71	2.53	0.813	0.0431
	2	49.40	2.53	0.842	0.0431
90	1	37.81	1.55	0.644	0.0264
	2	22.40	2.32	0.381	0.0395

Angle-ply orientations 0°/90°, 45°/45°and 30°/60° on tensile strength, tensile modulus, and peak load of Kevlar/glass fibre hybrid composites were studied [94]. It was concluded that angle ply orientation of 0°/90° showed significant increase in tensile properties as compared to the other orientations. Researchers Zhang et al., 2012 [95] had studied the effect of stacking sequence on the strength of woven fabric glass/carbon epoxy composite laminate. They found that tensile strength of glass/carbon hybrid composite was improved by placing the carbon layers at the exterior or by placing both fibres alternately.

2.9.2.2 Flexural properties

A 3-point bend flexure test was performed to evaluate the flexural modulus and strength of each of the material systems. This test was carried out according to ASTM D790-02 by researchers [96-97]. These researchers have described that although carbon fibre-reinforced polymer composites possess excellent overall mechanical properties, the relatively low ratio of compressive-to-tensile strength for carbon fibres. It was found that stress was significantly dependent on the support conditions.

Deshmukh et al., 2015 [98] has investigated carbon fibre/epoxy reinforced polymer laminates with two different fibre orientations that is 0/90 degrees and ±45 degree, further the laminates are manufactured for two different thickness 4mm and 5mm. It was found that the flexural strength is superior in case of 90-degree fibre orientation. More deflection is found in 45-degree orientation. The deflection is less in case of 90 degrees orientation. Flexural strength increases with thickness. The effect of laminate thickness and orientation on the tensile, flexural and hardness properties of the material had been tabulated in Table 2.2.

Table 2.2: Results of tensile test and bending test for carbon/epoxy reinforced polymer laminates. (Deshmukh et al., 2015)

Thick -ness (mm)	Orienta -tion (^{0})	Tensile Strength (N/mm$^{2)}$	Flexural Strength (N/mm$^{2)}$
4	0-90	377.49	60.62
5	0-90	368.94	240.19
4	±45^0	46.94	107.85
5	±45^0	72.59	175.57

The ANOVA method revealed that thermocycling, brand of material and diameter of specimen had a significant effect ($P< 0.001$) on the fracture load and flexural strength [99].

2.9.2.3 Impact properties

Impact resistance is a property crucial to the reliability and durability of the composite structures. It helps to design and generate improved materials for their different applications. It would be very desirable to be able to relate the extent of damage to the properties of the matrix, fibre, and interphase, along with factors such as reinforcement form. This would facilitate the development of more reliable materials and structures.

Considerable research has been conducted since long, making the fabrics stronger and increasing their ballistic penetration resistance while still maintaining their flexibility. In recent years, impact damage is an area of great concern. This high level of concern stems from the fact that impact damage occurs in various forms. Although having many applications, one of the most significant limitation of composites lies in their response impact loading. The damage zone of composite is complex and difficult to characterize. The problem is further complicated by the lack of existing standards or established testing techniques for the impact damage of composite materials. Impact loading of a laminated composite panel by a hard object results in a high local force causing two forms of deformation: one being indentation and the other bending [100].

A list of studies on the behaviour of composite materials and structures due to impact loading can be found in previous literatures by researchers [101-104]. This behaviour under impact loading is one of the major concerns, since impacts do occur during manufacture, normal operations, maintenance and so on. The resulting damage due to impacts, often in the form of delamination, matrix cracking and fibre failures may severely reduce the structural strength and stability. Even though fibre breakage is the ultimate failure mode, the damage would initiate in the form of matrix cracking/lamina splitting and would lead to delamination. Damage-free composites are necessary for their effective use as stated by researcher [4].

In contrast, composites can fail in a wide variety of modes and contain barely visible impact damage (BVID) which nevertheless severely reduces the structural integrity of the component. Most composites are brittle and so can only absorb energy in elastic deformation and through damage mechanisms, and not by plastic deformation. There was a significant reduction in flexural properties due to the impact induced damage [83]. Several studies are available on the impact behaviour of unidirectional laminated composites. Some researchers have studied the impact behaviour of woven fabric composites [4,105-109]. But majority of studies are based on fibres other than carbon. Consideration of carbon fibres is very minimal in these studies. So, further studies are necessary for effective use of carbon fibres in structural applications.

Raghunath et al., 2015 [108] has presented an experimental study to assess the impact response of bidirectional woven type of glass fibre reinforced composite material. Here, a falling weight drop impact tester has been used. Researcher such as Ramin and Larry, 2010[110] had presented studies on fibre reinforced composites plates by using standard drop weight with different impact energies. Yapici et al., 2009 and Mitvrevski et al., 2005 [111-112] has characterized the effect of impactor shape on the thin woven carbon/epoxy laminates. Mathivan et al.,2010 [113] characterized the type and extent of the damage observed in the laminate for a range of thickness subjected to different impact velocity.

Cantwell et al., 2010 [104] had given a view on the influence of various important parameters on the way damage is commenced. Here, the samples considered were of (0°, 90°) glass fibre reinforced epoxy resin. Kang et al., 1997 [114] had considered Kevlar multiaxial wrap-knit fabric composite for studying the impact loading. The impact behaviour of composite materials subjected to low velocity impact is influenced by the impactor parameters like impactor material, mass, incident velocity, impactor shape etc and specimen parameter like specimen thickness, history, specimen shape, clamping and specimen support. Low velocity impact tests on laminates with conical, flat, semi-spherical, and semi-cylinder impactors indicate that the impactor shape affects failure mechanism and energy dissipation capacity of the specimen. Studies on effect of different impactor shapes on woven carbon/epoxy laminates convey similar effects with conical impactor have been done by Mitvrevski et al., 2005 [112].

Nogueira et al.,2005 [115] had performed impact test on 100mm×100mm specimen dimensions by using an instrumented impact machine, assisted with a falling dart, and registered the impact energy, the displacement and the energy absorbed by specimens. The dart representing hemispherical steel tip of diameter 12.7 mm with different weights but same tip was dropped from 30 cm of height. Table 2.3 summarizes the conditions used for the impact tests.

Impact tests. Impact force is basically a high force or shock applied over a short time period when two or more bodies collide. Many instruments like bursting strength tester, cone drop test, impact strength tester is available for testing. Composite are tested by using standard Charpy impact test and Izod impact test.

Both Charpy and Izod impact testing are popular methods of determining impact strength, or toughness, of a material. In other words, these tests measure the total amount of energy that a material is able to absorb.

Table 2.3: Conditions of the impact tests carried out. [115]

Code	Weight of dart (Kgf)	Drop height (cm)	Impact velocity (m/s)	Impact energy (J)
CF-PP	5.3	30	2.48	15.48±0.04
CF-PP	5.3	60	3.47	30.24±0.04
CF-PP	5.3	90	3.96	39.51±0.05
CF-PP	12.1	90	3.91	92.61±0.03
CF-PP/PE	5.3	30	2.48	15.43±0.03
CF-PP/PE	5.3	60	3.47	30.27±0.01
CF-PP/PE	5.3	90	3.96	39.53±0.01
CF-PP/PE	12.1	90	3.91	92.61±0.02
CF-PP/PE	22.9	60	3.41	132.80±0.24
CF-PP/PE(AM1)	5.3	60	3.47	30.25±0.03
CF-PP/PE(AM1)	5.3	90	3.96	39.61±0.06
CF-PP/PE(AM1)	12.1	90	3.91	92.62±0.02
CF-PP/PE(AM2)	5.3	30	2.48	15.47±0.02
CF-PP/PE(AM2)	5.3	60	3.47	30.28±0.03
CF-PP/PE(AM2)	5.3	90	3.96	39.56±0.05
CF-PP/PE(AM2)	12.1	90	3.91	92.62±0.03
CF-PP/PE(AM2)	22.9	60	3.41	133.00±0.014
CF: Carbon fibre fabric reinforcement				

Charpy impact test. The Charpy impact test was developed by S.B. Russell and Georges Charpy at the turn of the 20th century as claimed by Toth et al.,2002 [116]. It remains to this day one of the most popular impact testing methods due to the relative ease of creating samples and obtaining results. The test apparatus consists of a weighted pendulum, which is dropped from a specified height to make contact with the specimen. The energy transferred to the material can be inferred by comparing the difference in the height of the pendulum before and after the fracture.

A Charpy test specimen, which is placed horizontally into the machine, is typically a 55 x 10 x 10mm (2.165" x 0.394" x 0.394") bar with a notch machined into one of the faces. This notch, which can be either V-shaped or U-shaped, is placed facing away from the pendulum and helps to concentrate the stress and encourage fracture.

