NPTEL [3.1.2 CIVIL ENGINEERING]

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COMPOSITE MATERIALS

[Web-based Course]

SYLLABUS VERSION 2.0 l7August 2004
12 MODULES: 48 HOURS with Lecture-Plan (Tentative)

Module 1: General Introduction : 4 hours

1.1 Introduction to Composites (1 hour)

General introduction & concept, Historical development, Concept of Composite materials, material properties that can be improved by forming a composite material& its engineering potential

1.2 Basic Definitions and Classification of Composites (2 hours)

Basic definitions, Various types of composites, Classification based on Matrix Material: Organic Matrix Composites(Polymer matrix composites (PMC)/Carbon Matrix Composites or Carbon-Carbon Composites, Metal Matrix composites (MMC), Ceramic Matrices composites (CMC); Classification based on reinforcements: Fiber Reinforced Composites/Fiber Reinforced Polymer (FR P) Composites, Laminar Composites, Particulate Composites

1.3 Advantages of Composites materials (1hour)

Comparison with Metals, Advantages & limitations of Composites

Module 2:Basic constituent materials in Composites : 4 hours

2.1 Reinforcements & Matrices for various types of composites (1hour)

2.2 Fibers/Reinforcement Materials (1hour)

Role and Selection of reinforcement materials, Types of fibers, Mechanical properties of fibers, Glass fibers, Carbon fibers, Aramid fibers, Metal fibers, Alumina fibers, Boron Fibers, Silicon carbide fibers, Quartz and Silica fibers, Multiphase fibers, Whiskers, Flakes etc.

2.3 Matrix Materials (1hour)

Functions of a Matrix, Desired Properties of a Matrix Polymer Matrix (Thermosets and Thermoplastics),Metal matrix, Ceramic matrix, Carbon Matrix, Glass Matrix etc.

2.4 Fiber reinforced Polymer (FRP) Laminated composites (1hour)

Lamina & Laminate Lay-up, Ply-orientation definition

Module 3: Behaviour of a Laminae-I : 4 hours

Linear Elastic Stress-Strain Characteristics of FRP Composites

3.l Stress and Strain concepts in 3-D (1 hour)

Stress and Strain components in 3-D, Generalized Hookes Law in 3-D. Stress-Strain relations in 3-Dfor Isotropic case.

3.2 Introduction to Anisotropic Elasticity (1 hour)

Stress-Strain relations for Anisotropic and Orthotropic cases

3.3 Tensorial concept and indicial notations (1 hour)

Concept of Cartesian tensor, indicial notation and tensorial representations in Elasticity, Voigot notations

3.4 Plane stress concept (1 hour)

2-D Elasticity and Plane-Stress concept. A stress-Strain relation for Plane Stress (Isotropic and Orthotropic cases) Stress-strain relations for a Lamina in material coordinates

Module 4: Behaviour of a Laminae-II : 4 hours

4.1 Micromechanics of Laminae (2 hours)

Mechanics of load-transfer in a Laminae, Prediction of Engineering Property in a Laminae

4.2 Macromechanics of a Laminae (2 hours)

Lamina Stress-Strain relations in material coordinates ,Transformation relations ,Lamina Stress-Strain relations in Structure/Global coordinates

Module *5:* Laminated Composites-I : 4 hours

5.1 Introduction to Mechanics of Plates (1 hour)

(Kirchhoff's Plate Theory)

5.2 Classical Laminated Plate Theory (2 hours)

Laminate Strain-Displacement relationship based on Kirchhoff's Hypothesis (1 hour)

5.3 Stress-resultants in a Laminate (1 hour)

Laminate forces and moments

Module 6: Laminated Composites-II: 4 hours

6.1 Structural Mechanics of Laminates (2 hours)

Laminate Stiffness and ABD Matrices

6.2 Special Classification of Laminates (2 hours)

Symmetric, Antisymmetric and Nonsymmetric laminates

Module 7: Strength and Failure theories : 4 hours

7.1 Strength of Laminates (1 hour)

7.2 Failure Mechanics of Composites (1 hour)

7.3 Macromechanical Failure Theories (1 hour)

Maximum stress theory,
Maximum Strain Theory ,
Tsai-Hill Theory ,
Tsai-Wu Theory,

7.4 Comparison of Failure Theories (1 hour)

Module 8: Design Concepts: 4 hours

8.1 Design Issues

8.2 Typical Structural Component Design process

8.3 Laminate Analysis/Design software

8.4 Composite Codes & Standards

Module 9 :Manufacturing Processes : 4 hours

9.1 Fabrication/Manufacturing Techniques. (1 hour)

Tooling and Specialty materials, Release agents, Peel plies, release films and fabrics, Bleeder and breather plies, bagging films.

9.2 Hand Lay-up (1 hour)

9.3 Processing (1 hour)

Overall considerations, Autoclave curing
Other Manufacturing Processes,
Fiber-only performs, Combined Fiber-Matrix performs.

9.4 Forming Structural Shapes (1 hour)

Wet Lay-up and Spray-up, Filament winding, Pultrusion, Resin Transfer Molding(R TM), Nonautoclave curing, Manufacturing defects,
General Safety Precautions

Module 10 : Special Topics : 4 hours

10.1 Testing of Composites

Mechanical testing of composites, Tensile testing, Compressive testing, Intralaminar shear testing, Inter laminar shear testing, Fracture testing etc.

10.2 Joining of composites

Adhesively Bonded Joints & Mechanically Fastened Joints

10.3 Environmental Effects on composites

10.4 Recycling of Composites

Categories of scrap composites, Recycling methods for: Thermoplastic matrix composites, Thermosets matrix composites.

Module 11 : Engineering Applications : 4 hours

11.1 General Engineering Applications of FRP composites.

Applications related to Aerospace, Automobile, Bridge and other Civil Engineering Structures, Case studies.

Module 12 :Civil Engineering Applications : 4 hours

12.1 Typical Applications of FRP Composites in Civil Engineering

Adhesively Bonded FRP composites in strengthening of civil engineering structural components such as beams, Columns, Masonry etc (1 hour)

12.2Various Strengthening Techniques (2 hours),

12.3Advantage and Disadvantage of FRP composites laminated plate bonding & Misc. issues (1 hour)

COMPOSITE MATERIALS (Web-based Course)

Module-1: General Introduction

1.1 INTRODUCTION TO COMPOSITES

Mankind has been aware **composite materials** since several hundred years before Christ and applied innovation to improve the quality of life. Although it is not clear has to how Man understood the fact that mud bricks made sturdier houses if lined with straw, he used them to make buildings that lasted. Ancient Pharaohs made their slaves use bricks with to straw to enhance the structural integrity of their buildings, some of which testify to wisdom of the dead civilization even today.

Contemporary composites results from research and innovation from past few decades have progressed from glass fiber for automobile bodies to particulate composites for aerospace and a range other applications.

Ironically, despite the growing familiarity with composite materials and ever-increasing range of applications, the term defines a clear definition. Loose terms like "materials composed of two or more distinctly identifiable constituents" are used to describe natural composites like timber, organic materials, like tissue surrounding the skeletal system, soil aggregates, minerals and rock.

Composites that forms heterogeneous structures which meet the requirements of specific design and function, imbued with desired properties which limit the scope for classification. However, this lapse is made up for, by the fact new types of composites are being innovated all the time, each with their own specific purpose like the filled, flake, particulate and laminar composites**.**

Fibers or particles embedded in matrix of another material would be the best example of modern-day composite materials, which are mostly structural.

Laminates are composite material where different layers of materials give them the specific character of a composite material having a specific function to perform. Fabrics have no matrix to fall back on, but in them, fibers of different compositions combine to give them a specific character. Reinforcing materials generally withstand maximum load and serve the desirable properties.

Further, though composite types are often distinguishable from one another, no clear determination can be really made. To facilitate definition, the accent is often shifted to the levels at which differentiation take place viz., microscopic or macroscopic.

In **matrix**-based structural composites, the matrix serves two paramount purposes viz., binding the reinforcement phases in place and deforming to distribute the stresses among the constituent reinforcement materials under an applied force.

The demands on matrices are many. They may need to temperature variations, be conductors or resistors of electricity, have moisture sensitivity etc. This may offer weight advantages, ease of handling and other merits which may also become applicable depending on the purpose for which matrices are chosen.

Solids that accommodate stress to incorporate other constituents provide strong bonds for the reinforcing phase are potential matrix materials. A few inorganic materials, polymers and metals have found applications as matrix materials in the designing of structural composites, with commendable success. These materials remain elastic till failure occurs and show decreased failure strain, when loaded in tension and compression.

Composites cannot be made from constituents with divergent linear expansion characteristics. The interface is the area of contact between the reinforcement and the matrix materials. In some cases, the region is a distinct added phase. Whenever there is interphase, there has to be two interphases between each side of the interphase and its adjoint constituent. Some composites provide interphases when surfaces dissimilar constituents interact with each other. Choice of fabrication method depends on matrix properties and the effect of matrix on properties of reinforcements. One of the prime considerations in the selection and fabrication of composites is that the constituents should be chemically inert non-reactive. Figure 1.1 helps to classify matrices.

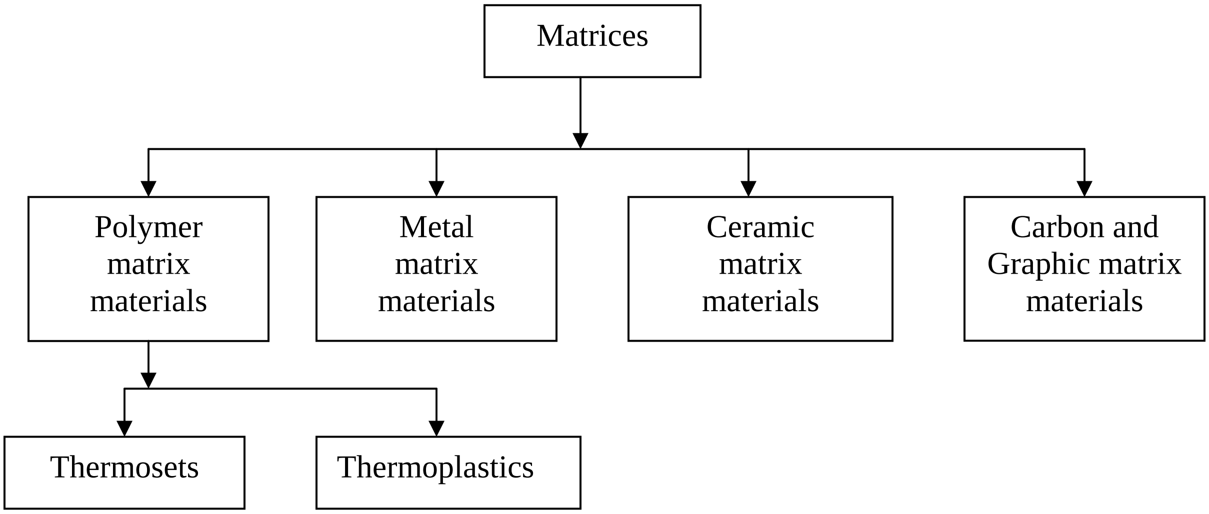


Fig.1.1

1.1.1 Polymer Matrix Materials

Polymers make ideal materials as they can be processed easily, possess lightweight, and desirable mechanical properties. It follows, therefore, that high temperature **resins** are extensively used in aeronautical applications.

Two main kinds of polymers are thermosets and thermoplastics. Thermosets have qualities such as a well-bonded three-dimensional molecular structure after curing. They decompose instead of melting on hardening. Merely changing the basic composition of the resin is enough to alter the conditions suitably for curing and determine its other characteristics. They can be retained in a partially cured condition too over prolonged periods of time, rendering Thermosets very flexible. Thus, they are most suited as matrix bases for advanced conditions fiber reinforced composites. Thermosets find wide ranging applications in the chopped fiber composites form particularly when a premixed or moulding compound with fibers of specific quality and aspect ratio happens to be starting material as in epoxy, polymer and phenolic polyamide resins.

Thermoplastics have one- or two-dimensional molecular structure and they tend to at an elevated temperature and show exaggerated melting point. Another advantage is that the process of softening at elevated temperatures can reversed to regain its properties during cooling, facilitating applications of conventional compress techniques to mould the compounds.

Resins reinforced with thermoplastics now comprised an emerging group of composites. The theme of most experiments in this area to improve the base properties of the resins and extract the greatest functional advantages from them in new avenues, including attempts to replace metals in die-casting processes. In crystalline thermoplastics, the reinforcement affects the **morphology** to a considerable extent, prompting the reinforcement to empower nucleation. Whenever crystalline or amorphous, these resins possess the facility to alter their **c**reep over an extensive range of temperature. But this range includes the point at which the usage of resins is constrained, and the reinforcement in such systems can increase the failure load as well as creep resistance. Figure 1.2 shows kinds of thermoplastics.

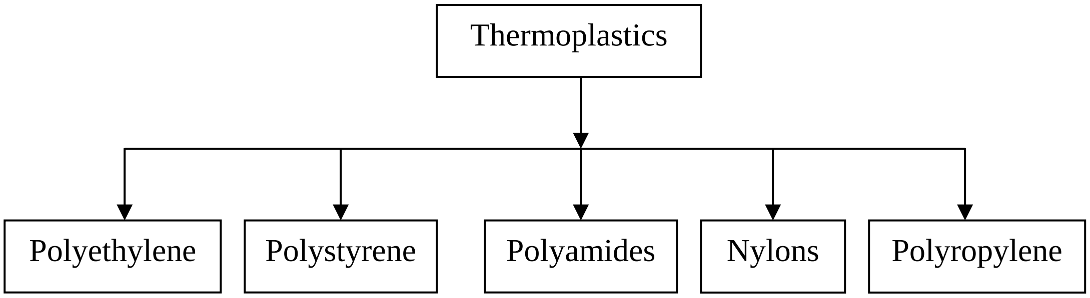


Fig. 1.2

A small quantum of shrinkage and the tendency of the shape to retain its original form are also to be accounted for. But reinforcements can change this condition too. The advantage of thermoplastics systems over thermosets are that there are no chemical reactions involved, which often result in the release of gases or heat. Manufacturing is limited by the time required for heating, shaping and cooling the structures.

Thermoplastics resins are sold as moulding compounds. Fiber reinforcement is apt for these resins. Since the fibers are randomly dispersed, the reinforcement will be almost isotropic. However, when subjected to moulding processes, they can be aligned directionally.

There are a few options to increase heat resistance in thermoplastics. Addition of fillers raises the heat resistance. But all thermoplastic composites tend loose their strength at elevated temperatures. However, their redeeming qualities like rigidity, toughness and ability to repudiate creep, place thermoplastics in the important composite materials bracket. They are used in automotive control panels, electronic products encasement etc.

Newer developments augur the broadening of the scope of applications of thermoplastics. Huge sheets of reinforced thermoplastics are now available and they only require sampling and heating to be moulded into the required shapes. This has facilitated easy fabrication of bulky components, doing away with the more cumbersome moulding compounds.

Thermosets are the most popular of the fiber composite matrices without which, research and development in structural engineering field could get truncated. Aerospace components, automobile parts, defense systems etc., use a great deal of this type of fiber composites. Epoxy matrix materials are used in printed circuit boards and similar areas. Figure 1.3 shows some kinds of thermosets.

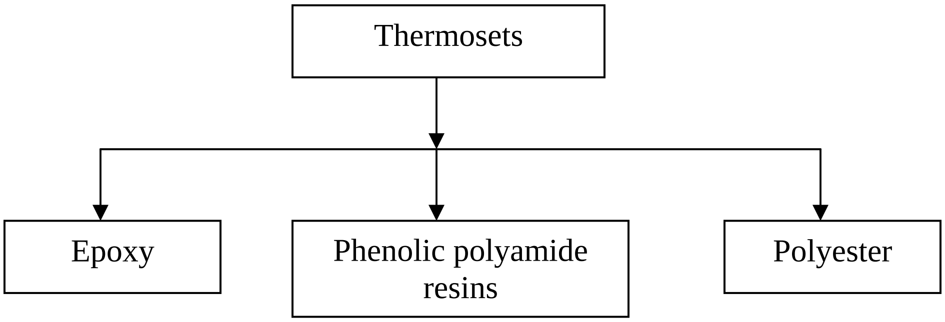


Fig. 1.3

Direct condensation polymerization followed by rearrangement reactions to form heterocyclic entities is the method generally used to produce thermoset resins. Water, a product of the reaction, in both methods, hinders production of void-free composites. These voids have a negative effect on properties of the composites in terms of strength and dielectric properties. Polyesters phenolic and Epoxies are the two important classes of thermoset resins.

Epoxy resins are widely used in filament-wound composites and are suitable for moulding prepress. They are reasonably stable to chemical attacks and are excellent adherents having slow shrinkage during curing and no emission of volatile gases. These advantages, however, make the use of epoxies rather expensive. Also, they cannot be expected beyond a temperature of 140ºC. Their use in high technology areas where service temperatures are higher, as a result, is ruled out.

Polyester resins on the other hand are quite easily accessible, cheap and find use in a wide range of fields. Liquid polyesters are stored at room temperature for months, sometimes for years and the mere addition of a catalyst can cure the matrix material within a short time. They are used in automobile and structural applications.

The cured polyester is usually rigid or flexible as the case may be and transparent. Polyesters withstand the variations of environment and stable against chemicals. Depending on the formulation of the resin or service requirement of application, they can be used up to about 75ºC or higher. Other advantages of polyesters include easy compatibility with few glass fibers and can be used with verify of reinforced plastic accountrey.

Aromatic Polyamides are the most sought after candidates as the matrices of advanced fiber composites for structural applications demanding long duration exposure for continuous service at around 200-250ºC .

1.1.2 Metal Matrix Materials

Metal matrix composites, at present though generating a wide interest in research fraternity, are not as widely in use as their plastic counterparts. High strength, fracture toughness and stiffness are offered by metal matrices than those offered by their polymer counterparts. They can withstand elevated temperature in corrosive environment than polymer composites. Most metals and alloys could be used as matrices and they require reinforcement materials which need to be stable over a range of temperature and non-reactive too. However the guiding aspect for the choice depends essentially on the matrix material. Light metals form the matrix for temperature application and the reinforcements in addition to the aforementioned reasons are characterized by high moduli.

Most metals and alloys make good matrices. However, practically, the choices for low temperature applications are not many. Only light metals are responsive, with their low density proving an advantage. Titanium, Aluminium and magnesium are the popular matrix metals currently in vogue, which are particularly useful for aircraft applications. If metallic matrix materials have to offer high strength, they require high modulus reinforcements. The strength-to-weight ratios of resulting composites can be higher than most alloys.

The melting point, physical and mechanical properties of the composite at various temperatures determine the service temperature of composites. Most metals, ceramics and compounds can be used with matrices of low melting point alloys. The choice of reinforcements becomes more stunted with increase in the melting temperature of matrix materials.

1.1.3 Ceramic Matrix Materials

Ceramics can be described as solid materials which exhibit very strong ionic bonding in general and in few cases covalent bonding. High melting points, good corrosion resistance, stability at elevated temperatures and high compressive strength, render ceramic-based matrix materials a favourite for applications requiring a structural material that doesn’t give way at temperatures above 1500ºC. Naturally, ceramic matrices are the obvious choice for high temperature applications.

High modulus of elasticity and low tensile strain, which most ceramics posses, have combined to cause the failure of attempts to add reinforcements to obtain strength improvement. This is because at the stress levels at which ceramics rupture, there is insufficient elongation of the matrix which keeps composite from transferring an effective quantum of load to the reinforcement and the composite may fail unless the percentage of fiber volume is high enough. A material is reinforcement to utilize the higher tensile strength of the fiber, to produce an increase in load bearing capacity of the matrix. Addition of high-strength fiber to a weaker ceramic has not always been successful and often the resultant composite has proved to be weaker.

The use of reinforcement with high modulus of elasticity may take care of the problem to some extent and presents pre-stressing of the fiber in the ceramic matrix is being increasingly resorted to as an option.

When ceramics have a higher thermal expansion coefficient than reinforcement materials, the resultant composite is unlikely to have a superior level of strength. In that case, the composite will develop strength within ceramic at the time of cooling resulting in microcracks extending from fiber to fiber within the matrix. Microcracking can result in a composite with tensile strength lower than that of the matrix.

1.1.4 Carbon Matrices

Carbon and graphite have a special place in composite materials options, both being highly superior, high temperature materials with strengths and rigidity that are not affected by temperature up to 2300ºC. This carbon-carbon composite is fabricated through compaction of carbon or multiple impregnations of porous frames with liquid carboniser precursors and subsequent pyrolization. They can also be manufactured through chemical vapour deposition of pyrolytic carbon.

Carbon-carbon composites are not be applied in elevated temperatures, as many composites have proved to be far superior at these temperatures. However, their capacity to retain their properties at room temperature as well as at temperature in the range of 2400ºC and their dimensional stability make them the oblivious choice in a garnut of applications related to aeronautics, military, industry and space.

Components, that are exposed to higher temperature and on which the demands for high standard performance are many, are most likely to have carbon-carbon composites used in them.

1.1.5 Glass Matrices

I n comparison to ceramics and even considered on their own merit, glass matrices are found to be more reinforcement-friendly. The various manufacturing methods of polymers can be used for glass matrices.

Glasses are meant to improve upon performance of several applications. Glass matrix composite with high strength and modulus can be obtained and they can be maintained upto temperature of the order of 650ºC.

Composites with glass matrices are considered superior in dimensions to polymer or metal system, due to the low thermal expansion behaviour. This property allows fabrication of many components in intricate shapes and their tribological characters are considered very special.

Since the elastic modulus of glass is far lower than of any prospective reinforcement materials, application of stress usually results in high elasticity modulus fiber that the tensile strength of the composite its considerably enhanced than that of the constituents, which is not case in ceramic matrices.

1.1.6 Reinforcements

Reinforcements for the composites can be fibers, fabrics particles or whiskers. Fibers are essentially characterized by one very long axis with other two axes either often circular or near circular. Particles have no preferred orientation and so does their shape. Whiskers have a preferred shape but are small both in diameter and length as compared to fibers. Figure 1.4 shows types of reinforcements in composites.

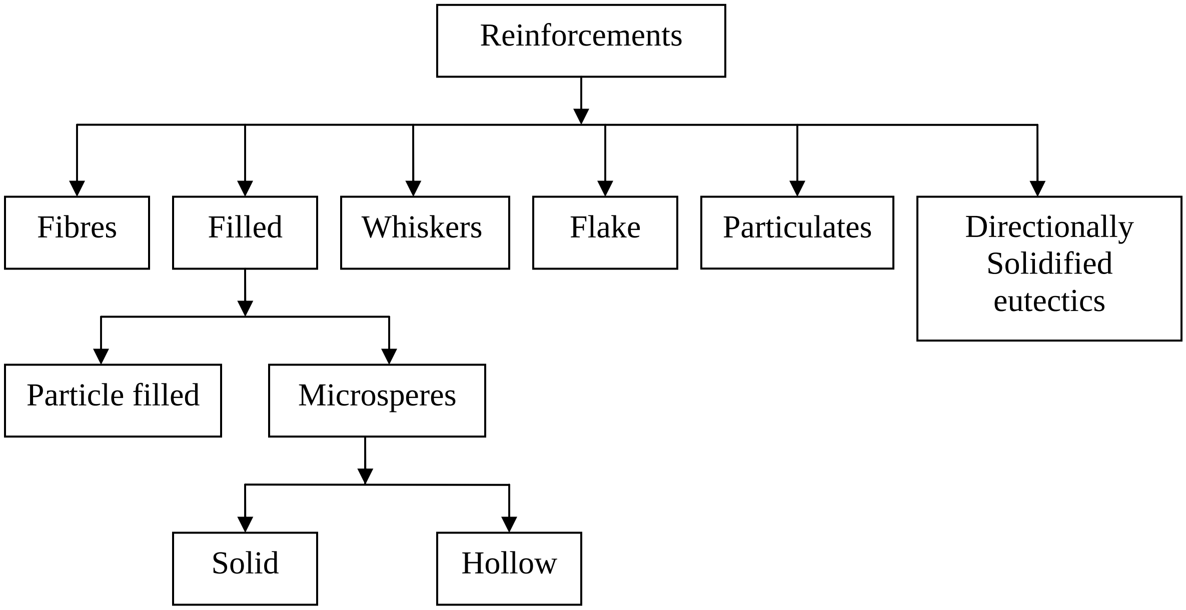


Fig. 1.4

Reinforcing constituents in composites, as the word indicates, provide the strength that makes the composite what it is. But they also serve certain additional purposes of heat resistance or conduction, resistance to corrosion and provide rigidity. Reinforcement can be made to perform all or one of these functions as per the requirements.

A reinforcement that embellishes the matrix strength must be stronger and stiffer than the matrix and capable of changing failure mechanism to the advantage of the composite. This means that the ductility should be minimum or even nil the composite must behave as brittle as possible.

1.1.7 Fiber Reinforcement

Fibers are the important class of reinforcements, as they satisfy the desired conditions and transfer strength to the matrix constituent influencing and enhancing their properties as desired.

Glass fibers are the earliest known fibers used to reinforce materials. Ceramic and metal fibers were subsequently found out and put to extensive use, to render composites stiffer more resistant to heat.

Fibers fall short of ideal performance due to several factors. The performance of a fiber composite is judged by its length, shape, orientation, composition of the fibers and the mechanical properties of the matrix.

The orientation of the fiber in the matrix is an indication of the strength of the composite and the strength is greatest along the longitudinal directional of fiber. This doesn’t mean the longitudinal fibers can take the same quantum of load irrespective of the direction in which it is applied. Optimum performance from longitudinal fibers can be obtained if the load is applied along its direction. The slightest shift in the angle of loading may drastically reduce the strength of the composite.

Unidirectional loading is found in few structures and hence it is prudent to give a mix of orientations for fibers in composites particularly where the load is expected to be the heaviest.

Monolayer tapes consisting of continuous or discontinuous fibers can be oriented unidirectional stacked into plies containing layers of filaments also oriented in the same direction. More complicated orientations are possible too and nowadays, computers are used to make projections of such variations to suit specific needs. In short, in planar composites, strength can be changed from unidirectional fiber oriented composites that result in composites with nearly isotropic properties.

Properties of angle-plied composites which are not quasi-isotropic may vary with the number of plies and their orientations. Composite variables in such composites are assumed to have a constant ratio and the matrices are considered relatively weaker than the fibers. The strength of the fiber in any one of the three axes would, therefore be one-third the unidirectional fiber composite, assuming that the volume percentage is equal in all three axes.

However, orientation of short fibers by different methods is also possible like random orientations by sprinkling on to given plane or addition of matrix in liquid or solid state before or after the fiber deposition. Even three-dimensional orientations can achieved in this way.

There are several methods of random fiber orientations, which in a two-dimensional one, yield composites with one-third the strength of an unidirectional fiber-stressed composite, in the direction of fibers. In a 3-dimension, it would result in a composite with a comparable ratio, about less than one-fifth.

In very strong matrices, moduli and strengths have not been observed. Application of the strength of the composites with such matrices and several orientations is also possible. The longitudinal strength can be calculated on the basis of the assumption that fibers have been reduced to their effective strength on approximation value in composites with strong matrices and non-longitudinally orientated fiberss.

It goes without saying that fiber composites may be constructed with either continuous or short fibers. Experience has shown that continuous fibers (or filaments) exhibit better orientation, although it does not reflect in their performance. Fibers have a high aspect ratio, i.e., their lengths being several times greater than their effective diameters. This is the reason why filaments are manufactured using continuous process. This finished filaments.

Mass production of filaments is well known and they match with several matrices in different ways like winding, twisting, weaving and knitting, which exhibit the characteristics of a fabric.

Since they have low densities and high strengths, the fiber lengths in filaments or other fibers yield considerable influence on the mechanical properties as well as the response of composites to processing and procedures. Shorter fibers with proper orientation composites that use glass, ceramic or multi-purpose fibers can be endowed with considerably higher strength than those that use continuous fibers. Short fibers are also known to their theoretical strength. The continuous fiber constituent of a composite is often joined by the filament winding process in which the matrix impregnated fiber wrapped around a mandrel shaped like the part over which the composite is to be placed, and equitable load distribution and favorable orientation of the fiber is possible in the finished product. However, winding is mostly confined to fabrication of bodies of revolution and the occasional irregular, flat surface.

Short-length fibers incorporated by the open- or close-mould process are found to be less efficient, although the input costs are considerably lower than filament winding.

Most fibers in use currently are solids which are easy to produce and handle, having a circular cross-section, although a few non-conventional shaped and hollow fibers show signs of capabilities that can improve the mechanical qualities of the composites.

