CHAPTER (1)
INTRODUCTION

1.1 Composite Materials History

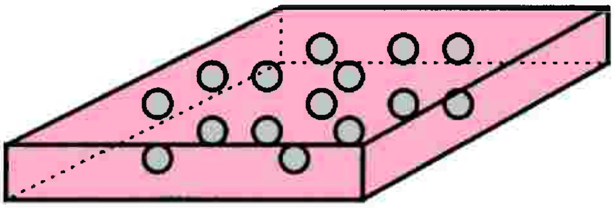
Composites have been used for a very long time since 1500 B.C. All the history recorded contains some source of composite. The reinforcing mud walls in houses with bamboo shoots, glue laminated wood was used by Egyptians in 1500 B.C, and the laminated metals in forging swords in A.D 1800. They found that in order to achieve greater strength and resistance to thermal expansion, the wood could be rearranged. Besides, the early uses of composite were shown by the early natives of South and Central America which used plant fibers in their pottery to keep the clay from cracking during drying rather than on structural reinforcement. In the 1930s, the composites were modernized when glass fibers rein forced resins were used. These glass composites or commonly called fiber glass were applied on the boats and aircrafts. Since the 1970s, application of composites has been widely used due to development of new fibers such as carbon, boron, and aramids and also new composite systems with matrices made of metals and ceramics [1]. Some of properties that can be improved by using a composite material include Strength, Stiffness, Corrosion resistance, Weight, Thermal insulation, Wear resistance and Fatigue life.

1.2 Definition of Composite Materials

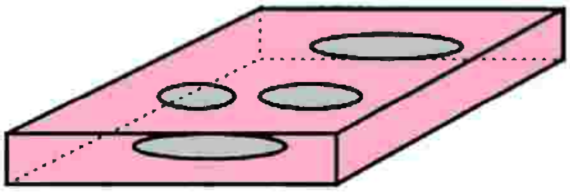
Composite materials consist of two or more materials which together produce desirable properties that cannot be achieved with any of the constituents alone [1]. Fiber-reinforced composite materials, for example, contain high strength and high modulus fibers in a matrix material. Reinforced steel bars embedded in concrete provide an example of fiber-reinforced composites. In these composites, fibers are the principal load-carrying members, and the matrix material keeps the fibers together, acts as a load-transfer medium between fibers, and protects fibers from being exposed to the environment (e.g., moisture, humidity, etc.) [1].

1.3 Classifications of composite Materials

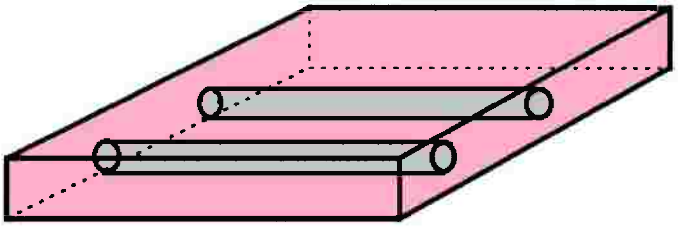
Composites can be classified either by the geometry of the reinforcement or by the type of matrix. Classification by geometry of the reinforcement generally consists of particulate, flake, and fibers composites [1], as shown in Figure 1.1.



(a) Particulate composites



(b) Flake composites



(c) Fiber composites

Figure 1.1 Types of composites based on reinforcement shape

1.3.1 Particulate composites

Particulate composites are referred as composites reinforced by particles having all dimensions of the same order of magnitude. They are usually isotropic because the particles are added randomly. It consists of particles immersed in matrices such as alloys and ceramics. The particles can be either metallic or nonmetallic. Particulate composites provide advantages such as improved strength, increased operating temperature, oxidation resistance and many more. Typical examples of particulate composites are the use of aluminum particles in rubber, and silicon carbide particles in aluminum, and gravel, sand, and cement to make concrete [1].

1.3.2 Flake composites

Composites reinforced by particles having two dimensions much larger than the third, are known as flake composites. It consists of flat reinforcements of matrices. Typical flake materials are glass, mica, aluminum, and silver. Flake composites have high out-of-plane flexural modulus, higher strength, and low cost. However, it cannot be easily oriented and only available for used in a limited number of materials [1].

1.3.3 Fiber composites

Fiber composites consist of matrices reinforced by short (discontinuous) or long (continuous) fibers. Generally, fibers such as carbon and aramids are anisotropic. Continuous fiber composites can be made either by aligning all the fibers or by weaving a cloth and then impregnating the resulting structure with matrix material. For discontinuous fiber composites, its materials containing short fibers whose length is about a hundred times the other two dimensions. These short fibers can either be aligned or arbitrarily distributed [2].

1.4 Fibers and Matrix

The bonding between fibers and matrix is created during the manufacturing phase of the composite material. This has fundamental influence on the mechanical properties of the composite material [3].

As shown in Figure 1.2, most man-made composite materials are made from two materials: a reinforcement material called fiber and a base material, called matrix material.

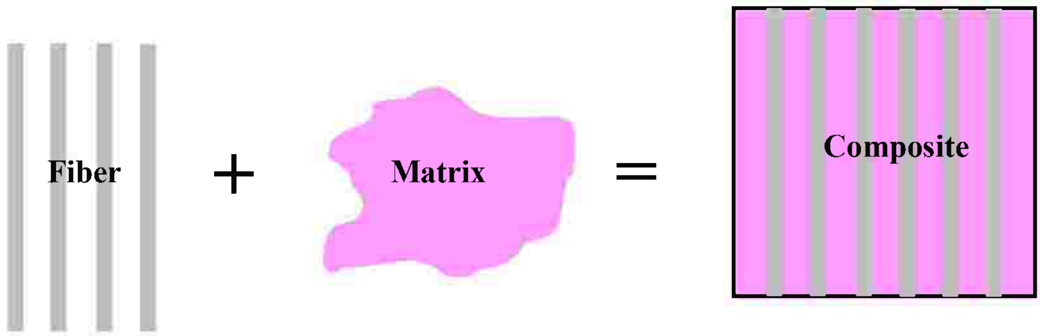


Figure1.2 Formation of a composite material using fibers and resin

1.4.1 Matrix Materials

Although it is undoubtedly true that the high strength of composites is largely due to the fiber reinforcement, the importance of matrix material cannot be underestimated as it provides support for the fibers and assists the fibers in carrying the loads. It also provides stability to the composite material. Resin matrix system acts as a binding agent in a structural component in which the fibers are embedded. When too much resin is used, the part is classified as resin rich. On the other hand if there is too little resin, the part is called resin starved. A resin rich part is more susceptible to cracking due to lack of fiber support, whereas a resin starved part is weaker because of void areas and the fact that fibers are not held together and they are not well supported [3].