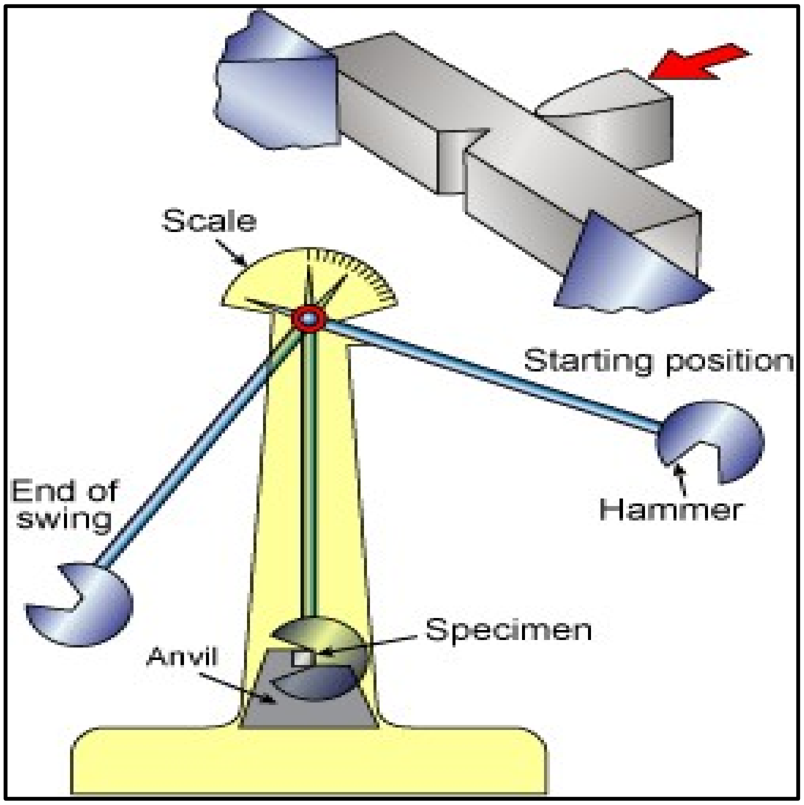

Figure 2.8: Charpy test set-up [117]

Charpy Impact Tester is a lab testing machine works, on principle working of the pendulum, which is designed for the calculation of the resistance of impact to metals and plastics. The Charpy test is most commonly used to evaluate the relative toughness or impact toughness of materials and as such is often used in quality control applications where it is a fast and economical test. It is used more as a comparative test rather than a definitive test. An arm is swung down in a pendulum motion to impact with the test material. The energy required to fracture the sample is recorded. The test comprises of vertical impact on the horizontally clamped sample, Charpy test is performed as shown in Figure 2.8.

Izod impact test. The Izod impact test was named for English engineer Edwin Gilbert Izod, who first described the test method in 1903. This test is very similar to Charpy impact test. But here, the specimen orientation the test apparatus and specimen design are very similar to Charpy impact, with some notable differences, including the orientation of the specimen, which is clamped into the apparatus vertically with the notch facing toward the pendulum. The pendulum then impacts the sample at a specified area above the notch [100]. The set up for Izod impact test is given in Figure 2.9.

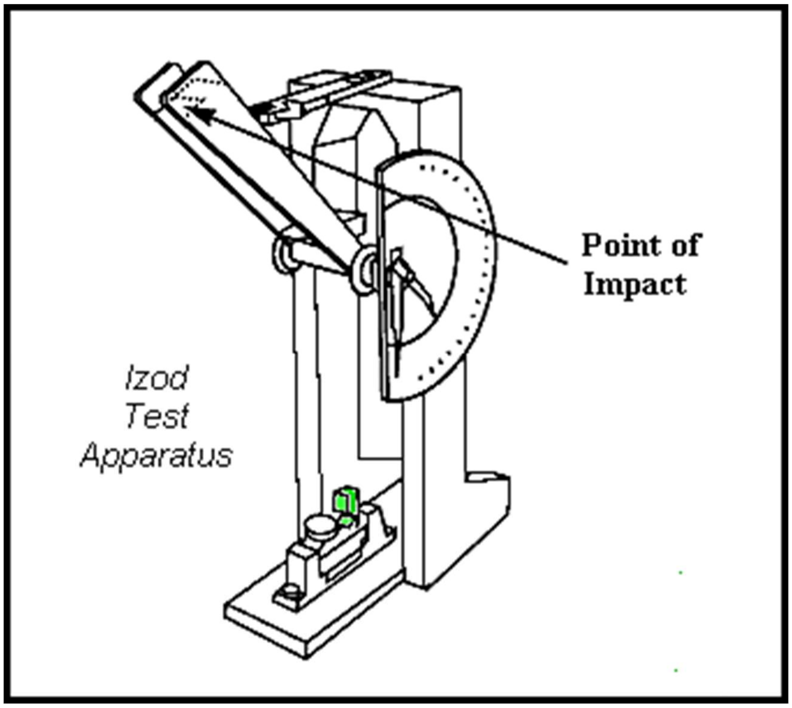

Figure 2.9: Izod test set-up [118]

One of the main differences from Charpy impact is that Izod impact testing can be performed on either plastic or metallic specimens. Plastic samples are typically a 64 x 12.7 x 3.2 mm bar with a machined V-shaped notch. The Charpy method includes striking an appropriate test material with a striker fastened at the end of a pendulum whereas in case of Izod method involved the striker, the testing material, and the pendulum. The striker was fixed at the end of the pendulum. In Charpy method, the specimen is secured horizontally in place at both ends, and the striker hits the centre of the test material, behind a machined notch whereas in Izod method the specimen was fastened at a vertical position at the bottom, and the notch was facing the striker. The striker swings downward, hitting the test material in the middle, at the bottom of its swing, and is left free at the top [119]. The schematic diagram for the comparison is shown in Figure 2.10.

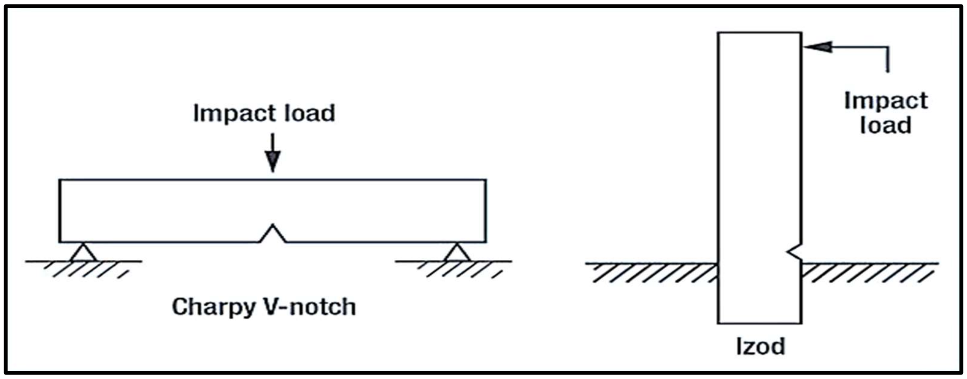

Figure 2.10: Impact load on Charpy and Izod test

2.9.2.4 Damage-resistance of composites

Several researchers worked on composites assessed damage resistance of composites [120-127]. Nettles and Douglas [128] stated that there are two distinct aspects to be consider when designing composite structures/components viz. damage resistance and damage tolerance of composite materials. They defined damage resistance as the measure of a material's ability to resist damage, whereas damage tolerance is a measure of capability of an impact-damaged composite laminate or structure to maintain its strength and stiffness. Adams [129] has considered damage resistance a *structural* rather than a *material* property due to its dependency on the layup, thickness of the laminate and the material used.

Nettles and Douglas [128] reported that it would be advantageous to simulate an impact event using a "quasi-static" loading test. They further stated that by using quasi-static test, damage initiation and propagation can be easily detected, and deflection can be directly measured with better accuracy. Due to this test maximum transverse force can be better controlled.

Many researchers compared drop-weight impact tests and quasi-static loading tests employing same size, shape, and location of damage for a given maximum transverse load. Nettles and Douglas [128] compared the data of drop-weight impact tests and quasi-static loading test and concluded that load vs deflection plot of static (quasi) indentation and low-velocity impact are similar (Figure 2.11). In the Figure 2.12 demonstrated that same data are determined independently from dynamic load v/s displacement curve and quasi/static indentation experiments.