Given the fact that the vast difference in length and effective diameter of the fiber are assets to a fiber composite, it follows that greater strength in the fiber can be achieved by smaller diameters due to minimization or total elimination of surface of surface defects.

After flat-thin filaments came into vogue, fibers rectangular cross sections have provided new options for applications in high strength structures. Owing to their shapes, these fibers provide perfect packing, while hollow fibers show better structural efficiency in composites that are desired for their stiffness and compressive strengths. In hollow fibers, the transverse compressive strength is lower than that of a solid fiber composite whenever the hollow portion is more than half the total fiber diameter. However, they are not easy to handle and fabricate.

1.1.8Types of Fibers

Organic and inorganic fibers are used to reinforce composite materials. Almost all organic fibers have low density, flexibility, and elasticity. Inorganic fibers are of high modulus, high thermal stability and possess greater rigidity than organic fibers and not withstanding the diverse advantages of organic fibers which render the composites in which they are used.

Mainly, the following different types of fibers namely, glass fibers, silicon carbide fibers, high silica and quartz fibers, aluminina fibers, metal fibers and wires, graphite fibers, boron fibers, aramid fibers and multiphase fibers are used. Among the glass fibers, it is again classified into E-glass, A-glass, R-glass etc.

There is a greater marker and higher degree of commercial movement of organic fibers.

The potential of fibers of graphite, silica carbide and boron are also exercising the scientific mind due to their applications in advanced composites.

1.1.8.1 Glass fibers

Over 95% of the fibers used in reinforced plastics are glass fibers, as they are inexpensive, easy to manufacture and possess high strength and stiffness with respect to the plastics with which they are reinforced.

Their low density, resistance to chemicals, insulation capacity are other bonus characteristics, although the one major disadvantage in glass is that it is prone to break when subjected to high tensile stress for a long time.

However, it remains break-resistant at higher stress-levels in shorter time frames. This property mitigates the effective strength of glass especially when glass is expected to sustain loads for many months or years continuously.

Period of loading, temperature, moisture and other factors also dictate the tolerance levels of glass fibers and the disadvantage is further compounded by the fact that the brittleness of glass does not make room for prior warning before the catamorphic failure.

But all this can be easily overlooked in view of the fact the wide range of glass fiber variety lend themselves amicably to fabrication processes like matched die-moulding, filament winding lay-up and so on. Glass fibers are available in the form of mates, tapes, cloth, continuous and chopped filaments, roving and yarns.

Addition of chemicals to silica sand while making glass yields different types of glasses.

1.1.8.2 Metals fibers

As reinforcement, metal fibers have many advantages. They are easily produced using several fabrication processes and are more ductile, apart from being not too sensitive to surface damage and possess high strengths and temperature resistance.

However, their weight and the tendency to react each other through alloying mechanisms are major disadvantages.

Ceramic fibers improve vastly in performance when a fine metal outline is incorporated with refractory ceramics by improving their thermal shock and impact resistance properties.

Metal wires, of the continuous version, also reinforce plastics like polyethylene and epoxy. Such combinations ensure high strength, light weight and good fatigue resistance.

Besides, continuous metal fibers are easily handled, unlike glass fibers. Better flexural properties are observed in some metal fibers reinforced plastic composites which also offer improved strength and weight, than glass fibers.

However, their poor tolerance of high temperature and the resultant steep variations of thermal expansion coefficient with the resins are a discouragement that limits their their application.

1.1.8.3 Alumina Fibers

Alumina aluminium oxide fibers, basically developed for use in metal matrices are considered a potential resin-matrix composite reinforcement. It offers good compressive strength rather than tensile strength. It’s important property is it’s high melting point of about 2000ºC and the composite can be successfully used at temperature up to about 1000ºC. Magnesium and aluminum matrices frequently use alumina fiber reinforced composites as they do not damage the fiber even in the liquid state.

1.1.8.4 Boron Fibers

They are basically composites, in which boron is coated on a substance which forms the substrate, usually made of tungsten.

Boron-tungsten fibers are obtained by allowing hot tungsten filament through a mixture of gases. Boron is deposited on tungsten and the process continued until the thickness is achieved. The tungsten however remains constant in its thickness.

Properties of boron fibers generally change with the diameter, because of the changing ratio of boron to tungsten and the surface defects that change according to size. However, they are known for their remarkable stiffness and strength. Their strengths often compare with those of glass fibers, but their tensile modulus is high, almost four to five that of glass. Boron coated carbons are much cheaper to make than boron tungsten fiber. But is low modulus of elasticity often works against it.

1.1.8.5 Silicon Carbide fibers

Silicon carbide can be coated over a few metals and their room temperature tensile strengths and tensile moduli are like those boron-tungsten. The advantages of silicon carbide-tungsten are several and are more desirable than uncoated boron tungsten fibers. Elevated temperature performance and the fact that they reported only a 35% loss of strength at 1350ºC are their best qualities. Silicon carbide-tungsten and silicon carbide-carbon have both been seen to have very high stress-rupture strength at 1100ºC and 1300ºC. Uncoated boron-tungsten fibers do not react with molten aluminum, unlike uncoated boron and they also withstand high temperatures used in hot-press titanium matrices.

However, Silicon carbide-tungsten fibers are dense compared to boron-tungsten fibers of the same diameters. They are prone to surface damage and need careful, delicate handling, especially during fabrication of the composite. Further, above 930ºC weakening reactions occur between tungsten and silicon carbide, making it different to maintain balance in high-temperature matrix formations.

Silicon carbide on carbon substrates have several advantages, viz. no reaction at high temperature, being lighter than silicon carbide tungsten and possessing tensile strengths and modulus that is are often better than those of silicon carbide-tungsten and boron fibers.

1.1.8.6 Aramid Fibers

Aramid fibers are made aromatic polyamides which are long polymeric chains and aromatic rings. They are structures in which six carbon s\atoms are bonded to each other and to combinations of hydrogen atoms. In aramid fibers, these rings occur and reoccur to form the fibers. They were initially used to reinforce automobile tires. Since then, they have also found other uses like bullet proof vests. As high strength applications, their use in power boats is not uncommon.

Aramids have high tensile strength, high modulus and low weight. Impact-resistant structures can be produced from aramids. The density of aramid fibers is less than that of glass and graphite fibers. They are fire resistant apart from being high-temperature resistant and unaffected by organic solvents fuels. But their resistance in acid and alkaline media is poor. They are supple and allow themselves to be woven into matrices by simple processes. Aramid fibers have a negative coefficient of thermal expansion in the fiber direction and failure of aramid fibers is unique. When they fail, the fibers break into small fibers, which are like fibers within the fibers. This unique failure mechanism is responsible for high strength.

1.1.8.7 Quartz and Silica Fibers

The glass-types typically contain about 50 to 70% silica. Silica glass is a purer glass fiber that can be made by treating fiberglass in an acid bath, which removes all impurities without affecting the silica. The final product contains 93 to 99% silica. Quartz is even more pure, and quartz fibers are made from natural quartz crystals that contain 99.9% silica, possessing nearly all the properties of pure solid quartz.

Ordinary fiberglass, high silica and quartz fibers share several characteristics and can be produced in a range of fiber diameter. Roving or yarns and other forms of fibers can be made from high silica as well as quartz too.

They differ from glass in many factors, however, especially in heat-related properties.

Although quartz crystals are commonly available, pure crystals are hard to come by. On the other hand, high silica comes from the same material as glass fibers and is easily accessible. However, quartz makes up for its rarity with its capacity to withstand high temperatures, which silica is incapable of.

Barring this difference, silica and quartz are similar in other respects. They are highly elastic and can be stretched to 1% of their length before break point. Both silica and quartz are not affected by acid attacks and are resistant to moisture.

Owing to their thermal properties, silica and quartz are the natural choice as fibers in several applications. They have good insulting properties and do not melt at temperature up to 1600ºC.

In addition, they have a low thermal expansion coefficient which makes them withstand high temperatures.

1.1.8.8 Graphite Fibers

While use of the term carbon for graphite is permissible, there is one basic difference between the two. Element analysis of poly-acrylo-nitrile (PAN) base carbon fibers show that they consist of 91 to 94% carbon. But graphite fibers are over 99% carbon. The difference arises from the fact that the fibers are made at different temperatures.

PAN-based carbon cloth or fiber is produced at about 1320ºC, while graphite fibers and cloth are graphitised at 1950 to 3000ºC.

The properties of graphite remain unchanged even at high temperatures, but its willingness to react readily with most metals at the fabrication stage or during use at very high temperatures is often a stumbling block, as seen in aluminium matrices when carbides are produced at the interface. These carbides react with moisture with disastrous effects on the composite material.

Graphite fibers are some of the stiffer fibers known. The stiffness of the fiber is as high as the graphite content. But a major drawback is that stiffness and strength are inversely proportional to each other.

Forbidding costs make the use of graphite fibers prohibitive. The best glass fibers are far less expensive than the cheapest, lowest quality of graphite, and in PAN-base fibers, other raw materials too are equally expensive. The carbonization and graphitisation are time-consuming, apart from demanding excessive energy, materials and close controls throughout the process.

Cheaper pitch base fiber are now being developed, with greater performance potential and there are possibilities of the increased use of graphite fibers.

1.1.8.9 Multiphase Fibers

Spoolable filaments made by chemical vapour deposition processes are usually the multiphase variety and they usually comprise materials like boron, silicon and their carbides formed on surface of a very fine filament substrate like carbon or tungsten. They are usually good for high temperature applications, due to their reduced reaction with higher melting temperature of metals than graphite and other metallic fibers. Boron filaments are sought after for structural and intermediate-temperature composites.

A poly-phase fiber is a core-sheath fiber consisting of a poly-crystalline core.

1.1.9 Whiskers

Single crystals grown with nearly zero defects are termed whiskers. They are usually discontinuous and short fibers of different cross sections made from several materials like graphite, silicon carbide, copper, iron etc. Typical lengths are in 3 to 55 N.M. ranges. Whiskers differ from particles in that, whiskers have a definite length to width ratio greater than one. Whiskers can have extraordinary strengths upto 7000 MPa.

Whiskers were grown quite incidentally in laboratories for the first time, while nature has some geological structures that can be described as whiskers. Initially, their usefulness was overlooked as they were dismissed as incidental by-products of other structure. However, study on crystal structures and growth in metals sparked off an interest in them, and also the study of defects that affect the strength of materials, they came to be incorporated in composites using several methods, including power metallurgy and slip-casting techniques.

Metal-whisker combination, strengthening the system at high temperatures, has been demonstrated at the laboratory level. But whiskers are fine, small sized materials not easy to handle and this comes in the way of incorporating them into engineering materials to come out with a superior quality composite system.

Early research has shown that whisker strength varies inversely with effective diameter. When whiskers were embedded in matrices, whiskers of diameter upto 2 to 10µm yielded fairly good composites.

Ceramic material's whiskers have high moduli, useful strengths and low densities. Specific strength and specific modulus are very high and this makes ceramic whiskers suitable for low weight structure composites. They also resist temperature, mechanical damage and oxidation more responsively than metallic whiskers, which are denser than ceramic whiskers. However, they are not commercially viable because they are damaged while handling.

1.1.10 Laminar Composites

Laminar composites are found in as many combinations as the number of materials. They can be described as materials comprising of layers of materials bonded together. These may be of several layers of two or more metal materials occurring alternately or in a determined order more than once, and in as many numbers as required for a specific purpose.

Clad and sandwich laminates have many areas as it ought to be, although they are known to follow the rule of mixtures from the modulus and strength point of view. Other intrinsic values pertaining to metal-matrix, metal-reinforced composites are also fairly well known.

Powder metallurgical processes like roll bonding, hot pressing, diffusion bonding, brazing and so on can be employed for the fabrication of different alloys of sheet, foil, powder or sprayed materials. It is not possible to achieve high strength materials unlike the fiber version. But sheets and foils can be made isotropic in two dimensions more easily than fibers. Foils and sheets are also made to exhibit high percentages of which they are put. For instance, a strong sheet may use over 92% in laminar structure, while it is difficult to make fibers of such compositions. Fiber laminates cannot over 75% strong fibers.

The main functional types of metal-metal laminates that do not posses high strength or stiffness are single layered ones that endow the composites with special properties, apart from being cost-effective. They are usually made by pre-coating or cladding methods.

Pre-coated metals are formed by forming by forming a layer on a substrate, in the form of a thin continuous film. This is achieved by hot dipping and occasionally by chemical plating and electroplating. Clad metals are found to be suitable for more intensive environments where denser faces are required.

There are many combinations of sheet and foil which function as adhesives at low temperatures. Such materials, plastics or metals, may be clubbed together with a third constituent. Pre-painted or pre-finished metal whose primary advantage is elimination of final finishing by the user is the best known metal-organic laminate. Several combinations of metal-plastic, vinyl-metal laminates, organic films and metals, account for upto 95% of metal-plastic laminates known. They are made by adhesive bonding processes.

1.1.11. Flake Composites

Flakes are often used in place of fibers as can be densely packed. Metal flakes that are in close contact with each other in polymer matrices can conduct electricity or heat, while mica flakes and glass can resist both. Flakes are not expensive to produce and usually cost less than fibers.

But they fall short of expectations in aspects like control of size, shape and show defects in the end product. Glass flakes tend to have notches or cracks around the edges, which weaken the final product. They are also resistant to be lined up parallel to each other in a matrix, causing uneven strength. They are usually set in matrices, or more simply, held together by a matrix with a glue-type binder. Depending on the end-use of the product, flakes are present in small quantities or occupy the whole composite.

Flakes have various advantages over fibers in structural applications. Parallel flakes filled composites provide uniform mechanical properties in the same plane as the flakes. While angle-plying is difficult in continuous fibers which need to approach isotropic properties, it is not so in flakes. Flake composites have a higher theoretical modulus of elasticity than fiber reinforced composites. They are relatively cheaper to produce and be handled in small quantities.

1.1.12 Filled Composites

Filled composites result from addition of filer materials to plastic matrices to replace a portion of the matrix, enhance or change the properties of the composites. The fillers also enhance strength and reduce weight.

Another type of filled composite is the product of structure infiltrated with a second-phase filler material. The skeleton could be a group of cells, honeycomb structures, like a network of open pores. The infiltrant could also be independent of the matrix and yet bind the components like powders or fibers, or they could just be used to fill voids. Fillers produced from powders are also considered as particulate composite.

In the open matrices of a porous or spongy composite, the formation is the natural result of processing and such matrices can be strengthened with different materials. Metal impregnates are used to improve strength or tolerance of the matrix. Metal casting, graphite, powder metallurgy parts and ceramics belong to this class of filled composites.

In the honeycomb structure, the matrix is not naturally formed, but specifically designed to a predetermed shape. Sheet materials in the hexagonal shapes are impregnated with resin or foam and are used as a core material in sandwich composites.

Fillers may be the main ingredient or an additional one in a composite. The filler particles may be irregular structures, or have precise geometrical shapes like polyhedrons, short fibers or spheres**.**

While their purpose is far from adding visual embellishment to the composites, they occasionally impart colour or opacity to the composite which they fill.

As inert additives, fillers can change almost any basic resin characteristic in all directions required, to tide over the many limitations of basic resins as far as composites are concerned. The final composite properties can be affected by the shape, surface treatment, blend of particle types, size of the particle in the filler material and the size distribution.

Filled plastics tend to behave like two different constituents. They do not alloy and accept the bonding. They are meant to develop mutually; they desist from interacting chemically with each other. It is vital that the constituents remain in co-ordination and do not destroy each others desired properties.

Matrix in a few filled composites provides the main framework while the filler furnishes almost all desired properties. Although the matrix forms the bulk of the composite, the filler material is used in such great quantities relatively that it becomes the rudimentary constituent.

The benefits offered by fillers include increase stiffness, thermal resistance, stability, strength and abrasion resistance, porosity and a favorable coefficient of thermal expansion.

However, the methods of fabrication are very limited and the curing of some resins is greatly inhibited. They also shorten the life span of some resins and are known to weaken a few composites.

1.1.13 Particulate Reinforced Composites

Microstructures of metal and ceramics composites, which show particles of one phase strewn in the other, are known as particle reinforced composites. Square, triangular and round shapes of reinforcement are known, but the dimensions of all their sides are observed to be more or less equal. The size and volume concentration of the dispersoid distinguishes it from dispersion hardened materials.

The dispersed size in particulate composites is of the order of a few microns and volume concentration is greater than 28%. The difference between particulate composite and dispersion strengthened ones is, thus, oblivious. The mechanism used to strengthen each of them is also different. The dispersed in the dispersion-strengthen materials reinforces the matrix alloy by arresting motion of dislocations and needs large forces to fracture the restriction created by dispersion.

In particulate composites, the particles strengthen the system by the hydrostatic coercion of fillers in matrices and by their hardness relative to the matrix.

Three-dimensional reinforcement in composites offers isotropic properties, because of the three systematical **orthogonal planes**. Since it is not homogeneous, the material properties acquire sensitivity to the constituent properties, as well as the interfacial properties and geometric shapes of the array. The composite's strength usually depends on the diameter of the particles, the inter-particle spacing, and the volume fraction of the reinforcement. The matrix properties influence the behaviour of particulate composite too.

1.1.14 Cermets

Cermets are one of the premier groups of particle strengthened composites and usually comprises ceramic grains of borides, carbides or oxides. The grains are dispersed in a refractory ductile metal matrix, which accounts for 20 to 85% of the total volume. The bonding between ceramic and metal constituents is the result of a small measure of mutual solutions.

Metal oxide systems show poor bonding and require additional bonding agents. Cermet structures are usually produced using power metallurgy techniques. Their potential properties are several and varied depending on the relative volumes and compositions and of the metal and ceramic constituents. Impregnation of a porous ceramic structure with a metallic matrix binder is another method used to produce cermets. Cermets may be employed as coating in a power form. The power is sprayed through a gas flame and fused to a base material. A wide variety of cermets have been produced on a small scale, but only a few have appreciable value commercially.

1.1.15 Microspheres

Microspheres are considered to be some of the most useful fillers. Their specific gravity, stable particle size, strength and controlled density to modify products without compromising on profitability or physical properties are its their most-sought after assets.

Solid glass Microspheres, manufactured from glass are most suitable for plastics. Solid glass Microspheres are coated with a binding agent which bonds itself as well as the sphere's surface to the resin. This increases the bonding strength and basically removes absorption of liquids into the separations around the spheres.

Solid Microspheres have relatively low density, and therefore, influence the commercial value and weight of the finished product. Studies have indicated that their inherent strength is carried over to the finished moulded part of which they form a constituent.

Hollow microspheres are essentially silicate based, made at controlled specific gravity. They are larger than solid glass spheres used in polymers and commercially supplied in a wider range of particle sizes. Commercially, silicate-based hollow microspheres with different compositions using organic compounds are also available. Due to the modification, the microspheres are rendered less sensitive to moisture, thus reducing attraction between particles. This is very vital in highly filled liquid polymer composites where **viscosity** enhancement constraints the quantum of filler loading.

Formerly, hollow spheres were mostly used for thermosetting resin systems. Now, several new strong spheres are available and they are at least five times stronger than hollow microspheres in static crush strength and four times long lasting in shear.

Recently, ceramic alumino silicate microspheres have been introduced in thermoplastic systems. Greater strength and higher density of this system in relation to siliceous microspheres and their resistance to abrasions and considerable strength make then suitable for application in high pressure conditions.

Hollow microspheres have a lower specific gravity than the pure resin. This makes it possible to use them for lightning resin dominant compounds. They find wide applications in aerospace and automotive industries where weight reduction for energy conservation is one of the main considerations.

But their use in systems requiring high shear mixing or high-pressure moulding is restricted as their crush resistance is in no way comparable to that of solid spheres. Fortunately, judicious applications of hollow spheres eliminate crazing at the bends in the poly-vinyl chloride plastisol applications, where the end component is subjected to bending stresses.

Microspheres, whether solid or hollow, show properties that are directly related to their spherical shape let them behave like minute ball bearing, and hence, they give better flow properties. They also distribute stress uniformly throughout resin matrices.

In spherical particles, the ratio of surface area to volume is minimum. In resin-rich surfaces of reinforced systems, the microspheres which are free of orientation and sharp edges are capable of producing smooth surfaces.

1.1.16 Solidification of Composites

Directional solidification of alloys is adopted to produce in-situ fibers. They are really a part of the alloy being precipitated from the melt, while the alloy is solidifying. This comprises eutectic alloys wherein the molten material degenerates to form many phases at a steady temperature. When the reaction is carried out after ensuring the solidifying phases, directionally solidified eutectics result.

During the solidification of alloy, crystals nucleate from the mould or some relatively cooler region. A structure with many crystalline particles or grains results from this and grows into each other. When unidirectionallly solidified, random coalescing is not allowed to occur.

1.2 CLASSIFICATION OF COMPOSITES

1.2.1 Classification

Composite materials are commonly classified at following two distinct levels:

- The first level of classification is usually made with respect to the matrix constituent. The major composite classes include Organic Matrix Composites (OMCs), Metal Matrix Composites (MMCs) and Ceramic Matrix Composites (CMCs). The term organic matrix composite is generally assumed to include two classes of composites, namely Polymer Matrix Composites (PMCs) and carbon matrix composites commonly referred to as carbon-carbon composites.
- The second level of classification refers to the reinforcement form - fibre reinforced composites, laminar composites and particulate composites. Fibre reinforced composites can be further divided into those containing discontinuous or continuous fibres.
- Fibre Reinforced Composites are composed of fibres embedded in matrix material. Such a composite is considered to be a discontinuous fibre or short fibre composite if its properties vary with fibre length. On the other hand, when the length of the fibre is such that any further increase in length does not further increase, the elastic modulus of the composite, the composite is considered to be continuous fibre reinforced. Fibres are small in diameter and when pushed axially, they bend easily although they have very good tensile properties. These fibres must be supported to keep individual fibres from bending and buckling.
- Laminar Composites are composed of layers of materials held together by matrix. Sandwich structures fall under this category.
- Particulate Composites are composed of particles distributed or embedded in a matrix body. The particles may be flakes or in powder form. Concrete and wood particle boards are examples of this category.

1.2.2 COMPARISON WITH METALS

Requirements governing the choice of materials apply to both metals and reinforced plastics. It is, therefore, imperative to briefly compare main characteristics of the two.

- Composites offer significant weight saving over existing metals. Composites can provide structures that are 25-45% lighter than the conventional aluminium structures designed to meet the same functional requirements. This is due to the lower density of the composites.

Depending on material form, composite densities range from 1260 to 1820 kg/in^3 (0.045 to 0.065 lb/in^3) as compared to 2800 kg/in^3 (0.10 lb/in^3) for aluminium. Some applications may require thicker composite sections to meet strength/stiffness requirements, however, weight savings will still result.

- Unidirectional fibre composites have specific tensile strength (ratio of material strength to density) about 4 to 6 times greater than that of steel and aluminium.
- Unidirectional composites have specific -modulus (ratio of the material stiffness to density) about 3 to 5 times greater than that of steel and aluminium.
- Fatigue endurance limit of composites may approach 60% of their ultimate tensile strength. For steel and aluminium, this value is considerably lower.
- Fibre composites are more versatile than metals, and can be tailored to meet performance needs and complex design requirements such as aero-elastic loading on the wings and the vertical & the horizontal stabilisers of aircraft.
- Fibre reinforced composites can be designed with excellent structural damping features. As such, they are less noisy and provide lower vibration transmission than metals.
- High corrosion resistance of fibre composites contributes to reduce life- cycle cost.

- Composites offer lower manufacturing cost principally by reducing significantly the number of detailed parts and expensive technical joints required to form large metal structural components. In other words, composite parts can eliminate joints/fasteners thereby providing parts simplification and integrated design.
- Long term service experience of composite material environment and durability behaviour is limited in comparison with metals.

1.3: ADVANTAGES AND DISADVANTAGE OF COMPOSITES

1.3.1 advantages

Summary of the advantages exhibited by composite materials, which are of significant use in aerospace industry are as follows:

- High resistance to fatigue and corrosion degradation.
- 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.
- Due to greater reliability, there are fewer inspections and structural repairs.
- Directional tailoring capabilities to meet the design requirements. The fibre pattern can be laid in a manner that will tailor the structure to efficiently sustain the applied loads.
- Fibre to fibre redundant load path.
- Improved dent resistance is normally achieved. Composite panels do not sustain damage as easily as thin gage sheet metals.
- 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.
- 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 & assembly costs are thus reduced.
- High resistance to impact damage.
- 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.
- Like metals, thermoplastics have indefinite shelf life.
- 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 minimise thermal stresses.
- Manufacture and assembly are simplified because of part integration (joint/fastener reduction) thereby reducing cost.
- The improved weatherability of composites in a marine environment as well as their corrosion resistance and durability reduce the down time for maintenance.
- Close tolerances can be achieved without machining.
- Material is reduced because composite parts and structures are frequently built to shape rather than machined to the required configuration, as is common with metals.
- Excellent heat sink properties of composites, especially Carbon-Carbon, combined with their lightweight have extended their use for aircraft brakes.
- Improved friction and wear properties.
- The ability to tailor the basic material properties of a Laminate has allowed new approaches to the design of aeroelastic flight structures.

The above advantages translate not only into airplane, but also into common implements and equipment such as a graphite racquet that has inherent damping, and causes less fatigue and pain to the user.

1.3.2 Disadvantage of Composites

Some of the associated disadvantages of advanced composites are as follows:

a). High cost of raw materials and fabrication.
b). Composites are more brittle than wrought metals and thus are more easily damaged.
c). Transverse properties may be weak.
d). Matrix is weak, therefore, low toughness.
e). Reuse and disposal may be difficult.
f). Difficult to attach.
g). 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.

h). Analysis is difficult.
i). Matrix is subject to environmental degradation.

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

New technology has provided a variety of reinforcing fibres and matrices those can be combined to form composites having a wide range of exceptional properties. Since the advanced composites are capable of providing structural efficiency at lower weights as compared to equivalent metallic structures, they have emerged as the primary materials for future use.

In aircraft application, advanced fibre reinforced composites are now being used in many structural applications, viz. floor beams, engine cowlings, flight control surfaces, landing gear doors, wing-to-body fairings, etc., and also major load carrying structures including the vertical and horizontal stabiliser main torque boxes.

Composites are also being considered for use in improvements to civil infrastructures, viz., earthquake proof highway supports, power generating wind mills, long span bridges, etc.

Module-2: Basic Constituent materials in Composites

Learning unit-3

2.3 Matrix Materials

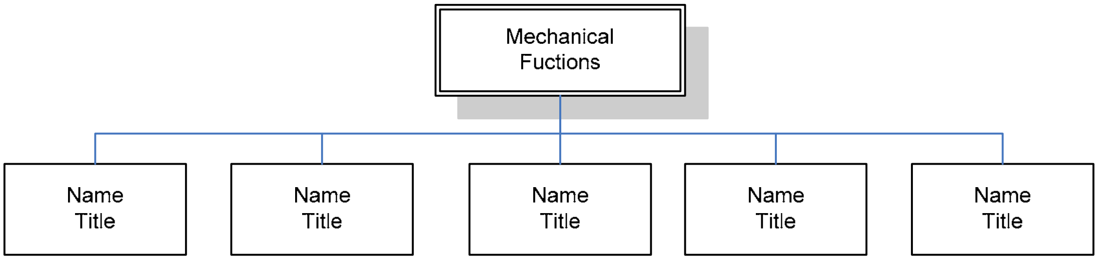
2.3.0 Introduction

Although it is undoubtedly true that the high strength of composites is largely due to the fibre reinforcement, the importance of matrix material cannot be underestimated as it provides support for the fibres and assists the fibres 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 fibres 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 fibre support, whereas a resin starved part is weaker because of void areas and the fact that fibres are not held together and they are not well supported.

2.3.1 Functions of a Matrix

In a composite material, the matrix material serves the following functions:

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



The matrix plays a minor role in the tensile load-carrying capacity of a composite structure. However, selection of a matrix has a major influence on the interlaminar shear as well as in-plane shear properties of the composite material. The interlaminar shear strength is an important design consideration for structures under bending loads, whereas the in-plane shear strength is important under torsion loads. The matrix provides lateral support against the possibility of fibre buckling under compression loading, thus influencing to some extent the compressive strength of the composite material. The interaction between fibres and matrix is also important in designing damage tolerant structures. Finally, the processability and defects in a composite material depend strongly on the physical and thermal characteristics, such as viscosity, melting point, and curing temperature of the matrix.

2.3.2 Properties of a Matrix

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

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

As stated above, the matrix causes the stress to be distributed more evenly between all fibres by causing the fibres to suffer the same strain. The stress is transmitted by shear process, which requires good bonding between fibre and matrix and also high shear strength and modulus for the matrix itself. One of the important properties of cured matrix system is its glass transition temperature (T_g) at which the matrix begins to soften and exhibits a decrease in mechanical properties. The glass transition temperature is not only an important parameter for dimensional stability of a composite part under influence of heat, but it also has effect on most of the physical properties of the matrix system at ambient temperature.