1.4.2 Functions of a Matrix

In a composite material, the matrix material serves the following functions [3]:

1. Holds the fibers together.
2. Protects the fibers from environment.
3. Distributes the loads evenly between fibers so that all fibers are subjected to the same amount of strain.
4. Enhances transverse properties of a laminate.
5. Improves impact and fracture resistance of a component.
6. Helps to avoid propagation of crack growth through the fibers by providing alternate failure path along the interface between the fibers and the matrix.
7. Carry interlaminar shear.

1.4.3 Properties of a Matrix

The needs or desired properties of the matrix which are important for a composite structure are as follows [3]:

1. Reduced moisture absorption.
2. Low shrinkage.
3. Low coefficient of thermal expansion.
4. Good flow characteristics so that it penetrates the fiber bundles completely and eliminates voids during the compacting/curing process.
5. Reasonable strength, modulus and elongation (elongation should be greater than fiber).
6. Must be elastic to transfer load to fibers.
7. Strength at elevated temperature (depending on application).
8. Low temperature capability (depending on application).
9. Excellent chemical resistance (depending on application).
10. Should be easily processable into the final composite shape.
11. Dimensional stability (maintains its shape).

1.4.4 General types of Matrix Materials

In general, the types of matrix materials are classified as in the following Figure 1.3 [3]:

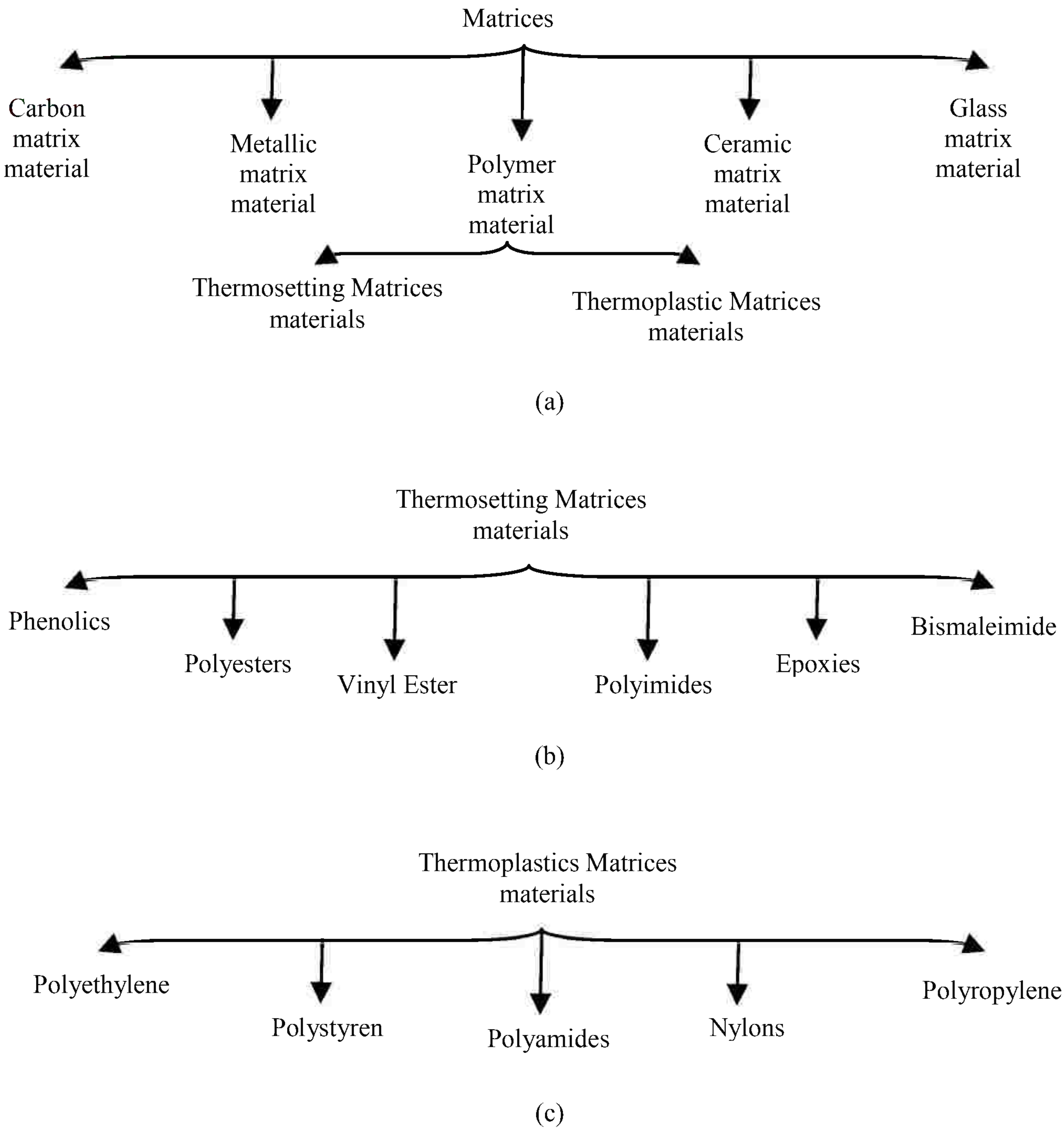


Figure 1.3.Types of matrix materials (a) Classification of matrix materials, (b) Thermosets matrices and (c) Thermoplastics matrices.

1.4.5 Fibers Materials

The fibers can be continuous or discontinuous, woven, unidirectional, bidirectional, or randomly distributed, see Figure 1.4. Unidirectional fiber-reinforced lamina exhibit the highest strength and modulus in the direction of the fibers, but they have very low strength and modulus in the direction transverse to the fibers. A poor bonding between a fiber and matrix results in poor transverse properties and failures in the form of fiber pull out, fiber breakage, and fiber buckling [3].