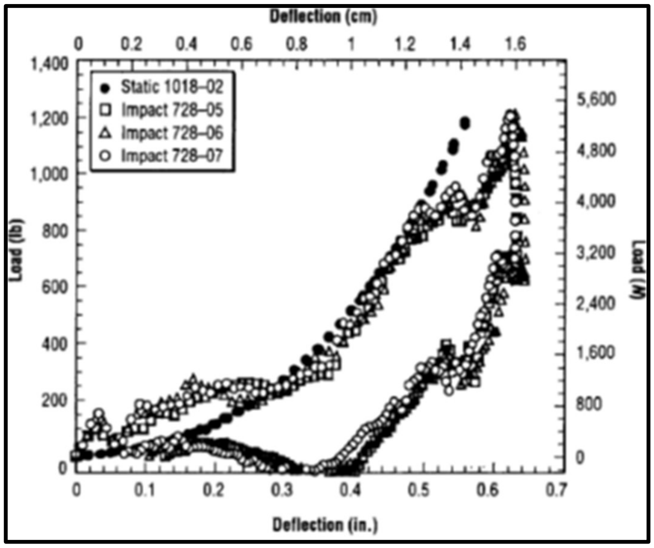

Figure 2.11: Static Indentation data superimposed over impact data for 16-ply simply supported specimens over a 12-inch opening as per Nettle and Douglas [128]

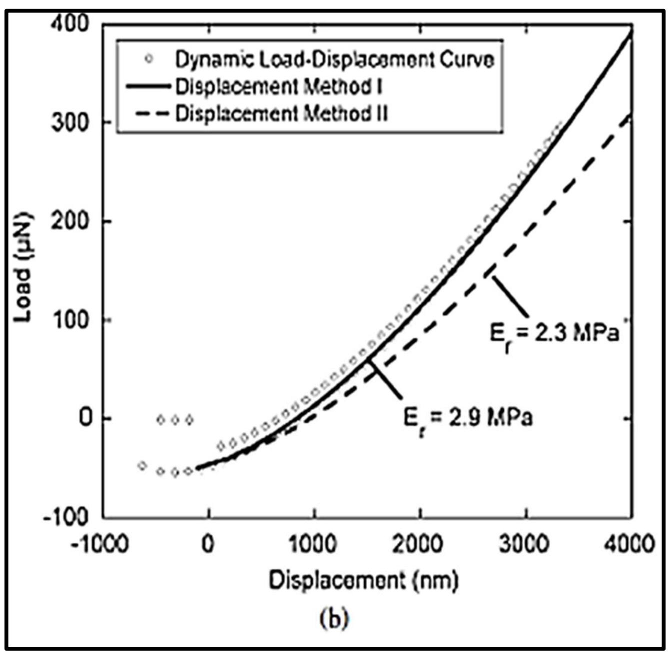

Figure 2.12: Comparison of JKR curves generated from the results of Displacement method I analysis and Displacement method II analysis for quasi static and dynamic as per Nettle and Douglas [128]

The experimental portion of this investigation consisted of quasi-static indentation experiments with a prescribed variation in both specimen thickness and in-plane clamping boundary conditions or span-to-punch ratio (SPR) [127]. The intent of these variations was to accentuate a variety of failure mechanisms and failure modes when deformation response behaviour transitions between variable combinations of shear and flexure. The span-to-punch ratio (SPR) is defined as:

$$SPR = \frac{d_s}{d_p} = 3.5(here) \qquad (2.7)$$

Where,

d_s = opening span diameter, mm

d_p= punch diameter, mm

Briggs et al.,2015 [127] also had similar observation. They performed series of quasi-static indentation experiment on carbon fibre reinforced polymer laminate. They found that the quasi-static indentation experiments achieve damage mechanisms similar to impact and penetration. They used span to punch ratio of 8 and 2. For SPR '2' they kept span of 25.4mm and punch diameter of 12.7mm. They varied thickness 2.1mm, 4.2mm and 8.4mm.

Ruan et. al., 2010 [124] conducted Quasi-static indentation tests using an MTS universal testing machine using sandwich panels either simply supported or fully fixed. They recorded Force–displacement curves and the total energy absorbed by sandwich panels. They discussed the effects of face-sheet thickness, core thickness, boundary conditions, adhesive and surface condition of face-sheets on the mechanical response and energy absorption of sandwich panels.

Afrouzian et al., 2016 [123] conducted the quasi-static indentation tests to study penetration resistance of the composite plates. They used electro-mechanic test machine at a constant rate (2 mm/min) until the occurrence of final perforation. The indenter was a surface hardened blunt nosed cylindrical steel with a diameter of 10mm and a shank length of 10 cm. The specimens were clamped between two steel plates. Figure 2.13. shows schematics and typical quasi-static indentation testing devices. The need for a static test method for modelling low-velocity foreign object impact events to composites would prove to be very beneficial to research velocity impact events are expected to occur during the manufacturing and service life of composite parts and/or structures. Foreign body impact can occur during manufacturing, routine maintenance or use of a laminated composite part.

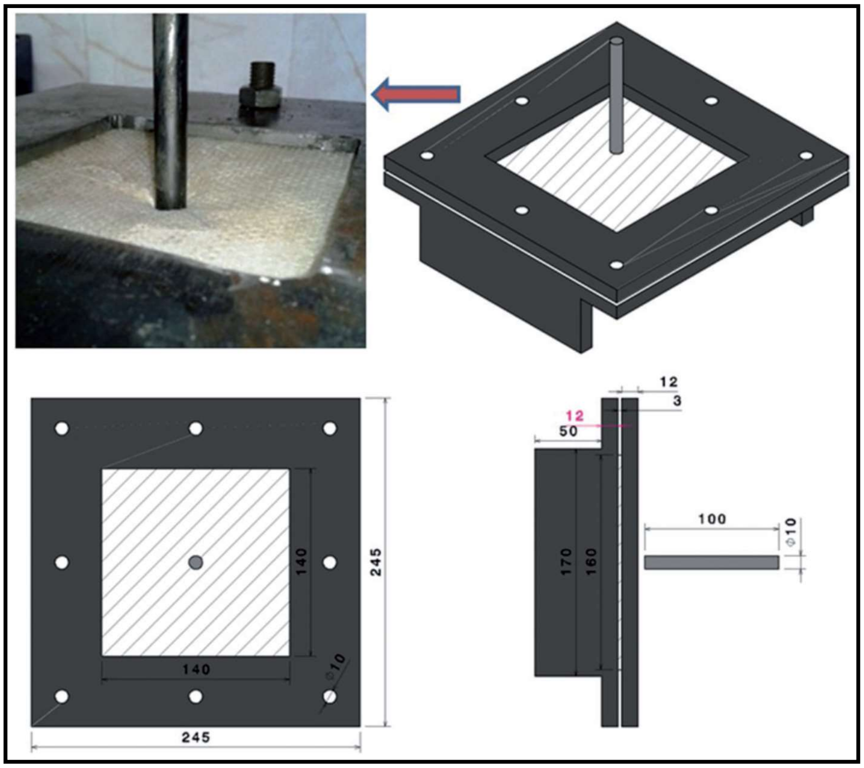

Figure 2.13. Schematic and test set up of the quasi-static indentation test [123]

2.9.3 Fracture analysis

Fracture analysis has been useful in providing information related to fractured specimens after the mechanical testing like tensile, flexural, impact and damage resistance (quasi static indentation). Since most of the fracture includes various types of behaviour like crack, delamination, matric breakage, debonding and fibre breakage etc. It becomes necessary to understand these fracture properties by using techniques like SEM analysis.

2.9.3.1 Scanning Electron Microscopy (SEM)

A scanning electron microscope (SEM) is a type of electron microscope that produces images of a sample by scanning the surface with a focused beam of electrons (Figure 2.14). The electrons beam is used to interact with atoms in the

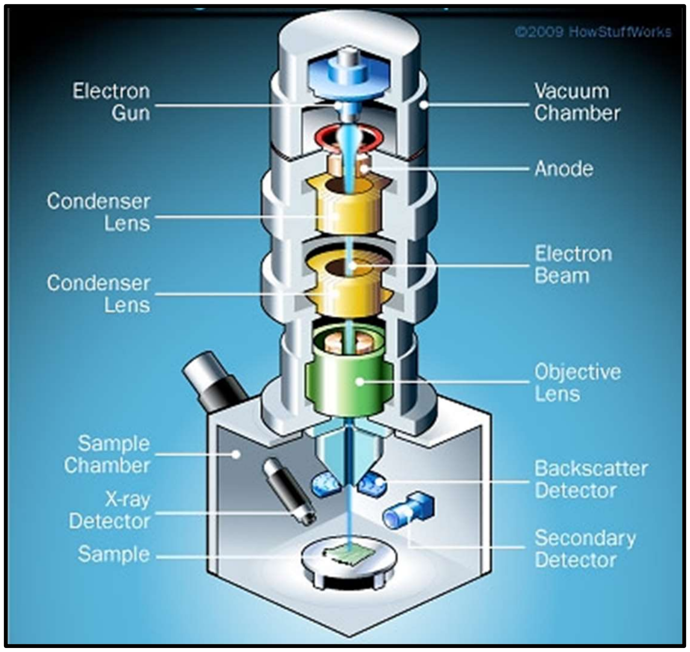

Figure 2.14: Schematic Diagram of Scanning Electron Microscope [131]

sample by striking it on the surface of the specimen, it gives information regarding the surface topography and composition by producing various signals. SEM can achieve resolution better than 1 nano-meter. Specimens can be observed in high vacuum in conventional SEM, or in low vacuum or wet conditions in variable pressure or environmental SEM, and at a wide range of cryogenic or elevated temperatures with specialized instruments [130]. The SEM shows very detailed three-dimensional images at much high magnification (up to x300000) as compared to light microscope (up to x 10000). But as the images are created without light waves, they are black and white. As high-resolution images are obtained SEM is the most suitable technique to study the failure of the composite structure. It gives the detailed knowledge about the type of the failure which has occurred.

