

1.1 Introduction

The requirement of lightweight structures in aerospace and automotive industries has inspired the engineers for the development of new materials without compromising on the structural integrity and reliability of such structures. There has been a significant increase in the use of advanced composite materials in lightweight structures now-a-days. The last two decades have observed a revolutionary attempt in modifying and implementing new methodologies and design concepts resulting in enhanced and successful implementation of laminated FRP composites in almost all areas, thereby gradually substituting traditional monolithic materials. It is oblivion to mention new areas of biomechanics; human body parts implantations, applications in nanotechnology areas etc. Still, there are several inhibiting factors, which have delayed the widespread use of composites in aircrafts, military armaments and spaceships, where the potential for weight reduction is at a premium. This is ascribed to the complex multi-mode failures in composites and the inherent anisotropic unpredictability, damage tolerance, sensitivity to 3D stresses and out-of-plane short duration loadings apart from the different stress strain behaviour in tension and compression and the residual thermal stresses induced during manufacturing stages of co-cured composites.

Composites with inherent flaws, discontinuities and delaminations or cracks behave in a different way in comparison to metals or alloys. In addition to it, such environmental or manufacturing induced effects as hygrothermal or residual stresses have a pronounced effect on the damage characteristics of laminated composite structures. The use of co-cured, co-bonded, or secondary bonded subcomponents and ease of manufacturing as a single

component for critical dimensioned and shaped assembly parts not only offers the possibility of a significantly lighter structure but also reduces production costs. However, in spite of all these advantages, composites have relatively low through-thickness (out-of-plane transverse) strength and susceptibility of bimodularity elastic property, which makes their analysis much involved in comparison to monolithic materials. Especially the later behaviour is ignored to simplify the design analysis based on classical assumptions.

Therefore, multimode real structure loadings, high shear or peeling stresses can cause delamination, which may subsequently propagate in an unstable fashion inflicting catastrophic failure of composite structural system. The analysis and design of structures made of such materials necessitates detailed understanding of their behavior for the development of appropriate design, analysis, fabrication and manufacturing techniques.

1.2 Composites and laminated structures

A composite material is having two or more constituent materials with significantly different physical or chemical properties that, when assembled, yield a material with characteristics dissimilar from the individual components. The individual components remain discrete and distinct within the finished structure. The new material or composite is stronger, lighter, and less expensive when compared to traditional materials. The harnessing of tailored properties of laminated fiber reinforced composites has seen their potential applications in such diversified fields as aerospace and avionics, buildings, bridges, and structures such as boat hulls, swimming pool panels, race car bodies, shower stalls, bathtubs, storage tanks, imitation granite, cultured marble sinks and countertops, automotive, marine, sporting goods, biomedical sciences, electronics and defense.

Composites are made up of individual materials known as constituent materials (Figure 1.1). The constituent materials include matrix, reinforcement and interface (or fillers). At least one portion of each constituent is needed. The matrix material surrounds and supports the reinforcement materials by maintaining their relative positions whereas the reinforcements spread their special mechanical and physical properties to intensify the matrix properties. Specific fillers, additives and core materials are also sometimes added to enhance and modify the final product. When fiber is used as reinforcement, composite is known as fiber composite. Fiber Reinforced Composite (FRC) is high-performance fiber composite achieved and made possible by cross-linking cellulosic fiber molecules with resins in the FRC material matrix through a proprietary molecular re-engineering process, yielding a product of exceptional structural properties.

Composite laminates are the assembly of layers of fibrous composite materials, as shown in Figure 1.2, which can be attached to furnish required engineering properties, in-plane stiffness, bending stiffness, strength, and coefficient of thermal expansion. The individual layer composed of high-modulus, high-strength fibers in a polymeric, metallic, or ceramic matrix material. Typical fibers usually include graphite, glass, boron, and silicon carbide, and matrix materials are epoxies, polyimides, aluminium, titanium, and alumina.

The reinforcement phase of a composite may be in the form of continuous or short fibers, particles of various shapes, and whiskers. It contributes to or determines the composite stiffness and strength. A large variety of fibers are available as reinforcement for composites. The desirable characteristics of most reinforcing fibers are high strength, high stiffness, and relatively low density. Different types of fiber with its advantages and disadvantages are listed in Table 1.1.

Carbon fibers are the most widely used for advanced composites because of its high stiffness and strength. The precursor fibers are initially drawn and oxidized under tension in air at temperatures between 200°C (400°F) and 315°C (600°F). Then, they are carbonized by pyrolysis at a temperature above 800°C (1500°F) in a nitrogen atmosphere. At this stage most fibers undergo surface treatment and sizing for use in composites manufacturing. This process yields high strength and high stiffness carbon fibers (AS4, T300, IM6, IM7). Graphite fibers, a subset of carbon fibers, are produced by further processing at temperatures above 2000°C (3600°F).

Epoxies of DGEBA type (diglycidyl ether of bisphenol A) has better mechanical and thermal properties. High temperature epoxies are cured at temperature around 175 °C to 200 °C. Typically Polyimide matrices are used for high temperature application around 370 °C. Advanced nano-impinged epoxy composites can withstand in excess of that for high temperature turbine applications. The numerical illustrations therefore consider the difference of temperature from cure state to room temperature and the procedure can be extended to metal matrices and carbon matrices with application temperature in excess of 800 °C to 1000 °C.

The individual layers are mostly orthotropic or transversely isotropic with the laminate then exhibiting anisotropic, orthotropic, or quasi-isotropic properties. Quasi-isotropic laminates display isotropic inplane response but are not restricted to isotropic out-of-plane (bending) response. Depending upon the stacking sequence of the individual layers, the laminate may show coupling between inplane and out-of-plane response.