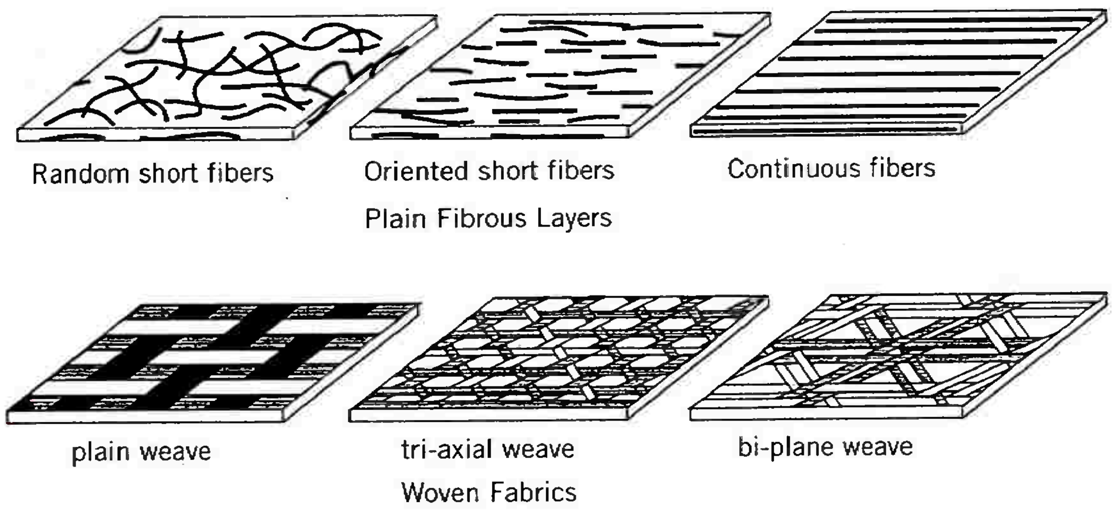


Figure 1.4 Various types of fiber-reinforced composite lamina

1.4.5.1 Functions of Fibers

The main functions of the fibers in a composite are [3]:

1. To carry the load. In a structural composite, 70 to 90 % of the load is carried by fibers
2. To provide stiffness, strength, thermal stability, and other structural properties in the composites
3. To provide electrical conductivity or insulation, depending on the type of fiber used.

1.4.6 General types of Fibers

The main types of fibers:

1. Glass Fibers
2. Carbon Fibers
3. Aramid Fibers
4. Silicon carbide

1.5 The Mechanics Behavior of Composite Materials

Composite materials have many mechanical behavior characteristics that are different from those of more conventional engineering materials. Some characteristics are merely modifications of conventional behavior; others are totally new and require new analytical and experimental procedures. Figure 1.5 shows the mechanical behavior of composite materials [1].

The most common engineering materials are classified according to mechanical behavior to:

1.5.1 Isotropic Material

1. Normal stress causes extension in direction of stress and contraction perpendicular to the stress.
2. Shear stress causes only shear deformation and this deformation is related to tensile properties.

1.5.2 Orthotropic Material

1. Like in isotropic material normal stresses cause only extension in direction of stress and contraction in direction perpendicular to it.
2. Shear stress causes only shear deformation but the shear deformation is not related to the tensile behavior.

1.5.3 Anisotropic Material

1. A normal stress will cause extension, contraction and shear deformation.
2. Off-axis loading of orthotropic materials result in anisotropic behavior.
3. Samples are distorted when pulled making it difficult to measure properties.

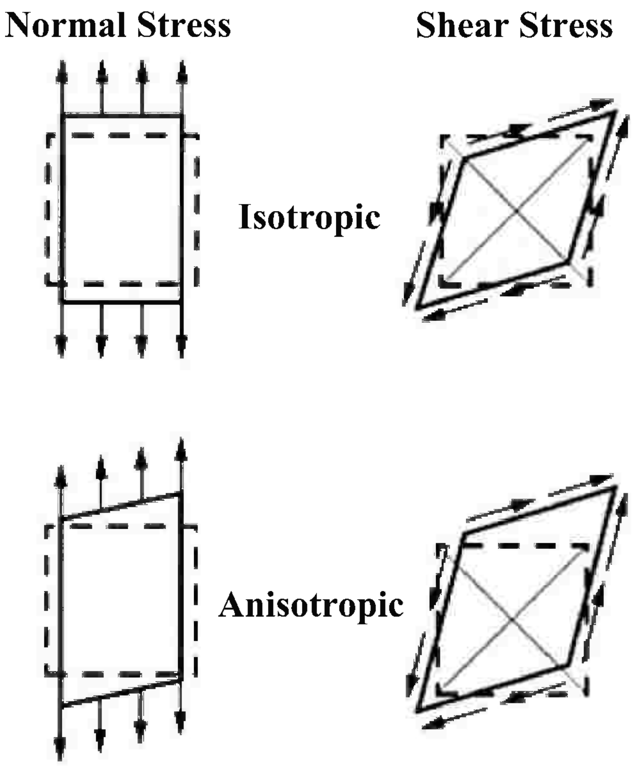


Figure 1.5 The mechanical behavior of composite materials

1.6 Lamina and Laminates

A lamina or ply is a typical sheet of composite material. It represents a fundamental building block. A fiber-reinforced lamina consists of many fibers embedded in a matrix material, which can be a metal like aluminum, or a non-metal like thermoset or thermoplastic polymer. Often, coupling (chemical) agents and fillers are added to improve the bonding between fibers and matrix material and increase toughness. Discontinuous fiber-reinforced composites have lower strength and modulus than continuous fiber-reinforced composites [4].

A laminate is a collection of lamina stacked to achieve the desired stiffness and thickness. For example, unidirectional fiber-reinforced lamina can be stacked so that the fibers in each lamina are oriented in the same or different directions, as shown in Figure 1.6. The sequence of various orientations of a fiber-reinforced composite layer in a laminate is termed the lamination scheme or stacking sequence. The layers are usually bonded together with the same matrix material as that in a lamina.