Basic principle. Primary electrons are focused into a small- diameter electron probe, scanned across the specimen.by backscattering them from a bulk specimen. This can release secondary electrons. A square or rectangular area of specimen which is known as a raster can be covered by scanning concurrently in two perpendicular directions. Thus, the formation of image at this area is obtained by collecting secondary electrons from each point on the specimen [132].

Working. SEM requires that the specimens should be conductive for the electron beam to scan the surface and that the electrons have a path to ground for conventional imaging. Non-conductive solid specimens are generally coated with a layer of conductive material by a low vacuum sputter coating or high vacuum evaporation. This is done to prevent the accumulation of static electric charge on the specimen during electron irradiation. Non-conducting specimen may also be imaged uncoated using specialized SEM instrumentation such as ESEM or FEG operated at low voltage, high vacuum or at low vacuum, high voltage.

2.9.3.2 Fracture mechanisms

As per Azzam, 2007 [133] investigated the compressive properties of SBCF/PA12 commingled unidirectional composites manufactured by the hot compression moulding technique. He analysed the failure mechanism and concluded that composites fail in a variety of mechanisms at the fibre/matrix (micro) level. Micro-level failure mechanisms include fibre fracture, fibre buckling (kinking), fibre splitting, fibre pull-out, fibre/matrix debonding, matrix cracking and radial cracks in unidirectional composite is shown in Figure 2.15

Azzam [133] studied that Fibre fracture (Figure 2.15a) occurs when maximum load is exceeded. Fibre pull-out (Figure 2.15b) occurs when the composite fractures. This is followed by debonding (Figure 2.15d). Matrix cracking (Figure 2.15c) occurs when the strength of the matrix is exceeded. When fibre buckle due to compressive stress fibre kinking (Figure 2.15e) occurs. When the interface bonding between the matric and reinforcement reached its maximum limit, it led to fibre splitting and radial interface cracks (Figure 2.15f). In case of carbon fibre reinforced plastics structures, there exists complexity in the crack path. Different crack formation along with delamination occurs between composite layers. This is attributed to the interface bonding according to Campilho and Silva, 2015 [134]. It is also mentioned to analyse the fractured surfaces optical or scanning electron microscopy (SEM). In SEM, samples of reduced size need to be cut from the specimens, preferably with a diamond saw for a clean cut and gold coated to ensure electrical conductivity of the sample.

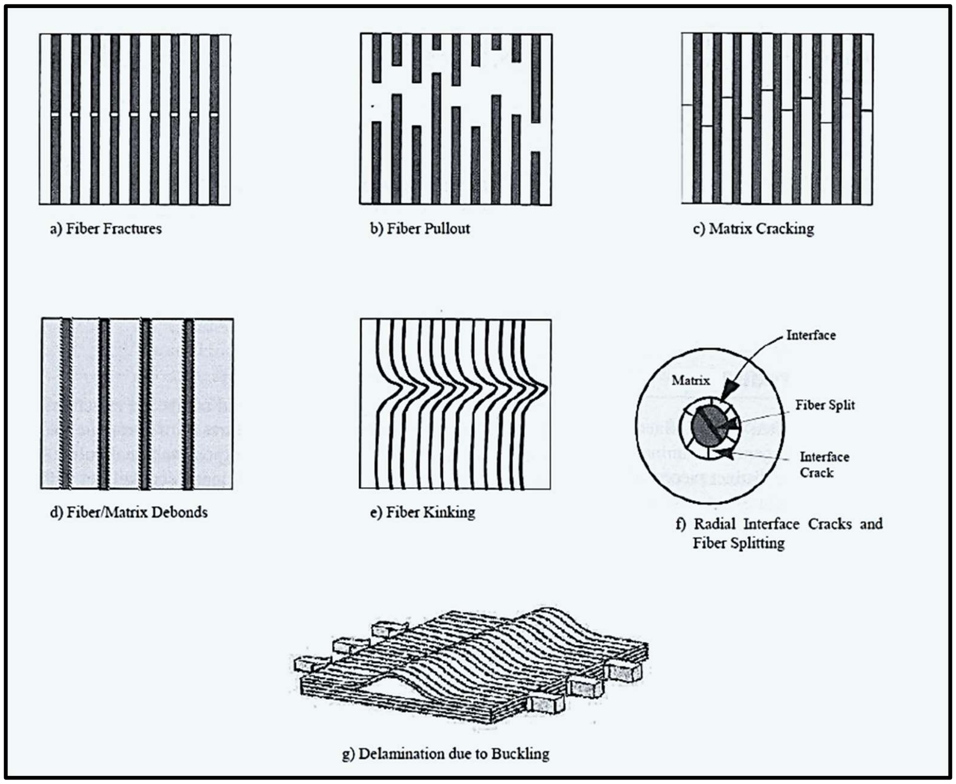

Figure 2.15: Schematic diagram for micro-level failure mechanism in unidirectional composite [133]

2.10 Application fields of textile composite

Today, the choice of a material is governed by demands of the competitive market for new and alternate source of new material. Industries like automobile industry is complete with models, options and changes in trends, the material selection and combinations offered by the materials is also wide-ranging. Materials used in automotive body parts show high tensile strength and flexural moduli. The requirement is of the materials which have high specific strength several times higher than the point of fracture for steel sheets, use of composites is suggested.

Reinforced plastic is a boon in the sense that it uses shorter lead times and tooling cost is considerably cheaper. Commitments to launch a new model are kept easily, since the time between production and introduction can be co-ordinated perfectly. The fatigue properties of the materials and the low weight, ability to sustain strains from the engine heat and low frequency road vibrations are features that favours composites in trucks and other heavy vehicles.

Application of composites	
Industry	**Examples**
Aerospace	Commercial and military aircrafts, parts such as elevators, doors, tail section, wings, cargo liners, rotor motor castings, rudder, engine etc.
Automotive	Body frames, engine components, seat structure, spare wheel containers, door modules, body panels, gates, carriers etc
Chemical	Pipes, Tanks, Pressure vessels etc
Construction	Structural & decorative panels, fuel tanks, reinforcing concrete, columns, bridges, beams etc
Marine	Decks, propellers, engine parts, heat exchangers, pipes, pumps, frames, super structures, watertight doors, shafting etc
Medicine	Medical implants, composite bone, plates, total hip replacement, total knee replacement, bone cement, dental implants, prosthesis, catheters, support frames etc
Electrical and electronic	Data memory, displays, laser diodes, glass fibres, optical switch, filters, conductive etc
Défense	Light weight mobile, easily transportable vehicles, ballistic combat, logistics applications
Space	Space Shuttle, Space stations, nozzles such as exit cone and throat elements etc
Protective	Helmets, bulletproof jackets, protective clothing, fireproof garments etc
Energy	Fuel cells, solar cells, batteries, capacitors etc.
Sport and leisure	Golf clubs, poles, bicycle frame, front forks, seat posts, tennis racket frames, kayaks etc
others	Wind energy application like wind mill blades, furniture industries, musical instruments etc

Figure 2.16: Applications of composites

Composite materials due to have wide range of applications like bullet-proofing, marine & underwater vehicles, aerospace vehicles, automotive structures and geotextiles etc. They have replaced metal and metal alloys successfully in many applications including automotive, aerospace, electronics, military and recreations, glass composite is used to make ship hulls[135] Boeing`s787 Dream liners the first commercial aircraft in which major elements are made of composite materials rather than aluminium alloys as depicted by Varshney et al., 2015 [32]. Other application includes drive shafts, side rails, doors, hoods, hinges, seat frames, bumpers, submarines, powerboats, racing yachts, and laminated sailcloth & interiors like overhead luggage compartments, sidewalls, partitions, cargo liners etc as stated by Ahmed et al., [82]. A broad depiction of the application field is being given in Figure 2.16. Here, detailed application parts in various fields like aerospace, automotive, marine, medicine, electrical and electronic industry, defence, space application, construction, protective, energy, sports, leisure and others.

2.11 Numerical simulation of woven composite laminates

The importance of fibre reinforced composite materials in the field of engineering is growing rapidly. Not only aerospace industry but also other industrial sectors as the automobile and naval industry are highly influenced by these kinds of materials.

A composite material is a material which consists of two or more components. Fibre reinforced composite materials consist of the fibre which acts as reinforcement and a matrix which holds the fibre in place. Due to the composition of two materials with highly different properties the analysis of components made of such materials is a complex task as depicted by Merlin et al., 2009 [136]

Misra et al.,2014 studied the behaviour of fibre reinforced composite materials following two different approaches. The micro-mechanical approach handles the composite material as a combination of various materials and derives the average properties considering the properties of the single materials of a unit-cell. Whereas, the continuum approach considers the composite material as a homogeneous material with uniform average properties [137].