As the load is primarily carried by the fibres, the overall elongation of a composite material is governed by the elongation to failure of the fibres that is usually 1-1.5%. A significant property of the matrix is that it should not crack. The function of the matrix in a composite material will vary depending on how the composite is stressed. For example, in case of compressive loading, the matrix prevents the fibres from buckling and is, therefore, a very critical part of the composite since without it, the reinforcement could carry no load. On the contrary, a bundle of fibres could sustain high tensile loads in the direction of the filaments without a matrix. Some of the *physical properties* of the matrix which influence the behaviour of composites are:

- Shrinkage during cure,
- Modulus of elasticity,
- Ultimate elongation,
- Strength (tensile, compressive and shear), and
- Fracture toughness.

2.3.3 Factors considered for Selection of Matrix

In selecting matrix material, following factors may be taken into consideration:

- The matrix must have a mechanical strength commensurate with that of the reinforcement i.e. both should be compatible. Thus, if a high strength fibre is used as the reinforcement, there is no point using a low strength matrix, which will not transmit stresses efficiently to the reinforcement.
- The matrix must stand up to the service conditions, viz., temperature, humidity, exposure to ultra-violet environment, exposure to chemic3l atmosphere, abrasion by dust particles, etc.
- The matrix must be easy to use in the selected fabrication process.
- Smoke requirements.
- Life expectancy.
- The resultant composite should be cost effective.

The fibres are saturated with a liquid resin before it cures to a solid. The solid resin is then said to be the matrix for the fibres.

2.3.4 General types of Matrix Materials

In general, following general following types of matrix materials are available:

- Thermosetting material;
- Thermoplastic material;
- Carbon;
- Metals;
- Ceramics;
- Glass Matrix.

A thermosetting material is the one which when cured by heat or chemical reaction is changed into an infusible and insoluble material. Thermosetting resins undergo irreversible chemical cross-linking reaction upon application of heat. On the other hand, thermoplastics do not undergo a chemical reaction on application of heat. They simply melt on application of heat and pressure to form a component. Thermoplastics can be softened and they undergo large and rapid change in viscosity with variation in temperature. Thermoplastics can be repeatedly softened by heating and hardened by cooling.

Some of the significant *differences* between thermosets and thermoplastics are given below:

Thermosets	**Thermoplastics**
• Resin cost is low.	• Resin cost is slightly higher.
• Thermosets exhibit moderate shrinkage.	• Shrinkage of thermoplastics is low
• Interlaminar fracture toughness is low.	• Interlaminar fracture toughness is high.
• Thermosets exhibit good resistance	• Thermoplastics exhibit poor resistance

to fluids and solvents.	to fluids and solvents.
• Composite mechanical properties are good.	• Composite mechanical properties are good.
• Prepregability characteristics are excellent.	• Prepregability characteristics are poor.
• Prepreg shelf life and out time are poor.	• Prepreg shelf life and out time are excellent.

Different types of thermosets and thermoplastic resins commonly in use are as follows:

Thermosets	**Thermoplastics**
• Phenolics & Cyanate ester	• Polypropylene
• Polyesters & Vinyl esters	• Nylon (Polyamide)
• Polyimides	• Poly-ether-imide (PEI)
• Epoxies	• Poly-ether-sulphone (PES)
• Bismaleimide (BMI)	• Poly-ether -ether-ketone (PEEK)

2.3.4.1 Thermosetting Materials

The major group of materials used today in the aircraft industry contains thermosetting matrix resins.

Thermoset Resin

Polyesters, epoxy and other resins in liquid form contain monomers (consisting of simple molecules), which convert into polymers (complex cross-linked molecules) when the resin is cured. The resulting solid .is called **thermosets**, which is tough, hard, insoluble and infusible. The property of infusibility distinguishes thermosets from the thermoplastics. Cure and **polymerisation** refer to the chemical reactions that solidify the resin. Curing is accomplished by heat, pressure and by addition of curing agents at room temperature.

Thermosetting materials can be further divided into two groups depending on how they react to form their network structure. For example, epoxies and polyesters react to form a network structure without formation of a volatile by-product. Phenolics react to form a volatile by-product i.e., water. The fact that some thermosets form volatile by-products means that high pressure laminating techniques must be used to prevent the formation of voids or other defects. Epoxies and polyesters can be cured at atmospheric pressures and also at ambient temperatures.

Polyester matrices have been in use for the longest period in the widest range of structures. Polyesters cure with the addition of a catalyst (usually a peroxide) resulting in an exothermic reaction, which can be initiated at room temperature. The most widely used matrices for advanced composites have been the epoxy resins. These resins cost more than polyesters and do not have the high temperature capability of the Bismaleimides or Polyimides. However, they are widely used due to the following advantages.

- Adhesion to fibres and to resin;

- No by-products formed during cure;
- Low shrinkage during cure;
- High or low strength and flexibility;
- Resistance to solvents and chemicals;
- Resistance to creep and fatigue;
- Wide range of curative options;
- Adjustable curing rate;
- Good electrical properties.

Epoxies do have few inherent disadvantages also, viz.

- Resins and curatives are somewhat toxic in uncured form;
- Moisture absorption resulting into change in dimensions and physical properties;
- Limited to about 200°C (392°F) upper temperature use;
- Difficult to combine toughness and high temperature resistance;
- High thermal coefficient of expansion;
- High degree of smoke liberation in a fire;
- May be sensitive to ultraviolet light degradation;
- Slow curing.

There are two resin systems in common use for higher temperatures, bismaleimides and polyimides. New designs of aircraft demand a 177°C (350°F) operating temperature requirement not met with by other common structural resin systems. Bismaleimides, with higher modulus values and established higher thermal ratings, earned a strong position for use in military aircraft primary structures with recent selection for the F-22 fighter. Bismaleimides offer mechanical properties higher than those of epoxies at elevated temperature resulting in either lower weight or increased safety margins; epoxy-like processing using standard autoclave cure processes; and cost comparable to epoxy parts. Polyimides are the highest temperature polymers in advanced composite use with a long-term upper temperature limit (Tg) of 232°C (450°F) or 316°C (600°F).

The Cyanate ester resins have shown superior dielectric properties and much lower moisture absorption than any other structural resin for use in composites. The dielectric properties have enabled their use as adhesives in multilayer microwave printed circuit boards and the low moisture absorbance have caused them to be the resin of universal choice for structurally stable spacecraft components. The phenolic triazine resins also have superior elevated temperature properties along with excellent properties at cryogenic temperature. Both Bismaleimide and Cyanate ester resins have been evolved as easy-to-process thermosetting resins qualified for 177°C (350°F) hot-wet service.

Vinyl ester resins are the most recent addition to the family of thermosetting polymers. There are two basic types of vinyl esters having commercial significance, viz., the general-purpose lower molecular weight vinyl esters and the higher heat resistant vinyl esters. General-purpose vinyl esters have excellent mechanical properties and outstanding chemical resistance to acids, bases and many solvents. Heat resistant vinyl esters increase the heat resistance of composites by 17-27°C (30-50°F) over the general-purpose type. This often translates into higher useful operating temperatures for vinyl esters based reinforced plastics even in corrosive environment. Resins of this type are more reactive and more caution is required in fabrication of composite laminates.

2.3.4.1.0 Typical Properties of Thermosetting Materials

Salient properties of some of the above-referred thermosetting materials are given in the following paras.

2.3.4.1.1 Phenolics

- Low cost,
- Capability to be B-Staged,
- Excellent high temperature resistance up to 205-260°C (400-500°F),
- Good mechanical strength,
- Dimensional and thermal stability,
- Good laminate properties,
- Hot molding (cold molding very rarely),
- Good fire resistance and very low smoke emission,
- Curing temperature is 175°C (350°F),
- High chemical resistance, and
- Good dielectric properties.

Some of the disadvantages are: by-products are produced during curing, there is high shrinkage on cure, and phenolic laminates are porous.

2.3.4.1.2 Polyesters

- Low cost,
- Good handling characteristics,
- Low viscosity and versatility,
- Good mechanical strength,
- Good electrical properties,
- Good heat resistance,
- Cold and hot molding,
- Flame resistant with fire proof additive ,and
- Curing temperature is 120°C (250°F).

Some of the disadvantages are: interlaminar shear is less than that of epoxies, lower strength than that of epoxies, fair weatherability, high curing shrinkage, and poor chemical resistance.

2.3.4.1.3 Vinyl Ester

- Vinyl ester combines inherent toughness with outstanding heat and chemical resistance,
- Corrosion-resistance, and
- Possesses low ester content and low unsaturation resulting in greater resistance to hydrolysis and less shrinkage during cure.

Some of the disadvantages are: vinyl esters are not as good as epoxy resins with regard to bondability to other surfaces and high cost.

2.3.4.1.4 Polyimides

- Excellent strength retention for long term in 260-315°C (500-600°F) range and short term in 370°C (700°F) range,
- Excellent electrical properties,
- Excellent mechanical strength,
- Good fire resistance and low smoke emission,
- Hot molding under pressure, and
- Curing temperature is 175°C (350°F) and 315°C (600°F).

Some of the disadvantages are: laminates are porous, volatile by-products are given off during cure, and long post cure is required.

2.3.4.1.5 Epoxies

- Make an excellent matrix material because of their versatility,
- Good handling characteristics,
- Low shrinkage,
- Excellent adhesive properties,
- Flame resistant,
- Good chemical resistance,
- Good mechanical properties including toughness,
- Offer considerable variety for formulating Prepreg resins,
- Hot molding (cold molding rarely),
- High smoke emission,
- Curing temperature is 120-175°C (250-3500F), and
- No by-products formed during cure.

Some of the disadvantages are: require 4.4°C (40°F) storage and shipment, service temperature is only 93-1O7°C (200-225°F) and laminate displays light brittleness.

2.3.4.1.6 Bismaleimide

- Superior to epoxy in maximum hot-wet use temperature.
- In comparison to conventional epoxies, bismaleimides have higher temperature resistance.
- Damage tolerance is generally comparable to that of commercial aerospace epoxy resins.

One factor that limits wider use of Bismaleimide is that they require higher curing temperatures than used for epoxies.

2.3.4.2 Thermoplastic Resin

As stated earlier, thermoplastics can be repeatedly softened by heating, and hardened by cooling. Thermoplastics possess several advantages over the thermosets, one of the most important being that they do not need storing under refrigeration. They also possess improved damage tolerance, environmental resistance, fire resistance, recyclability and potential for fast processing. Primary reason for the use of thermoplastics is their cost effective processing. Increased use for thermoplastics is also due to three different reasons, viz.

- First - Processing can be faster than that of thermoset composites since no curing reaction is required. Thermoplastic composites require only heating, shaping and cooling.
- Second - The properties are attractive, in particular, high delamination resistance and damage tolerance, low moisture absorption and the excellent chemical resistance of semi-crystalline polymers.
- Third- In the light of environmental concerns, thermoplastic composites offer other advantages also. They have low toxity since they do not contain reactive chemicals (therefore storage life is infinite).

Because it is possible to remelt and dissolve thermoplastics, their composites are also easily recycled or combined with other recycled materials in the market for molding compounds. Since the release of gases during processing and inherent brittleness is serious disadvantage of some thermoset resins, thermoplastic composites are of great interest. Thermoplastics usually require high temperature and pressure during processing and generally lack good solvent resistance. Process conditions for high performance thermoplastics are temperature in the range of 300 to 400°C (570 to 750°F) and pressure between atmospheric pressure for thermofolding process to 20 times the atmospheric pressure for high performance press forming. Due to their high strains to failure, thermoplastics are the only matrices currently available that are suited to thermo-forming and other forms of rapid manufacture. Thermo-loading is the most straight forward thermoplastic forming technique where a straight line is heated and folded. The process is used in volume applications like aircraft floor boards. Thermofolding operations can be carried out on solid laminate materials as well as on sandwich panels.

Press Forming process for thermoplastic composites is related to that used for metals, the difference being that the blank material is heated to a high temperature and processed within a very short time span. Applications for press forming are reinforcement ribs.

To date, applications of thermoplastic composites have ranged from small, simple, structural details such as ribs or spars up to relatively large structures. Table given below lists some of these applications in aircraft industry.

Polymer Type	*Applications*
• PEEK	• *Airbus A320 vertical stabilizer brackets* • *EH-101 helicopter floor* • *F-117 rudder assembly* • *F-22 weapons bay doors* • *F-22 access covers* • *OH-58d helicopter horizontal stabiliser*
• Poly-phenylene-sulphide	• *Airbus A320-200 rudder nose ribs* • *Airbus A340 aileon ribs*

	• *Airbus A340-500/600 inboard wing leading edge assemblies* • *Airbus A340-500/600 inboard wing access panels* • *Airbus A340-500/600 keel beam connecting angles* • *Airbus A340-500/600 keel beam ribs* • *AirbusA340-500/600pylon panels* • *Fokker50 main landing gear door*
• PEI	• *737 smoke detector pans* • *737/757 galleys* • *747. stowage bins* • *767 aircraft acoustical tiles* • *767andotherBoeingaircraftbrackets* • *AirbusA320 bulk cargo floor sandwich structural Panels* • *Airbus A330 lower wing fairings* • *A3XX main stair case (developmental)* • *Beluga heavy duty entrance floor panel* • *Dornier 328 landing flap ribs* • *Dornier 328 ice protection plates* • *Fokker 50 ice protection plates* • *Fokker 50 trailing edge wing shroud skins* • *Fokker 70/100 structural floor panels* • *Gulfstream G-V structural floor panels* • *Gulfstream IV and V rudder ribs* • *Gulfstream IV and V rudder trailing edges* • *Learjet air steps* • *Galleys on most commercial aircraft*

Amongst the thermoplastics, polypropylene and polyamides are used in applications where moderate temperatures are experienced. On the other hand, poly-ether-imide (PEI), poly-ether-sulphone (PES) and PEEK are used in applications where temperature requirements are comparatively high. Characteristic temperatures of these thermoplastics along with their mechanical properties are given below:

Thermoplastic	T_g° C	T_m° C	Processing Temperature (° C)	Tensile Modulus (GPa)	Tensile Strength (MPa)	Fracture Toughness (kJ/m^2)
Polypropylene	-10	165	200 - 240	1.1 – 1.6	30 - 40	-
Polyamide	55	265	270 - 320	2.5 – 3.8	50 – 80	-
PEEK	143	343	380 – 400	3.1 – 3.8	90 – 100	4.0
PES	220	None	300 - 320	2.6	80	1.9
PEI	217	None	335 - 420	3.0	105	3.3

As indicated above, thermoplastics with low T_g such as polypropylene and Polyamides have lower modulus and strength. However, their fracture toughness is higher and valid data is difficult to obtain. Thermoplastics with continuous use temperature above 150°C (302°F) are of particular interest since they perform better than epoxies. Table given below gives the T_g and the heat deflection temperature (HDT) for various thermoplastics. HDT is the temperature at which a critical deflection of the sample is obtained. HOT is determined by subjecting the material to static load (typically1.8 MPa) and slowly increasing the temperature till critical deflection takes place.

Thermoplastic	Structure	T_g (° C)	HDT (° C)	Variation of HDT
PES	Amorphous	220	203	Below Tg
Polyamide	Amorphous	217	200	Below Tg
PEEK	Crystalline	-10	60	Above Tg
PES	Crystalline	55	75	Above Tg
PEI	Crystalline	143	160	Above Tg

In crystalline thermoplastics, HDT is some what higher than T_g. On the other hand, HDT is below T_g for amorphous thermoplastics. Creep effects in thermoplastics are very strong close to and above T_g. For this reason, the maximum temperature for continuous service under significant load is unlikely to exceed a temperature of 20°C (68°F) below T_g for crystalline thermoplastics. The primary advantage of crystallinity is, therefore, chemical resistance. Table given below shows that crystalline thermoplastics have better chemical resistance than the amorphous ones.

Material	Hydraulic Fluid	Chlorinated Hydro-carbons	Ketones	Esters	H_2O absorption (%)
Polyamide	-	No effect	No effect	No effect	8
PEEK	No effect	No effect	No effect	No effect	0.5
PES	Absorbed	Dissolved	Absorbed	Absorbed	0.3
PEI	No effect	Dissolved	Absorbed	Absorbed	1.2

Due to the above advantages, PEEK is a widely used thermoplastic. As stated above, it possesses glass transition temperature of 143°C (290°F).Above this temperature, as expected, there is a drop in mechanical properties but it maintains useful properties up to its melting point of 343°C (650°F).The polymer can be reinforced to further improve properties and maintain them up to a higher temperature. Glass or carbon fibres are the commonly used reinforcements. Some of the significant properties of PEEK are as follows:

- Retention of useful mechanical properties at temperatures up to 315°C (600°F).
- PEEK exhibits a high fatigue resistance. It is also resistant to thermal fatigue when the temperature cycle is less than 150°C (300°F).
- PEEK has higher impact strength as compared to other thermoplastics but lower than most metals.
- Although there is drop in mechanical properties after glass transition temperature, PEEK is significantly stronger than most of other thermoplastics at higher temperatures.

- Many thermoplastics are vulnerable to continuously applied loads as they are susceptible to creep. PEEK exhibits higher creep over a wide range of temperature.
- Fracture toughness of PEEK is about 50-100 times higher than epoxies.
- It exhibits low water absorption characteristics, which is less than 0.5% at 23°C (73°F) compared to 4-5% for conventional aerospace epoxies.
- It offers resistance to a wide range of process chemicals.
- PEEK offers good resistance to wear and chemicals.
- It shows good resistance to gamma radiation thereby offering its use as wire covering material for control cabling within the containment area of nuclear reactors.

One of the major advantages of using thermoplastics is their ability to produce parts to finished shape and tolerance .The most common processing technique employed for thermoplastics is injection molding. However, for larger parts and short production, compression molding has proved cost effective. It is frequently possible to produce thermoplastic parts, which function more efficiently than conventionally manufactured parts. By using a thermoplastic, which can be molded to almost any shape, it is possible to produce parts to the optimum design in a single step.

2.3.4.3 Carbon matrices

Carbon fibre reinforced carbon is a high strength composite material, which is also resistant to high temperature in a non-oxidising atmosphere. It is composed of a carbon matrix into which reinforcing carbon fibres are embedded. Such a material was first used under extreme thermal and mechanical loads in space technology. The criteria for selection of carbon-carbon composites as a thermal protection system are based on the following requirements:

- Maintenance of reproducible strength levels at 1650°C (3002°F).
- Sufficient stiffness to resist flight loads and large thermal gradients.
- Low coefficient of thermal expansion to minimize induced thermal stresses.
- Tolerance to impact damage.

Carbon-carbon composites are used in many applications due to their
Following properties:

- Low specific weight.
- High heat absorption capacity.
- Resistance to thermal shock.
- High resistance to damage.
- Exceptional frictional properties at high energy levels.
- Resistance to high temperatures.
- Chemical inertness.

The disadvantages of carbon-carbon composites are the lack of resistance to oxidation at temperatures in excess of 500°C (930°F) and economic problems namely long manufacturing time and high production cost.

To allow the use of carbon-carbon composites in an oxidising atmosphere, they must be compounded with materials that produce oxidation protective coatings through thermo-chemical reaction with oxygen above 2000°C (3630°F).

Important areas of use of carbon-carbon composites are aircraft brakes, brake system for high-speed trains and racing cars. Its application as braking material is due to high-energy absorption capacity, low specific weight and the fact that it does not contain any environmentally harmful elements like asbestos. Some other examples of its use include heavy duty clutches, tools for high temperature production of alloys like titanium, etc.

There are two production methods to obtain a carbon matrix reinforced with carbon fibres.

1. Chemical vapour impregnation - where a preform is compressed by deposition of carbon from a gaseous phase.
2. The liquid phase impregnation - where a carbon preform is compressed by means of multiple impregnations with resin and intermediate carbonisation steps.

Carbon-Carbon Brakes

As we know, conventional aircraft landing gear brakes are made up of three principal parts:

1. A torque tube,
2. A loading system for the heat sink, and
3. A heat sink.

The heat sink is made of rotors and stators. The stators are located around the torque tube while the rotors are fitted to the wheel. The object of the heat sink is to transform kinetic energy to thermal energy through the friction between stators and rotors. Consequently, the performance of brakes depends almost completely upon the heat sink material. The material, which can be used for a heat sink, should have the following properties:

- Very high specific heat - the higher the specific heat, the greater the amount of kinetic energy absorbed and better will be the brake efficiency.
- Good mechanical properties at high temperature - since the temperature of the heat sink can be very high, the mechanical properties of the rotors and stators should stay good enough so as to ensure a good brake torque transmission.
- Good resistance to thermal shock - at the beginning of the braking, the heat sink material is very cold and within a few seconds reaches a very high temperature due to large amount of absorbed energy. Therefore, the heat sink material should have good resistance to thermal shock.
- Good frictional characteristics at high temperatures - the brake torque should stay as smooth as possible all along the braking process- even at the end when the temperature is very high.
- Low thermal expansion to avoid deformation.
- As light as possible so as to save on weight.

Due to the above mentioned properties of these composites, carbon-carbon brakes are able to meet the brake requirements in normal and overweight landing conditions and also during rejected take-offs. The performance of carbon-carbon brakes, therefore, is superior to that of brakes made of conventional materials. In case of a normal landing, the maximum temperature allowed is limited by the metallic parts, which are in the heat sink environment. They must not be damaged if we want to reuse the brake, which is the case after normal landing .In case of rejected take-off, the only requirement is to stop the aircraft and, therefore, the maximum allowed temperature is dependent on the heat sink material. The limit for steel is about 1000°C (1830°F) beyond which it exhibit mechanical frictional properties will no longer. Steel brakes absorb, rather than release, a great deal of heat. This eventually melt the brakes and poses safety problems. The brakes can overheat and leave an aircraft stranded on the runway after landing. On the other hand, carbon can handle 3-4 times the amount of heat, as compared to steel, without melting. For carbon-carbon, the maximum allowed temperature is about 2000°C (3630°F). Thus if carbon-carbon brakes are used in place of steel brakes, we will have, for the same weight, a much more efficient and secure system or in other words for the same efficiency, the system will be much lighter.

Disk brakes for aircraft are the representation of a heat sink. They are composed of a number of disks ,half of which are keyed to the non-rotating brake mechanism (stators), and the other half rotate with the wheel to which they are keyed (rotors). Braking is accomplished by forcing the disks together, at which time friction is converted into heat that must be dissipated. This requires a material that is resistant to thermal shock, stable at very high temperatures, and has low thermal expansion as well as good thermal conductivity. In addition, the material should have a friction coefficient of about0.3 to 0.5 to ensure good stopping performance.

Carbon-carbon composites have all of these properties, which provide nearly four times the stopping power of copper or steel brakes. In conclusion, the advantages of the carbon-carbon brakes may be summarised as:

- Smooth braking,
- Lighter brake (carbon brakes weigh approximately 1!3rd less than the steel brakes),
- High efficiency brake,
- Increased life (nearly 2-3 times), and
- Cost effectiveness.

Carbon-carbon brakes are presently being used in number of aircraft viz. Concord, Airbus and Boeing family, etc. As an example, the weight saving by using carbon-carbon brakes on Boeing family of aircraft is as follows:

Aircraft	Weight Saving (Kg)
B-747	635
B-757	272
B-767	408

Life projection of carbon-carbon brakes and steel brakes is as follows:

Aircraft	Estimated Loading	
	Carbon-carbon	Steel
B-747	2000	800
B-757	3000	1500

B-767	3000	1500

Other application of carbon-carbon composites is the one piece, bladed turbine rotor that is coated to prevent oxidation. The rotor offers higher temperature performance without cooling. Gas turbine engine applications using carbon-carbon composites include exhaust nozzle flaps and seals, augmenters, combustors and acoustic panels. Carbon-carbon composite are being used in products such as the nozzle in the F-l00 jet engine afterburner, turbine wheels operating at a speed more than 40000 rpm, leading edges for missiles and for the space shuttle. Pushing the state of the art in carbon-carbon composite is the piston for internal combustion engines. The carbon-carbon pistons have exhibited reduction in weight and increase in mechanical and thermal efficiencies of the engine. The carbon-carbon piston concept features a low piston-to-cylinder wall clearance. Carbon-carbon material maintains its strength at elevated temperatures. Allowing the piston to operate at higher temperatures and pressures than those of a comparable metal piston. The high emittance and low thermal conductivity of the carbon-carbon piston should improve the thermal efficiency of the engine because less heat energy is lost to the piston and cooling system. The elimination of rings reduces friction, thus improving mechanical efficiency. Besides being lighter than conventional pistons, the carbon-carbon piston can produce cascading effects that could reduce weight of other reciprocating components such as the crankshaft, connecting rods, flywheels and balances, thus improving specific engine performance.

2.3.4.4 Metallic Matrices

Metallic matrices are essential constituents for fabrication of Metal Matrix Composites (MMC), which have potential for structural materials at high temperatures. Metal matrix has the advantage over polymeric matrix in applications requiring a long-term resistance to severe environments, such as high temperature. The yield strength and modulus of most metals are higher than those for polymers, which is an important consideration for applications requiring high transverse strength and modulus as well as compressive strength for the composite. Another advantage of using metals is that they can be plastically deformed and strengthened by a variety of thermal and mechanical treatments. However, metals have a number of disadvantages, namely, they have high specific gravities, high melting points (therefore, high process temperatures), and a tendency toward corrosion at the fibre/matrix interface.

While a variety of matrix materials has been used for making MMCs, the major emphasis has been on the development of lighter MMCs using aluminum and titanium alloys, due to the significant potential of improvement in the thrust to-weight ratio for the aerospace, space and automotive engines.

Aluminium alloy matrix composites are suited to applications below the temperatures of 400°C (750°F). For higher temperatures, titanium based alloys offer promise as matrices. For applications in excess of 900°C (1650°F), fibre reinforced super alloys are used with most promising reinforcements being tungsten alloy wires. In spite of their high density, such composites are being considered for turbine blades and vanes in aircraft and rocket motors. Compared to un-reinforced super alloys, they exhibit improved creep and fatigue strength as well as higher thermal conductivity.

Aluminium and titanium have comparatively low specific gravities and are available in a variety of alloy forms. Although magnesium is even lighter, its great affinity toward oxygen promotes atmospheric corrosion and makes it less suitable for many applications. Beryllium is the lightest of all structural metals and has a tensile modulus higher than that of steel. However, it suffers from extreme brittleness, which is the reason for its exclusion as a potential matrix material. Nickel-and cobalt-based super alloys have also been used as matrix, however, the alloying elements in these materials tend to accentuate the oxidation of fibres at elevated temperatures.

Aluminium and its alloys have attracted the most attention as matrix material in metal matrix composites. Commercially, pure aluminium has been used for its good corrosion resistance. Aluminium alloys, such as 201, 6061, and 1100, have been used for their higher tensile strength to weight ratios. Carbon fibre is used with aluminium alloys, however, at typical fabrication temperatures of 500°C (932°F) or higher, carbon reacts with aluminium to form aluminium carbide, which severely degrades the mechanical properties of the composite. Protective coatings of either titanium boride or sodium are used on carbon fibres to reduce the problem of fibre degradation as well as to improve their wetting with the aluminium alloy matrix. Carbon fibre reinforced aluminium composites are inherently prone to galvanic corrosion, in which carbon fibres act as a cathode owing to a corrosion potential of one volt higher than that of aluminium. Amore common reinforcement for aluminium alloys is Silicon Carbide (SiC).

Titanium alloys that are most useful in metal matrix composites are alpha, beta alloys (e.g. Ti-6AI-4V) and metastable beta alloys (e.g. Ti-lOV-2Fe-3AI). These titanium alloys have higher tensile strength to weight ratios as well as better strength retention at 400-500°C (752-932°F) over those of aluminium alloys. The thermal expansion coefficient of titanium alloys is closer to those for reinforcing fibres, which reduces the thermal mismatch between them. One of the problems with titanium alloys is their high reactivity with boron fibres at normal fabrication temperatures. **Borsic** (boron fibres coated with silicon carbide) and SiC fibres Show less reactivity with titanium. Improved tensile strength retention is obtained by coating boron and SiC fibres with carbon-rich layers.

Continuous silicon carbide fibre reinforced metals have been successfully applied on aerospace development programs fulfilling primary design objective of high specific strength over conventional monolithic materials. The high specific strength of silicon carbide metal matrix composites has generated significant interest for the' aircraft industry. The principal areas of interest are for high performance structures such as aircraft, missiles and engines. Some of the materials in this category under consideration are:

Silicon carbide/aluminium	Development of missile body casings. Wing structural elements
Silicon carbide/titanium	Drive shaft for core of the engine requiring increased stiffness and increased critical vibratory speed ranges. Disks for turbine engine. Hollow fan blades.