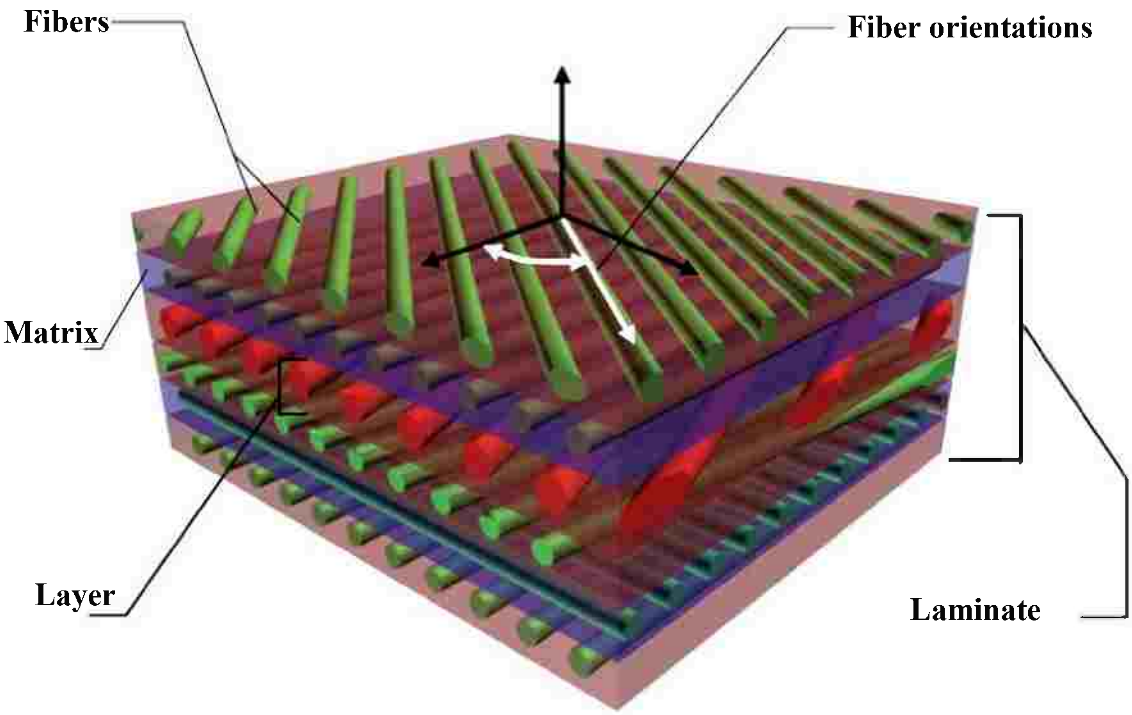


Figure 1.6 A laminate made up of lamina with different fiber orientations [6].

Laminates made of fiber-reinforced composite materials also have disadvantages, because of the mismatch of material properties between layers, the shear stresses produced between the layers, especially at the edges of a laminate, may cause delamination. Similarly, because of the mismatch of material properties between matrix and fiber, fiber debonding may take place. Also, during manufacturing of laminates, material defects such as interlaminar voids, delamination, incorrect orientation, damaged fibers, and variation in thickness may be introduced. It is impossible to eliminate manufacturing defects altogether; therefore, analysis and design methodologies must account for various mechanisms of failure [4].

1.7 Failure Modes of Composite Materials

In composites the main modes of failure can be:

1. Microcracking of the matrix.
2. Debonding (separation of fibers and matrix).
3. Delamination.
4. Breaking of fibers.

Figure 1.7 shows schematically different types of failure leading to damage of a laminate.

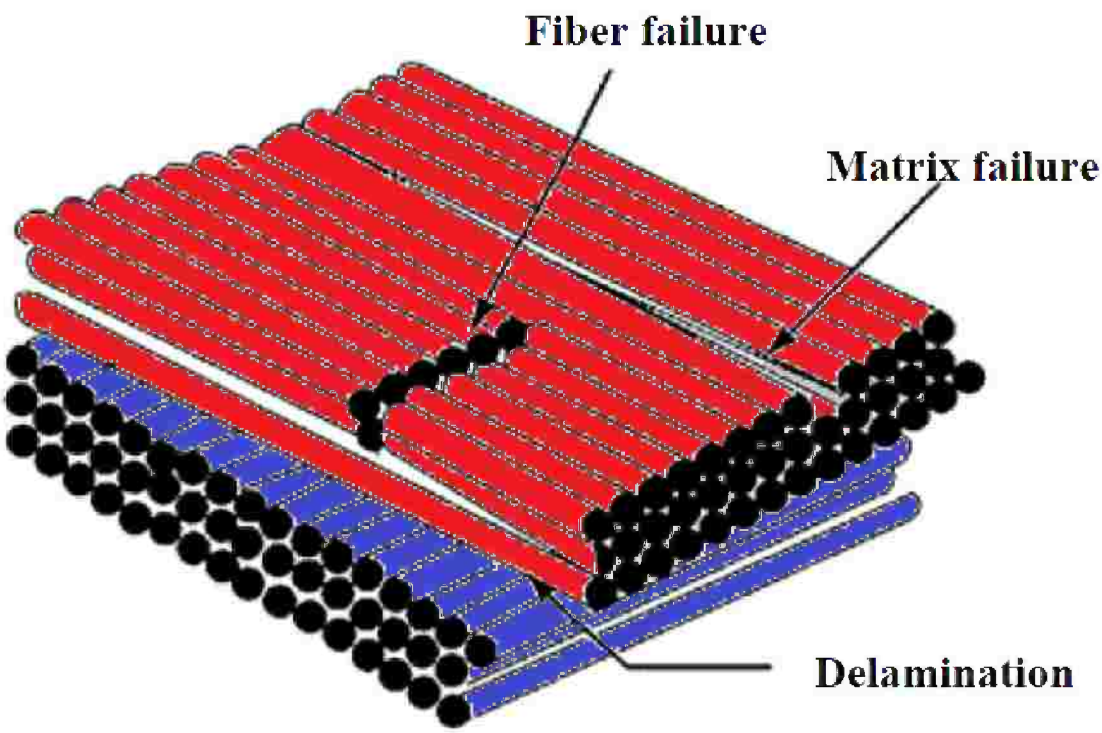


Figure 1.7 Different Modes of Failure

1.7.1 Microcracking of the matrix

The first form of damage in laminates is often matrix micro cracking. They are intralaminar or ply cracks that traverse the thickness of the ply and run parallel to the fibers of the ply. The most common observable micro cracking is cracking in the 90° plies during axial loading in the 0° direction. These micro cracks are transverse to the loading direction and are often termed as the transverse cracks. Micro cracks may be observed during tensile loading, during fatigue loading, during changes in temperature and during thermo cycling. Micro cracks can form in any plies but predominantly they are found implies off axis to the loading axis. The immediate effect of the micro cracks is to cause degradation in the thermo-mechanical properties of the laminate including changes in all effective modules, Poisson's ratio and thermal expansion coefficients. Another detrimental effect of the micro cracks is that they nucleate other forms of damage such as induction of delamination, fiber breakage or provide pathways for the entry of corrosive liquids. Such damage modes may subsequently lead to laminate failure.

The first micro crack causes very little changes in the thermo-mechanical properties of the laminate. Continued loading however normally leads to additional micro cracks and continued degradation in the thermo-mechanical properties [5].