Woven fabrics are being ever more widely used in modern industries due to their balanced mechanical properties, ease of handle and good drape-ability together with reduced manufacturing cost as compared to the unidirectional reinforcements as stated by Dixit et.al., [138] These are particularly suited for manufacturing of inflatable structures, membranes and double curved structures as described by Cavallaro et al.,[139]. Laminated composite plates generally offer good in-plane properties but are prone to delamination due to their poor mechanical properties in the thickness direction. In an attempt to overcome this drawback, woven-fabric composites, also termed textile composites, are put to use, as they offer a 3D reinforcement in a single layer and provide better mechanical properties in both in-plane and transverse directions Dixit and Mali [138].

Woven fabrics are available in different weaving pattern such as plain, twill, satin and basket weave in the dry form which further can be consolidated with matrix material (resin. etc.) via resin transfer molding (RTM) or any other manufacturing process to form a composite as researched by Boisse et.al., [56].

At macro scale dry fabrics are composed of number of yarns interlaced into each other in different weaving sequences. There are usually four important levels in the manufacturing process of textile composites i.e. Fibre -Yarn-Fabric-Composite. Yarns at meso level can be considered as a heterogeneous media made of bundles of very thin and long fibres at micro level. The interaction and behaviour of these yarns at fabric level can greatly influence the macro-level material behaviour. Amongst different existing modelling approaches, meso-scopic modelling approach of woven fabrics is known and a strong tool for predicting their effective mechanical properties at macro-level.

During service, woven fabric composites are subjected to failure in tension, compression, shear and impact load. Shear deformation of woven fabric is quite complicated as it is dominated by yarn trellising/rotation at crossovers. During forming of textile reinforcement's shear is generally considered to be the primary deformation mechanism [80,140]. Therefore, it is essential to understand fabric shear compliance for precise modelling of forming or draping processes. However, during actual forming process, a combined mode of the axial and shear deformation may perhaps be experienced by woven fabrics [56]. Researchers in the past have worked on the characterization of fabric shear with the aim to determine the non-linear response of the material under shear loading and to characterize their deformation limit [141]. The Kawabata Evaluation Systems for fabrics [142] and the picture frame test [143] are generally used for characterization of fabric shear behaviour in the region at small and large strain respectively.

The bending and tensile properties in various directions for both engineered fabrics and clothing are affected by and shear deformation of fabrics [144-145]. However, considering the potential applications and importance of woven composites it is necessary to predict its mechanical properties with minimal possible errors. Numerous modelling schemes are available in the open literature to correctly anticipate the shear behaviour of fabric but still they lack somewhere in terms of their accuracy, the level of validation and their computational efficiency. The quite common place statement, however, has important consequences. The complexity of the structure and the presence of a hierarchy of structural and scale levels (10^{-5} m – fibres, 10^{-3} m – yarns, 10^{-1} m – fabrics, 100 m – composite parts) lead to complexity of the predictive models, high level of approximation in them, and to high uncertainty of the predictions, with errors accumulating when the model progresses from one hierarchical level to another.

Thus, the strategic questions to be answered are: How to integrate models representing to different levels? What are the scales needed for a particular problem? What are building blocks for each level? The same hierarchy provides a generic, systematic and modular approach for creation of a predictive model: homogenization on a certain level encapsulates the relevant properties of building blocks for the subsequent level. This strategy is universally recognized. However, for textile composites quite important challenges are still there: How to build up a reliable description of the textile architecture? How to implement this architecture in FE models avoiding manual building of volumes? How to describe nonlinear, irreversible, friction-controlled mechanical behavior of textile yarns and fibrous assemblies in general? How to account for damage development in homogenization procedures?

The progress of Composite Materials Group of Department MTM (Metallurgy and materials engineering), Lomov to implement this approach is depicted in a number of recent publications [144,146] where additional references can be found.

Considering homogenization on a certain hierarchical level, several different classes of problems can be identified:

1. Description of textile architecture. This applies, naturally, to the description of interlacing of yarns, which implies such issues as generic coding of the topology of the structure and application of the principle of minimum energy. This also can apply to the description of fibrous structure of a textile yarn, addressed in literature only marginally. The two mentioned issues will be discussed below.

2. Deformation of a dry textile in composite processing. This involves a description of "strange" behavior of fibrous assemblies and presents a lot of difficulties in connection with precision of this description. The task is not made easier by the frictional phenomena involved.

3. Flow of resin through a textile structure in RTM process. There are two major difficulties: geometrical complexity and two scales (inter-yarn and intra-yarn) of pores in textiles and uncertainty of conditions on yarn boundaries. The most promising way to deal with them is to use a through-computation method, which eliminates at least the former difficulty. We shall show the first results of the application of Lattice Boltzmann approach.

4. Homogenization of mechanical properties of a composite unit cell. Unless damage is developing, this is quite straightforward, providing the geometry of reinforcement is well known and easily imported into an

approximate (cell model, inclusion model…) or FE meso-mechanical tool. The key to the success of the integrated approach is a "happy marriage" between composites mechanics and textile material science, which has its own treasury of theories and predictive models. In fact, the subject of the present paper can be described as "virtual textile", which opens a route to "virtual composite" – a computer tool for prediction of properties and optimization of processing of textile composites.

2.11.1 Hierarchy of Textile structure:

The hierarchy of textile structure is given through the below three levels:

i. Fabric to Yarn: Fibrous structure and mechanical properties of Yarn
ii. Yarn to Fabric
    1. Internal Geometry of woven Fabric
    2. Deformation of Dry Fabric: Compression
    3. Deformation of Dry Fabric: Tension, shear, Bending
iii. Fabric to Unit Cell of Composite

As per researcher Kozhanov [147], in the plain weave, a regular periodic structure with a repeated unit cell (RUC) can be taken. It is assumed generally that this RUC contains a warp yarn, a weft yarn and a weave architecture. The expected appearance of RUC is signified with a rectangle in Figure 2.17.

Considering specifically plain weave, it is being assumed that the shape of the of weave changes by the same law over the whole fabric area. In the longitudinal cross section, the warp direction the RUC features as in Figure 2.18. Further it was stated that reinforcing yarn has shape close to sine curve. For the ease of modelling this whole structure is simplified wherein, straight line took place of curves and rectangular shape took place of elliptical cross section of the yarns as shown in Figure 2.19. This simplified geometry of RUC describes the behaviour of the material as whole. Textile composites have innovative characteristics because of their complex reinforcement geometries as per researcher Andrei et al., (Figure 2.20) [148]. As per researcher [149],

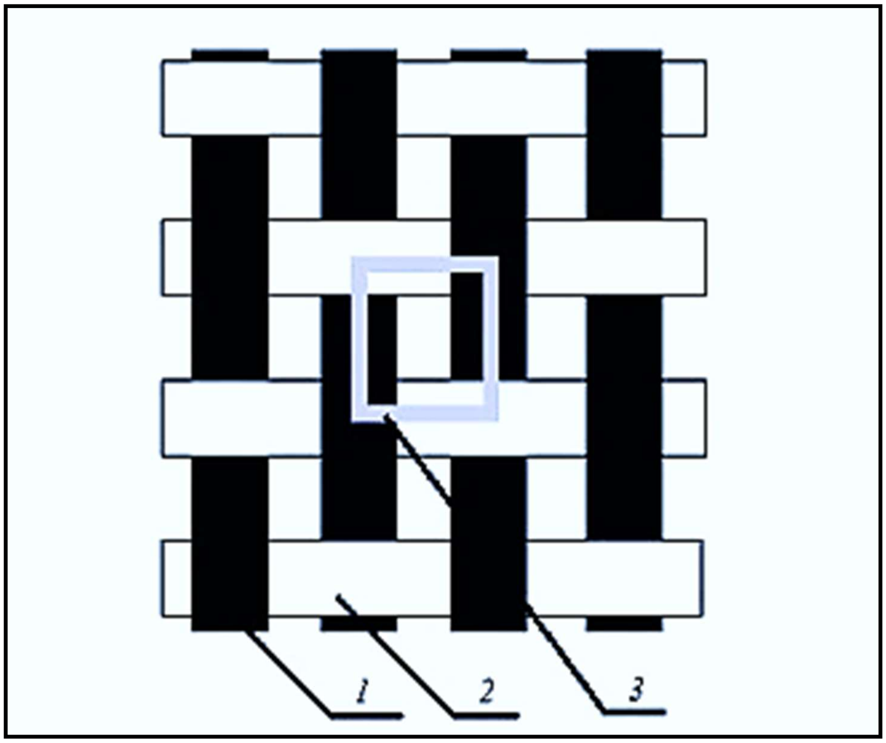

Figure 2.17: Schematic diagram of plain weave
(1=warp yarn; 2 = weft yarn and 3= repeated unit cell (RUC) [147]

Mechanical behaviour of a fibre reinforced composite material depends on the properties of each component, the proportion of the components, the shape and orientation of the yarns relative to the direction of stress, the mechanical strength of the interface matrix-yarn. If considering the layers sequencing, in case of multilayer for identical orientation, the characteristics of the structure can follow similar pattern but in case of different orientations of the yarns (Figure 2.21), to meet the design criteria, quasi-isotropic material properties are created.