Silicon carbide/Copper	For high temperature missile application
Silicon carbide/bronze	Propellers for naval application

MMC production technology is complicated and requires satisfaction of the following conditions, of which the most significant are as follows:

- Maintaining the reinforcing fibres strength.
- Ensuring a strong bond of fibres with matrices and between the matrix layers.
- Providing the correct fibre length, greater than the critical length.
- Even distribution of fibres in the matrix.
- Orientation of fibres in the direction of the applied load.
- Achieving the required shape and dimensions of the MMC.
- Obtaining MMC strength reasonably near to theoretical.

2.3.4.4 Ceramic Matrices

While ceramic matrix composites are still in the early stages of component design, fabrication and testing, these materials, with their damage' tolerant mechanical behaviour, are considered as prime candidates for application of futuristic aircraft gas turbine engines. The selection of matrix materials for ceramic composites is strongly influenced by thermal stability and processing considerations. These include oxides, carbides, nitrides, borides and **silicides**. All these materials have melting temperatures above 1600°C (2912°F).

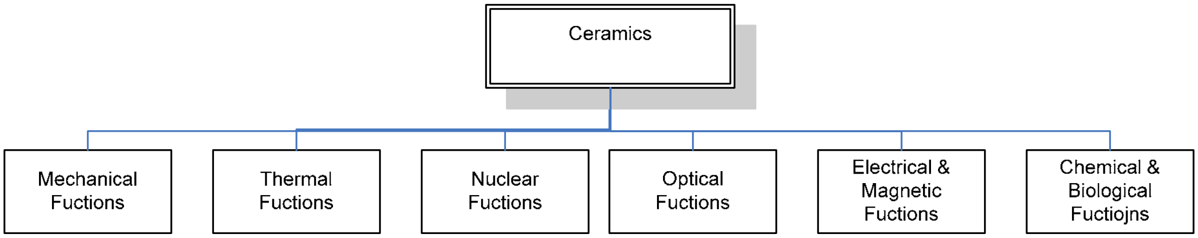


Fig 2.1

2.3.4.5 Glass Matrix

2.3.5 Curing of Resins

Thermoset resin like polyester is cured by adding a catalyst, which causes a chemical reaction without changing its own composition. The catalyst initiates the chemical reaction of the unsaturated polyester and monomer ingredient from liquid to a solid state. When used as a curing agent, catalysts are referred to as catalytic hardeners. Proper care is required to be taken while handling the catalysts as they can cause skin burning and permanent eye damage. Epoxy resin is cured by adding hardener. Unlike the catalytic hardeners used for curing polyester resin, epoxy resin hardener contains monomers, which contribute to the curing reaction. Proper care is required to be taken while handling the epoxy resin liquids and hardeners as they give off potentially harmful vapour causing skin rashes.

After curing, low shrinkage is desirable in order to minimise in-built stressing and distortion of the fibres and matrix. Desirable qualities for a matrix are that it should be tough, durable and thermally stable over a wide range of temperatures and t hat it should resist cracking, chemical attack, ultra violet light and moisture.

2.3.5.1 Ingredients and Additives used in Manufacturing of Resins

Manufacturers of all types of resins use various ingredients and additives, in different proportions, to give their resins differing properties and characteristics suited to particular applications. Some general classes of additives used are as follows:

Catalysts, Promoters, Inhibitors

In polyesters, the most important additive is catalyst or initiator. Typically, organic peroxide such 3SMEKP (Methyl Ethyl Ketone Peroxide) is used for room temperature cured processes, or benzoyl peroxide is added to the resin for heat cured molding. When triggered by heat, or used in conjunction with a promoter (such as cobalt napthenate), peroxides convert to a reactive state (exhibiting free radicals), causing the unsaturated resin to react (cross-link) and become solid. Some additives such as TBC (Tertiary Butyl Catechol) are used to slow the rate of reaction and are called inhibitors. They are used in polyester resins to extend their shelf life. Accelerators such as DMA (Dimethyl Aniline) speed up curing process.

Additives and Modifiers

A wide variety of additives are used in composites to modify materials properties and tailor the laminates performance. Although these materials are generally used in relatively low quantity by weight compared to resins, reinforcements and fillers, they perform critical functions. Additive used in thermoset and thermoplastic composites exhibits the following properties:

- **Low shrink/low profile** - When parts with smooth surfaces are required, a special thermoplastic resin, which moderates resin shrinkage, can be added to thermoset resins.
- **Fire resistance** –Combustion resistance is improved by proper choice of resin, use of fillers or flame retardant additives. Included in this category are materials containing antimony trioxide, bromine, chlorine, borate and phosphorus.
- **Air release**- Most laminating resins, gel coats and other polyester resins might entrap air during processing and application. This can cause air voids and improper fibre wet-out. Air release additives are used to reduce such air entrapment and to enhance fibre wet-out.

- **Emission control** - In open mold applications, styrene emission suppressants are used to lower emissions for air quality compliance.
- **Viscosity control**-In many composite types, it is critical to have a low, workable viscosity during production. Lower viscosity in such filled systems is usually achieved by use of wetting and dispersing additives. These additives facilitate the wet-out and dispersion of fillers resulting in lower viscosity.
- **Electrical conductivity**- Most composites do not conduct electricity. It is possible to obtain a degree of electrical conductivity by the addition of metal, carbon particles or conductive fibres. Electromagnetic interference shielding can be achieved by incorporating conductive materials.
- **Toughness**- Toughness can be enhanced by the addition of reinforcements. It can also be improved by special additives such as certain rubber or other **elastomeric** materials.
- **Antioxidants** - Plastics are sometimes modified with antioxidants, which retard or inhibit polymer oxidation and the resulting degradation of the polymer.
- **Antistatic agents** – Antistatic agents are added to polymers to reduce their tendency to attract electrical charge. Control of static electricity is essential in processing and handling operation of certain plastics, as well as in finished products. Static charges on plastics can produce shocks, present fire hazard and attract dust. The effect of static charge in computer/data processing applications, for example, is particularly detrimental.
- **Foaming agents**- Foaming agents are added to polymers during processing to form minute cells throughout the resin. Foamed plastics exhibit lower density, decrease material costs, improves electrical and thermal insulation, increase strength to weight ratio and reduce shrinkage and part warping.
- **Plasticisers**- Plasticisers are added to compounds to improve processing characteristics and offer a wide range of physical and mechanical properties. Slip and blocking agents - They provide surface lubrication. This results in reduced coefficient of friction on part surfaces and enhances release of parts from the mold.
- **Heat stabilisers**- They are used in thermoplastic resins to inhibit polymer degradation that results from exposure to heat.
- **Ultraviolet Stabilisers**- Both thermoset and thermoplastic composites use special materials which are added to prevent loss of gloss, crazing, chalking, discoloration, changes in electrical characteristics, embrittlement and disintegration due to ultraviolet (UV) radiation. Additives, which protect composites by absorbing the UV, are called ultraviolet absorbers. Materials, which protect the polymer in some other manner, are known as ultraviolet stabilisers.

2.3.5.2 Fillers

Fillers are inert substances added to reduce the resin cost and/or improve its physical properties, viz., hardness, stiffness and impact strength. Commonly used fillers are calcium carbonate, hydrated alumina and clay.

Calcium carbonate is the most widely used inorganic filler. It is available in a variety of particle sizes and treatments, especially for composite applications. They assist in reducing shrinkage of the molded parts. Most common grades of calcium carbonate filler are derived from limestone or marble.

Kaolin (hydrous aluminium silicate) is commonly known as clay. Mined clays are processed either by air flotation or by water washing to remove impurities and to classify the product for use in composites. They serve to control viscosity, promote flow, and improve resistance **to cracking in molded parts.**

Hydrated alumina is frequently used when improved fire/smoke performance is required. They provide flame retardancy while maintaining good electrical properties. When exposed to high temperature, this filler gives off water, thereby reducing the flame spread and development of smoke. They are used in most electrical and construction applications.

Calcium sulphate is a major flame/smoke retarding filler. Other commonly used fillers include mica, feldspar, silica, talc, flake glass, milled glass fibres, etc.

2.3.5.3 Colorants

Colorants are often used in composites to provide colour throughout the part. Additives can be mixed in as part of the resin or applied as part of the molding process (as a gel coat). Also, a wide range of coatings can be applied after molding.

2.3.5.4 Release Agents

Release agents facilitate removal of parts from molds. These products can be added to the resin, applied to molds, or both. Correct selection of release agents can optimise not only cycle time, but also consistency of surface finish, minimising post mold operation prior to painting or bonding. Zinc stearate is a popular mold release agent that is mixed into resin for compression molding. Waxes, silicones and other release agents may be applied directly to the surface of molds.

Release agents must be used at the lowest possible concentration. Use of excessive amounts can reduce mechanical strength and affect adhesion characteristics.

2.4 Fibre Reinforced Polymer (FRP) Laminated Composites

2.4.0 Laminate Lay-up

A structural laminate is designed to have a specific lay-up or ply arrangement, based on the various design criteria imposed on it. A laminate lay-up definition refers to the fibre orientation of successive pies in a laminate with respect to an established reference coordinate system.

2.4.1 Ply Orientation definition

The ply orientation symbol is shown in Fig 7.1. It designates the tape fibre direction or the warp direction, as applicable.

Fig 7.1

It is important that for positive and negative angles should be consistent with the coordinate system chosen.

One of the advantages of using a modern composite is its potential to orient the fibres to respond to the load requirement s. this means that the composite designer must take into consideration the characteristics of the material including the aspects of the fibre orientation in each ply and how the plies arte arranged.

Each **ply (lamina)** is defined by a number representing the direction of the fibre in degrees with respect to the reference (x) axis. 0º fibres of both tape and fabric are oriented at angles equal in magnitude but opposite in sign, (+) and (-) are used. Each (+) or (-) sign represents one ply.

2.4.1.1 Criteria used during Ply Orientation

Following criteria should be used during ply orientation:

- Attention to ply orientation on strength controlled laminates can prevent matrix and stiffness degradation. The 0º ply orientation is used to carry the longitudinal loading, the 90º ply orientation is suited to the transverse loading and the ±45º ply orientation is for shear loading.
- In order to minimise the in-plane shear, place the ±45º and -45º plies together; the in-plane shear is carried as tension and compression in the 45º plies.
- To minimise warpage and interlaminar shear within a laminate, maintain the symmetry about the centre line of the laminate.
- Stress orientation can be minimised by proper designing or by stepped laminate thickness changes.
- The placement of specific ply orientations can influence the buckling strength and damage tolerance. The outer ply orientations influence the laminate bending characteristics more than plies placed at or near the laminate bending characteristics more than the plies placed at or near the neutral axis.

2.4.2 Influence of Fibre Orientation

Strength and stiffness of a composite laminate depends on the orientation of the plies with reference to the load direction. Proper selection of ply orientation is necessary to provide a structurally efficient design. As stated above, a composite part might require 0º plies to react to the axial loads, ±45º to react to the shear loads and 90º plies to react to the side loads. For example, a lay-up of 50% of 0º plies and 50% of ±45º plies will have strength and stiffness equivalent to those of aluminium when loaded in the 0º direction.

2.4.3 Laminate Lay-up Code

Laminate lay-up code must be able to specify the following:

- The orientation of each ply relative to the reference axis;
- Number of plies, with orientation;

- Exact geometric sequence of plies;
- Adjacent plies oriented at angles equal in magnitude but opposite in sign, appropriate positive or negative signs should be assigned.

Laminate lay-up definition codes are given below:

2.4.3.1 Total Lay-up code

Fibre orientation of all the plies is sequentially written. Subscript ‘T’ outside the bracket denotes total laminate definition code, and ± sign denotes fibre orientation.

Laminate Lay-up	Code
• 45°	$[45/0/-60_2/30]_T$
0°	
-60°	
-60°	
30°	
• 45°	$[\pm45/-30/+30/0]_T$
-45°	
-30°	
30°	
0°	

2.4.3.2 Symmetric Lay-up Code

In a laminate with symmetric lay-up code, every ply above the mid-plane has an identical ply below the mid-plane. One half of the laminate, from the first ply to the mid-plane, is written sequentially within brackets. A subscript ‘S’ outside the bracket denotes symmetrical laminate definition code. When the laminate mid-plane divides a physical ply into case of symmetric laminate with odd number of plies.

Laminate Lay-up	Code
• 90°	$[90/0]_S$
0°	
0°	
90°	
• 0°	$[0/45/90/\overline{90}]_S$
45°	
90°	
90°	
90°	
45°	
0°	

2.4.3.3 Hybrid Laminate Code

A hybrid laminate includes plies of different materials within its lay-up. In this case, every ply is identified by its fibre orientation angle and a subscript on the angle identified the type or material.

Laminate Lay-up	Code
0°_B	$[0_B/\pm45_{GR}/90_{GR}]_S$
45°_{GR}	
-45°_{GR}	
90°_{GR}	
90°_{GR}	
-45°_{GR}	
-45°_{GR}	
0°_B	

2.4.3.4 Quasi Symmetric Lay-up Code

A laminate lay-up is quasi symmetric when every ply above the mid-plane has a correspondence ply below the mid-plane, with a change in the sign of its fibre orientation angle.

Laminate Lay-up	Code
45°	$[45/0/90]_{2S}$
0°	
0°	
-45°	

2.4.3.5 Set Identification Code

In this case, sets of plies repeat within a laminate lay-up. These are identified by including them within parenthesis. An integer prefix to the subscript ‘S’ refers to the laminate mid-plane.

Laminate Lay-up	Code
45°	$[45/0/90]_{2S}$
0°	
90°	
45°	
0°	
90°	
90°	
0°	
45°	
90°	
0°	
45°	

In addition to the above, following additional stacking sequences are also used design consideration points of view:

2.4.4 Special classification of Laminates

The laminates also classified based on the symmetricity of Reinforced fibres, viz:

- Symmetric laminates
- Anti-symmetric laminates
- Non-symmetric laminates

2.4.4.1 Symmetric laminates (Simplification of Analysis)

2.4.4.1.1 Mid-plane Symmetric laminates

The geometric mid-plane is the reference surface for determining if a laminate is symmetrical or not. In a mid-plane symmetric laminate, identical plies are located is above and below the mid-plane, at locations that are mirror reflections of each about the fibre orientation. In general, in order to reduce out-of-plane strains, coupled bending and stretching of the laminate and complexity of analysis; laminates should be used. The in-plane response and the bending response of a mid-plane symmetric laminate are uncoupled or independent of each other because all the B_{ij} terms are zero. This means that there is no coupling between in-plane loads and curvature nor between the bending loads and in-plane deformations. The in-plane load ($N_{x,}$ $N_{y,}$ and N_x) will only cause in-plane strains ($\varepsilon°_{x,}$ $\varepsilon°_{y,}$ $\gamma°_{xy)}$, and will not cause the laminate to bend (the mid-plane curvature is equal to zero). A laminate that is not mid-plane symmetric has non-zero $B_{ij\ terms}$ that couple the membrane and bending response. In this case, an in-plane load will cause the laminate to bend (a response that is unique in laminates and is not seen in metals). Likewise, an applied bending moment will cause the laminate mid-plane to be strained. Almost all the structural laminates are designed to be mid-plane symmetric so as to avoid the generally undesirable coupling between membrane and bending reactions.

2.4.4.1.2 Balanced Laminates

All laminates should be balanced to achieve in-plane orthotropic behaviour. A laminate is considered balanced when there are equal number of off-axis plies in the +θ and –θ directions with equal thickness and same material properties. If the laminate contains only 0^o and/or 90^o layers, it satisfies the requirements for balance. Laminates may be mid-plane symmetric but not balanced and vice versa. In a balanced laminate, A_{16}=A_{26}=0. In this case, an in-plane (membrane) normal load will only induce mid-plane normal strains and will not induce any mid-plane shear strains. Likewise, an applied shear load will only induce a mid-plane shear strain with no accompanying normal strain. Thus, there is no coupling between extension loads and shear strain. If, in addition, these +θ and –θ plies are at the same distance from the mid-plane, then the corresponding B and D-matrix coefficients tend towards zero. When the balanced laminate is also mid-plane symmetric, its response emulates the behaviour of metals.

2.4.4.1.3 Angle Ply Laminates

An angle ply laminate has a lay-up where successive plies alternate between + θ and- θ in fibre orientation. Based on this definition, angle ply laminates with an odd number of plies are mid-plane symmetric but are not balanced and angle ply laminates with an even number of alternating + θ and – θ plies above the mid-plane. A $[\pm 45]_s$ lay-up is an example.

The mechanical response of angle ply laminates provides an explanation for the use of ±45º plies at structural locations that require large shear stiffness. A set of ±45º plies increase the shear stiffness to a great extent. In the axial stiffness, 90º, plies are selected to maximize the transverse stiffness and ±45º plies are selected to maximize the shear stiffness of the laminates.

2.4.4.1.4 cross-ply Laminates

Cross-ply laminates contain only 0º and 90º plies. In a cross-ply laminate, $A_{16}=A_{26}=B_{16}=B_{26}=D_{26}=0$. Mid-plane symmetric cross-ply laminates are also referred to as orthotropic laminates. Their in-plane normal and shear behaviours are uncoupled and their pure bending and twisting behaviours are also uncoupled. This means that N_x and N_y induce only $\varepsilon^\circ_{x,}$ ε°_y ($\gamma^\circ_{xy}=0$) and M_x and M_y induce only K_x and K_y ($K_{xy}=0$). Likewise, N_{xy} induce only γ°_{xy} ($\varepsilon^\circ_{x,}$ $\varepsilon^\circ_y=0$) and K_{xy} ($K_x = K_y=0$)

2.4.4.1.5 Quasi-Isotropic Laminates

Quasi-isotropic laminates behave like isotropic materials at the laminate level though their individual plies are orthotropic or anisotropic with respect to the reference coordinates. In case of quasi-isotropic laminates, only the elastic in-plane properties are isotropic. The strength properties, however, will vary with direction.

The goal of composite design is to achieve the lightest as well as most efficient structure by aligning most of the fibres in the direction of the load. Many times there is a need; however, to produce a composite, which has some isotropic properties, similar to metal, because of multiple or unified load paths. A quasi-isotropic laminates lay-up accomplishes this for the x- and y-planes only; the z- or through-the-laminate-thickness plane is quite different and lower. Laminates with plies distributed every 45º are called Π/4 laminates (plies can be in the 0º, 45º, 90º and -45º directions). Another class of laminates (plies can be in the 0º, 60º, or -60º directions). In both cases, an equal percentage of plies in each of the pre-selected orientations result in a quasi-isotropic laminate. Most laminates produced for aircraft applications have been, with few exceptions, quasi-isotropic. For a quasi-isotropic laminate, the following are the main design requirements:

- It must have three layers or more.
- Individual layers must have identical stiffness matrices and thickness.

The layers must be oriented at equal angles. For example, if total number of layers is ‘n’, the angle between two adjacent layers should be 360º/n. If a laminate is constructed from identical sets of three or more layers each, the condition on orientation must be satisfied by the layers in each set, for example, $(0^\circ \pm 60^\circ)_S$ or(0º/±45º/90º).

2.4.4.2 Anti-symmetric Laminates

Symmetry of a laminate about the mid-plane is often desirable to avoid coupling between bending and extension. However, many physically applications design requirements. An even number of plies may be necessary at orientations that alternate from ply to ply i.e. –θ/+ θ/ θ/+ θ. Thus, symmetry about the mid-planes is destroyed and the characteristics of a laminate can be changed from that of the symmetric case. The laminate is not symmetric but antisymmetric about the mid-plane. The general class of antisymmetric laminates must have an even number of plies. Further, each ply should have same thickness.

An antisymmetric cross-ply laminate consists of an even number of plies with principal material directions alternating at 0º and at 90º to the laminate axes. The thickness of the plies is also the same.

An antisymmetric angle ply laminate has plies orientated at + θº to the laminate coordinate axes on one side of the mid-plane and corresponding equal thickness ply orientated at - θº on the other side.

Antisymmetric Laminates

The general class of antisymmetric laminates must have a number of layers. In such laminates, A_{16}=A_{26} =D_{16}=D_{26}=0. The coupling stiffness B_{ij} vary for different classes of antisymmetric laminates.

In case of antisymmetric cross-ply laminates, A_{16}=A_{26}=B_{16}=B_{26} =D_{16}=D_{26}=0. As the number of layers in a laminate increases, coupling stiffness B_{11} also approaches zero.

In case of antisymmetric angle ply laminates, A_{16}=A_{26}=B_{11}=B_{12}=B_{66}=D_{16}=D_{26}=0. As the number of layers in a laminate increases, coupling stiffness B_{16} and B_{26} also approaches zero.

The designer should, therefore, take advantage of the orthotropic nature of the fibre composite ply in order to –

- Orient the individual plies as per the above criteria.
- Intersperse the ply orientation. If a design requires a laminate with 16 plies at ±45°, 16 plies at 0°, and 16 plies at 90°, use the intersperse design $(90_2/\pm45_2/0_2)_{4S}$ rather than $(90_8/\pm45_8/0_8)_S$ design. Concerning plies at nearly the same angle provides the opportunity for large matrix cracks to form thereby producing lower laminate allowable. Even if a design requires all 0º plies, some 90º plies and some off-angle plies should be interspersed in the laminate to provide some biaxial strength and stability and also to accommodate unplanned loads. This improves handling characteristics of the laminates and serves to prevent large matrix cracks from forming. Ensure that the laminate has sufficient fibre orientations to avoid dependence on the matrix for stability.
- Use multiple ply angles. Typical composites are constructed from multiple unidirectional or fabric layers which are positioned at angular orientations in a specified stacking sequence. The multiple layers are usually oriented in at least two different angles, and possibly three or four; (±θ°/0°/±θ°) or (0°/±θ°/90°) cover most of the applications with θ between 30° and 60°. Unidirectional laminates are rarely used except when the basic composite material is only mildly orthotropic or when the load path is absolutely known or carefully oriented parallel to the reinforcement.

2.4.4.3 Spirally Stacked Laminates/Nonsymmetric laminates

It has been shown by experiments that interlaminar stresses are less in a spirally stacked laminate as composed to any other laminate with similar fibre orientation. Interlaminar stresses arise out the difference between the angles of two adjacent plies- smaller difference is better than larger difference.

Most laminates used today are symmetric so as to eliminate or reduce any tendency of the structure to warp unexpectedly. Most laminates are also balanced, often because it is erroneously thought to be preventing the structure from warping. A balanced laminate is really necessary in situations with reversible shear loading conditions.

Module 3: Behaviour of a laminae (Elastic Constitutive Equations of a Laminate)

3.0 Introduction
3.0.1 Equations of Motion
3.0.2 Symmetric of Stresses

3.3 Tensorial concept and indicial notations
(Tensorial and Engineering Strains **)**

3.3.2 Tensorial and Engineering Strains

3.1 Stress-Strain concepts in 3-D
(Three-Dimensional Constitutive Equations)
3.1.1 Stress and Strain componts in 3-D,
- General Anisotropic Materials
- Orthotropic Materials
- Transversely Isotropic Materials
- Isotropic Materials

3.2 Relation between Mathematical & Engineering Constants
- Isotropic Materials
- Orthotropic Materials

3.3 Constitutive Equations for an Orthotropic Lamina
- Plane Strain Condition
- Plane Stress Condition

3.4 Constitutive Equations for an Arbitrarily Oriented Lamina
- Coordinate Transformation
- Stress Transformation
- Strain Transformation
- Stiffness and Compliance Matrix Transformation

3.5 Engineering Constants of a Laminate
- Lamina
- Laminate

3.6 Hygrothermal Coefficients of a Lamina

3.7 Summary

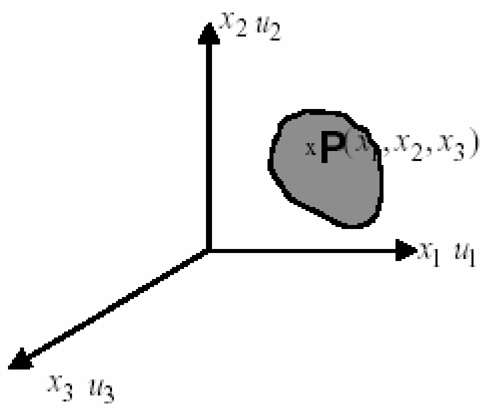
3.0 INTRODUCTION
3.0.1 Equations of Motion of Elastic Solids
- Equations of Equilibrium (Kinetics)

3.0 INTRODUCTION

3.0.1 Equations of Motion of Elastic Solids

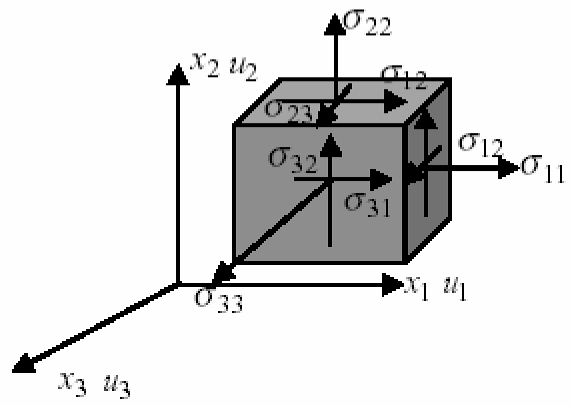
3.0.1.1 Equations of Equilibrium (Kinetics)

$$\sigma_{ij,j} + f_i = \rho \frac{\partial^2 u_i}{\partial t^2} \qquad i,\ j = 1,\ 2,\ 3$$



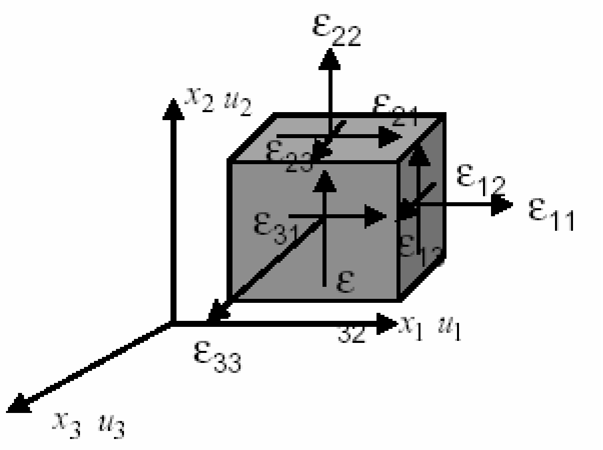
3.0.1.2 Equations of Kinematics (strain-displacement)

$$\varepsilon_{ij} = 1/2\left(u_{i,j} + u_{j,i}\right)$$



3.0.1.3 Constitutive Equations (stress-strain)

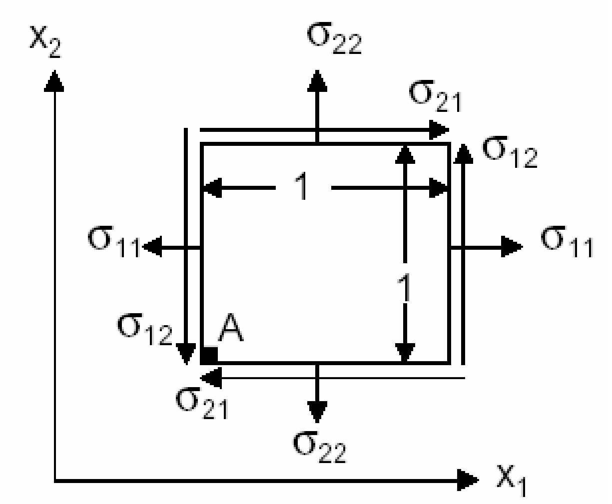
$$\sigma_{ij} = C_{ijkl}\varepsilon_{kl} \qquad i,\ j,\ k,\ l = 1,\ 2,\ 3$$



3.0.2 Symmetry of Stresses

Equilibrium

Consider a plane 1-2.



in x_1 $\quad \sigma_{11}*1*t-\sigma_{11}*1*t+\sigma_{21}*1*t-\sigma_{21}*1*t=0$

in x_2 $\quad (\sigma_{22}-\sigma_{22})*1*t-(\sigma_{12}-\sigma_{12})*1*t=0$

Moment about A: $\quad \sigma_{12}*1*t-\sigma_{21}*1*t=0$

$$\therefore \quad \sigma_{12}=\sigma_{21}$$

Similarly we can show, from 2-3 plane $\quad \sigma_{23}=\sigma_{32}$

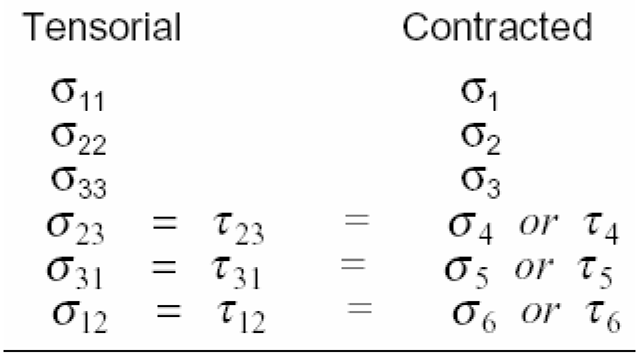
1-3 plane $\quad \sigma_{13}=\sigma_{31}$

Therefore, $\quad \sigma_{ij}=\sigma_{ji} \quad i,\ j\ =\ 1,\ 2,\ 3$

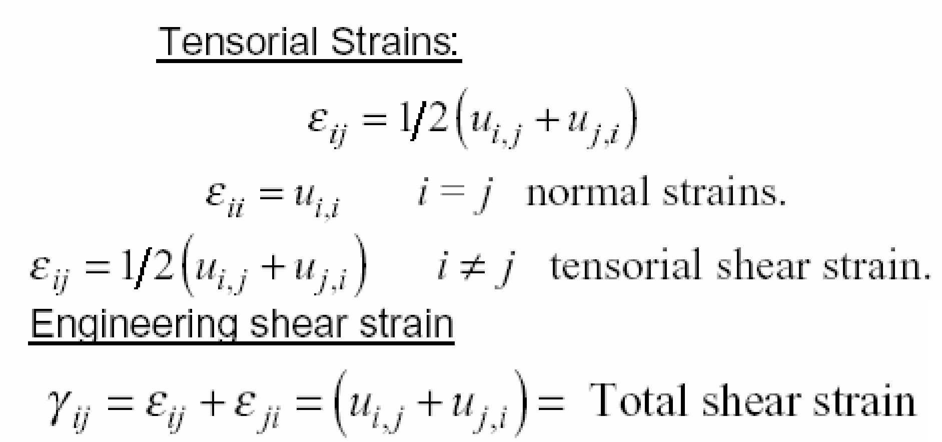
∴ Stress tensor is Symmetric.