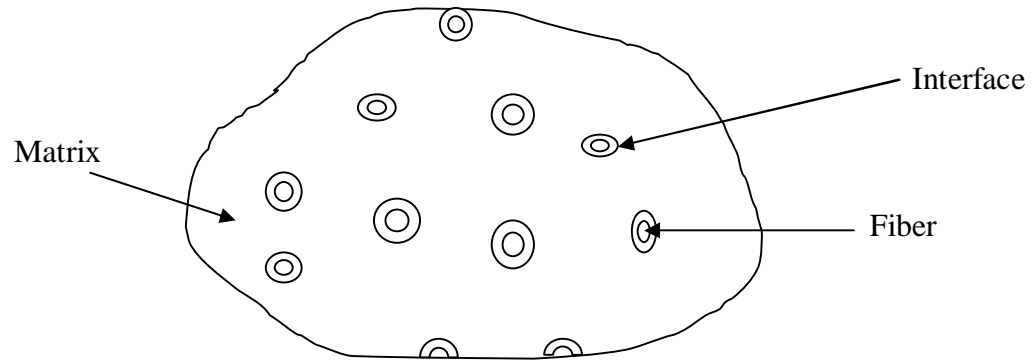


Figure 1.1 Constituents of composite

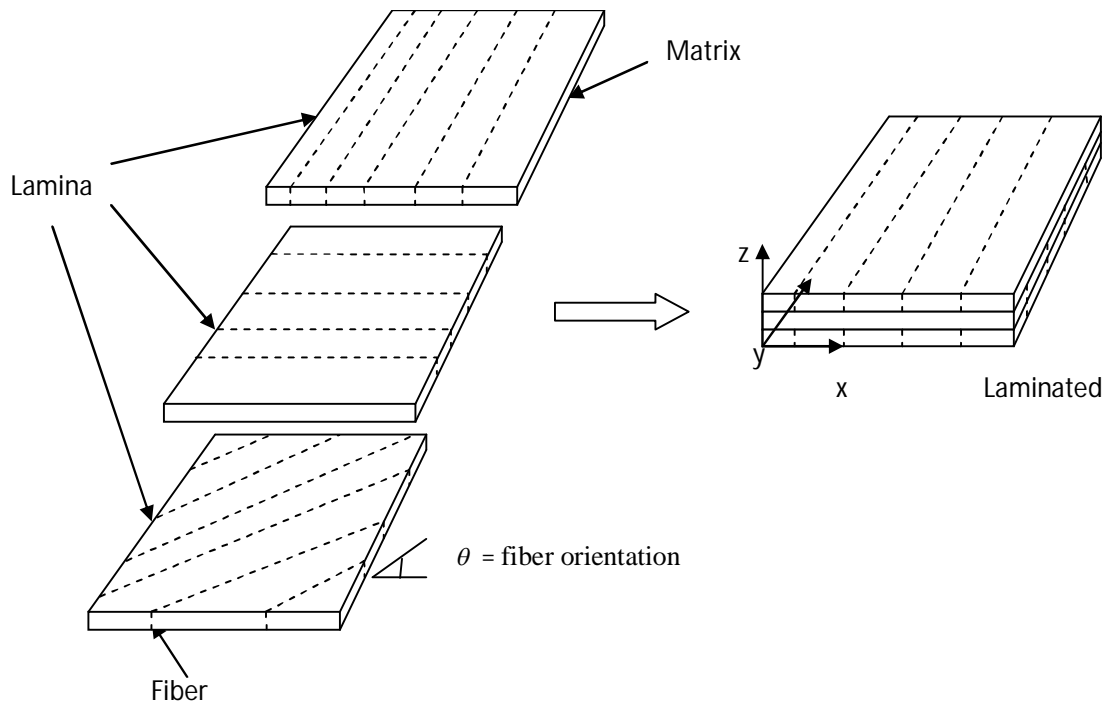


Figure 1.2 Laminated composite material

Table 1.1 Advantages and disadvantages of reinforcing fibers

Fiber	Advantage	Disadvantage
Aramid (Kevlar)	High tensile strength Low density	Low compressive strength High moisture absorption
Boron	High stiffness High compressive strength	High cost

Carbon (AS4, T300, IM7)	High strength High stiffness	Moderately high cost
Ceramic (Silicon carbide, alumina)	High stiffness High use temperature	Low strength High cost
E-glass, S-glass	High strength Low cost	Low stiffness Short fatigue life High temperature sensitivity
Graphite (GY-70, pitch)	Very high stiffness	Low strength High cost

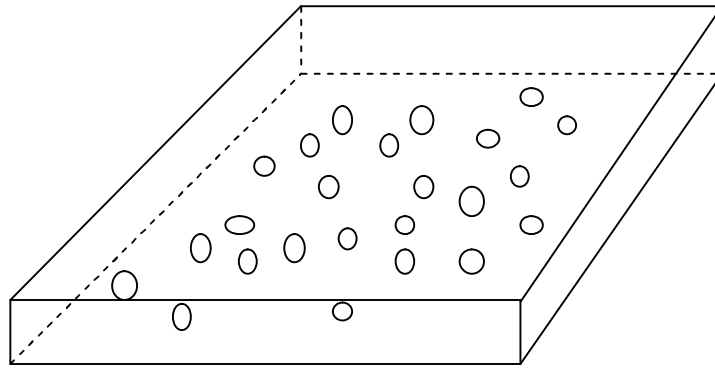
1.3 Classification of composite

Composites are classified according to the geometry of the reinforcement — particulate, flake, and fibers (Figure 1.3) — or by the type of matrix — polymer, metal, ceramic, and carbon [1].

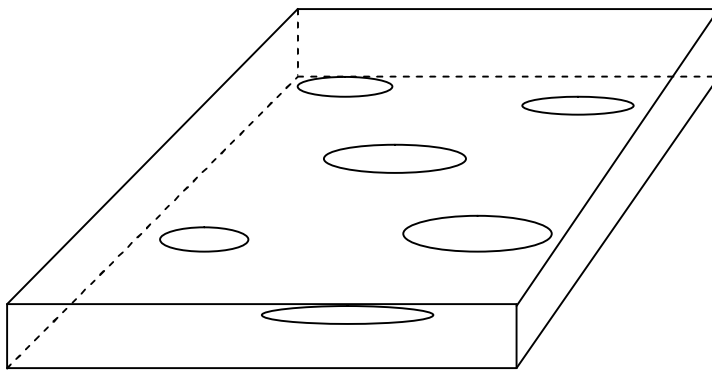
- *Particulate* composites are made up of particles immersed in matrices such as alloys and ceramics. They are generally isotropic because the particles are added randomly. These composites have advantages such as improved strength, increased operating temperature, oxidation resistance, etc. Typical examples include use of aluminum particles in rubber; silicon carbide particles in aluminum; and gravel, sand, and cement to make concrete.
- *Flake* composites composed of flat reinforcements of matrices. Typical flake materials are glass, mica, aluminum, and silver. These composites provide advantages such as high out-of-plane flexural modulus, higher strength, and low cost. However, flakes cannot be oriented easily and only a limited number of materials are available for use.
- *Fiber* composites comprise of matrices reinforced by short (discontinuous) or long (continuous) fibers. Fibers are usually anisotropic and examples are carbon and aramids. Examples of matrices are resins such as epoxy, metals such as aluminum, and ceramics

such as calcium–alumino silicate. The fundamental units of continuous fiber matrix composite are unidirectional or woven fiber laminas. Laminas are stacked on top of each other at various angles to form a multidirectional laminate.

- *Nanocomposites* are the materials that are the scale of nanometers (10^{-9} m). The accepted range to be classified as a nanocomposite is that one of the constituents is less than 100 nm.