FEM is the most promising, because it enables analysis of nonlinear systems with general boundary conditions and can be adapted to complex geometries [149]. The realistic stress-strain behaviour which is anisotropic, retains permanent deformations and nonlinear can be captured correctly by shaping the fabric. The geometric characteristics of the preform ca can be studied at three different scales, (Figure 2.22) firstly, microscopic scale (about 10 μm to 100 μm, used for diameter of fibres) secondly, mesoscopic scale (from 1 mm to 1 cm, used for yarns and unit cell (UC) thirdly, macroscopic scale of the composite material (–over 1 cm)[150].

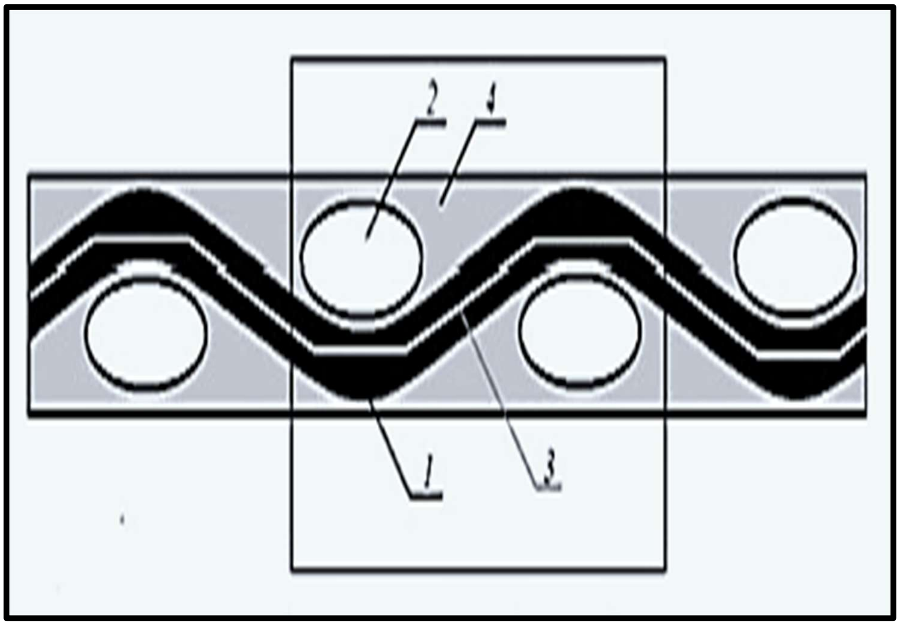

Figure 2.18: longitudinal cross section oriented along the weft yarn. (1=warp yarn; 2 = weft yarn and 3= linear approximation of sine shape of warp yarn and 4= matrix of the flexible woven composite) [147]

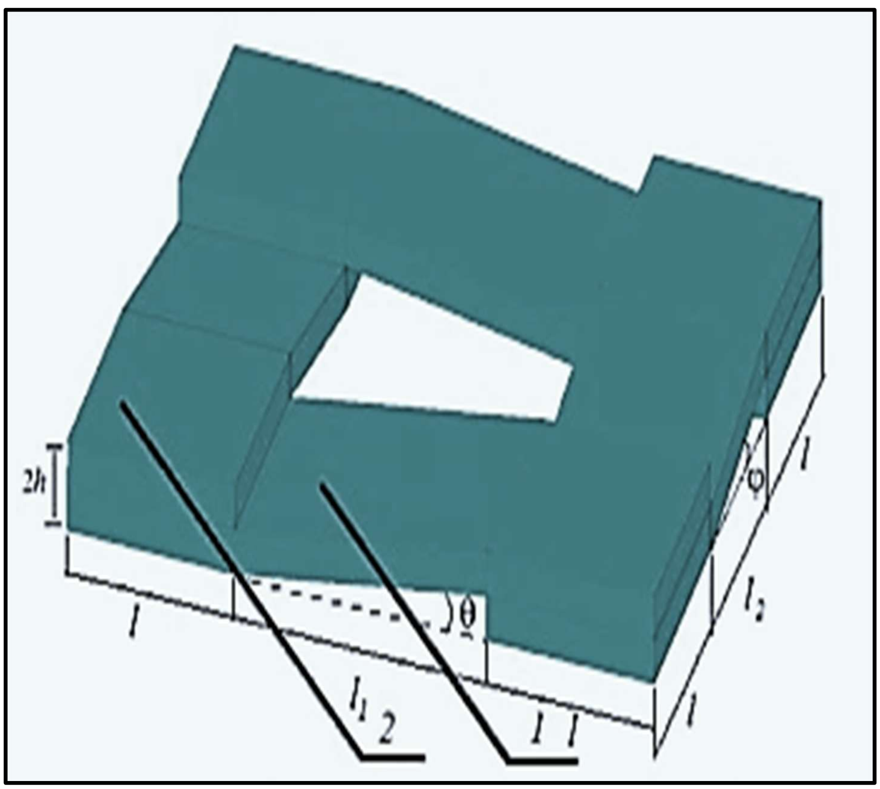

Figure 2.19: Geometry of a RUC of the reinforcing yarn of a flexible woven composite (1=warp yarn; 2 = weft yarn) [147]

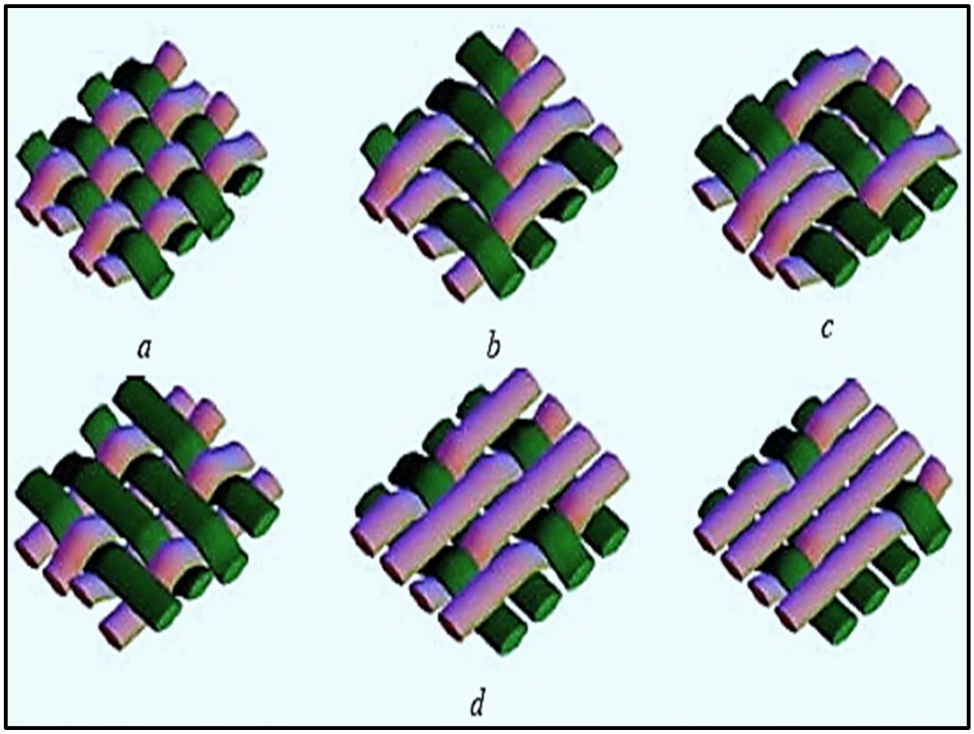

Figure 2.20: Schematics of woven composites (a-plain weave; b-twill weave (2 x 2); c- basket weave; d- satin weave: 4 harness, 5 harness and 8 harness) [148]