3.3.2 Tensorial and Engineering Strains

Tensorial and Contracted Notation



Tensorial				Contracted
σ_{11}				σ_1
σ_{22}				σ_2
σ_{33}				σ_3
σ_{23}	=	τ_{23}	=	σ_4 or τ_4
σ_{31}	=	τ_{31}	=	σ_5 or τ_5
σ_{12}	=	τ_{12}	=	σ_6 or τ_6



Tensorial Strains:

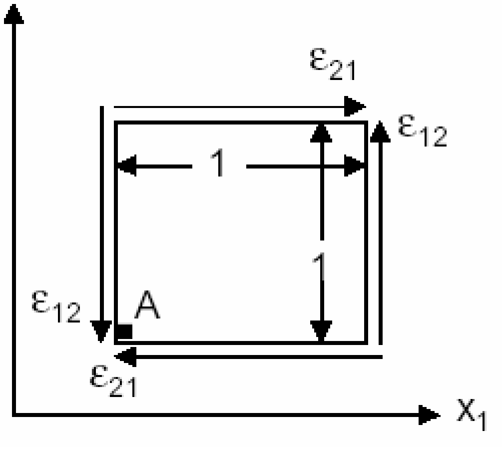
$$\varepsilon_{ij} = 1/2\left(u_{i,j} + u_{j,i}\right)$$

$$\varepsilon_{ii} = u_{i,i} \qquad i = j \quad \text{normal strains.}$$

$$\varepsilon_{ij} = 1/2\left(u_{i,j} + u_{j,i}\right) \qquad i \neq j \quad \text{tensorial shear strain.}$$

Engineering shear strain

$$\gamma_{ij} = \varepsilon_{ij} + \varepsilon_{ji} = \left(u_{i,j} + u_{j,i}\right) = \text{ Total shear strain}$$

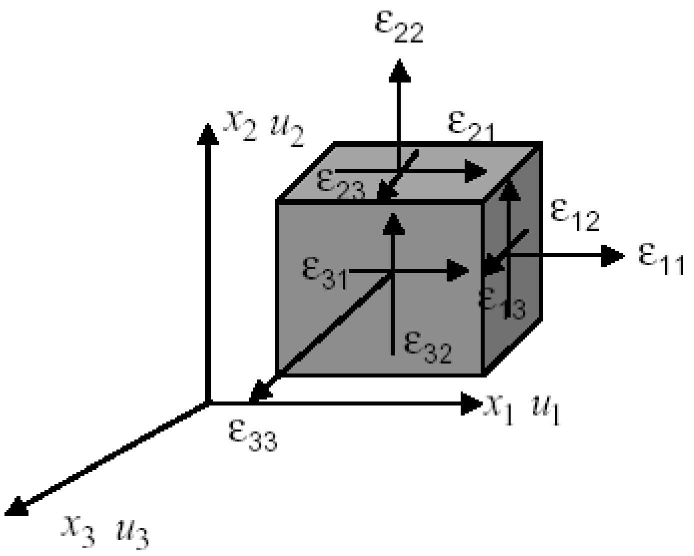


Engineering Strains

$$\varepsilon_1 = \varepsilon_{11} = \frac{\partial u_1}{\partial x_1} \qquad \varepsilon_4 = \gamma_4 = \frac{\partial u_2}{\partial x_3} + \frac{\partial u_3}{\partial x_2}$$

$$\varepsilon_2 = \varepsilon_{22} = \frac{\partial u_2}{\partial x_2} \qquad \varepsilon_5 = \gamma_5 = \frac{\partial u_3}{\partial x_1} + \frac{\partial u_1}{\partial x_3}$$

$$\varepsilon_3 = \varepsilon_{33} = \frac{\partial u_3}{\partial x_3} \qquad \varepsilon_6 = \gamma_6 = \frac{\partial u_1}{\partial x_2} + \frac{\partial u_2}{\partial x_1}$$



3.1 Stress-Strain concepts in 3-D

3.1.1 Stress-Strain relations in 3-D

3.1.2 Generalized Hooke's Law (3-D Constitutive Equation)

- Stress-Strain Equation

$$\sigma_i = C_{ij}\varepsilon_j \qquad \mathrm{i,j} = 1,2,3,4,5,6$$

$$\begin{Bmatrix}\sigma_1\\ \sigma_2\\ \sigma_3\\ \tau_4\\ \tau_5\\ \tau_6\end{Bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16}\\ C_{21} & C_{22} & C_{23} & C_{24} & C_{25} & C_{26}\\ C_{31} & C_{32} & C_{33} & C_{34} & C_{35} & C_{36}\\ C_{41} & C_{42} & C_{43} & C_{44} & C_{45} & C_{46}\\ C_{51} & C_{52} & C_{53} & C_{54} & C_{55} & C_{56}\\ C_{61} & C_{62} & C_{63} & C_{64} & C_{65} & C_{66}\end{bmatrix} \begin{Bmatrix}\varepsilon_1\\ \varepsilon_2\\ \varepsilon_3\\ \gamma_4\\ \gamma_5\\ \gamma_6\end{Bmatrix}$$

C is called the stiffness matrix.

- **<u>Strain-Stress Equation</u>**

$$\varepsilon_i = S_{ij}\sigma_j \qquad \text{i, j} = 1,2,3,4,5,6$$

$$\begin{Bmatrix}\varepsilon_1\\ \varepsilon_2\\ \varepsilon_3\\ \gamma_4\\ \gamma_5\\ \gamma_6\end{Bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} & S_{15} & S_{16}\\ S_{21} & S_{22} & S_{23} & S_{24} & S_{25} & S_{26}\\ S_{31} & S_{32} & S_{33} & S_{34} & S_{35} & S_{36}\\ S_{41} & S_{42} & S_{43} & S_{44} & S_{45} & S_{46}\\ S_{51} & S_{52} & S_{53} & S_{54} & S_{55} & S_{56}\\ S_{61} & S_{62} & S_{63} & S_{64} & S_{65} & S_{66}\end{bmatrix} \begin{Bmatrix}\sigma_1\\ \sigma_2\\ \sigma_3\\ \tau_4\\ \tau_5\\ \tau_6\end{Bmatrix}$$

S is called the compliance matrix.

2.0.4 Symmetry of Constitutive Matrix

Strain energy density,

$$U_0 = \frac{1}{2}\sigma_i\varepsilon_i \text{.................................}(1)$$

$$U_0 = \frac{1}{2}C_{ij}\varepsilon_j\varepsilon_i$$

$$\sigma_i = \frac{\partial U_0}{\partial \varepsilon_i} = C_{ij}\varepsilon_j$$

$$\frac{\partial^2 U_0}{\partial \varepsilon_j \partial \varepsilon_i} = C_{ij}$$

Eqn. (1) can be written as:

$$U_0 = \frac{1}{2}\sigma_j \varepsilon_j$$

$$U_0 = \frac{1}{2}C_{ji}\varepsilon_i \varepsilon_j$$

$$\sigma_j = \frac{\partial U_0}{\partial \varepsilon_j} = C_{ji}\varepsilon_i$$

$$\frac{\partial^2 U_0}{\partial \varepsilon_i \partial \varepsilon_j} = C_{ji}$$

Since the order of differentiating a scalar quantity U_0 should not change the result. Therefore, $C_{ij} = C_{ji}$ .Stiffness matrix is symmetric. Similarly, $S_{ij} = S_{ji}$.

2.1 3-D CONSTITUTIVE EQUATIONS

(a) General Anisotropic Material (no plane of material symmetry).

$$\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \tau_4 \\ \tau_5 \\ \tau_6 \end{Bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \\ C_{21} & C_{22} & C_{23} & C_{24} & C_{25} & C_{26} \\ C_{31} & C_{32} & C_{33} & C_{34} & C_{35} & C_{36} \\ C_{41} & C_{42} & C_{43} & C_{44} & C_{45} & C_{46} \\ C_{51} & C_{52} & C_{53} & C_{54} & C_{55} & C_{56} \\ C_{61} & C_{62} & C_{63} & C_{64} & C_{65} & C_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \gamma_4 \\ \gamma_5 \\ \gamma_6 \end{Bmatrix}$$

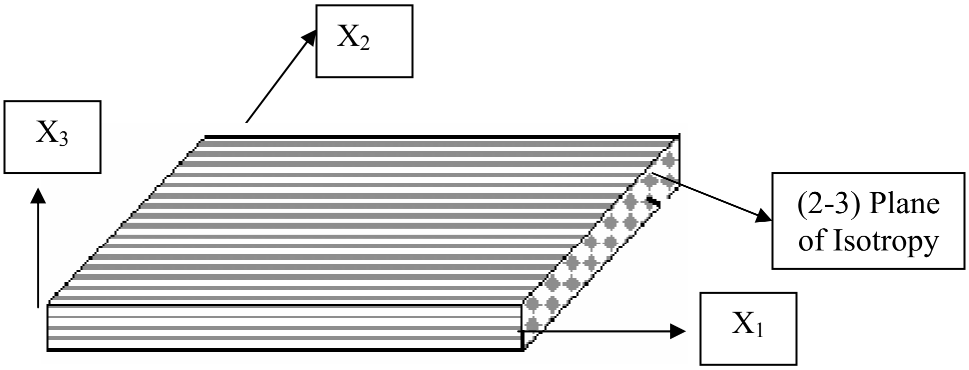
- Number of unknowns = 6x 6 = 36
- Because symmetry of Cij, number of unknowns = 6x 7/ 2 = 21

(b). Specially Orthotropic Materials (3-mutually perpendicular planes of material symmetry). Reference coordinate system is parallel to the material coordinate system.

$$\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \tau_4 \\ \tau_5 \\ \tau_6 \end{Bmatrix} = \begin{bmatrix} C_{11} & & & & & \\ C_{21} & C_{22} & & & Sym & \\ C_{31} & C_{32} & C_{33} & & & \\ 0 & 0 & 0 & C_{44} & & \\ 0 & 0 & 0 & 0 & C_{55} & \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \gamma_4 \\ \gamma_5 \\ \gamma_6 \end{Bmatrix}$$

Number of unknowns = 9

(c). <u>Transversely Isotropic Material</u>
An orthotropic material is called transversely isotropic when one of its principal plane is a plane of isotropy. At every point on this plane, the mechanical properties are the same in all directions.



$$\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \tau_4 \\ \tau_5 \\ \tau_6 \end{Bmatrix} = \begin{pmatrix} C_{11} & & & & & \\ C_{21} & C_{22} & & & & \\ C_{12} & C_{23} & C_{22} & & Sym & \\ 0 & 0 & 0 & \frac{C_{22}-C_{23}}{2} & & \\ 0 & 0 & 0 & 0 & C_{55} & \\ 0 & 0 & 0 & 0 & 0 & C_{55} \end{pmatrix} \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \gamma_4 \\ \gamma_5 \\ \gamma_6 \end{Bmatrix}$$

Number of unknowns = 5

(d) Isotropic Material
A material having infinite number of planes of material symmetry through a point.

$$\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \tau_4 \\ \tau_5 \\ \tau_6 \end{Bmatrix} = \begin{bmatrix} C_{11} & & & & & \\ C_{12} & C_{11} & & Sym & & \\ C_{12} & C_{12} & C_{11} & & & \\ 0 & 0 & 0 & C_{44} & & \\ 0 & 0 & 0 & 0 & C_{44} & \\ 0 & 0 & 0 & 0 & 0 & C_{44} \end{bmatrix} \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \gamma_4 \\ \gamma_5 \\ \gamma_6 \end{Bmatrix}$$

$$\text{where} \quad C_{44} = \frac{C_{11}-C_{12}}{2}$$

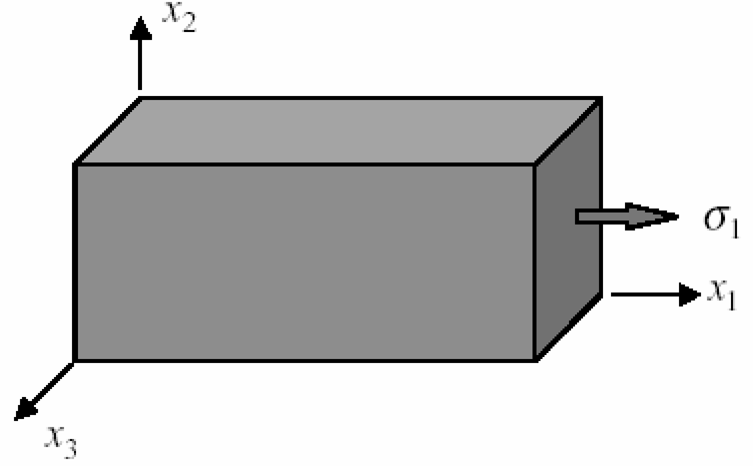
Number of unknowns = 2

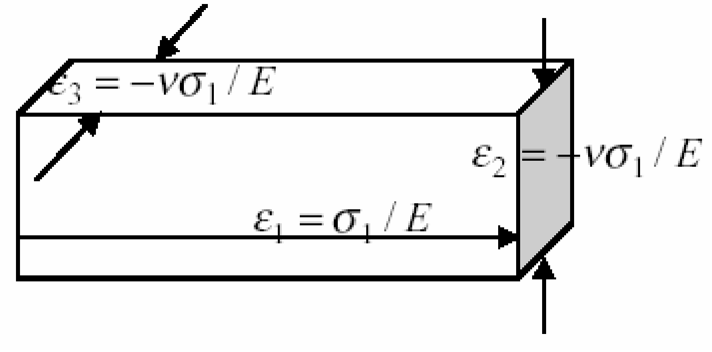
Summary

Material	Independent Elastic constants
1. Anisotropic material	36
2. Anisotropic elastic materials	21
3. Orthotropic material	9
4. Orthotropic material with transverse isotropy	5
5. Isotropic material	2

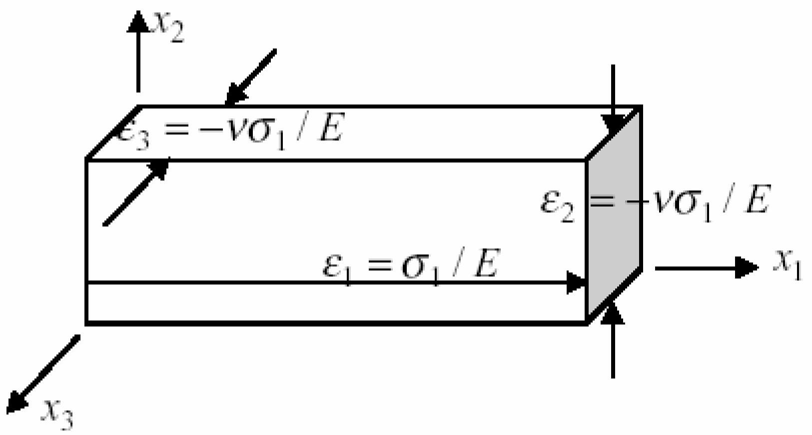
2.2 Relations Between Mathematical and Engineering Constants

(a) Isotropic Materials (E & n)





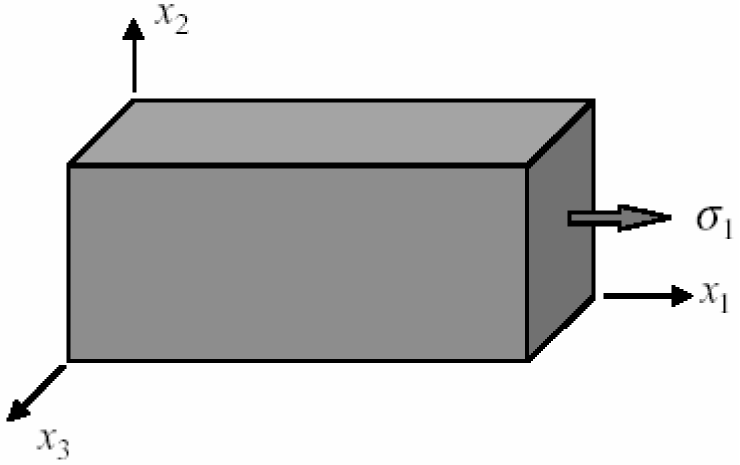
Definition:
Elastic Modulus (E) = Stress/Strain = s1/e1
Poisson’s Ratio (n) = - Transverse strain/Applied strain = - e2 /e1



Normal Strains	**Applied Stresses**		
	σ_1	σ_2	σ_3
$in - x_1$	σ_1 / E	$-\nu\sigma_2 / E$	$-\nu\sigma_3 / E$
$in - x_2$	$-\nu\sigma_1 / E$	σ_2 / E	$-\nu\sigma_3 / E$
$in - x_3$	$-\nu\sigma_1 / E$	$-\nu\sigma_2 / E$	σ_3 / E

Shear Strains	**Shear stresses**		
	Planes X2-X3, τ_{23}	X3 - X1 τ_{31}	X1 - X2 τ_{12}
γ_4	τ_{23} / G		
γ_5		τ_{31} / G	
γ_6			τ_{12} / G

Constitutive Equation



$$\varepsilon_i = S_{ij}\sigma_j$$

$$\begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \varepsilon_4 = \gamma_{23} \\ \varepsilon_5 = \gamma_{31} \\ \varepsilon_6 = \gamma_{12} \end{bmatrix} = \begin{bmatrix} 1/E & -\nu/E & -\nu/E & 0 & 0 & 0 \\ -\nu/E & 1/E & -\nu/E & 0 & 0 & 0 \\ -\nu/E & -\nu/E & 1/E & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/G & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/G & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/G \end{bmatrix} \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 = \tau_{23} \\ \sigma_5 = \tau_{31} \\ \sigma_6 = \tau_{12} \end{bmatrix}$$

$$\{\sigma\} = [S]^{-1}\{\varepsilon\} \qquad \underline{or} \qquad \{\sigma\} = [C]\{\varepsilon\}$$

<u>Restrictions of Elastic Constants</u>
*Shear modulus

$$G = \frac{E}{2(1+\nu)}$$

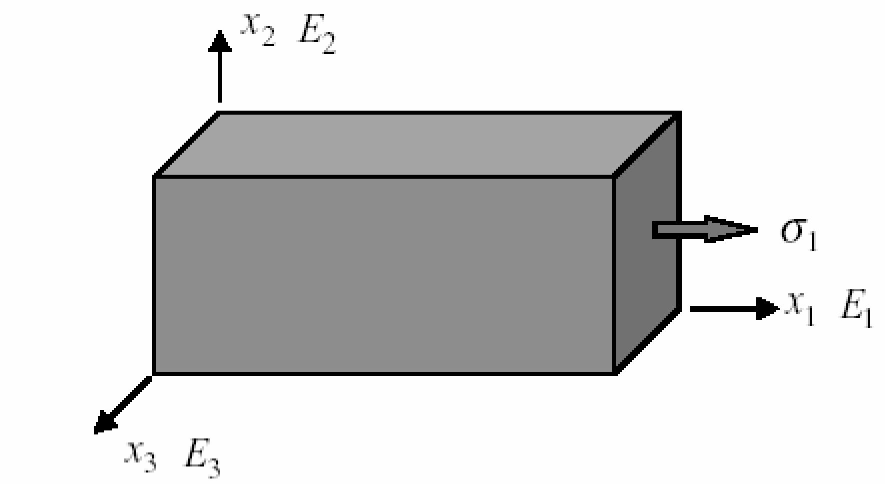
for Shear modulus to be positive, n > - 1

*Bulk modulus

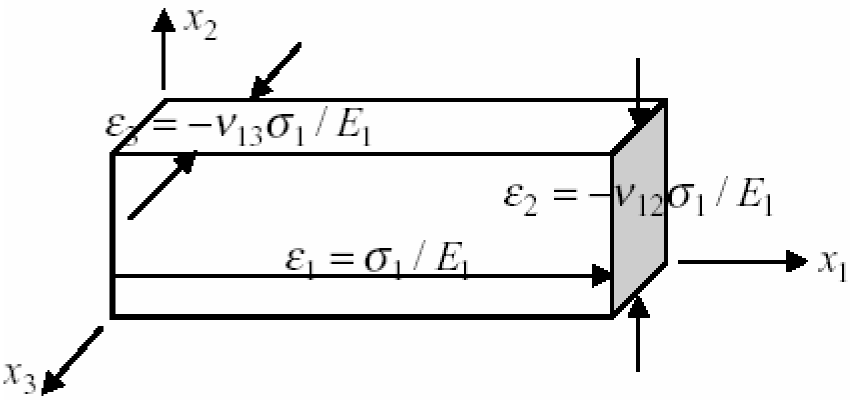
$$K = \frac{E}{3(1-2\nu)}$$

for Bulk modulus to be positive, n < ½
-1 < n < 1/2

(b) Orthotropic Materials



Definition:
Elastic Modulus (E1) = Stress/Strain = s1/e1
Poisson's Ratio (n12) = - Transverse strain/Applied strain = - e2 /e1



	Applied Stresses		
Normal Strains	σ_1	σ_2	σ_3
$in - x_1$	σ_1 / E_1	$-\nu_{21}\sigma_2 / E_2$	$-\nu_{31}\sigma_3 / E_3$
$in - x_2$	$-\nu_{12}\sigma_1 / E_1$	σ_2 / E_2	$-\nu_{32}\sigma_3 / E_3$
$in - x_3$	$-\nu_{13}\sigma_1 / E_1$	$-\nu_{23}\sigma_2 / E_2$	σ_3 / E_3

	Shear stresses		
Shear Strains	Planes X2-X3, τ_{23}	X3 - X1 τ_{31}	X1 - X2 τ_{12}
γ_4	τ_{23} / G_{23}		
γ_5		τ_{31} / G_{31}	
γ_6			τ_{12} / G_{12}

Constitutive Equation

$$\{\varepsilon\} = [S]\{\sigma\}$$

$$\begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \varepsilon_4 = \gamma_{23} \\ \varepsilon_5 = \gamma_{31} \\ \varepsilon_6 = \gamma_{12} \end{bmatrix} = \begin{bmatrix} 1/E_{11} & -\nu_{21}/E_{22} & -\nu_{31}/E_{33} & 0 & 0 & 0 \\ -\nu_{12}/E_{11} & 1/E_{22} & -\nu_{32}/E_{33} & 0 & 0 & 0 \\ -\nu_{13}/E_{11} & -\nu_{23}/E_{22} & 1/E_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/G_{23} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/G_{31} & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/G_{12} \end{bmatrix} \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 = \tau_{23} \\ \sigma_5 = \tau_{31} \\ \sigma_6 = \tau_{12} \end{bmatrix}$$

$$\{\sigma\} = [S]^{-1}\{\varepsilon\} \qquad \underline{or} \qquad \{\sigma\} = [C]\{\varepsilon\}$$

from Symmetry of S- matrix:

$$S_{ij} = S_{ji} \qquad \text{when } i \neq j$$

$$S_{12} = S_{21} \qquad S_{13} = S_{31} \qquad S_{23} = S_{32}$$

Therefore,

$$\boxed{\frac{\nu_{ij}}{E_i} = \frac{\nu_{ji}}{E_j} \quad \text{or} \quad \frac{\nu_{ij}}{\nu_{ji}} = \frac{E_i}{E_j}}$$

i.e., $\dfrac{\nu_{12}}{E_1} = \dfrac{\nu_{21}}{E_2}$, $\dfrac{\nu_{13}}{E_1} = \dfrac{\nu_{31}}{E_3}$, and $\dfrac{\nu_{23}}{E_2} = \dfrac{\nu_{32}}{E_3}$

This is the well known Betti's reciprocal law of orthotropic material properties.

Stress-Strain Equation

$$\{\sigma\} = [C]\{\varepsilon\}$$

where, $[C] = [S]^{-1}$

Coefficients of C are given by:

$$C_{11} = \frac{1-\nu_{23}\nu_{32}}{E_2E_3\Delta} \qquad C_{12} = \frac{\nu_{21}+\nu_{13}\nu_{23}}{E_2E_3\Delta} = \frac{\nu_{12}+\nu_{13}\nu_{32}}{E_1E_3\Delta}$$

$$C_{22} = \frac{1-\nu_{13}\nu_{31}}{E_1E_3\Delta} \qquad C_{23} = \frac{\nu_{32}+\nu_{12}\nu_{31}}{E_1E_3\Delta} = \frac{\nu_{23}+\nu_{21}\nu_{31}}{E_1E_2\Delta}$$

$$C_{33} = \frac{1-\nu_{12}\nu_{21}}{E_1E_2\Delta} \qquad C_{13} = \frac{\nu_{13}+\nu_{12}\nu_{23}}{E_1E_2\Delta} = \frac{\nu_{31}+\nu_{21}\nu_{32}}{E_2E_3\Delta}$$

$$C_{44} = G_{23},$$

$$C_{55} = G_{13},$$

and $C_{66} = G_{12}$

where,

$$\Delta = \frac{1}{E_1E_2E_3}\begin{vmatrix} 1 & -\nu_{21} & -\nu_{31} \\ -\nu_{12} & 1 & -\nu_{32} \\ -\nu_{13} & -\nu_{23} & 1 \end{vmatrix}$$

Transversely Isotropic Material: (Plane: x_2 - x_3)

$$E_2 = E_3$$

$$G_{12} = G_{13}$$

$$\nu_{12} = \nu_{13}$$

$$G_{23} = \frac{E_2}{2(1+\nu_{23})}$$

Restrictions on Elastic Constants of Orthotropic Materials

From Energy Principles, Lempriere showed that the Strain Energy is Positive if the Stiffness and Compliance Matrices are Positive Definite.

Mathematical Argument

(a) If only one stress is applied at a time, then the work done is positive if and only when the corresponding direct strain is positive. That is when $S_{ii} > 0$

Therefore, E_1, E_2, E_3, G_{12}, G_{23} and $G_{13} > 0$

(b) Under suitable constraints, it is possible to deform a body in one-direction.
Then the work done will be positive if only when $C_{ii} > 0$

$$C_{11} = \frac{1-\nu_{23}\nu_{32}}{E_2 E_3 \Delta} > 0$$

$$1-\nu_{23}\nu_{32} > 0 \quad or \quad \nu_{23}\nu_{32} < 1$$

or

$$\nu_{23} < \sqrt{\frac{E_2}{E_3}}$$

In general,

$$\nu_{ij} < \sqrt{\frac{E_i}{E_j}}$$

Note all through □was assumed to be greater than 0. This condition would give additional equations. (refer to R. M. Jones.)