(a)



(b)

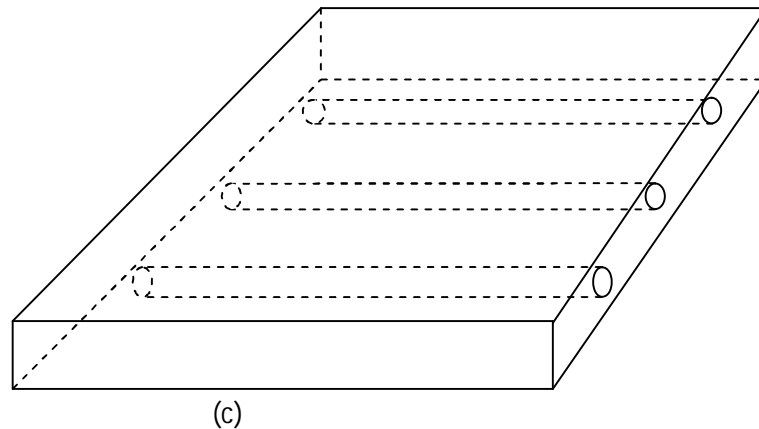


Figure 1.3 Types of composites: (a) Particulate composite (b) Flake composite (c) Fiber Composite.

1.4 Mechanics of composites

As such the study of laminated composites follows the procedures of either a micromechanics, or even a ply-mechanics or macromechanics analysis [2,3].

Micromechanics

- The study of composite material behavior where the interactions of constituent material is examined in detail.
- The formulations describing the thermal and mechanical characteristics are generally based on the interaction of constituent materials in a microscopic level emphasizing the heterogeneity of the material system.
- In micromechanics, the material properties have been obtained with the volume fraction of constituents for a composite ply from matrix and fiber properties.

Ply mechanics considers average material properties for a single ply with any fiber orientation angle. The strain and deformation continuity assumptions in ply mechanics study dictate the constitutive formulations of an intact ply [4]. As delineated in Figure 1.4,

the micromechanics and macromechanics are different analysis domains for characterizing the behavior of Fiber Reinforced Polymeric (FRP) composite structures.

Macromechanics

- The study of composite material behavior where material is supposed to be homogeneous and to obtain the average apparent properties of the material.
- In macromechanics, several plies have been put together in order to access stresses and strains within each ply when a composite laminate is subject to force or displacement boundary conditions.

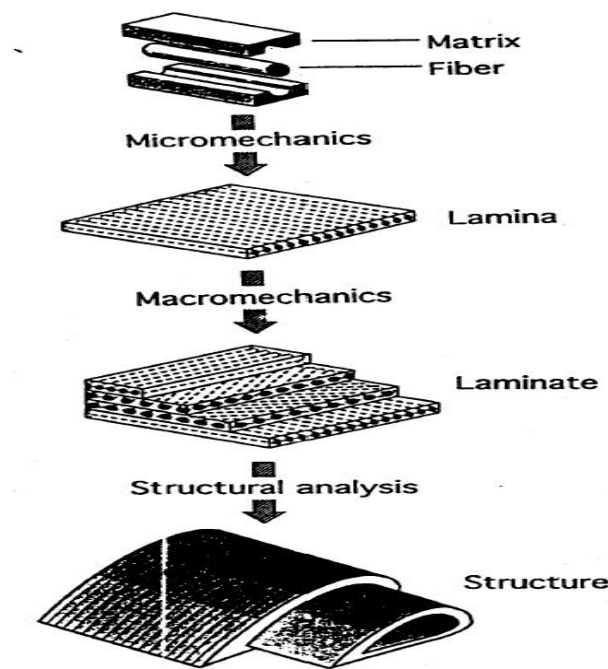


Figure 1.4 Schematic of Laminate construction and analysis methods [4].

1.5 Material system of typical aerospace structure

Modern aviation, both military and civil, is a prime example of application of composites. In fact, these industries require light and strong materials which are the main driving force for the development of composites. It is custom now to find wing and tail sections, propellers and rotor blades made from advanced composites, along with much of the internal structure and fittings (Figure 1.5). The airframes of some smaller aircraft are made entirely from composites, as are the wing, tail and body panels of large commercial aircraft. When the specific modulus and specific strength of graphite/epoxy composite has been compared with steel and aluminum alloy, it has been found that both values are high for composite which is the required property for aerospace structures and this is the one of the main reason of replacing the composites with other material system in aircraft (Table 1.2).

Table 1.2 Specific modulus and specific strength of different materials

Mechanical Properties	Steel (ASTM A 36 steel)	Aluminum alloy (7075 T6)	Graphite/epoxy (IM7/977-3)
Density (kg/m ³)	8050	2800	1779
Young's Modulus (GPa)	200	71.7	127.5
Tensile Strength (MPa)	400	570	1870
Specific Modulus	0.0248	0.0253	0.0716
Specific Strength	0.0496	0.2035	1.05