1.7.2 Fiber pull out and Debonding (separation of fibers &matrix)

At some distance ahead of the crack the fibers are intact. In the high stress region near the tip, they are broken, not necessarily along the crack plane. Immediately behind the crack tip fibers pull out of the matrix. In some composites the stress near the crack tip could cause the fibers to debond from the matrix before they break. When brittle fibers are well bonded to a ductile matrix, the fibers tend to snap ahead of the crack tip, leaving bridges of matrix material that neck down and fracture in a completely ductile manner. In addition to these local failure mechanisms, on reaching the interface of the two laminate in a laminated composite, a crack can split and propagate along the interface, thus producing the delamination crack as shown in the Figure 1.8 [5].

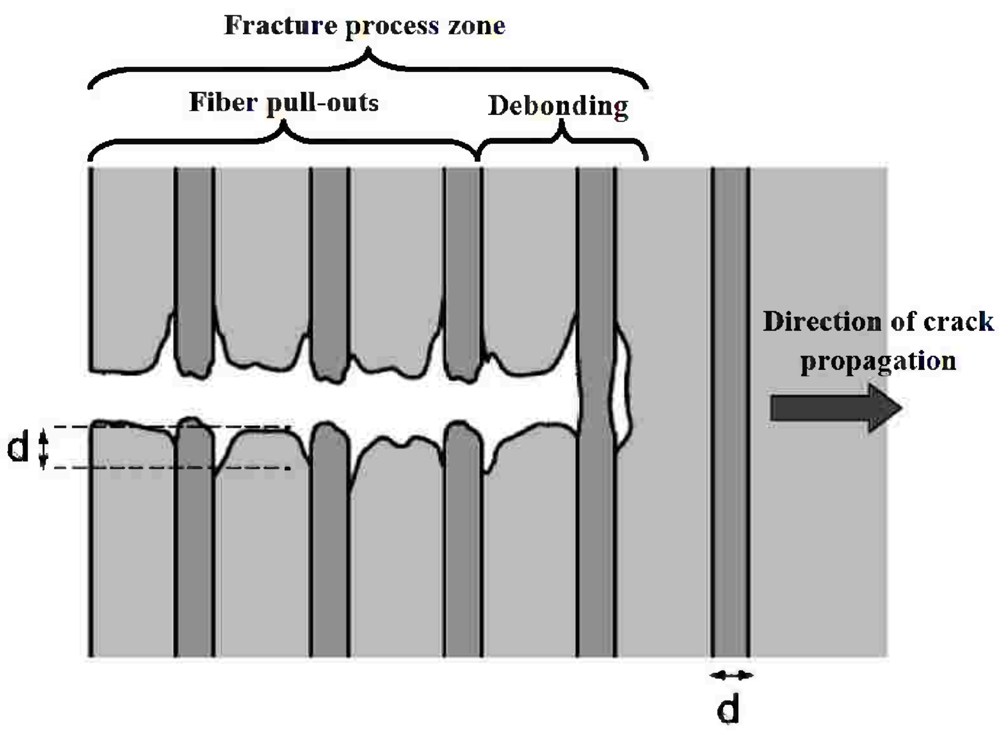


Figure 1.8 Crack tip showing local failure events

1.7.3 Delamination

Delamination is a critical failure mode in composite structures, not necessarily because it will cause the structure to break into two or more pieces, but because it can degrade the laminate to such a degree that it becomes useless in service. The interfacial separation caused by the delamination may lead to premature buckling of the laminate, excessive vibration, intrusion of moisture, stiffness degradation and loss of fatigue life [6]. The delamination though in some cases may provide stress relief and actually enhance the performance of the component.

Delamination may be introduced during processing or in service conditions. It may result from low velocity impact, from eccentricities in the structural load path or from discontinuities in the structures which may induce a large out of plane stress.

Even in the absence of such discontinuities delamination may also result from in plane compressive loading causing global or local buckling.

The delamination may lead to redistribution of stresses which would eventually promote gross failure.

1.7.4 Breaking of fibers

Fiber breakage is the final sequence of the failure mode in composite materials. When it occurs the specimen is considered to have lost its structural integrity before progressing quickly to total failure. Combinations of damage modes spread within laminates until either tensile stress in the fibers exceeds the limiting strength of the glass or macro cracks which have nucleated from combinations of interlaminar and intralaminar cracks grow catastrophically. This is often followed by sudden failure of structure. This type of failure is also sometimes referred to as total structural failure since load can no longer be borne [7].

1.8 Manufacture of Composite Materials

Composites are made available through a variety of different manufacturing processes. The variety in resins, fibers, and core materials will lead to a unique set of properties depending on which combination is used. Ultimately the way the materials are designed in the product and processed also affect the final properties of the composite structure.

Different manufacturing processes will require different types of tooling and will vary in total manufacture cost. The main composite manufacturing processes are [8]:

1.8.1 Open Mold Process

1.8.1.1 Wet Lay-up/Hand Lay-up

Hand Lay-up which is also known as wet lay-up, Figure 1.9, uses fibers in the form of woven, knitted, stitched or bonded fabrics. Once the fibers have been placed in a mould, they are impregnated by hand using rollers or brushes, the laminates then cure under ambient conditions. Any kind of fiber resin can be used in this process as long as it in low in viscosity in order to be workable by hand, and tends to be low on tooling costs [8].