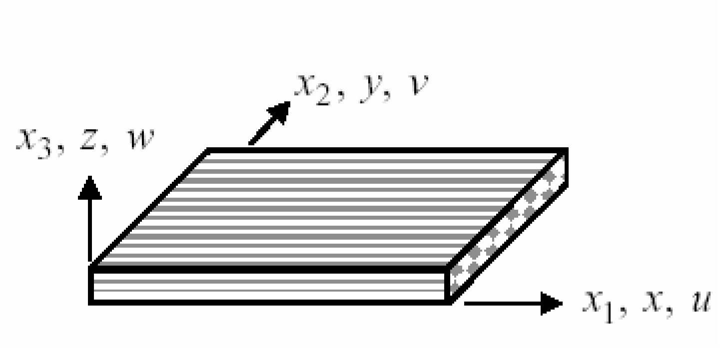
2.3 Constitutive Equations of a Thin Orthotropic Lamina

Two-Dimensional Bodies: Variation in stress and strain can be defined by two-coordinates. There are two types of problems.

(a) Plane strain - Thick bodies

$$\varepsilon_z = \gamma_{xz} = \gamma_{yz} = 0$$

$$\therefore \ \tau_{xz} = \tau_{yz} = 0$$

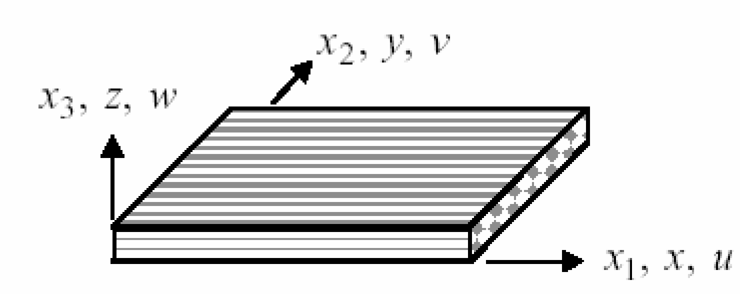


(b) Plane Stress - Thin bodies

$$\sigma_z = \tau_{xz} = \tau_{yz} = 0$$

$$\therefore \varepsilon_z = \gamma_{xz} = \gamma_{yz} = 0$$

Strain-Stress Equation:



$$\begin{Bmatrix}\varepsilon_1\\ \varepsilon_2\\ \gamma_{12}\end{Bmatrix}=\begin{bmatrix}S_{11} & S_{12} & 0\\ S_{21} & S_{22} & 0\\ 0 & 0 & S_{66}\end{bmatrix}\begin{Bmatrix}\sigma_1\\ \sigma_2\\ \sigma_{12}\end{Bmatrix}$$

OR

$$\begin{Bmatrix}\varepsilon_1\\ \varepsilon_2\\ \gamma_{12}\end{Bmatrix}=\begin{bmatrix}\frac{1}{E_1} & \frac{-\nu_{12}}{E_1} & 0\\ \frac{-\nu_{12}}{E_1} & \frac{1}{E_2} & 0\\ 0 & 0 & \frac{1}{G_{12}}\end{bmatrix}\begin{Bmatrix}\sigma_1\\ \sigma_2\\ \sigma_{12}\end{Bmatrix}$$

Stress -Strain Equation:

$$\begin{Bmatrix}\sigma_1\\ \sigma_2\\ \sigma_{12}\end{Bmatrix}=\begin{bmatrix}Q_{11} & Q_{12} & 0\\ Q_{21} & Q_{22} & 0\\ 0 & 0 & Q_{66}\end{bmatrix}\begin{Bmatrix}\varepsilon_1\\ \varepsilon_2\\ \gamma_{12}\end{Bmatrix}$$

OR

$$\begin{Bmatrix}\sigma_1\\ \sigma_2\\ \sigma_{12}\end{Bmatrix}=\begin{bmatrix}E'_1 & E'_{12} & 0\\ E'_{12} & E'_2 & 0\\ 0 & 0 & G_{12}\end{bmatrix}\begin{Bmatrix}\varepsilon_1\\ \varepsilon_2\\ \gamma_{12}\end{Bmatrix}$$

where,

$$E'_1=\frac{E_1}{1-\nu_{12}\nu_{21}}$$

$$E'_2 = \frac{E_2}{1-\nu_{12}\nu_{21}}$$

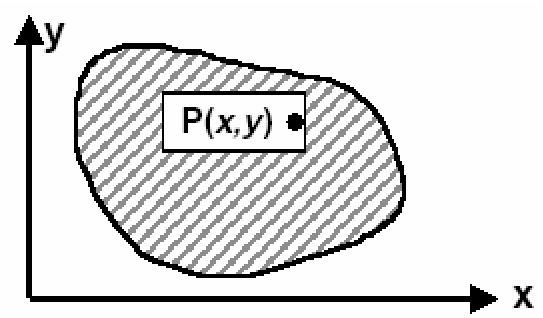
$$E'_{12} = \frac{\nu_{21}E_1}{1-\nu_{12}\nu_{21}} = \frac{\nu_{12}E_2}{1-\nu_{12}\nu_{21}}$$

2.4 Stress-Strain Relations for Arbitrary Orientation of a Lamina

(a) Transformation of coordinates

$x_1 - x_2$ - Material coordinate system

$x - y$ - Reference coordinate system



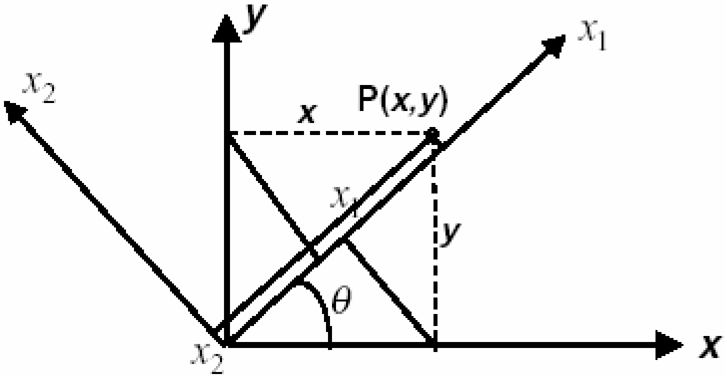
Consider a point P(x,y), its coordinates in $x_1 - x_2$ - system is

$$x_1 = xCos\theta + ySin\theta$$

$$x_2 = -xSin\theta + yCos\theta$$

OR

$$\begin{Bmatrix} x_1 \\ x_2 \end{Bmatrix} = \underbrace{\begin{bmatrix} Cos\theta & Sin\theta \\ -Sin\theta & Cos\theta \end{bmatrix}}_{\text{Direction cosine matrix } \alpha_{ij} \text{ where } I = 1,2 \text{ and } j = 1,2} \begin{Bmatrix} x \\ y \end{Bmatrix} \quad \text{or} \quad \begin{Bmatrix} x_1 \\ x_2 \end{Bmatrix} = \begin{bmatrix} \alpha_{1x} & \alpha_{1y} \\ \alpha_{2x} & \alpha_{2y} \end{bmatrix} \begin{Bmatrix} x \\ y \end{Bmatrix}$$



(b) Stress Transformation

We use tensors transfer stresses between the two coordinate systems

$$\sigma_{ij} = \alpha_{ik}\alpha_{jl}\sigma_{kl} \qquad i,j = 1,2 \ \text{ and } \ k,l = x,y$$

Example:

$i=j=1$

$$\sigma_{11} = \alpha_{11}\alpha_{11}\sigma_{xx} + \alpha_{11}\alpha_{12}\sigma_{xy} + \alpha_{12}\alpha_{11}\sigma_{yx} + \alpha_{12}\alpha_{12}\sigma_{yy}$$

If $m = Cos\theta$ and $n = Sin\theta$ Then

$$\sigma_{11} = m^2\sigma_{xx} + 2mn\sigma_{xy} + n^2\sigma_{yy}$$

Similarly we can establish the other two stress components. Finally we can write

$$\begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{12} \end{Bmatrix} = \begin{bmatrix} m^2 & n^2 & 2mn \\ n^2 & m^2 & -2mn \\ -mn & mn & m^2 - n^2 \end{bmatrix} \begin{Bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{xy} \end{Bmatrix}$$

$$\{\sigma\}_{x_1 - x_2} = [T]\{\sigma\}_{x-y}$$

OR

$$\{\sigma\}_{x-y} = [T_\sigma]\{\sigma\}_{x_1 - x_2} \quad \text{where} \quad [T_\sigma] = [T]^{-1}$$

$[T_\sigma]$ - is the stress transformation matrix.

$$[T_\sigma] = [T]^{-1} = [T(-\theta)] = \begin{bmatrix} m^2 & n^2 & -2mn \\ n^2 & m^2 & 2mn \\ mn & -mn & m^2 - n^2 \end{bmatrix}$$

(c) Strain Transformation

$$\{\varepsilon\}_{x-yTen} = [T_\sigma]\{\varepsilon\}_{x_1 - x_2 Ten}$$

$$\{\varepsilon\}_{x-yTen} = [T_\sigma] \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & \frac{1}{2} \end{bmatrix} \begin{Bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \gamma_{12} \end{Bmatrix}_{Eng}$$

$$\{\varepsilon\}_{x-yTen} = [T_\sigma][H]\{\varepsilon\}_{x_1 - x_2 Eng}$$

Where,

$$[H]^{-1} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 2 \end{bmatrix}$$

and

$$\{\varepsilon\}_{x-yEng} = [T_\varepsilon]\{\varepsilon\}_{x_1-x_2Eng}$$

Where strain transformation matrix is:

$$[T_\varepsilon] = \begin{bmatrix} m^2 & n^2 & -mn \\ n^2 & m^2 & mn \\ 2mn & -2mn & m^2-n^2 \end{bmatrix} \{\sigma\}_{xy} = [Q]_{xy}\{\varepsilon\}_{xy}$$

(d) Stiffness Transformation

Let $\{\sigma\}_{XY} = [Q]_{XY}\{\varepsilon\}_{XY}$ in x-y system.

Let us start with stress equation

$$\{\sigma\}_{xy} = [T_\sigma]_{xy}\{\sigma\}_{1-2}$$

$$= [T_\sigma]_{xy}[Q]_{1-2}\{\varepsilon\}_{1-2}$$

where,

$$\{\sigma\}_{1-2} = [Q]_{1-2}\{\varepsilon\}_{1-2}$$

$$\{\sigma\}_{xy} = [T_\sigma][Q]_{1-2}[T_\varepsilon]^{-1}\{\varepsilon\}_{xy}$$

$$\{\varepsilon\}_{1-2} = [T_\varepsilon]^{-1}\{\varepsilon\}_{xy}$$

$$\{\sigma\}_{xy} = [T_\sigma][Q]_{1-2}[T_\sigma]^{T}\{\varepsilon\}_{xy}$$

$$[Q]_{xy} = [T_\sigma][Q]_{1-2}[T_\sigma]^{T}$$

$$\begin{bmatrix} Q_{xx} & Q_{xy} & Q_{xs} \\ Q_{yx} & Q_{yy} & Q_{yx} \\ Q_{sx} & Q_{sy} & Q_{ss} \end{bmatrix} = [T_\sigma] \begin{bmatrix} Q_{11} & Q_{21} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix} [T_\sigma]^T$$

Where,

$$Q_{11} = \frac{E_{11}}{1 - \nu_{12}\nu_{21}}$$

$$Q_{22} = \frac{E_{22}}{1 - \nu_{12}\nu_{21}}$$

$$Q_{12} = \frac{\nu_{12}E_{22}}{1 - \nu_{12}\nu_{21}} = \frac{\nu_{21}E_{11}}{1 - \nu_{12}\nu_{21}}$$

$$Q_{66} = G_{12}$$

Elements pf $[Q]_{xy}$ matrix

$$Q_{xx} = m^4 Q_{11} + n^4 Q_{22} + 2m^2n^2 Q_{12} + 4m^2n^2 Q_{66}$$

$$Q_{yy} = n^4 Q_{11} + m^4 Q_{22} + 2m^2n^2 Q_{12} + 4m^2n^2 Q_{66}$$

$$Q_{xy} = m^2n^2 Q_{11} + m^2n^2 Q_{22} + \left(m^4 + n^4\right) Q_{12} - 4m^2n^2 Q_{66}$$

$$Q_{xs} = m^3n Q_{11} - mn^3 Q_{22} + \left(mn^3 - m^3n\right) Q_{12} + 2\left(mn^3 - m^3n\right) Q_{66}$$

$$Q_{ys} = mn^3 Q_{11} - m^3n Q_{22} + \left(m^3n - mn^3\right) Q_{12} + 2\left(m^3n - mn^3\right) Q_{66}$$

$$Q_{ss} = m^2n^2 Q_{11} + m^2n^2 Q_{22} - 2m^2n^2 Q_{12} + \left(m^2 - n^2\right)^2 Q_{66}$$

Notice in the matrix $[Q]_{xy}$

- It is fully populated - means normal-shear coupling.
- Although 4 independent constants were used; we have ‘6’ unknowns.

(d) Compliance Matrix

$$\{\varepsilon\}_{xy} = [T_\varepsilon]\{\varepsilon\}_{x_1-x_2}$$

$$= [T_\varepsilon][S]_{x_1-x_2}\{\sigma\}_{x_1-x_2}$$

$$\{\varepsilon\}_{xy} = [T_\varepsilon][S]_{x_1-x_2}[T_\sigma]^{-1}\{\sigma\}_{x-y}$$

$$\{\varepsilon\}_{xy} = [S]_{x-y}\{\sigma\}_{x-y}$$

where, $[S]_{x-y} = [T_\varepsilon][S]_{1-2}[T_\varepsilon]^T$

$$\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} = \begin{bmatrix} S_{xx} & S_{xy} & S_{xs} \\ S_{yx} & S_{yy} & S_{ys} \\ S_{sx} & S_{sy} & S_{ss} \end{bmatrix} \begin{Bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{xy} \end{Bmatrix}$$

$$S_{xx} = m^4 S_{11} + n^4 S_{22} + 2m^2n^2 S_{12} + m^2n^2 S_{66}$$

$$S_{yy} = n^4 S_{11} + m^4 S_{22} + 2m^2n^2 S_{12} + m^2n^2 S_{66}$$

$$S_{xy} = m^2n^2 S_{11} + m^2n^2 S_{22} + \left(m^4 + n^4\right) S_{12} - m^2n^2 S_{66}$$

$$S_{xs} = 2m^3n S_{11} - 2mn^3 S_{22} + 2\left(mn^3 - m^3n\right) S_{12} + \left(mn^3 - m^3n\right) S_{66}$$

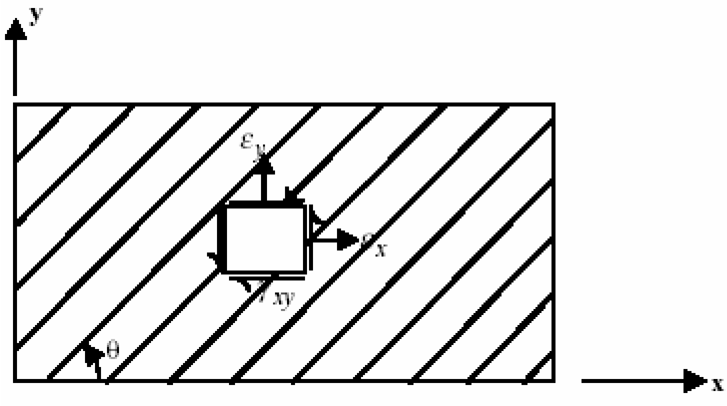
$$S_{ys} = 2mn^3 S_{11} - 2m^3n S_{22} + 2\left(m^3n - mn^3\right) S_{12} + \left(m^3n - mn^3\right) S_{66}$$

$$S_{ss} = 4m^2n^2 S_{11} + 4m^2n^2 S_{22} - 8m^2n^2 S_{12} + \left(m^2 - n^2\right)^2 S_{66}$$

2.5 Engineering Constants of an Arbitrarily Oriented Laminate

Arbitrarily Oriented Lamina

Let us examine what happens when you apply s_x in x-direction.
We get, ε_x – in X-direction, ε_y –in Y-direction and shear strain γ_{xy} .



$$E_x = \frac{\sigma_x}{\varepsilon_x} \quad \textbf{or} \quad \varepsilon_x = \frac{\sigma_x}{E_x}$$

$$\nu_{xy} = -\frac{\varepsilon_y}{\varepsilon_x}$$

where,

$$\varepsilon_y = -\nu_{xy}\varepsilon_x = -\frac{\nu_{xy}}{E_x}\sigma_x$$

Shear coupling coefficient is,

$$\eta_{xs} = \frac{\gamma_{xy}}{\varepsilon_x}$$

OR

$$\gamma_{xy} = \eta_{xs}\varepsilon_x = \frac{\eta_{xs}}{E_x}\sigma_x$$

$$\therefore \quad S_{xx} = \frac{1}{E_x} \qquad E_x = \frac{1}{S_{xx}}$$

$$S_{yx} = -\frac{\nu_{xy}}{E_x} \qquad \nu_{xy} = -S_{yx}E_x$$

$$S_{sx} = \frac{\eta_{xs}}{E_x} \qquad \eta_{xs} = S_{sx}E_x$$

Shear Coupling Coefficients:

□xs ->Ratio of shear strain □xy to normal strain □x due to applied □x.

$$S_{xx} = \frac{1}{E_x} \qquad E_x = \frac{1}{S_{xx}}$$

□sx ->Ratio of normal strain □x to shear strain □xy due to applied □xy.

$$S_{yx} = -\frac{\nu_{xy}}{E_x} \qquad \nu_{xy} = -S_{yx}E_x$$

$$S_{sx} = \frac{\eta_{xs}}{E_x} \qquad \eta_{xs} = S_{sx}E_x$$

Similarly we have: □$_{ys}$, □$_{sy}$

$$\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} = \begin{bmatrix} \frac{1}{E_x} & -\frac{\nu_{yx}}{E_y} & \frac{\eta_{sx}}{G_{xy}} \\ -\frac{\nu_{xy}}{E_x} & \frac{1}{E_y} & \frac{\eta_{sy}}{G_{xy}} \\ \frac{\eta_{xs}}{E_x} & \frac{\eta_{ys}}{E_y} & \frac{1}{G_{xy}} \end{bmatrix} \begin{Bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{xy} \end{Bmatrix}$$

Engineering Constants of an Arbitrarily Oriented Lamina

$$\frac{1}{E_x}=\frac{m^2}{E_1}\left(m^2-n^2\nu_{12}\right)+\frac{n^2}{E_2}\left(n^2-m^2\nu_{21}\right)+\frac{m^2n^2}{G_{12}}$$

$$\frac{1}{E_y}=\frac{n^2}{E_1}\left(n^2-m^2\nu_{12}\right)+\frac{m^2}{E_2}\left(m^2-n^2\nu_{21}\right)+\frac{m^2n^2}{G_{12}}$$

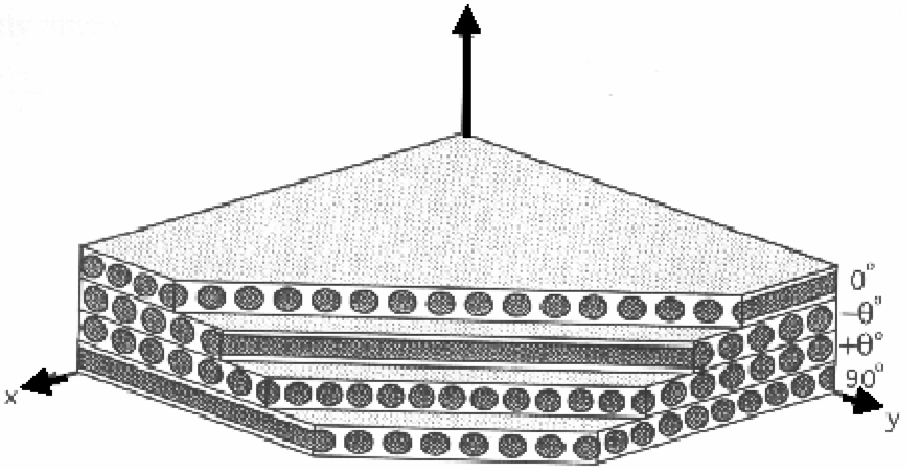
$$\frac{1}{G_{xy}}=\frac{4m^2n^2}{E_1}\left(1+\nu_{12}\right)+\frac{4m^2n^2}{E_2}\left(1+\nu_{21}\right)+\frac{\left(m^2-n^2\right)^2}{G_{12}}$$

$$\frac{\nu_{xy}}{E_x}=\frac{\nu_{yx}}{E_y}=\frac{m^2}{E_1}\left(m^2\nu_{12}-n^2\right)+\frac{n^2}{E_2}\left(n^2\nu_{21}-m^2\right)+\frac{m^2n^2}{G_{12}}$$

$$\frac{\eta_{sx}}{G_{12}}=\frac{\eta_{xs}}{E_x}=\frac{2mn}{E_1}\left(m^2-n^2\nu_{12}\right)-\frac{2mn}{E_2}\left(n^2-m^2\nu_{21}\right)+\frac{\left(mn^3-m^3n\right)}{G_{12}}$$

$$\frac{\eta_{sy}}{G_{12}}=\frac{\eta_{ys}}{E_y}=\frac{2mn}{E_1}\left(n^2-m^2\nu_{12}\right)-\frac{2mn}{E_2}\left(m^2-n^2\nu_{21}\right)+\frac{\left(m^3n-mn^3\right)}{G_{12}}$$

Engineering Constants of a Laminate



- N-Layers
- Each Layer can have different
Thickness, Orientation, and Material

$$T = \sum_{i=1}^{N} t_i$$

Stress-Strain in the Layer,

$$\{\sigma\}_i = [C]_i\{\varepsilon\}_i$$

$$\{\sigma\}_{av} = \tfrac{1}{T}\int [C]dz\{\varepsilon\}$$

Assumption: Strain is constant through out the laminate
Average Stress in the laminate is:

$$\{\sigma\}_{av} = \int [C]\tfrac{dz}{t}\{\varepsilon\}$$

$$= \tfrac{1}{T}\left\{\sum_{i=1}^{N}[C]_i t_i\right\}\{\varepsilon\}$$

$$\{\sigma\}_{av} = [C]_{av}\{\varepsilon\} \qquad \text{or} \qquad \{\varepsilon\}_{av} = \left[\overline{S}\right]_{x-y}\{\sigma\}_{av}$$

For 3-D model stress-strain are six
For 2-D model stress-strain are three

Engineering Constants are:

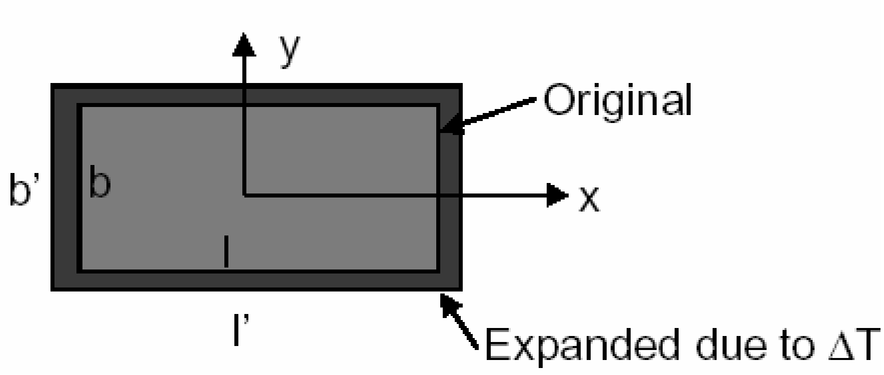
$$\begin{array}{lll}
E_x = \frac{1}{\overline{S}_{xx}} & G_{yz} = \frac{1}{\overline{S}_{44}} & \nu_{xy} = -\frac{\overline{S}_{yx}}{\overline{S}_{xx}} \\[2ex]
E_y = \frac{1}{\overline{S}_{yy}} & G_{xz} = \frac{1}{\overline{S}_{55}} & \nu_{xz} = -\frac{\overline{S}_{zx}}{\overline{S}_{xx}} \\[2ex]
E_z = \frac{1}{\overline{S}_{zz}} & G_{xy} = \frac{1}{\overline{S}_{66}} & \nu_{yz} = -\frac{\overline{S}_{zy}}{\overline{S}_{yy}}
\end{array}$$

MmLamCode:
Micromechanics and laminate analysis unidirectional code
MmTEXlam:
Micro and laminate analysis of textile fabric composite code

2.6 Hygrothermal Coefficients of a Lamina

2.6.1 Coefficients of Thermal Expansion

(a) Isotropic Materials

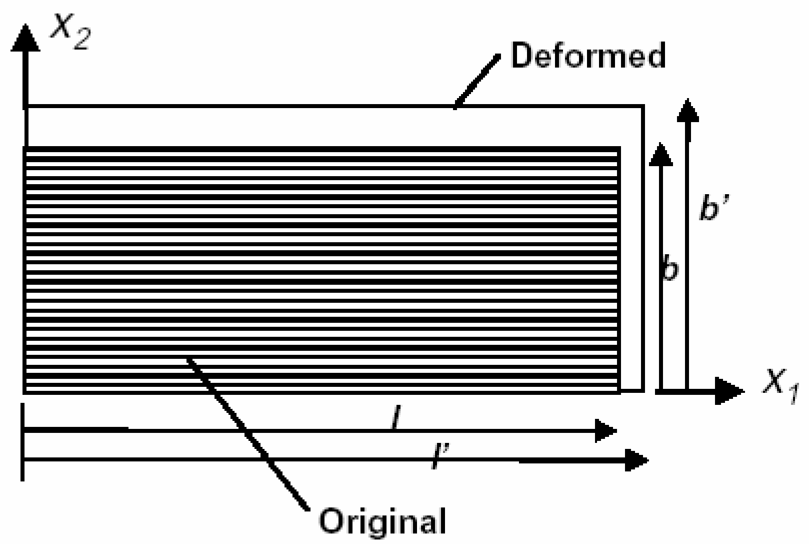


Coefficient of thermal expansion,

$$\alpha_x^T = \alpha_y^T = \alpha^T = \frac{l' - l}{l\Delta T}$$

Units: in/in/°F or m/m /°C

(B) Orthotropic Materials



Coefficient of thermal expansion

- In x direction

$$\alpha_1^T = \frac{l' - l}{l\Delta T}$$

- In x direction

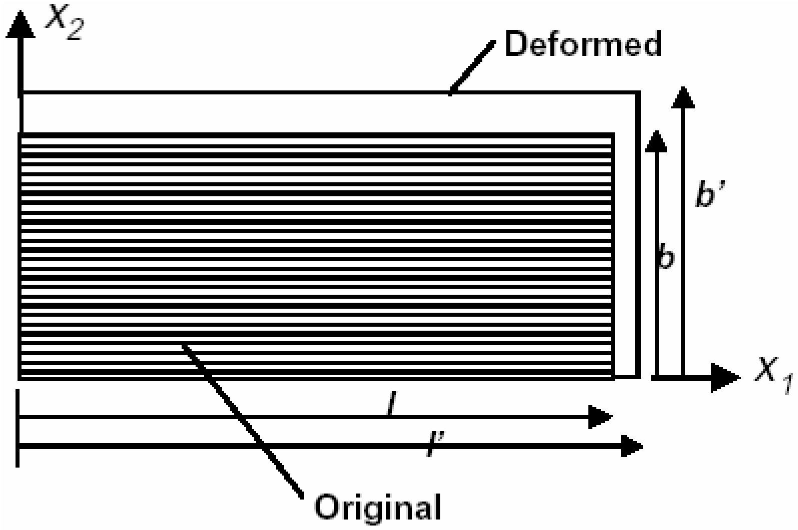
$$\alpha_2^T = \frac{b' - b}{b\Delta T}$$

Thermal strains:

$$\{\varepsilon\} = \begin{Bmatrix} \alpha_1^T \\ \alpha_2^T \\ 0 \end{Bmatrix} \Delta T$$

2.6.2 Coefficients of Moisture Expansion

All organic composites absorb moisture. The absorption depends on the relative humidity to which it is exposed and its moisture content. For a given RH, temperature, and atmospheric pressure composite will have a saturation value. This is moisture content that the material will reach, if it is exposed for a very long time. This is a fixed value for a material. The moisture content is expressed as percent change in weight of the material. Like thermal expansion, increase in moisture would also expand the material. The orthotropic materials have two coefficients of moisture expansion, one along the fiber and the other across the fiber.