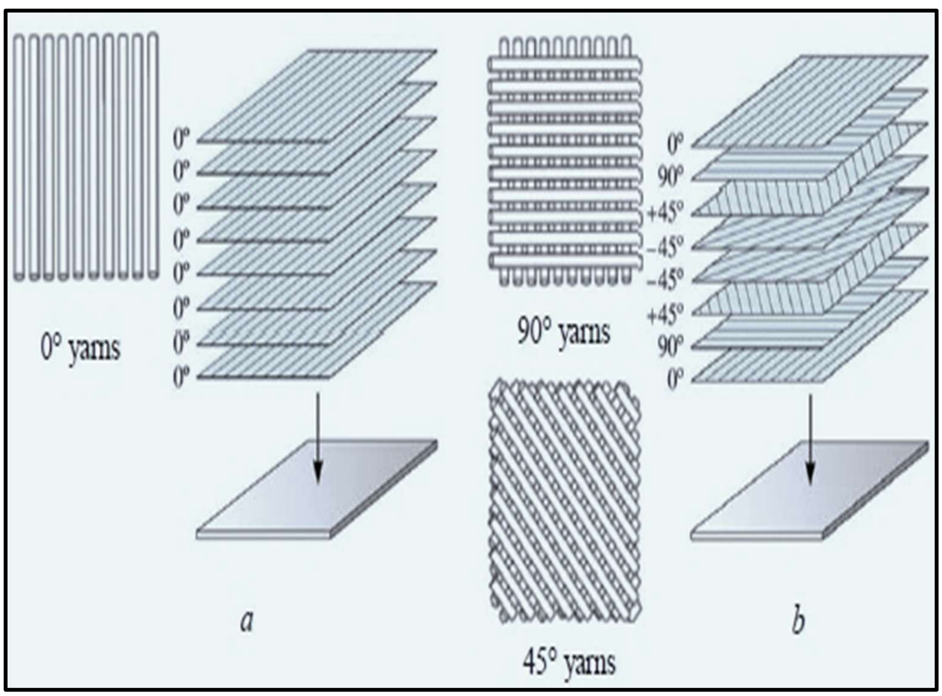

Figure 2.21: Schematic diagram of composite types by yarn orientation. (a-unidirectional orientation; b- multidirectional orientation) [149]

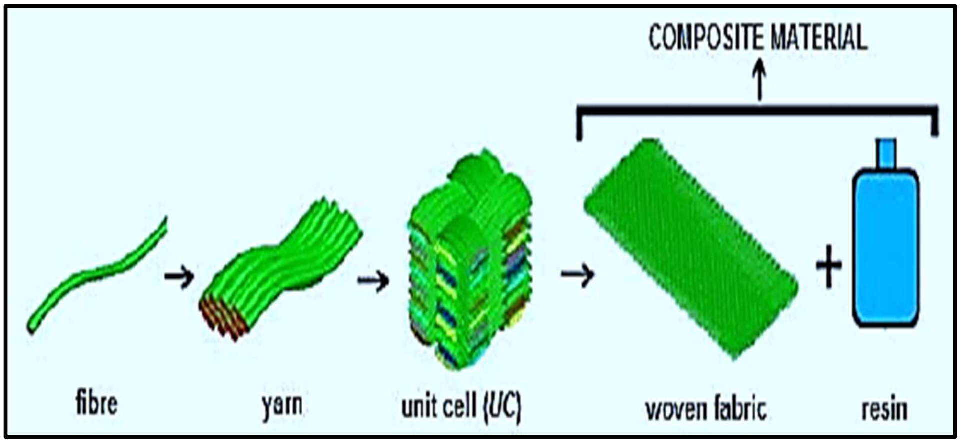

Figure 2.22: Schematics for steps involved in manufacturing and análysis of textile reinforced composites [150]

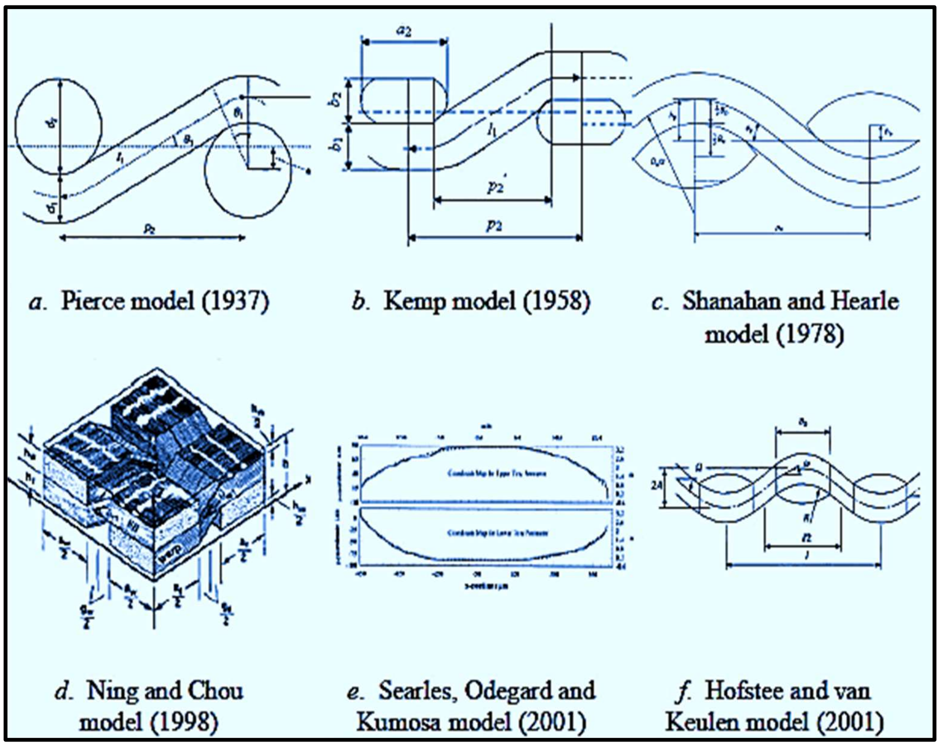

Figure 2.23: Geometric models for fabric's Unit Cell using variable section yarns [148]

Analytical/numerical textile modelling techniques are using a small representative piece of material, called unit cell (UC), which repeats over and over, completely describing the whole fabric. Therefore, the properties of the textile materials are predicted on this UC. One of the first geometric patterns, extremely idealized, for the UC of a plain weave fabric was presented in 1937 by Peirce. Peirce's model (Figure 2.23a) considers yarns cross-sections to be circular and incompressible. In 1958, Kemp [151] altered Peirce's model by using elliptic shape for the yarns cross-sections (Fig. 2.23b), thereby achieving a more realistic representation for the geometry of the fabric. Later on, in 1978, Shanahan and Hearle [152] came with a new geometric pattern for the yarns, with cross-section of lenticular shape (Fig. 2.23c) and introduced energy-based calculation methods. Then, Ning and Chou [153] have developed a more idealized UC model (Fig. 2.23d), in order to find the effective thermal conductivity for a plain weave fabric. Another representation of the yarns section was proposed by Searles [154] who has used functions to describe the upper and lower half of the cross section of the yarns, relative to the position of centre of gravity line (Fig. 2.23e). Concurrently, Hofstee and Keulen [154] developed a geometric model for the fabric's UC, using variable section yarns (Fig. 2.23f).

Various analytical approaches were developed to establish constitutive equations of the textile composite material by researchers [156-159]. They were primarily used as code analysis to predict the general properties and mechanical response. The simplest of these methods are based on the rule of mixtures and classical lamination theory. In this method, laminated composites are considered to be homogeneous materials. Volume partition approaches were developed for the description of the fabric's geometry and of the system of heterogeneous materials.

Tabiei and Jiang [160] proposed a method to mesh the UC by dividing it in sub-cells. As shown in Fig. 2.17, for plain weave textile type, the repetitive unit cell is divided into four sub-cells [161]. Later, in 2002, Tabiei and Yi [162] have extended this method using finite element analysis, which can provide a more accurate prediction on the effective stiffness of woven composites.

A new technique, based on finite volume elements (voxel) was tried by Bogdanovich [163] to represent architecture textile composite woven into three-dimensional space (3-D), where the volume of representative composite fabric was defined as homogeneous and anisotropic. The elastic properties of representative volume were determined by volumetric averaging the stresses and strains in the sub-volumes (sub-voxel) [148].

2.11.2 History and Advantage: FEM for composite Structures.

The Finite Element Analysis (FEA) Method is a powerful tool to analyze components made of fibre reinforced materials. FEA software mostly uses two dimensional elements with layer capabilities to simulate fibre reinforced composite materials. These elements require average material properties of fibre and matrix material, such as average Young's modulus, shear modulus and Poisson's ratio. To obtain these properties continuum approaches are customarily used. Also experiments on the real material are used to obtain these required properties [149].

Analytical methods to describe the behaviour of fibre reinforced materials are using FOURIER expansions which can be solved exactly to obtain closed analytical models of the material. Such Analytical Methods are described by Varadan and Savithri [164]. C^1 function theories assume that the displacement is varying continuously differentiable across the thickness, the most common C^1 function theory is the Classical Laminate Theory [CLT]. Researcher [165] presented a 3-D micromechanical model based on the CLT for predicting the elastic behaviour of woven laminates. By assuming displacement continuity at layer interfaces, C^1 function theories can be achieved. A detailed overview of the most important publications about analytical methods and C^1 /C^0 function theories have been provided by Rohwer [166].

A micro model for fabric composite materials to perform structural analysis was developed by Tabiei, 2001 [161]. In this approach the analysed woven composite material is simulated with an equivalent homogeneous anisotropic material in FEM software. A subroutine which interfaces with the FEM software contains the heterogeneous woven composite material model. A hybrid FEA model to simulate textile composite materials in a stamping process was introduced by Sidhu [167].