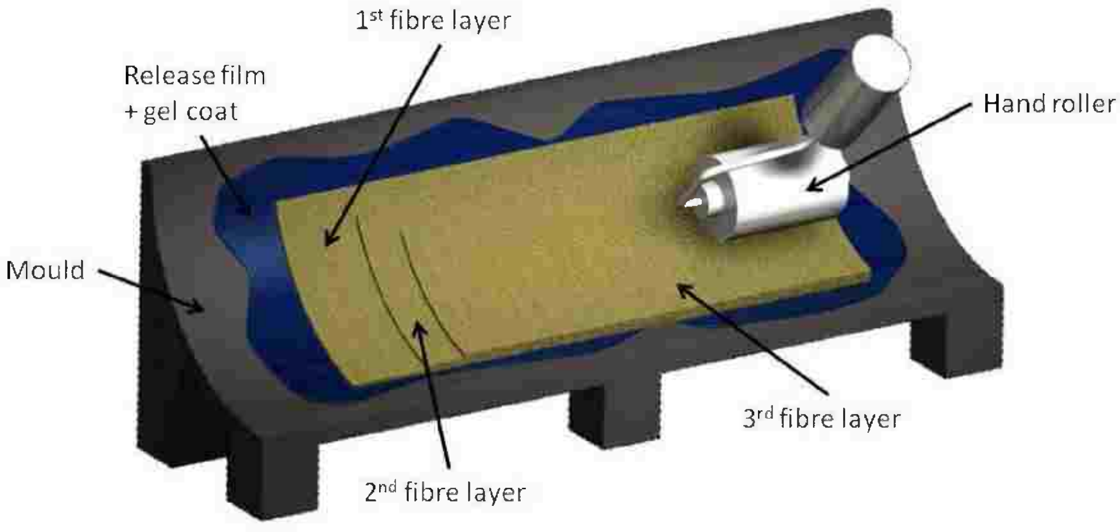
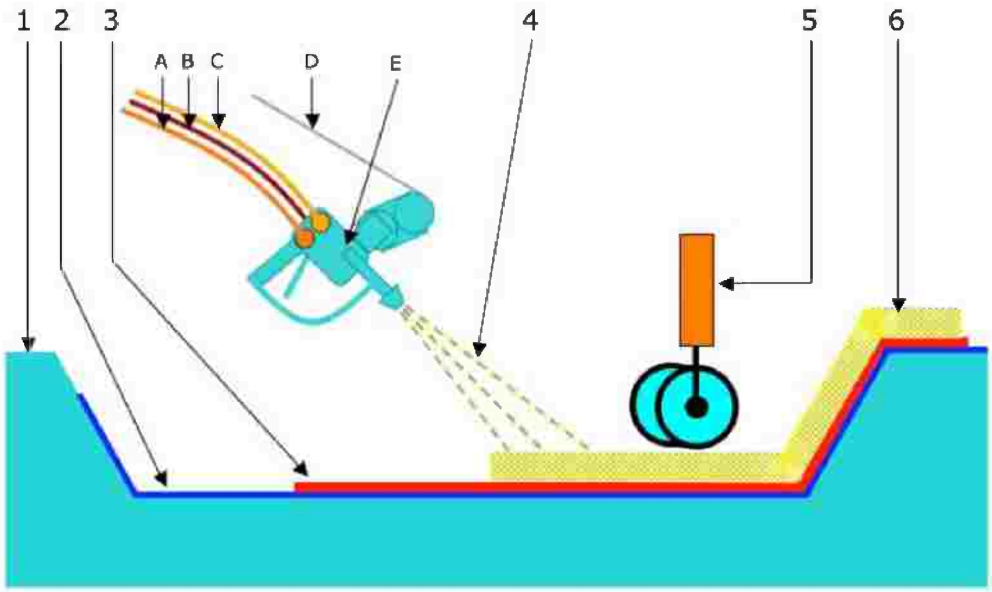


Figure 1.9 Hand lay-up process technique

1.8.1.2 Spray Lay-up

Spray Lay-up, shown in Figure 1.10, which uses a hand held spray gun which shops the fibers and then feeds it into a spray of resin aimed at the mould. The materials then cure under ambient conditions. This process can only make use of glass fibers and since the laminates tend to resin rich it can add extra weight, the resin also needs to be low in viscosity in order to be sprayable [8].



1. Mold Tool.
2. Gel Coat.
3. Laminate.
4. Chopped Spray Gun.
5. Roller.
6. Mixed Resin & Chopped Fiber.

A. Resin.
B. Continuous Strand Roving.
C. Catalyst.
D. Fiber.
E. Chopper.

Figure 1.10 Spray lay-up process technique

1.8.1.3 Filament Winding

Filament winding which is the process where bands of continuous resin impregnated rovings or monofilaments is wrapped around a rotating mandrel and then cured at room temperature or in an oven, Figure 1.11. The mandrel can be cylindrical, round, or any shape that does not have re-entrant curvature. This is generally used for circular or oval sectioned products, where the winding pattern is controlled by the rotational speed of the mandrel and the movement of the fiber feeding mechanism [8].

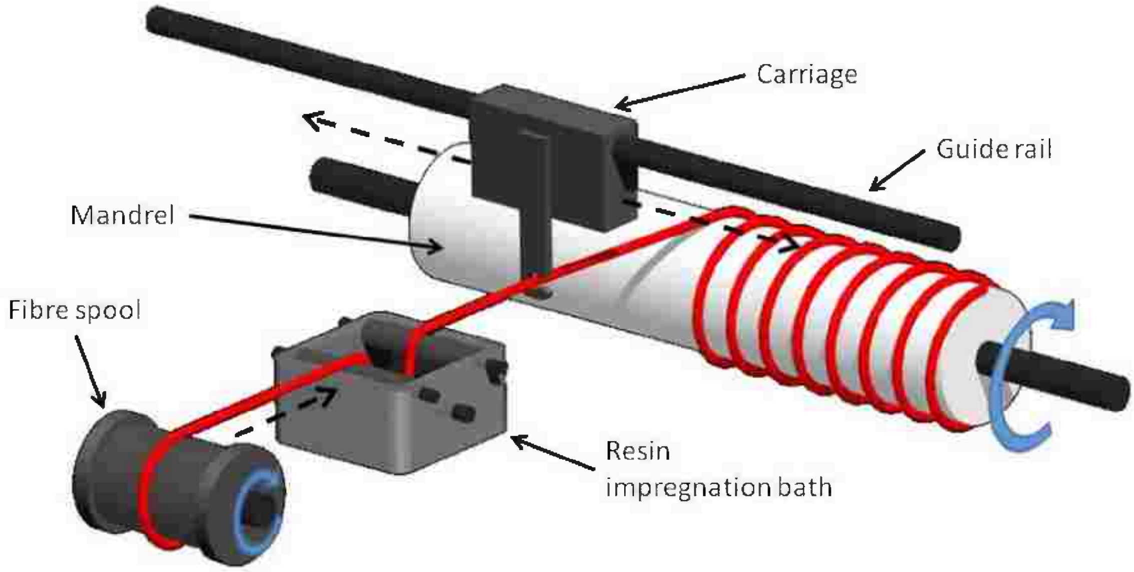


Figure 1.11 Filament Winding process technique

1.8.2 Closed Mold Process

1.8.2.1 Vacuum Bag Processing

Vacuum bagging which is another form of wet lay-up where the consolidation of the laminate is improved by an application of pressure up to 1 Atm., Figure 1.12. A plastic film is sealed over the laminate and onto the mould, the air underneath is extracted by a vacuum pump. Epoxy is primarily used in combination with any kind of fibers. This process tends to be more expensive due to the tooling and labor costs [8].