Change in moisture DM

Coefficient of moisture expansion

- In x1-direction

$$\beta_1^T = \frac{l'-l}{l\Delta M}$$

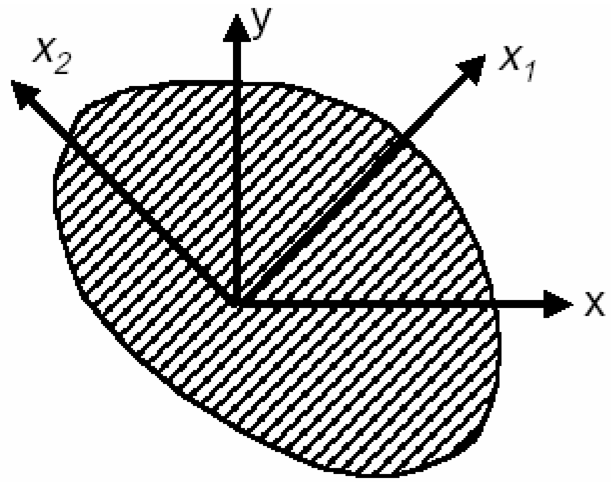
- In x direction

$$\beta_2^T = \frac{b'-b}{b\Delta M}$$

- Moisture strains:

$$\left\{\varepsilon^M\right\} = \begin{Bmatrix} \beta_1^M \\ \beta_2^M \\ 0 \end{Bmatrix} \Delta M$$

2.6.3 Coefficients of Thermal & Moisture Expansion for Lamina in Arbitrary Orientation



Recall the strain transformation:

$$\left\{\varepsilon^T\right\}_{xy} = \left[T_\varepsilon\right]\left\{\varepsilon^T\right\}_{1-2}$$

where,

$$\left[T_\varepsilon\right] = \begin{bmatrix} m^2 & n^2 & -mn \\ n^2 & m^2 & mn \\ 2mn & -2mn & m^2-n^2 \end{bmatrix}$$

$$m=\cos\theta \text{ and } n=\sin\theta$$

Thermal strains in x-y due to DT are:

$$\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} = \begin{bmatrix} m^2 & n^2 & -mn \\ n^2 & m^2 & mn \\ 2mn & -2mn & m^2 - n^2 \end{bmatrix} \begin{Bmatrix} \alpha_1^T \\ \alpha_2^T \\ 0 \end{Bmatrix} \Delta T \quad = \begin{Bmatrix} \alpha_x^T \\ \alpha_y^T \\ \alpha_{xy}^T \end{Bmatrix}$$

Coefficients of thermal expansion in x-y:

$$\alpha_x^T = m^2 \alpha_1^T + n^2 \alpha_2^T$$

$$\alpha_y^T = n^2 \alpha_1^T + m^2 \alpha_2^T$$

$$\alpha_{xy}^T = 2mn(\alpha_1^T - \alpha_2^T)$$

Coefficients of thermal expansion in x-y:

$$\alpha_x^T = m^2 \alpha_1^T + n^2 \alpha_2^T$$

$$\alpha_y^T = n^2 \alpha_1^T + m^2 \alpha_2^T$$

$$\alpha_{xy}^T = 2mn(\alpha_1^T - \alpha_2^T)$$

Coefficients of moisture expansion in x-y:

$$\beta_x^M = m^2 \beta_1^M + n^2 \beta_2^M$$

$$\beta_y^M = n^2 \beta_1^M + m^2 \beta_2^M$$

$$\beta_{xy}^M = 2mn(\beta_1^M - \beta_2^M)$$

3.1 Micromechanics Analysis Of Composite Materials

So far we have talked on apparent homogenized properties of a fiber reinforced lamina. Now we will examine how we can calculate the homogeneous lamina properties from the heterogeneous composite material constituent properties.

Micromechanics: Study of mechanical behavior of a composite material in terms of its constituent materials”

Macromechanics: Study of mechanical behavior of a homogenized composite material.

Constituent Materials:

Fiber (Graphite, boron, Silicon): E_f, ν_f, G_f, and V_f

Matrix (Resin): E_m, ν_m, G_m V_m

Volume fraction: 1 - Unit volume of composite

V_f = Fiber volume fraction = Vol. of fiber / Total volume

V_m = Matrix volume fraction = volume of matrix / Total volume

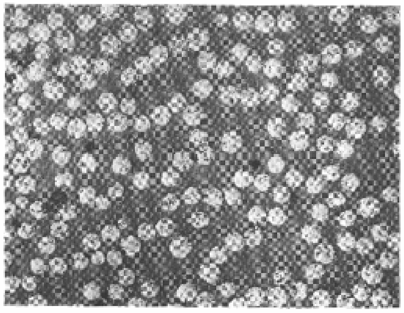
If no voids in the composites.

Then $V_f + V_m$ = volume of composite = 1

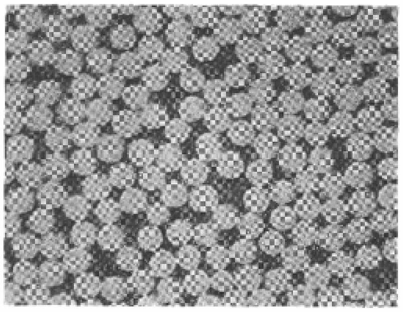
$\therefore V_f + V_m = 1$, if Volume of voids = 0

3.2 Representative Volume & Limits on Fiber Volume Fraction

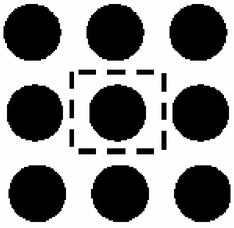
Photomicrographs of Transverse Section of Unidirectional Composites



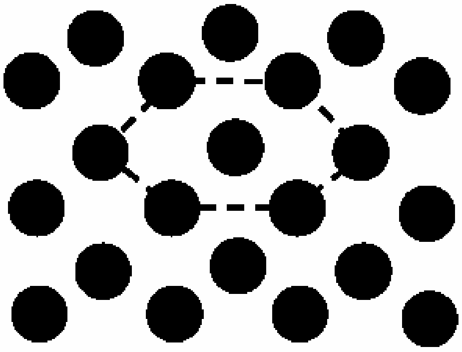
Silicon carbide/glass ceramic composite (Vf=.40)



Carbon/epoxy (AS4/3501-6) composite (Vf=.70)



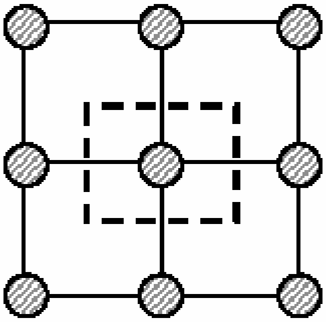
Square array

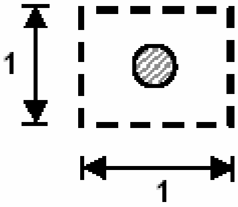


Hexagonal array

Representative Unit Cell (Cont.)

(a) Square array fiber distribution





1 x 1 x 1 (unit length)

$\mathbf{d_f}$ diameter of the fiber

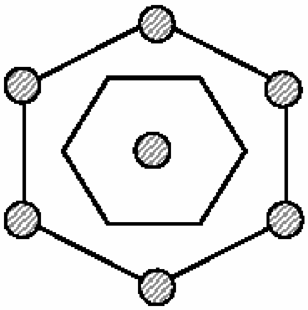
$$V_f = \frac{\pi d_f^2}{4}$$

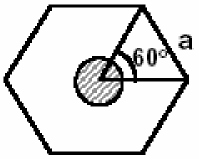
V_f is maximum when $d_f = 1$

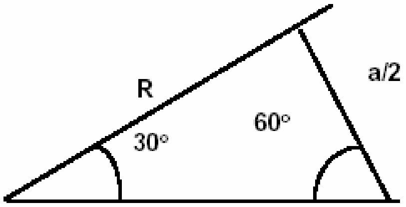
$$\therefore \quad V_f = \frac{\pi d^2}{4} = \frac{\pi}{4} = 0.785$$

$$\mathbf{V_f = 0.785}$$

(b) Hexagonal Array fiber distribution







$$\tan 30 = (a/2)/R$$

$$R = \frac{a}{2\tan 30} = \frac{\sqrt{3}}{2}a$$

$$A_t = 12\left(\frac{1}{2}\frac{a}{2}R\right) = 3a\frac{\sqrt{3}}{2}a = \frac{3\sqrt{3}}{2}a^2$$

$$A_f = \pi {R_f}^2$$

$$\frac{A_f}{A_t} = \pi {R_f}^2 \bigg/ \frac{3\sqrt{3}}{2}a^2$$

Fiber area fraction is max when $R_f = R$

$$\frac{A_f}{A_t} = \frac{3}{4}\pi a^2 \bigg/ \frac{3\sqrt{3}}{2}a^2 = \frac{\pi}{2\sqrt{3}} = 0.907$$

$$\mathbf{V_f = 0.907}$$

3.3 METHODS OF MICROMECHANICS

1. Mechanics of Materials

2. Elasticity Approach:
(i) Boundary principles
(ii) Exact solutions
(iii) Approximate solutions

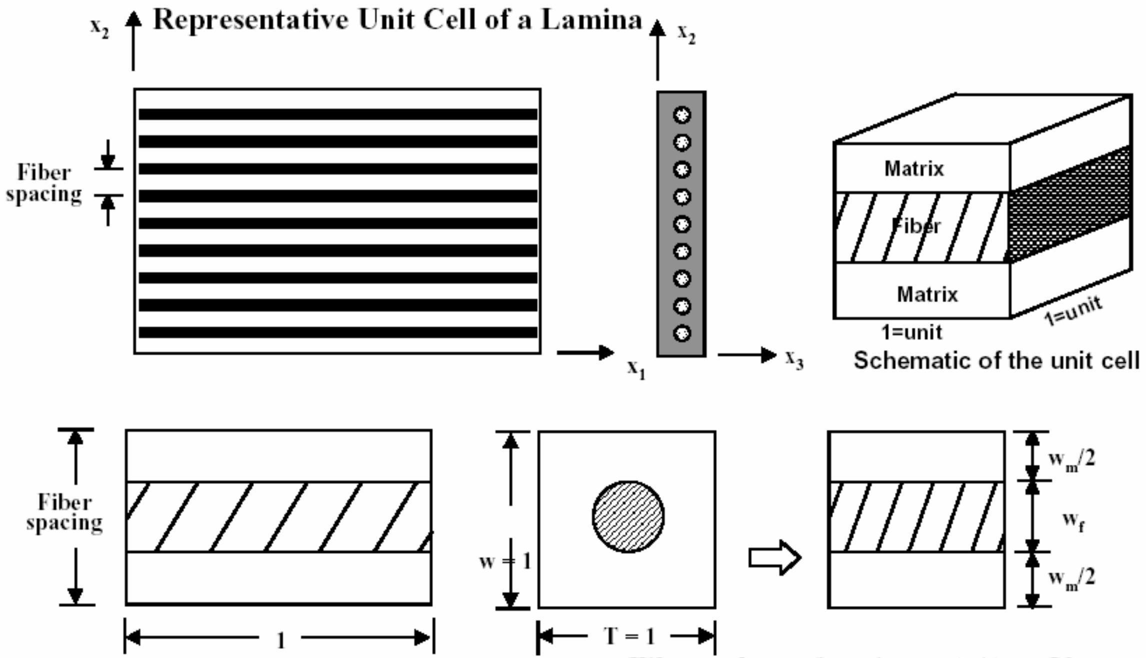
3. Numerical:
(i) Finite-difference,
(ii) Finite element,
(iii) Boundary element method

4. Experimental: **Photoelasticity**
In this course we address only the simple “Mechanics of materials” method.

Assumptions in Micromechanics of Composites

The Lamina is :	Macroscopically homogeneous Linearly elastic Macroscopically Orthotropic Initially stress free
The fibers are :	Homogeneous Linearly elastic Isotropic/Orthotropic Regularly spaced Perfectly aligned
The matrix is :	Homogeneous Linearly elastic Isotropic

3.4 Mechanics of Materials Method



Volume of fiber = $A_f \times 1 = A_f$

Volume of matrix = $A_m \times 1 = A_m$

Volume of composite = $V_c = A_c \times 1$

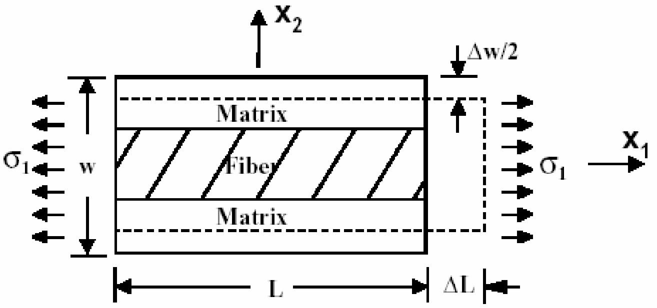
$\therefore$ Fiber volume fraction = $A_f/A_c = V_f$

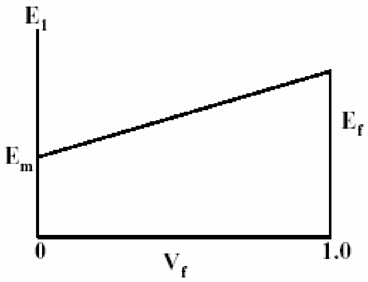
Matrix volume fraction = $A_m/A_c = V_m$

Also $W_f/W = V_f$

and $W_m/W = V_m$

(a) Determination of E_1





Assumption: Axial (x-) strain is same for the lamina, fiber and matrix

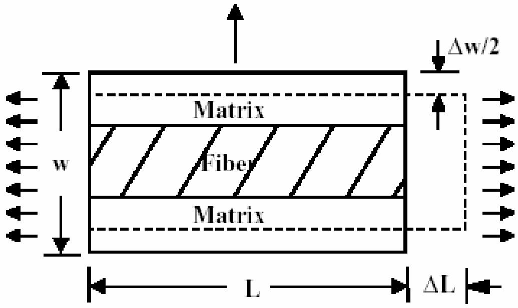
$\therefore$ **Strain in the composite** $\varepsilon_1 = \frac{\Delta L}{L} = \varepsilon_f = \varepsilon_m$

Total force in composite $\sigma_1 A_c = \sigma_f A_f + \sigma_m A_m$

$\therefore$ **Stress in the composite** $\sigma_1 = \sigma_f \frac{A_f}{A_c} + \sigma_m \frac{A_m}{A_c} = \sigma_f V_f + \sigma_m V_m$

$$\varepsilon_1 E_1 = \varepsilon_1 E_f V_f + \varepsilon_1 E_m V_m$$

(b) Determination of ν_{12}



Lateral strain due to σ_1, $\varepsilon_2 = \frac{\Delta W}{W}$

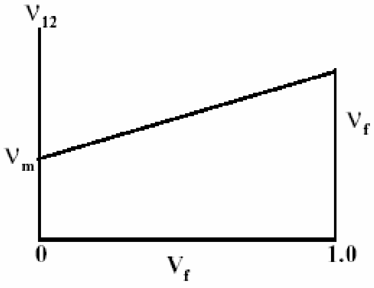
Poisson's ratio (Major) $\nu_{12} = -\frac{\varepsilon_2}{\varepsilon_1}$

$$\varepsilon_2 = \frac{\Delta W}{W} = \frac{-\varepsilon_1 \nu_f W_f - \varepsilon_1 \nu_m W_m}{W}$$

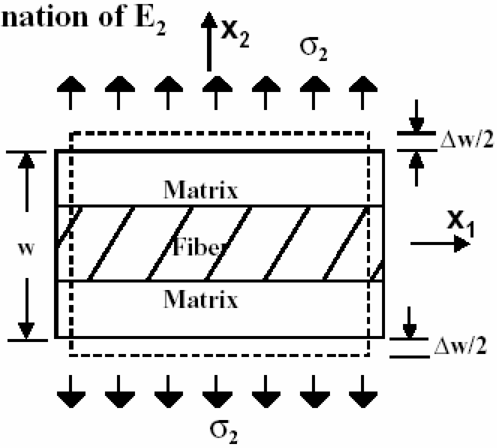
$$\varepsilon_2 = -\varepsilon_1 \nu_f V_f - \varepsilon_1 \nu_m V_m$$

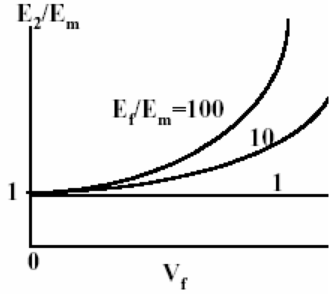
$$\therefore \quad \nu_{12} = -\frac{\varepsilon_2}{\varepsilon_1} = \nu_f V_f + \nu_m V_m$$

$$\boxed{\nu_{12} = \nu_f V_f + \nu_m V_m}$$



(c) Determination of E_2





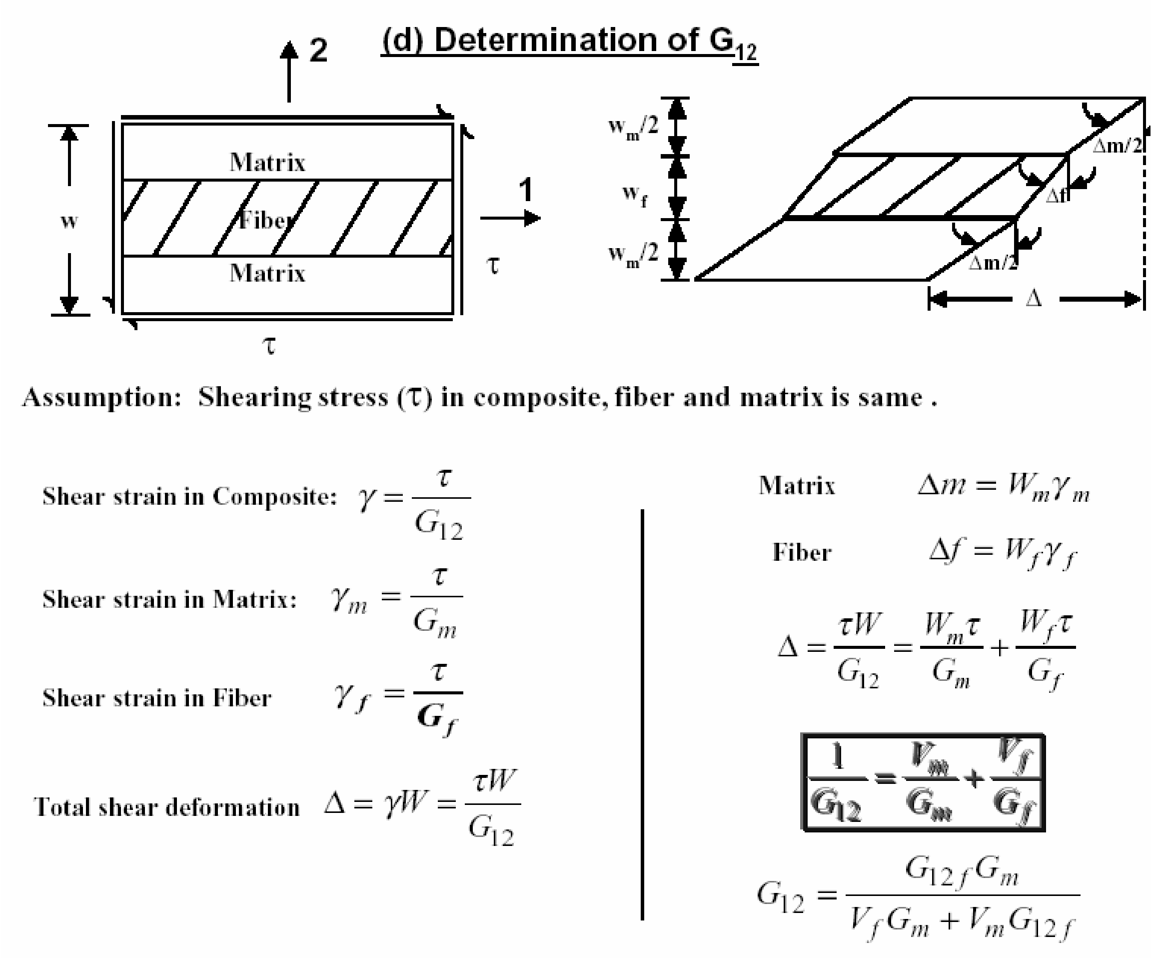
Assumption: Transverse stress, σ_2, is same in composite, fiber, and the matrix

$$\therefore \quad \Delta W = \varepsilon_2 W = \frac{\sigma_2}{E_f} W_f + \frac{\sigma_2}{E_m} W_m$$

$$or \quad \frac{\sigma_2}{E_2} = \sigma_2 \frac{W_f}{E_f W} + \sigma_2 \frac{W_m}{E_m W}$$

$$\boxed{\therefore \frac{1}{E_2} = \frac{V_f}{E_f} + \frac{V_m}{E_m}}$$

Reciprocal theory



(d) Determination of G_{12}

Assumption: Shearing stress (τ) in composite, fiber and matrix is same .

Shear strain in Composite: $\gamma=\dfrac{\tau}{G_{12}}$

Shear strain in Matrix: $\gamma_m=\dfrac{\tau}{G_m}$

Shear strain in Fiber $\gamma_f=\dfrac{\tau}{\boldsymbol{G_f}}$

Total shear deformation $\Delta=\gamma W=\dfrac{\tau W}{G_{12}}$

Matrix $\Delta m=W_m\gamma_m$

Fiber $\Delta f=W_f\gamma_f$

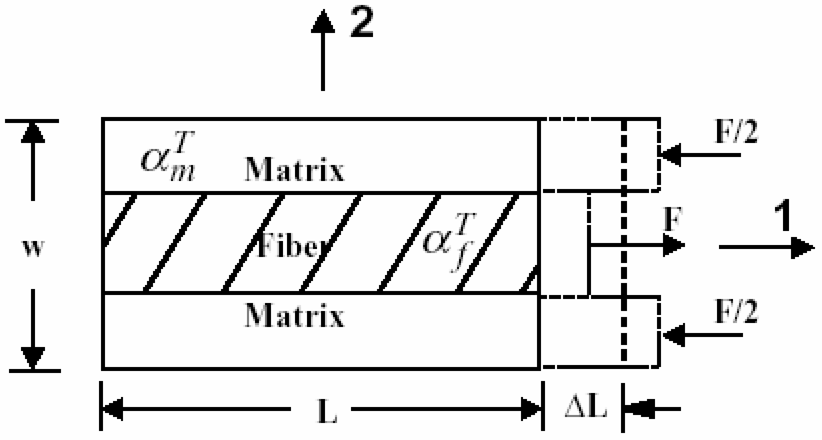
$$\Delta=\frac{\tau W}{G_{12}}=\frac{W_m\tau}{G_m}+\frac{W_f\tau}{G_f}$$

$$\boxed{\frac{1}{G_{12}}=\frac{V_m}{G_m}+\frac{V_f}{G_f}}$$

$$G_{12}=\frac{G_{12f}G_m}{V_fG_m+V_mG_{12f}}$$

Thermal Expansion Coefficients

Longitudinal expansion coefficients α_1^T



Assumption: Longitudinal thermal strains are same in fiber, matrix and lamina.

hermal expansion of the unit cell $= \Delta L = \alpha_1^T L$ — ①

Fiber $= \alpha_f^T L + \dfrac{FL}{V_f W E_f}$ — ②

Matrix $= \alpha_m^T L - \dfrac{FL}{V_m W E_m}$ — ③

① = ② = ③

$$\therefore \quad \alpha_1^T = \alpha_m^T - \frac{F}{V_m W E_m} \qquad \text{——} ④$$

$$\alpha_1^T = \alpha_f^T + \frac{F}{V_f W E_f} \qquad \text{——} ⑤$$

From 4 & 5

$$\alpha_m^T - \alpha_f^T = \frac{F}{W}\left\{\frac{1}{V_m E_m} + \frac{1}{V_f E_f}\right\} \qquad \text{——} ⑥$$

$$F = \left(\alpha_m^T - \alpha_f^T\right)\frac{\left(V_m E_m + V_f E_f\right)}{\left(V_m E_m V_f E_f\right)}$$

Solving for F from Eq. 6 and substituting in Eq. 4 we get

$$\boldsymbol{\alpha_1^T = \frac{\alpha_m^T E_m V_m + \alpha_f^T E_f V_f}{E_m V_m + E_f V_f}}$$

(b) Transverse Expansion Coefficient α_2^T

Note: Accounting for the Poisson's deformation due to tension/compression forces F; we can refine expression to (using energy principles)

$$\alpha_2^T = \alpha_m^T V_m \left(1 + \nu_m\right) + \alpha_f^T V_f \left(1 + \nu_f\right) - \nu_{12}\alpha_1^T$$

Halpin-Tsai's Equations

Of all the micromechanics equations Halpin- Tsai's semi-empirical equations are accurate and simple. Halpin and Tsai showed that the Hermans solution to Hill's self consistent model can be reduced to the approximate form

$$E_1 = E_f V_f + E_m V_m$$

$$\nu_{12} = \nu_f V_f + \nu_m V_m$$

$$E_2 = E_m \frac{1 + \xi_1 \eta_1 V_f}{1 - \eta_1 V_f}$$

where,

$$\eta_1 = \frac{E_f - E_m}{E_f + \xi_1 E_m}$$

$\xi_1 = 2$ **gives accurate E_2 values**

$$\boldsymbol{G}_{12} = \boldsymbol{G}_m \frac{1 + \xi_2 \eta_2 \boldsymbol{V}_f}{1 - \eta_2 \boldsymbol{V}_f}$$

$$\eta_2 = \frac{G_f - G_m}{G_f + \xi_2 G_m}$$

Best results were found for $\xi_2 = 1$

Thermal expansion coefficients for Orthotropic fibers

Hashin, "analysis of properties of fiber composites with anisotropic constituents" J. of App. Mec
vol. 48, 1979, p543.