Li et al., 2004 [168] modified this approach for the simulation of woven commingled glass- polypropylene composite fabrics and compared the results of the simulation with experiments on the real material. The modelled woven commingled materials consist of fabric yarns which are commingled fibreglass and polypropylene. The polypropylene melts upon heating and infuses the fibreglass, so that no resin is needed.

The hybrid FEA model (Xiang et al.) was the basis to develop the plane fibre approach discussed in this paper [168]. Multi-layered circuit boards containing of copper and woven fibre reinforced composite layers are modelled in FEA software and simulated for bending by Li et al., 2008 [169]. The procedure to simulate the differed layers of the material with different orthotropic layers in FEA software was relevant for the investigation made in this paper.

Cao et al., 2008 [170] studied the mechanical behaviour of woven composites cloth material using experiments and benchmarking. Although these investigations were performed on woven composite fabrics without resin, the described behaviour turned out to be useful to understand the behaviour of the fibre reinforced composite material discussed in this paper, especially for loads applied transverse the fibre direction.

The mechanical behaviour of woven composites was analysed by Ryou et al., 2007 [171] focused on nonlinear and rate dependent asymmetric/anisotropic deformation behaviour. The studies of Ryou et al., are based on the CLT.

Djordjevic et al., 2007 [172] studied the nonlinear elastic behaviour of different carbon fibres. These Investigations are to be used to integrate nonlinear behaviour in the models introduced in this paper. A plane stress constitutive law to describe the inelastic nonlinear, anisotropic, and asymmetric mechanical behaviour of fibre reinforced composites based on the kinematic hardening model was developed by Kim et al., 2008 [173].

2.11.3 Finite Element Modeling

The Finite Element Method is a well-known numerical technique to obtain solutions to a variety of engineering problems e.g. Temperature distribution in

Electrical Transformer, flow around Turbine and Wings of Aero-plane and also strength of composite materials.

The method uses integral formulations instead of finite difference equations to create a system of algebraic equations. Moreover, an approximate continuous function is assumed to represent the solution for each element. The complete solution is then generated by connecting or assembling the individual solutions, allowing for continuity at the inter elemental boundaries. To obtain a complete solution the two conditions of (a) displacement compatibility and (b) equilibrium have to be satisfied throughout. For any system of nodal displacements, a;

$$a = \{a_1, a_2, a_3, a_4 \ldots \ldots, a_n\} \tag{2.8}$$

listed for the system in which all the elements participate, automatically satisfies the first condition. As the conditions of overall equilibrium have already been satisfied within element, all that is necessary is to establish equilibrium conditions at the nodes of the system. The resulting equations will contain the displacements as unknowns, and once these have been solved the system problem is determined. The internal forces in elements, or the stress. can easily be found by using the established characteristics. Consider the 2D system to be loaded by external forces r;

$$r = \{r_1, r_2, r_3, r_4 \ldots \ldots, r_n\} \tag{2.9}$$

applied at the nodes in addition to the distributed loads applied to the individual elements. Again, any one of the forces r_i must have the same number of components as that of the element reactions considered.

$$r_i = \{ X_i, Y_i\} \tag{2.10}$$

Each component of r_i has, in turn, to be equated to the sum of the component forces contributed by the elements meeting at the node. Thus, considering all the force components,

$$r_i = \sum_{e=1}^{m} q_i^e = q_i^1 + q_i^2 \ldots \ldots \ldots \ldots \tag{2.11}$$

in which q_i^1 is the force contributed to node *i* by element 1, q_i^2 by element 2, etc. Clearly, only the elements which include point *i* will contribute non-zero forces, but for tidiness all the elements are included in the summation. Assuming linear elastic behavior of the element, the characteristic relationship be of the form,

$$q^e = K^e a^e + f_p^e + f_{\varepsilon_0}^e \ldots\ldots\ldots\ldots \qquad (2.12)$$

in which f_p^e represents the nodal forces required to balance any distributed loads acting on the element, $f_{\varepsilon_0}^e$ the nodal forces required to balance any initial strains such as may be caused by temperature change if the nodes are not subject to any displacement and K^e is known as the stiffness matrix. The first of the terms represents the forces induced by displacements of the nodes. Substituting the forces contributing to node *i* from the eq. 2.12,

$$r_i = \left(\sum_{e=1}^{m} K_{i\,1}^e\right) a_1 + \left(\sum_{e=1}^{m} K_{i\,2}^e\right) a_2 + \ldots + \sum_{e=1}^{m} f_i^e \qquad (2.13)$$

where,

$$f^e = f_p^e + f_{\varepsilon_0}^e \qquad (2.14)$$

The summation again only concerns the elements which contribute to node *i.* If all such equations are assembled, formation of equation will be,

$$Ka = r - f \qquad (2.15)$$

in which the sub-matrices are,

$$K_{ij} = \sum_{e=1}^{m} K_{ij}^e \quad and \quad f_i = \sum_{e=1}^{m} f_i^e \qquad (2.16)$$

with summations including all elements. This simple rule for assembly is very convenient because as soon as a coefficient for a particular element is found it can be put immediately into the appropriate location specified in the computer. This general assembly process can be the common and fundamental feature of all finite element calculations. In general, the procedure for analyzing a system can be divided into three steps as shown in Figure 2.24.

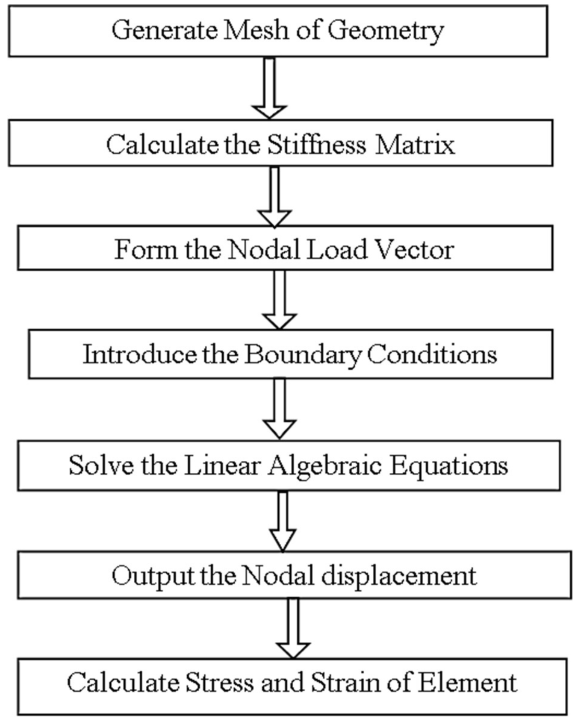

Figure 2.24: Steps of Finite Element Method

2.12 Objectives

Textile composite provides one of most promising opportunity to provide application-based product. The research in textile composite are being carried out not only in textiles but other fields like aerospace, automobile, construction, chemical, marine, electrical, space, defense, sports etc. and creating a huge market. The focus is on functional enhancement in performance of the products. Now a day's research has been concentrated on preparation of textile composite materials with properties like high modulus, increased strength and light weight. Research is concentrated on selection of reinforcement material and matrix used for preparation of required composite, mainly for unidirectional composite. As stated by researchers, the cautious assortment of stacking sequence can give high strength and the weave structure of the laying fabrics affects the tensile strength of the composite [7-9]. Very scanty literature available is of hybrid composite and in these also, negligible literature related to interply and intra-interply hybrid composite is available. There is a lack of comprehensive single study which covers effects of angle of layering sequence (skew angle), weave structure and type of reinforcement etc. High performance yarn is used as reinforced yarn primarily in the preparation of composite used in automobiles, aerospace, windmill etc. The objective of this research is to develop textile polymer composite by laying layers of fabric differently in terms of angle, yarn type and weave structure. To accomplish this high-performance yarn like Carbon and Kevlar is being used. Though composites having specific properties are available but most of them are proprietary knowledge.

The research aims to manufacture composites with woven fabric as reinforcement and polymeric matrix so that the resulting products gives favorable mechanical strength.

Another area in research and development of composite materials is the cost parameter of these composites. The purpose of the research is to produce and study composite materials with favorable mechanical properties in terms of tensile, flexural, impact and damage resistance strengths in different directions for application in areas such as automotive, aerospace, marine etc.

In order to characterize the effect of the stacking sequence, weave structure and reinforcement yarn on strength of the prepared composites, this research is focused on evaluation of physical properties and mechanical properties of the prepared composites. To attain cost effectiveness and improve ductility of composite, it is being aimed to consider economical yarn like HDPE along with high performance yarn to produce a hybrid composite.

Another purpose of the study is to investigate failure mechanism occurring in these composites during application of force. The failure mechanism will be analyzed by SEM technique.

The parameters such as fibre architecture, fibre properties and matric properties which affects the mechanical behaviour of composites put ahead a challenging task for researchers to perform the modelling of textile composites. The numerous assumptions made during this modelling procedure were applied only to simple structure and not to the complex. Here, FEM analysis with ANSYS software is used to achieve this aim.