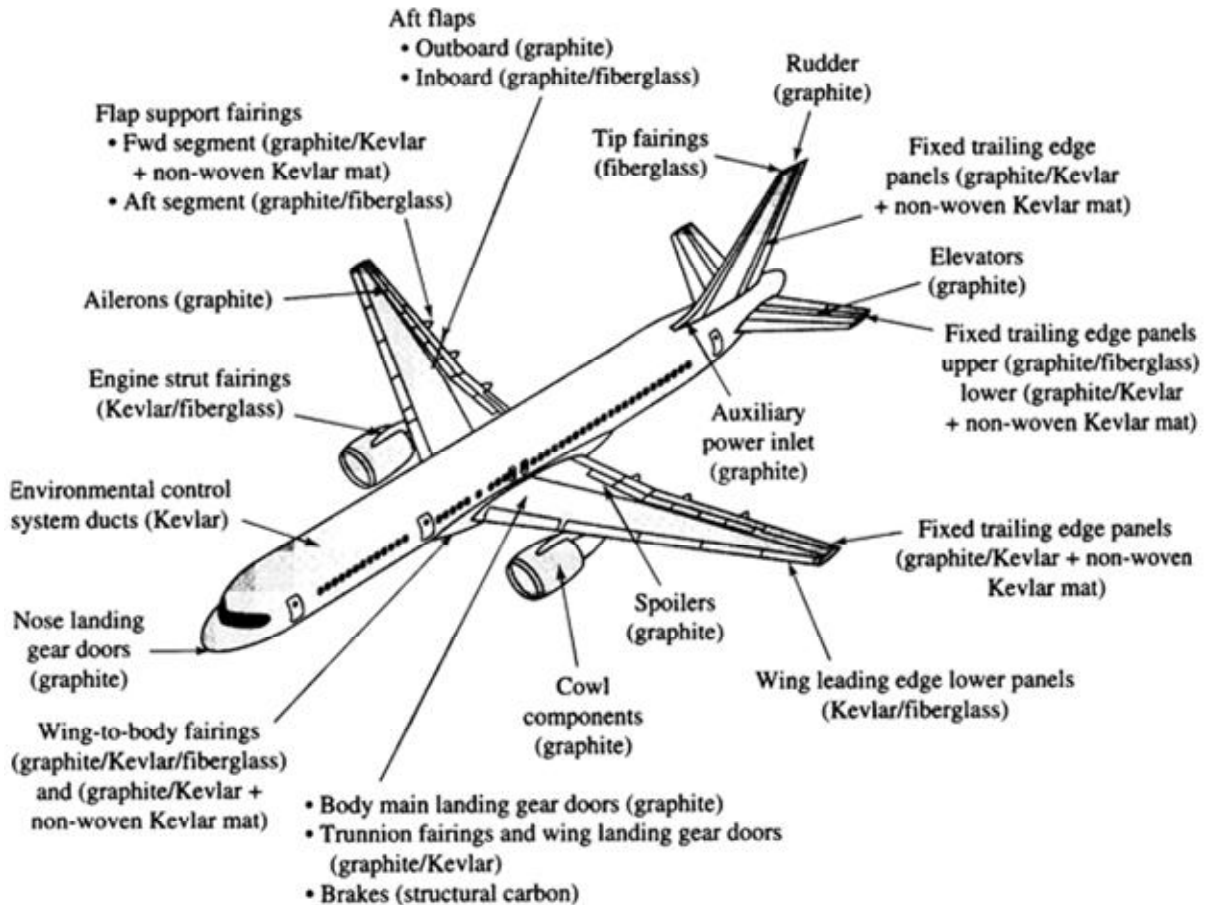


Figure 1.5 List of Composite parts in the main structure of the boeing 757-200 aircraft
(Source: Boeing commercial Airplane company)

1.6 Graphite-epoxy laminated composite

In case of graphite-epoxy laminated composite, graphite is the fiber and epoxy acts as matrix which helps in binding the fiber.

1.6.1 Graphite

Graphite is usually an allotrope of carbon. Graphite is the most stable form of carbon under normal conditions. It has a planar, layered structure. In each layer, the carbon atoms are arranged in a hexagonal lattice with space of 0.142 nm, and the distance between planes is 0.335 nm. There are two common forms of graphite, i.e., alpha (hexagonal) and beta (rhombohedral). They have almost similar physical properties (except that

the graphene layers stack slightly differently). The structure of hexagonal graphite is generally flat or buckled. The alpha form can be transformed into the beta form by means of mechanical treatment and the beta form reverts to the alpha form when it is heated above 1300⁰C. The graphite has lower density due to its layered structure.

There is a sheet like structure of graphite where the atoms lie in a plane and are only weakly bonded to the graphite sheets above and below. Also, graphite is opaque and metallic-to earthy looking and it is very soft. The carbon-carbon bonds are actually quite strong. It is electrically conductive due to the vast electron delocalization within the carbon layers. These valence electrons are free to move, which makes it conductive. However, the electricity is basically conducted within the plane of the layers. The conductive properties of powdered graphite allowed its use as a semiconductor substitute in early carbon microphones. Also, it is non-toxic in nature.

1.6.2 Types of graphite

There are two main classifications of graphite, i.e., natural and synthetic.

1.6.2.1 Natural Graphite

Natural Graphite is a mineral consists of graphitic carbon. It varies considerably in crystalline form. Most commercial (natural) graphites are mined and usually contain other mineral. There are three principal types of natural graphite, each occurring in different types of ore deposit:

- Crystalline flake graphite (or flake graphite) exists as isolated, flat, plate-like particles with hexagonal edges if unbroken and when broken the edges can be irregular or angular.

- Amorphous graphite is a very fine flake graphite and also known as amorphous in the trade.
- Lump graphite (or vein graphite) exists in fissure veins or fractures and appears as massive platy intergrowths of fibrous or acicular crystalline aggregates, and is probably hydrothermal in origin.

1.6.2.2 Synthetic graphite

These fibers are manufactured synthetically. So, they show superior qualities than the natural fibers. But, synthetic fibers are not bio-degradable and therefore, a threat to the environment pollution.

1.6.3 Key properties of graphite

The general properties of commercial graphite are specified in Table 1.3.

Table 1.3 Properties of graphite

Property	Commercial Graphite
Bulk Density (g/cm ³)	1.3-1.95
Porosity (%)	0.7-53
Modulus of Elasticity (GPa)	8-15
Compressive strength (MPa)	20-200
Flexural strength (MPa)	6.9-100
Coefficient of Thermal Expansion (x10 ⁻⁶ °C)	1.2-8.2
Thermal conductivity (W/m.K)	25-470
Specific heat capacity (J/kg.K)	710-830
Electrical resistivity (Ω.m)	5x10 ⁻⁶ -30x10 ⁻⁶

Another most important property of graphite is bimodularity. According to Classical Elasticity Theory, it is assumed that materials have the same elastic properties in tension and compression, but this interpretation is only for simplicity and it does not account for material non-linearity. Studies have indicated that material such as concrete, ceramics, graphite, and some composites, show different tensile and compressive strains even when the same stress is applied in tension or compression. The materials which exhibit different elastic moduli in tension and compression (E_T and E_C respectively) are known as *bimodular materials* [5]. Certain polymers, composites and a group of graphites are categorized as bimodulus material. The linearized constitutive model as replicated in Figure 1.6 simplifies the tension-compression stress strain plots into two straight lines, whose tangents at the origin are discontinuous.

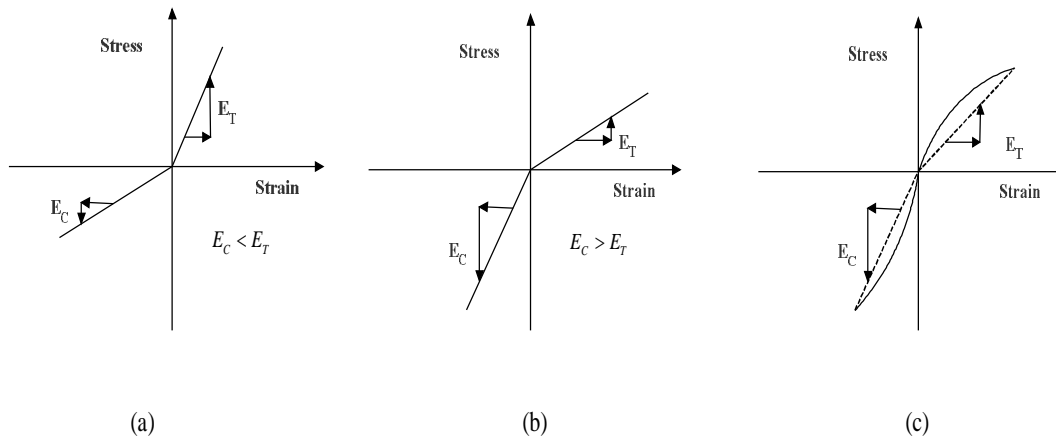


Figure 1.6 Bimodular constitutive model for (a) bilinear model when $E_T > E_C$ (b) bilinear model when $E_T < E_C$ and (c) non-linear model for actual condition

1.6.4 Applications

Initially graphite is mainly used in the steel industry in the form of liner for ladles and crucibles, as a component in bricks which line furnaces (refractories), and as an agent to

enhance the carbon content of steel. In the automotive industry it is applied in brake linings, gaskets and clutch materials. It also has a myriad of other uses in batteries, thermal management in consumer electronics, lubricants, fire retardants, and reinforcements in plastics. Other applications in different industries are as follows:

- Refractory materials
- Chemical industries
- Nuclear industries
- Electrical applications
- Mechanical applications

1.6.5 Epoxy

Epoxy is a thermosetting resin has an ability of forming tight cross-linked polymer structures having properties like toughness, strong adhesion and low shrinkage, used primarily in surface coating and adhesives. Epoxy resins may be cross-linked either with themselves through catalytic homopolymerisation, or with a wide range of co-reactants such as polyfunctional amines, acids (and acid anhydrides), phenols, alcohols and thiols. Reaction of polyepoxides with themselves or with polyfunctional hardeners creates a thermosetting polymer, often with high mechanical properties, temperature and chemical resistance. The various applications of epoxy are in metal coatings, electronics / electrical components/LED, high tension electrical insulators, paint brushes manufacturing, fiber-reinforced plastic materials and structural adhesives.