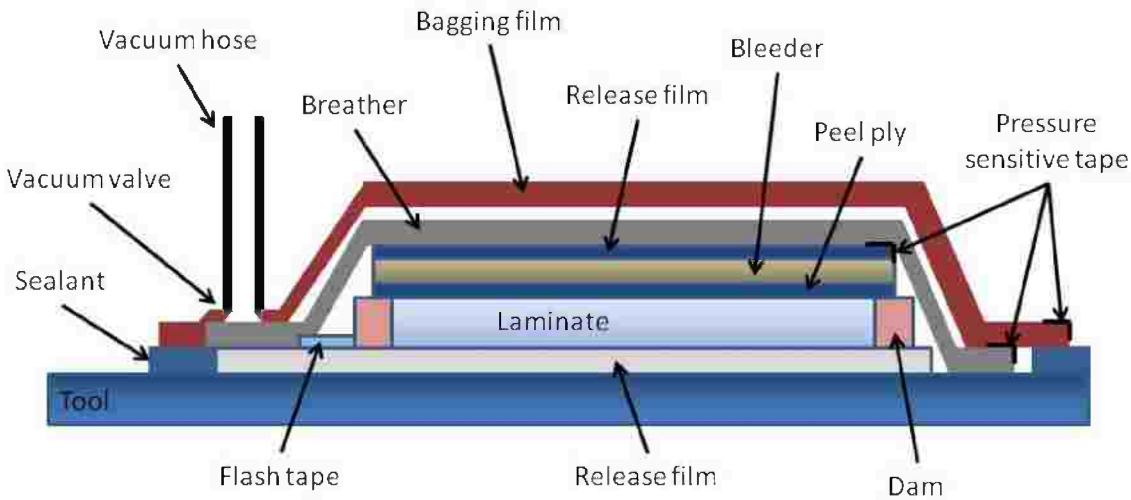


Figure 1.12 Vacuum Bag process technique

1.8.2.2 Injection Molding

With resin injection molding, Figure 1.13, the reinforcements (mats, fabrics) is put in place between the mold and countermold. The resin (Polyester or Epoxy) is injected. The mold pressure is low. This process can produce up to 30 pieces per day. The investment is less costly and has application in automobile bodies [9].

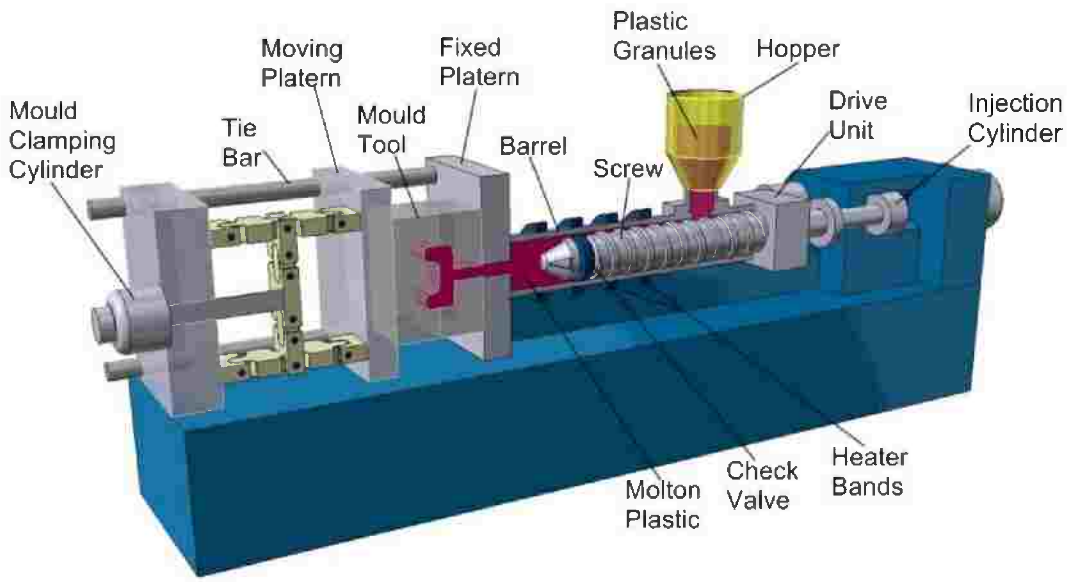


Figure 1.13 Injection Molding process technique

1.8.3 Continuous Processes

1.8.3.1 Pultrusion

Pultrusion in which fibers pulled from a creel through a resin bath then on through a heated die which completes the impregnation of the fiber and controls the resin content to cure the material into its final shape as it passes through the die, Figure 1.14. Pultrusion can process any kind of continuous fiber. Generally used resins are polyester, vinylester and epoxy [8].