1.7 Adhesively bonded joints

A permanent joint with the help of adhesive between parts of machines, building structures, furniture, and products of light industry. It can hold together various materials, including

materials of different types, by providing uniform distribution of stresses. Bonded joints are used in the fabrication of articles from steel, aluminum, brass, glass, plywood, wood, cloth, plastic, cured rubber, and other materials that can be joined in various combinations. The advantages of adhesively bonded joints over other mechanical joints are small stress concentration in adherends, stiff connection, excellent fatigue properties, no fretting problems, sealed against corrosion, smooth surface contour, relatively lightweight and damage tolerant. Some disadvantages are limits to thickness that can be joined with simple joint configuration, inspection other than for gross flaws difficult, prone to environmental degradation, sensitive to peel and through-thickness stresses, residual stress problems when joining to metals, cannot be disassembled, may require costly tooling and facilities and requires high degree of quality control.

1.8 Adhesive and adhesion

Adhesion is the tendency of clinging the dissimilar particles or surfaces to one another. Adhesive is a substance that put on one surface, or both surfaces, of two separate items that binds them together and resists their separation. The adhesive has an ability to stick different materials together, to distribute stress more efficiently across the joint, the cost effectiveness of an easily mechanized process, an improvement in aesthetic design, and increased design flexibility. The disadvantages of adhesive application involve decreased stability at high temperatures, relative weakness in bonding large objects with a small bonding surface area, and greater difficulty in separating objects during testing. Adhesion, a process of attaching adhesive and substrate, may happen either by mechanical means, in which the adhesive works its way into small pores of the substrate, or by one of several chemical mechanisms. Figures 1.7 and 1.8 show the various zones of the adhesive joints.

The use of adhesively bonded joint technology has been growing in many structural components to improve the joint performance due to inherent advantages. Adhesively bonding techniques have been widely used due to its ability to distribute a load over a larger area. It has also found a good place in joining advanced composite materials. These joints are typical type of connections and are commonly used in many structural applications such as in skin stiffened panel of aerospace structures, ship hulls of marine machineries, etc.

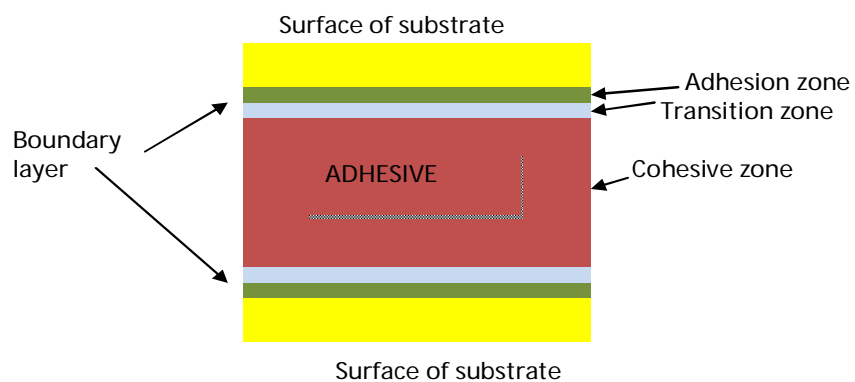


Figure 1.7 Cross-section of a bond

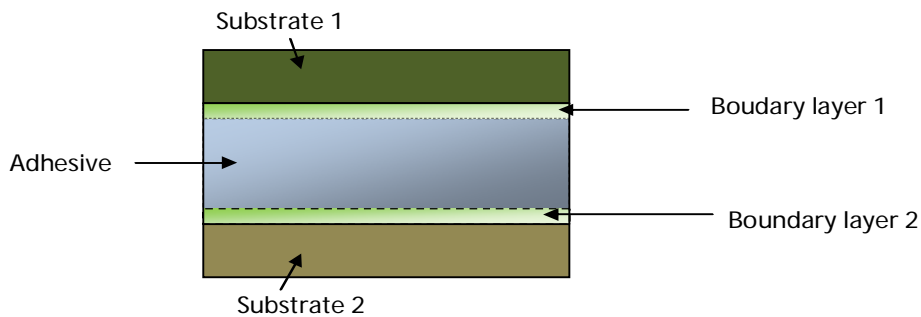


Figure 1.8 Structure of adhesive joint

1.8.1 Failure of adhesive joints

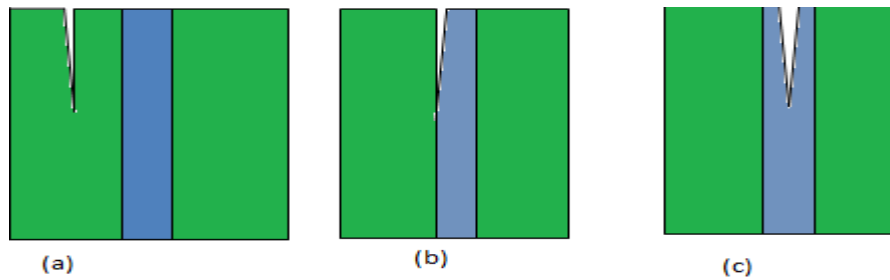


Figure 1.9 Failure mechanism of adhesive bonding (a) Structural failure (b) adhesive failure (c) Cohesive failure

There are several reasons that initiate and enhance the failure of two adhered surfaces. Sunlight and heat may weaken the adhesive. Solvents can also deteriorate or dissolve adhesive. Physical stresses are the main cause of the separation of surfaces. When subjected to loading, debonding may take place at different locations in the adhesive joint. The various failure mechanism of adhesive bonding is described in Figure 1.9. The major fracture types are the following:

(a) Adhesive fracture

Adhesive fracture or interfacial fracture is happened when debonding occurs between the adhesive and the adherend. In most of the cases, the appearance of adhesive fracture for a given adhesive goes along with smaller fracture toughness.

(b) Cohesive fracture

Cohesive fracture is occurred when the crack enhances in the bulk polymer which constitutes the adhesive. In this type of fracture, the surfaces of both adherends after debonding will be covered by fractured adhesive. The crack may proceed in the center of the layer or near an interface.

(c) Other types of fracture

Other types of fracture include:

- The mixed type involves the crack propagation at some portion in a cohesive and in others in an interfacial manner. Mixed fracture surfaces can be described by a certain percentage of adhesive and cohesive areas.
- The alternating crack path type happens when the cracks jump from one interface to the other. This type of fracture occurs when there are tensile pre-stresses in the adhesive layer.
- Fracture can also occur in the adherend when the adhesive is tougher than the adherend. In this particular case, the adhesive remains intact and is still bonded to one substrate and remnants of the other. For example, on removing a price label, the adhesive usually remains on the label and the surface. This is cohesive failure.

Different modes of failures are as follow:

- matrix cracking
- fiber fracture
- debonding or interface failure
- delamination or interlayer failure
- fiber pullout
- micro-buckling
- kink bands
- cone of fracture

Laminated fiber-reinforced composites typically fail in a unique or a combined form of the following fundamental failure modes: matrix cracking, fiber-matrix debonding, fiber breakage and delamination. The complete understanding of the mechanisms behind these fundamental failure modes is essential for the failure evaluation of laminated composites. Most of research work has further distinguished the failure of laminated composites in two distinct modes. That is, the in-plane failure mode of matrix cracking, fiber-matrix debonding and fiber breakage is considered to be caused by the in-plane stress state, while the delamination mode occurs as a result of the inter-laminar stress state.

1.9 Damage mechanism of laminated composites

Classically damage in a structure signifies any irreversible change in material or degradation pertaining to prevalent workability/functioning due to a multitude of distributed micro-structural rearrangements such as micro-cracks, micro-voids, and internal delaminations. Damage in FRP laminated composites may manifest itself in the forms of interlaminar/intralaminar delamination, debonding of fiber matrix interface, matrix cracking and fiber breakage [6-8] introduced the complex variable formulation for the problems of two-dimensional linear anisotropic elasticity. Also, Amartsumyan [9] illustrated the fundamental theory and equations based on the anisotropic laminar shell. While all or some of the above damage modes that discussed may simultaneously be present in the material, but delamination is of prime concern, because it may reduce the appreciable amount of strength and stiffness of material. So this has been a subject of major concern in engineering applications of the composites because of the problems of structural integrity and stability, reduction in load carrying capacity, stiffness reduction, and exposure of the interior to adverse environment, disintegration of the material and final catastrophic

failure of the structure. Composite materials are anisotropic, inhomogeneous and inelastic exhibiting a failure mechanism more complex with various interacting modes.

Failure rate of structures can be predicted by several failure distribution theories. Some of the distribution theories are Normal distribution, Binomial distribution, Exponential distribution, Poisson's distribution and Weibull distribution.

Weibull [10] proposed a distribution to describe the life length of materials under fatigue and fracture loads. This distribution is commonly used for the life estimation of graphite composite.

1.10 Delamination

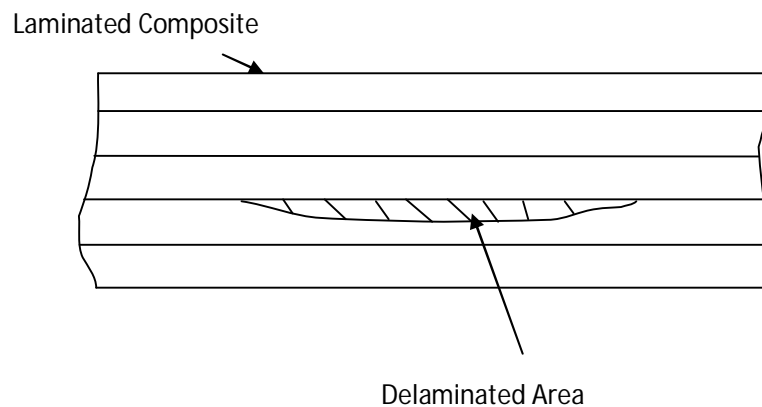


Figure 1.10 Delamination in composite structure

Composites may fail on the microscopic or macroscopic scale. Compression failures can occur at both the macro scale or at each individual reinforcing fiber in compression buckling. Tension failures is the net section failures of the part or degradation of the composite at a microscopic scale where one or more of the layers in the composite fail in tension of the matrix or failure of the bond between the matrix and fibers. In laminated materials, repeated cyclic stresses, impact, and such mechanical loadings can cause layers

to separate, forming a mica-like structure of separate layers, with significant loss of mechanical toughness (Figure 1.10).

Fiber pull-out (individual fibers can separate from the matrix) and delamination can occur, in part, because of weak adhesive bonding between the fibers and the polymer matrix. It may also reduce the strength and stiffness of the composite structure significantly and expose the interior to an adverse environment, when subjected to different kinds of loading for a prolonged period.

Delamination is more likely to occur when:

- The underlying concrete sets slowly because of a cool sub-grade.
- Set is retarded by retarders and/or fly ash.
- Entrained air is used (or is higher than normal).
- Use of a jitterbug or vibrating screed brings too much mortar to the surface.
- A dry shake is used, particularly with air entrained concrete.
- The concrete is sticky from higher cementations material or sand content.
- The slab is thick.
- The slab is placed directly on a vapor barrier.

1.10.1 Origin of delamination

Delaminations can originate in the following situations:

1. At the manufacturing stage, e.g., adhesion failures and shrinkage cracks.
2. At the stage of transportation and installation, when the loads and actions may be different in character and level from the design ones, e.g. impacts upon the surface of the structure such as tool drop. Even relatively light impacts can lead to the delamination of the near-surface layers. Low velocity impact of foreign objects is the most important cause of

delamination. It can create multiple delaminations which increase in size away from the point of impact.

3. At the stage of operation as a result of off-design situations or of an inadequate design.

Numerous analytical, numerical and experimental studies have been conducted over the past two decades modeling the buckling and post-buckling behavior of delaminated composite laminates with different shapes of delamination including:

1. Through-the-width delamination (strip delamination)
2. Circular embedded delamination
3. Elliptical embedded delamination
4. Rectangular embedded delamination
5. Triangular embedded delamination

1.10.2 Skin-stiffener debonding

Skin-stiffener debonding involves detachment of the stiffener from the skin in stiffened panels, which significantly reduces the structural support for both skin and stiffener, and results in the buckling and failure of both structural elements at lower loads than for an intact structure. Skin-stiffener debonds take place between the skin and stiffener in co-cured or secondary bonded structures, either through the initiation and growth of delaminations, or failure in the secondary bonding. Skin-stiffener debonding is a common, and usually violent, which has occurred in a large number of experimental investigations into postbuckling stiffened structures. Figure 1.11 clearly explains the position of skin, flange and stiffener in skin-stiffener composite panel.