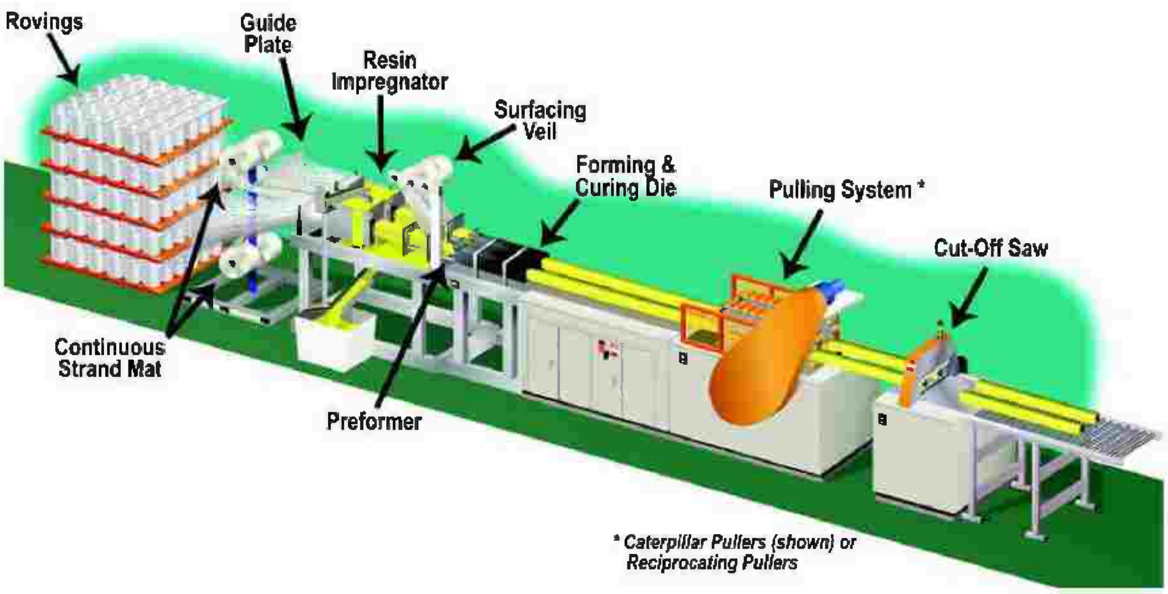


Figure 1.14 Pultrusion process technique

1.9 Applications of composite Materials

Glass fiber-reinforced Epoxy (GFRE) has been successfully employed in many engineering applications, notably in the aerospace, marine, automotive parts, sporting, oil and gas industries and consumer goods. This is due to their attractive physical and mechanical properties, particularly their strength to weight ratio and resistance to fatigue and corrosion [10-13]. Other features such as ease of installation, high durability and low maintenance and life cycle costs make them more desirable than conventional materials such as steel. In addition, due to their anisotropic nature, GFRE can be tailored to specific applications to achieve the highest levels of performance required.

The present work concerns applications in the oil and gas industry, particularly in composite pipelines.

1.9.1 Glass fiber reinforced epoxy (GFRE) pipes

GFRE pipes are usually designed to withstand high pressure. Their lightweight, relatively thick-walled structure provides ease of handling and transportation [11-14], which results in reduced installation costs. Their corrosion resistance properties have led to extensive use in the offshore industry to transport highly corrosive fluids (including seawater, aerated water and hydrocarbons) [11].

One of the reasons GFRE pipes have proliferated recently in the oil and gas industry and for the transportation of corrosive fluids is their excellent mechanical properties. These are highly dependent on the types of resin used, orientation and placement, and also the volume fraction of the glass fiber reinforcement. Unlike metals, which are homogenous and isotropic materials, the GFRE pipe is considered to be orthotropic in nature. The mechanical properties of GFRE pipes are distinct in three mutually perpendicular planes, where the intersection of these planes is known as the principal material axes [7]. This special property permits engineers to design pipes so that they will have greater strength and stiffness in the anticipated load direction. In cases of GFRE pipes for transporting fluids, the ideal fiber orientation angle of $\pm\theta°$ is very important here, just according to the maximum stress is aligned to the direction of the fibers. The mould method of GFRE pipes layers during manufacture is one of major reasons to select the reliable design termination in stress distribution, is investigated in the present work.

However, GFRE pipes have low modulus of elasticity in the hoop direction and particularly in the axial direction. Nevertheless, they show promises in their high strength to weight ratio and stiffness, in addition to other excellent properties such as abrasion, corrosion and chemical resistance. As with stiffness and strength, the thermal behavior of GFRE pipes is also dependent on the characteristics and arrangement of their constituents.

As the use of GFRE pipe increases, so does the need to define reliable design limit in terms of performance. This will provide engineers with basic guidelines to enable GFRE systems to be designed with confidence to a common standard. One of the major challenges concerning the use of GFRE pipe is to predict the onset of first ply damage under combinations of internal pressure and fatigue loading. As has been thoroughly investigated and documented.

The stress-strain behavior of GFRE pipe is initially linear elastic, and followed by non-linearity at later stages close to failure, first by weepage and then ultimately bursting. In earlier investigations, many have explained this non-linear response as a consequence of matrix cracking within plies. As the crack density increases with increasing load, the non-linearity becomes more pronounced at higher loads and is found to correspond to degradation in the mechanical properties of the pipe.

1.10 Advantages and disadvantages of Composite Materials

1.10.1 Advantages of Composite Materials

Summary of the advantages exhibited by composite materials, which are of significant use in tubes and vessels industry are as follows [3]:

1. High resistance to fatigue and corrosion degradation.
2. High 'strength or stiffness to weight' ratio. As enumerated above, weight savings are significant ranging from 25-45% of the weight of conventional metallic designs.
3. Due to greater reliability, there are fewer inspections and structural repairs.
4. Directional tailoring capabilities to meet the design requirements. The fiber pattern can be laid in a manner that will tailor the structure to efficiently sustain the applied loads.
5. Fiber to fiber redundant load path.
6. Improved dent resistance is normally achieved. Composite panels do not sustain damage as easily as thin gage sheet metals.
7. It is easier to achieve smooth aerodynamic profiles for drag reduction. Complex double-curvature parts with a smooth surface finish can be made in one manufacturing operation.
8. Composites offer improved torsional stiffness. This implies high whirling speeds, reduced number of intermediate bearings and supporting structural elements. The overall part count and manufacturing and assembly costs are thus reduced.
9. High resistance to impact damage.
10. Thermoplastics have rapid process cycles, making them attractive for high volume commercial applications that traditionally have been the domain of sheet metals. Moreover, thermoplastics can also be reformed.
11. Like metals, thermoplastics have indefinite shelf life.
12. Composites are dimensionally stable i.e. they have low thermal conductivity and low coefficient of thermal expansion. Composite materials can be tailored to comply with a broad range of thermal expansion design requirements and to minimize thermal stresses.
13. Manufacture and assembly are simplified because of part integration (joint/fastener reduction) thereby reducing cost.
14. The improved weatherability of composites in a marine environment as well as their corrosion resistance and durability reduce the down time for maintenance.

15. Close tolerances can be achieved without machining.
16. Material is reduced because composite parts and structures are frequently built to shape rather than machined to the required configuration, as is common in metals.
17. Excellent heat sink properties of composites, especially Carbon-Carbon, combined with their lightweight have extended their use for aircraft brakes.
18. Improved friction and wear properties.
19. The ability to tailor the basic material properties of a Laminate has allowed new approaches to the design of tubes.

The above advantages translate not only into tubes and vessels, but also into common implements and equipments such as air ducts that have inherent damping, and causes less fatigue and pain to the user.

1.10.2 Disadvantages of Composite Materials

Some of the associated disadvantages of advanced composites are as follows [3]:

1. High cost of raw materials and fabrication.
2. Composites are more brittle than wrought metals and thus are more easily damaged.
3. Transverse properties may be weak.
4. Matrix is weak, therefore, low toughness.
5. Re-use and disposal may be difficult.
6. Difficult to attach.
7. Repair introduces new problems, for the following reasons:
   - Materials require refrigerated transport and storage and have limited shelf life.
   - Hot curing is necessary in many cases requiring special tooling.
   - Hot or cold curing takes time.
8. Analysis is difficult.
9. Matrix is subject to environmental degradation.

However, proper design and material selection can circumvent many of the above disadvantages.