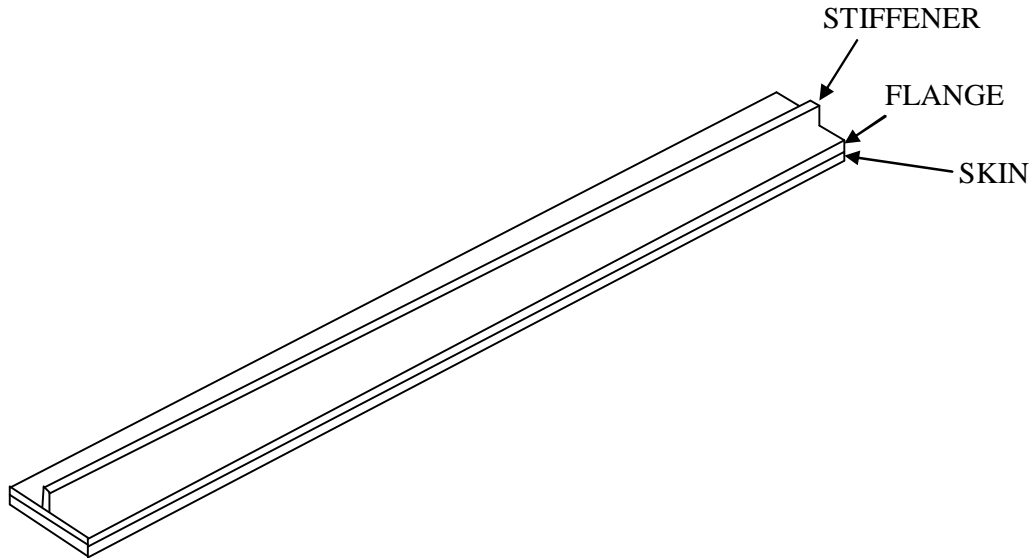


Figure 1.11 Skin-stiffener composite panel

1.10.3 Difference between debonding and delamination

Debonding comes into existence when an adhesive stops sticking (adhering) to an adherend or substrate material. The adhesive is an inorganic coating. Debonding happens if the physical, chemical or mechanical forces that hold the bond together are broken, perhaps by a force or environmental attack.

Delamination is a failure in a laminated material, usually in composite, which leads to the separation of the layers of reinforcement or plies. Delamination failure can be of different types, such as

- fracture within the adhesive or resin
- fracture within the reinforcement
- debonding of the resin from the reinforcement

The various types of defect that occur in adhesive bonds are shown in Figure 1.12 below, which shows debonding in the form of disbonds.

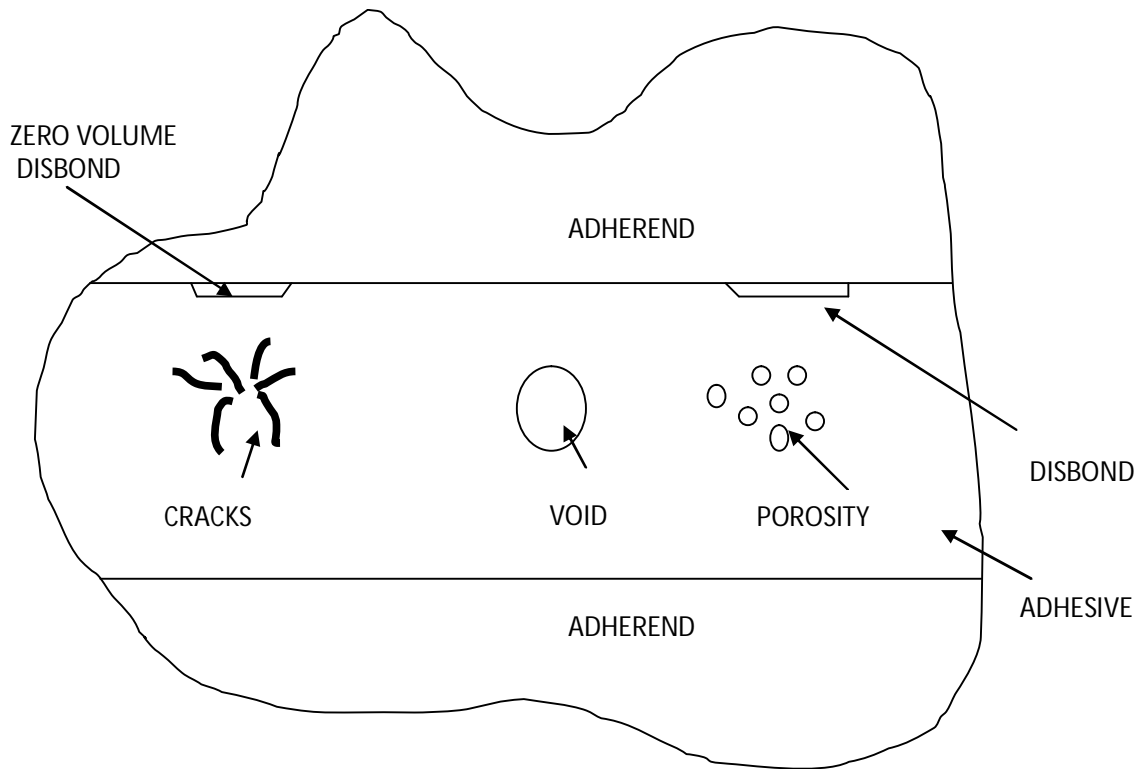


Figure 1.12 Types of defects in adhesive bond

Some common defects that are found in adhesively bonded joints discussed below:

- **Porosity:** it is due to gases and volatiles in the adhesive.
- **Void:** it is formed by coalescence of pores, but is more often caused by air entrapment during application of the adhesive, by volatiles or by insufficient adhesive being applied.
- **Incorrect cure:** it happens locally because of contaminants or poor mixing, but it is more likely to occur throughout the whole bondline, because of incorrect formulation or mixing, or thermal exposure.
- **Cracks in adhesive:** it is associated with curing and thermal shrinkage during manufacture, especially with some brittle, high temperature adhesives.

1.11 Analysis of interlaminar fracture

Since fibrous composites are most commonly used as laminates, they are susceptible to internal defects such as delamination during manufacture or in service. The stress analysis of laminated composites with defects for predicting the mechanical behavior of structures is important and received considerable attention. However, due to anisotropic properties of laminated composites the stress distribution around the defects is complex and a global theory for precise prediction of delamination from such defects in composite materials is not available. Finite Element Method [11], because of its ability to model real life structures, has been extensively used for stress analysis of such laminates with defects. However, for complete understanding of behavior of such laminates and delamination initiation from such defects, a 3D finite element analysis is necessary. In retrospect, with the popularity of damage tolerance, fracture mechanics concepts have been in use for analysis of such structures. Effective analytical and numerical methods are necessary for analysis of laminated FRP composites with defects.

1.12 Loading effects on laminated composite materials

During normal operation time, composite structures are subjected to various types of loading, such as change in temperature and stresses. These effects are known as thermo-elastic effects. Elastic material expands when thermal energy is added to it. Thermal deformation simply means that as the temperature of a material increases, so does the vibration of its atoms/molecules; and this increases the vibration which results in stretching of the molecular bonds which causes the material to expand. Also, when the thermal energy (and temperature) of a material decreases, the material will shrink or contract.

1.12.1 Thermo-elastic effect on delamination

The composite material undergoes reversible deformations related to thermal expansion coefficients. Intra laminar and inter laminar stresses are developed as a result of the thermo elastic and hydro elastic inhomogeneity and anisotropy of the material. Thermal stresses are induced in the composite laminae, whenever the temperature of the laminate differs from the temperature of its stress free state. Residual thermal stress parameters affect adversely the true nature of material fracture toughness values. Delamination fracture behavior is greatly altered due to the thermo-elastic interaction of thermal and mechanical stresses.

When residual thermal stress effects are taken into account, large asymmetries occur in the energy release rate components along the delamination front. The delamination crack growth characteristics are significantly affected by the presence of thermal residual stresses at the interface. It enhances the mechanism of delamination growth, when the laminate is subjected to out-of-plane transverse loadings and causes premature failure of an otherwise intact laminate.

1.13 Motivation

Graphite/epoxy has superior high-temperature sustaining property and hardness results in reduced erosion rates when compared to monolithic materials and some other specific advantages make it a main component for aerospace and defence industries. The material system has to be characterized properly from a microscopic point of view to its macroscopic complexity of structural failure modes. However, failure as an event can only be predictable under certain circumstances to a finite degree of accuracy, provided the physics of compo-mechanization is well understood, which nevertheless poses uncertainty in itself. Reconciling this, the failure strength of graphite/epoxy is treated as a continuous

random variable problem determined by the flaw population in the light of Weibull Statistical Model [10,12,13]. Capturing these types of uncertainty, a correct prediction of the reliability of structural components is a formidable task. It is very complex and rather difficult to examine any defect or inherent flaw and subsurface cracks which might be otherwise invisible to naked eye. Apart from this, even during manufacturing stages such defects might promulgate which even the best of the non-destructive techniques cannot detect at initial stages rendering the system vulnerable in a high stressed thermo-mechanical corrosive environment. Apart from this, the bimodular behavior of graphite necessitates a three-dimensional analysis for properly characterizing the scattering strength of graphite/epoxy components. Furthermore, the dimensional change (strain) in graphite components can lead to similar internal stress distributions to those generated by thermal loading and these additive stress distributions may be critical in design [14-18]. The widely accepted deterministic theory for fracture of graphite/epoxy composite defines a critical maximum principal stress. However, due to the heterogeneity of graphite/epoxy, the local maximum principal stress distribution can be noticeably different in similar specimens under identical loading condition. Crack nucleation may therefore occur with prolonged operation. The design and safety assessment of graphite/epoxy composite is often based on empirical rules derived from material irradiation. Due to the complex behavior and properties of composite and prone to fracture, it is very necessary to study and analyze the strength and life of component under loading conditions. Also, it is important to find the methods for crack arrest and crack delay of the structure to enhance its strength.

1.14 Thesis overview

Chapter-1 presents a brief introduction of composite and laminated structures. This chapter includes the various damage modes and influence of ply orientation and stacking sequence in laminated composites. Observations of bimodulus polarity and thermoelastic anisotropy for layered materials have also been discussed.

Chapter-2 includes the detailed literature review based on fracture behavior and delamination of laminated composite structures. Damage mechanism of tee joint structures and skin-stiffener under thermo-mechanical loading is presented. Also, the detailed objectives are listed of present investigation.

Chapter-3 includes the theoretical background. This chapter deals with the detailed derivation of formulation of the shifting of neutral axis. Finite element formulation for generalized thermoelasticity is also presented in the chapter. Also, Strain Energy Release Rate has been computed under thermo-mechanical loading. It also includes the governing equation of functionally-graded bimodular thermo-elasticity. It also deals with the bimodular property of composites. Calculation of bimodulus ratio and shifting of neutral axis of graphite/epoxy composite has been done through FE based software.

Chapter-4 includes the fracture behavior of adhesively bonded joint. Adhesively bonding techniques has been widely used due to its ability to distribute a load over a larger area. When the adhesive joints undergo thermal load as well as structural load, stress and deformation fields play an important role in the strength of the adhesive joints. Adhesive bonding technology has also found a good place in joining advanced composite materials. 3D finite element analysis has been conducted to evaluate the effect of multi lay-up laminate, varying orientation and stacking sequence on stress, gradient and flux.

Chapter-5 includes the failure analysis of adhesive bonded technology with bimodular adhesive. Adhesion methodology has become so versatile and such diversified into the new frontiers of aerospace, marine and automotive applications for joining of composite-composite and composite-metal structural parts thereby rendering inconclusive failure and fracture behavior coming into play limiting their proposed life span. It is apprehended that either the earlier nomenclatured bonding parameters need to be reanalyzed in view of new design requirements or else there might be some new adhesion mechanism controlling the stress and deformation characteristics of these bonded structures. Therefore, the impetus of the present study has been to address the issues of bimodular functionally graded adhesive tee joint. Hence, modified stress dependent elasticity problem has to be addressed properly for enhancing joint reliability and design. It has been found that the bimodularity significantly reduces the interfacial failure propagation rate.

Chapter-6 presents the thermo-elastic effect of material anisotropy and residual thermal stresses on interlaminar delamination fracture characteristics of composite stiffened panels. Composite stiffened panels are being predominantly used as aerospace structures due to their outstanding weight/ stiffness and strength ratio and also ease of repair and assembly under in-situ loading conditions. However, these composite structures are susceptible to interfacial or interlaminar damage mechanisms such as delamination, debonding or such other involvement like matrix crack and fiber breakage due to defects or flaws arising even during manufacturing stages, service or maintenance induced damages, or from low-velocity impact damage or from operational malfunctioning. The residual thermal stresses arise when differently oriented stiffeners are assembled and cured from an elevated temperature to room temperature. It is found that strain energy release rate is significantly

influenced by thermal residual stresses and it may magnify the delamination growth depending upon the loading type.

Chapter-7 presents strain energy release rate as a fracture parameter has been used to evaluate the skin-stiffener debonding in stiffened composite panel with functionally-graded (FG) bimodular material property under thermo-mechanical coupled field. The influence of bimodularity along with ply lay-up and interaction of residual thermal stresses on the skin-stiffener has been investigated. Variation of energy release rate along the interface delamination front has been plotted for both mechanical and thermo-mechanical coupled loading with bimodulus ratio R varying from 1 (unimodular) to 5. Asymmetric variation of energy release rate along the interfacial front has been observed for the bimodular stiffened composite panel. It has been found that the bimodularity significantly reduces the failure growth.

Chapter-8 includes the conclusion of the full thesis work and scope of the work that can be done further.