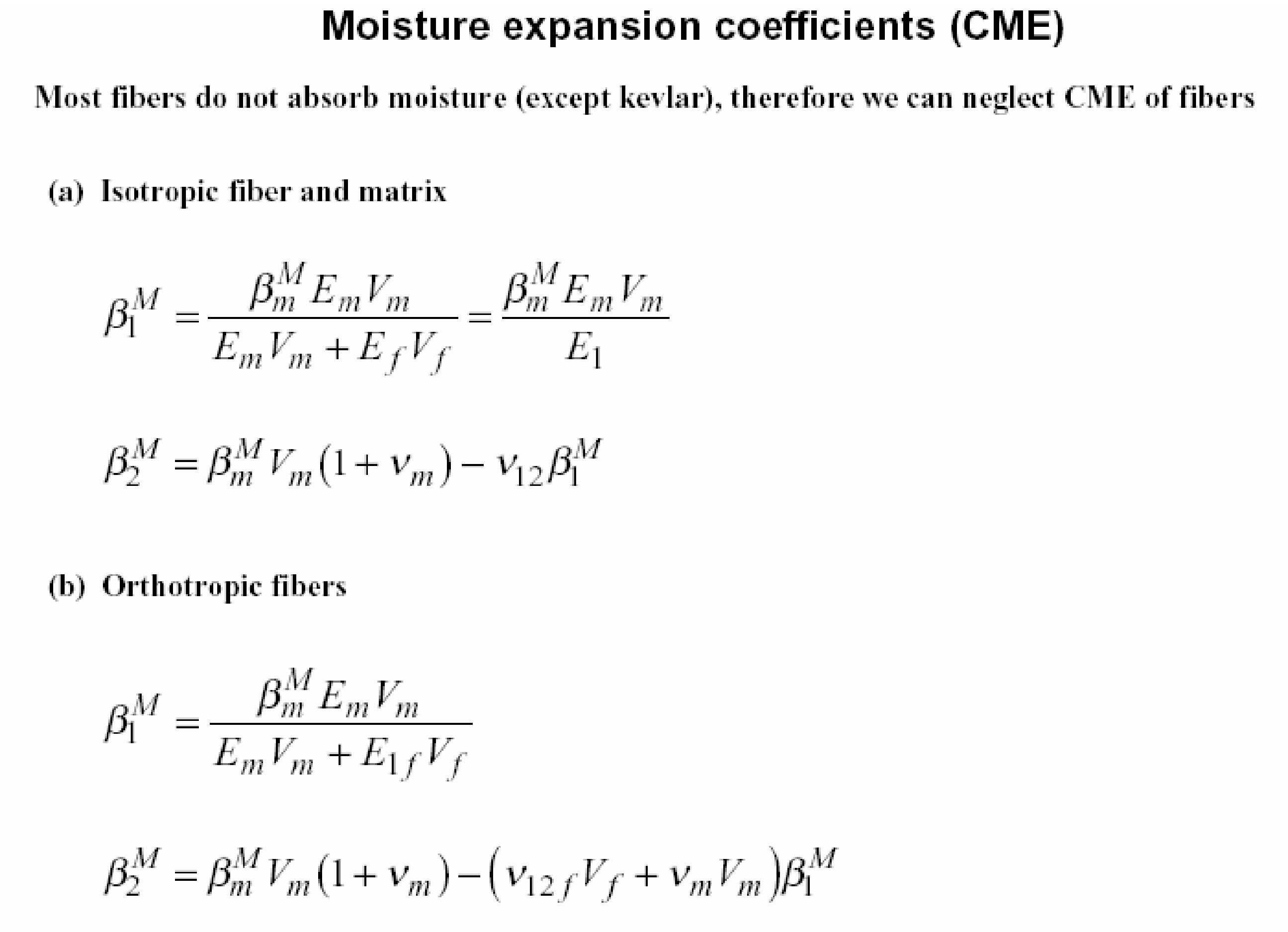
$$\alpha_1^T = \frac{E_{1f}\alpha_{1f}^T V_f + E_m \alpha_m V_m}{E_{1f} V_f + E_m V_m}$$

α_{1f}^T & α_{2f}^T **are axial and transverse thermal expansion coefficients of fiber respectively**

ν_{12f} **is the major Poisson's ratio of fiber**

$$\alpha_2^T = \alpha_{2f}^T V_f \left(1 + \nu_{12f} \frac{\alpha_{1f}^T}{\alpha_{2f}^T}\right) + \alpha_m^T V_m (1 + \nu_m) - \left(\nu_{12f} V_f + \nu_m V_m\right)\alpha_1^T$$

Material	α_1 10^{-6}/ °C	α_2 10^{-6}/ °C
Boron/Epoxy (boron/AVCO5505)	6.1	30.3
Carbon/Epoxy (AS4/3501-6)	-0.9	27.0
S-Glass / Epoxy (S-Glass / ERLA4617)	6.6	19.7
Kevlar / Epoxy (Kevlar49 / ERLA4617)	-4.0	57.6



Moisture expansion coefficients (CME)

Most fibers do not absorb moisture (except kevlar), therefore we can neglect CME of fibers

(a) Isotropic fiber and matrix

$$\beta_1^M = \frac{\beta_m^M E_m V_m}{E_m V_m + E_f V_f} = \frac{\beta_m^M E_m V_m}{E_1}$$

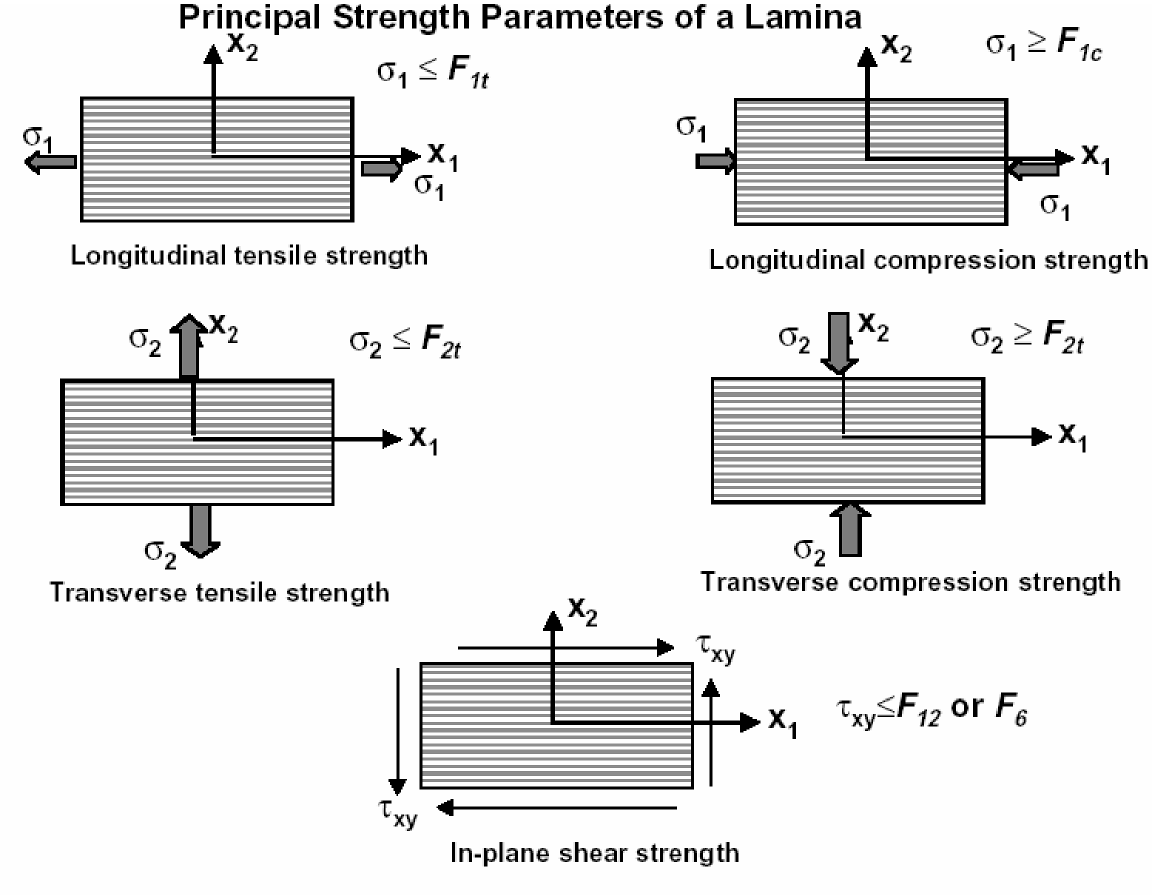
$$\beta_2^M = \beta_m^M V_m (1 + \nu_m) - \nu_{12} \beta_1^M$$

(b) Orthotropic fibers

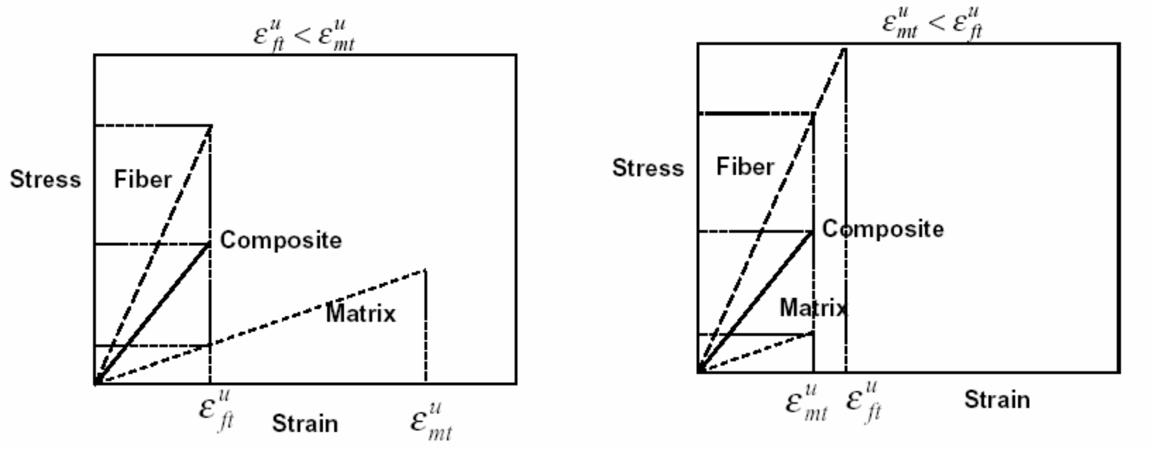
$$\beta_1^M = \frac{\beta_m^M E_m V_m}{E_m V_m + E_{1f} V_f}$$

$$\beta_2^M = \beta_m^M V_m (1 + \nu_m) - \left(\nu_{12f} V_f + \nu_m V_m \right) \beta_1^M$$

3.6.0 Micromechanics of Strength Models


Principal Strength Parameters of a Lamina

3.6.1 Longitudinal Tensile Strength

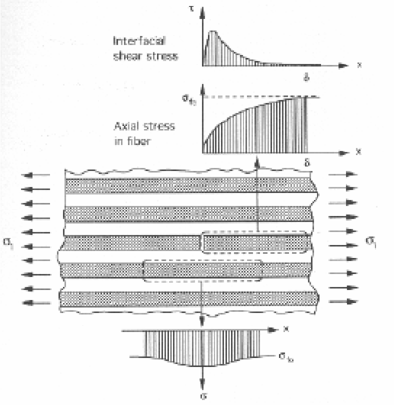


$$F_{1t} = E_f \varepsilon^u_{ft} V_f + E_m \varepsilon^u_{ft} V_m$$

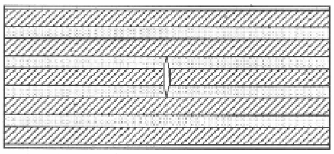
$$F_{1t} = E_f \varepsilon^u_{mt} V_f + E_m \varepsilon^u_{mt} V_m$$

<u>(b) Fiber Dominated Failure Mechanism</u>

Fiber strength varies from point-point and fiber to fiber.

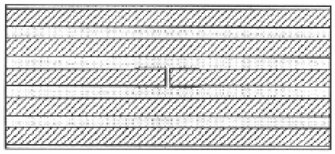


(a) Transverse Matrix Cracking



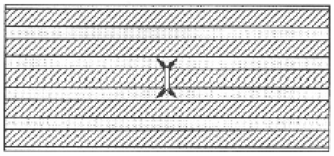
Brittle matrix & strong interface
Ceramic composites
(Silicon carbide/glass ceramic)

(b) Fiber Matrix Debond



Weak interface and/or high
ultimate fiber strain
(Glass/epoxy)

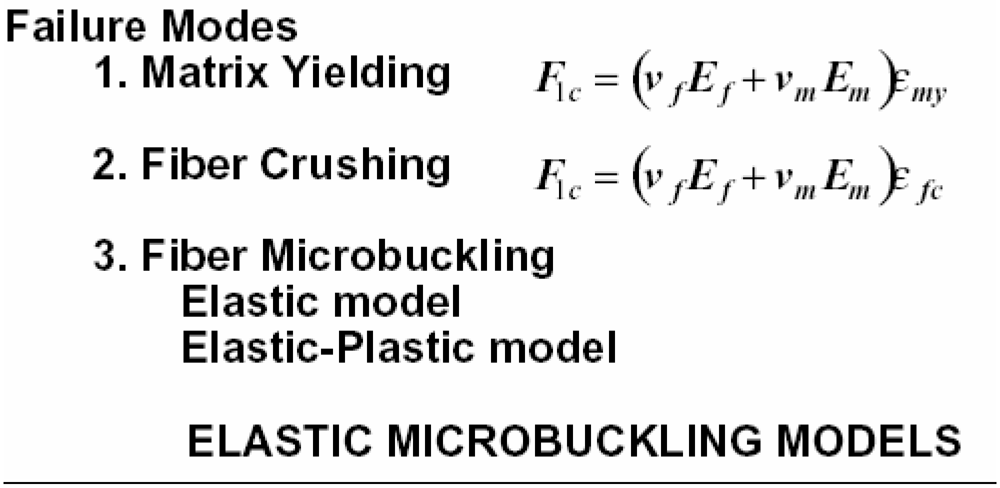
(c) Conical Shear Fracture



Ductile matrix & strong interface
Metal matrix composites

3.6.2 COMPRESSION FAILURE MODES
Unidirectional Composites

1.

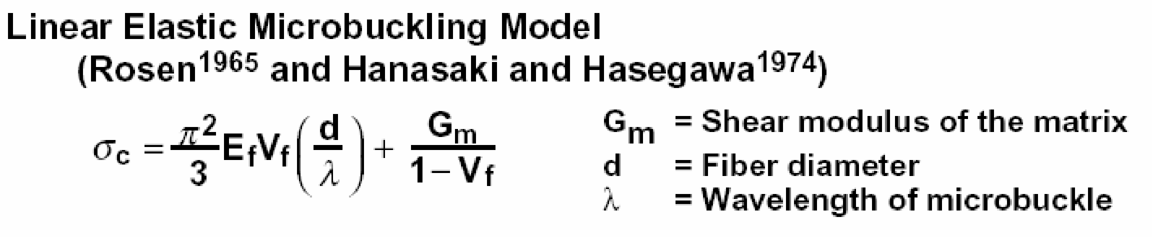


Failure Modes

1. Matrix Yielding $F_{1c} = \left(v_f E_f + v_m E_m\right)\varepsilon_{my}$
2. Fiber Crushing $F_{1c} = \left(v_f E_f + v_m E_m\right)\varepsilon_{fc}$
3. Fiber Microbuckling
    - Elastic model
    - Elastic-Plastic model

ELASTIC MICROBUCKLING MODELS

2.

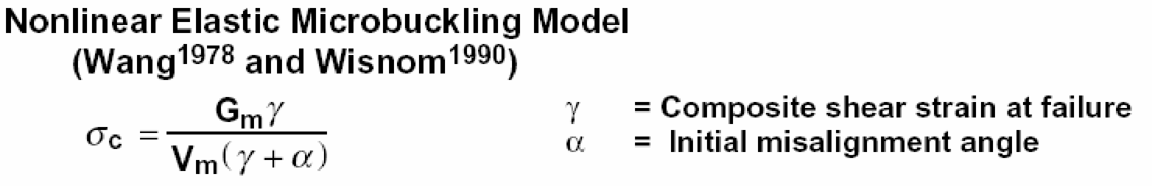


Linear Elastic Microbuckling Model
(Rosen^{1965} and Hanasaki and Hasegawa^{1974})

$$\sigma_c = \frac{\pi^2}{3} E_f V_f \left(\frac{d}{\lambda}\right) + \frac{G_m}{1-V_f}$$

G_m = Shear modulus of the matrix
d = Fiber diameter
λ = Wavelength of microbuckle

3.



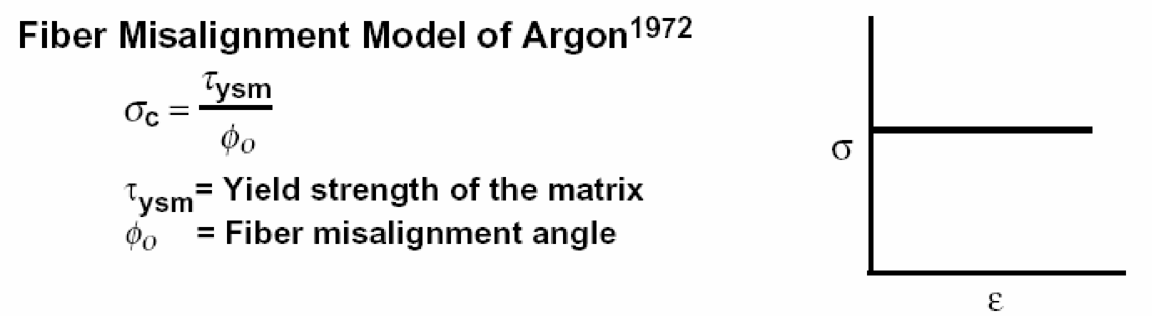
Nonlinear Elastic Microbuckling Model
(Wang^{1978} and Wisnom^{1990})

$$\sigma_c = \frac{G_m \gamma}{V_m(\gamma + \alpha)}$$

γ = Composite shear strain at failure
α = Initial misalignment angle

RIGID-PLASTIC MICROBUCKLING MODELS
Unidirectional Composites

1.

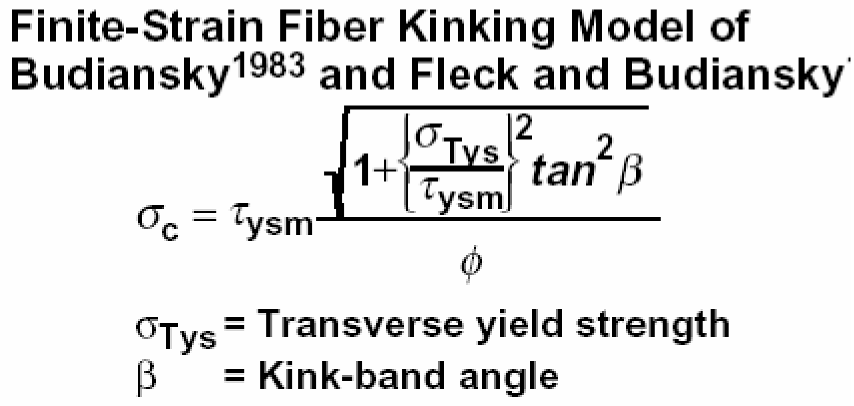


Fiber Misalignment Model of Argon^{1972}

$$\sigma_c = \frac{\tau_{ysm}}{\phi_o}$$

τ_{ysm} = Yield strength of the matrix
ϕ_o = Fiber misalignment angle

2.



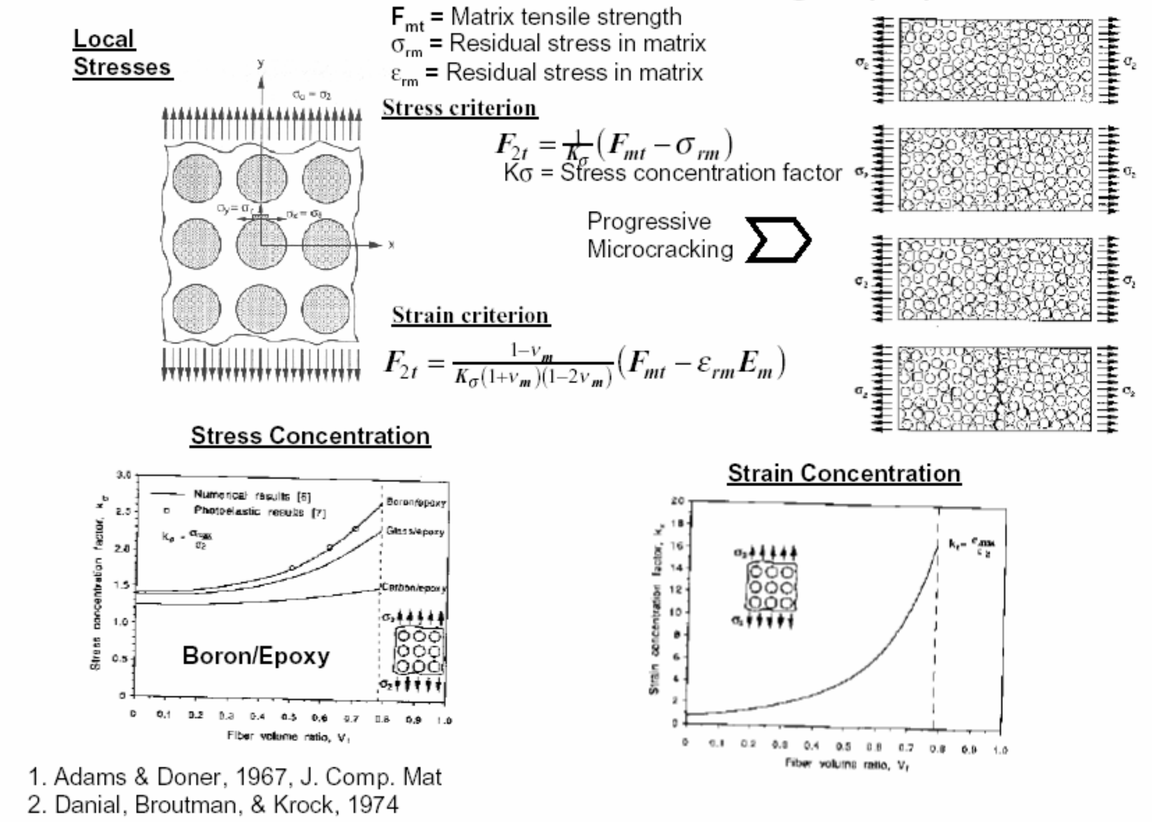
Finite-Strain Fiber Kinking Model of
Budiansky^{1983} and Fleck and Budiansky

$$\sigma_c = \tau_{ysm} \frac{\sqrt{1 + \left\{\frac{\sigma_{Tys}}{\tau_{ysm}}\right\}^2 tan^2 \beta}}{\phi}$$

σ_{Tys} = Transverse yield strength
β = Kink-band angle

α=2 to 5 deg | for unidirectional composites
β =15-25 deg

3.6.3 Transverse Tension Strength



Local Stresses

F_{mt} = Matrix tensile strength
σ_{rm} = Residual stress in matrix
ε_{rm} = Residual stress in matrix

Stress criterion

$$F_{2t} = \frac{1}{K_\sigma}\left(F_{mt} - \sigma_{rm}\right)$$

Kσ = Stress concentration factor

Progressive Microcracking

Strain criterion

$$F_{2t} = \frac{1-\nu_m}{K_\sigma(1+\nu_m)(1-2\nu_m)}\left(F_{mt} - \varepsilon_{rm}E_m\right)$$

Stress Concentration

Boron/Epoxy

Strain Concentration

1. Adams & Doner, 1967, J. Comp. Mat
2. Danial, Broutman, & Krock, 1974

Module 8: Design Concepts for Composite Materials/Structures

This part is divided into four chapters:

8.1	The methodology and management of a design project/Design Issues
8.2	The Procedures for designing materials/Typical Structural Component Design processes
8.3	The structural component design techniques/Laminate Analysis and
8.4	The limit state design method.

The emphasis is on design methods for simple laminate analyses and component design and is based upon formulae associated with especially **orthotropic laminates** (i.e. those that are symmetric about their mid-plane with balanced reinforcement) and design charts and tables. Attention is directed towards mechanical behaviour of units; the in- service properties are not discussed. The mechanical properties of the composites are assumed to be modified to take account of **anisotropy and viscoelastic behaviour**, such as creep, and of the rate of dependence of polymer materials. A consequence of this is that the polymer material data values are reduced from that of their short term values.

The design of composites is an **interactive process** between the three processes viz: the material design, the structural design and the manufacturing techniques for the composite material/structure. These three processes must be considered simultaneously because of the many different **fibre arrays** that can be incorporated into the **matrix material** and the diverse manufacturing methods that are available, all of which will affect the final product in terms of ultimate failure under certain loading conditions.

Only stress analyses of the materials and structures under load have been discussed, but it should be remembered, however, that the criteria for design of composite beams are generally based upon displacement although complete collapse of the structural system is stress-related.

8.1 Methodology and management of a design project/Design Issues

8.1.1 Introduction

Competent designers, engineers and analysts can all execute their trade if given the data and design methodologies. That is what this book is all about: providing the data and design methodologies for composite materials.

There are, however, a number of design considerations particular to these materials of which those new to the subject need to be aware. There is also the need for a great deal more interaction between the members of the design team, because of the many influencing factors. This puts a greater emphasis on the role of design management to control all the activities in order to achieve an optimum solution.

It is also essential that a-quantified design process is followed in order to avoid overlapping of skills and to ensure that the right skills are introduced at the most appropriate point in the design programme.

The designers need therefore to have not only a good technical grounding in the subject, but also a sound knowledge of all the other activities an understanding of how the design process works and a sympathy with the needs of good management

8.1.2 Design considerations

A polymeric composite material is made up of at least two materials: a fibre and a matrix. These are combined to exploit the individual characteristics, thereby providing additional qualities that they are unable to provide individually

They differ markedly from metals in the following ways:

- Composites are mostly orthotropic and inhomogeneous
- Generally Stiffness is less than that of steels leading to greater attention to local and overall structural stability
- Material properties are influenced by the manufacturing process, temperature and the environment.
- Most resins are combustible
- Material costs particularly for the high strength and stiffness fibres, form a high proportion of the product cost

Furthermore, when comparing composite materials to metals it is found that:

- They are lighter, leading to excellent specific strength and stiffness values.

- They have very good environmental resistance and do not corrode like many metals.
- Fibres can be used strategically leading to ease in optimising weight.
- They are readily formed into complex shapes.
- They have low thermal conductivity.

With the above points in mind, the designer new to the subject of composite materials needs to address a number of particular areas.

8.1.2.1 Designing the laminate

Many structural materials generally have isotropic properties and they are homogeneous, that is to say, they are uniform in all directions.

A composite material can take a number of different forms. The material may be orthotropic, such as a unidirectionally reinforced polymer, where the strength and stiffness in the fibre direction considerably exceeds that at 90° to the fibre. It may be **planar-isotropic**, such as a random chopped strand glass mat reinforced polymer. It may approach isotropy by the use of very short fibres randomly, placed in a polymer by injection moulding. In all cases, though, composite materials are inhomogeneous.

It is these anisotropic properties of composite materials that are the key to developing highly efficient structures. Fibres can be strategically placed so that they locally engineer the required strength and stiffness properties. Furthermore, by combining different fibre types - glass, aramid, carbon, etc - the particular properties of each fibre can be exploited. For instance, the low cost of glass, the extreme toughness of aramid fibre and the high strength and stiffness of carbon can all be used within a single laminate.

A composite material is not ductile like metal, and failure, when it occurs, is abrupt. The stiffness properties are generally lower than those of steel, but the lower weight of composite materials results in excellent specific strength and stiffness properties, leading to reduced- weight components and structures.

The properties of the laminate are affected by the amount of fibre in the matrix, which in turn is influenced by the manufacturing process.

8.1.2.2 Establishing property data

Obtaining reliable data for any material is essential to the success of the design function. Obtaining reliable data for composite materials is aggravated by fragmentation of supplier. One set of companies produces the fibre, white others produce the matrix or resins. Further companies produce yet more materials – prepregs, sandwich cores, bonding agents, etc. It is therefore quite often difficult to obtain reliable data for a combination of materials that makes up the finished laminate. Furthermore, the properties will be affected by the manufacturing process and the working environment.

It generally therefore falls to the designers to create their own data bank of properties by testing materials on an ongoing basis. This is an essential function within the design process and a useful data bank can be slowly achieved.

Reliance on manufacturer's data, where available, requires an element of caution. Often the data are not adequately quantified and testing standards ate not made available.

8.1.2.3 Designing for the environment

The environmental factors of heat, cold, moisture, ultraviolet light and aggressive materials (such as acids) can all have an adverse effect on the performance of a composite laminate over a period of time. The extent of the effect is a function of the fibres and resins selected, and, of course, the degree of the environmental condition.

Needless to say, composite materials behave extremely well in many arduous environmental situations: The marine and chemical industries have shown this to be the case where fibre reinforced polymers are accepted materials. But care is needed, particularly in a hot, wet atmosphere where the mechanical performance of some polymeric composites can fall by as much as half from those at normal ambient condition. This requires particular attention if long term loading conditions are envisaged.

Adequate testing of materials in the expected environment is the only way to ensure a satisfactory structural integrity.

8.1.2.4 Designing for joints and assemblies

Composites have the principal advantage of being chemically joined during their manufacture. Consequently, a carefully manufactured large component need not have any joints requiring mechanical fasteners or secondary bonded joints. However, it is not always possible, desirable or even practical to make a single unit and more often than not a complete assembly is obtained from a number of components or sub-assemblies.

To this end, the designer needs to have a good understanding of the performance of mechanical joints, which are often governed by the strength of the matrix as opposed to the fastener itself. Consequently, long term loads may be affected by the creep properties of the matrix.

Alternatively, use can be made of bonded joints, which has the advantage of less concentration of load through the joint. Provided care is exercised in avoiding stress concentrations caused by abrupt changes in section, excellent joints can be designed that are suitable for bonding, and made in a properly controlled environment.

8.1.2.5 Designing for robustness and through life performance

Robustness is difficult to quantify as it is a measure of the ability of a structure or component to survive knocks, shocks and rough handling. Composite materials can be shown to have good resilience and toughness, particularly aramid reinforced polymers which are also favoured in ballistic missile protection. The ability of a structure to withstand through-life impacts can be enhanced by good manufacturing quality, eliminating production flaws such as voids, excessive air inclusions and shrinkage cracks, but good design plays an equally important role. The correct selection of materials, the provision of adequate load paths and the avoidance of stress concentrations are the most important aspects.

Composite materials generally have good fatigue resistance and they can be used to overcome through-life problems often associated with metals, particularly where the metal has been welded.

8.1.2.6 Designing for manufacture

A most important aspect of designing in composite materials is the interaction with the manufacturing processes, which are varied and diverse. The designer needs to have a good understanding of how the many processes work and how the design will be affected by the process. For instance, the quality control achievable with contact moulding falls very short of that available with an oven-cured fibre and resin system. Consequently, factors of safety used in design need to reflect these differences and the selection of design stresses may need to reflect the variation in properties that will occur.

It is also essential that the design process incorporates a very early involvement from those people who are truly versed in the manufacturing processes, as an incorrect choice could have disastrous results with respect to the product’s performance and cost.

8.1.2.7 Designing for cost

Expensive materials do not necessarily lead to expensive components. Reduced handling costs reduce product cost, reduced weight enhances the through-life performance, increased environmental resistance prolongs life, etc.

Composite materials have many unique characteristics which the designer can exploit to advantage, but cost must be carefully quantified. For any dynamic structure or component, this must include a through-life cost assessment to ensure that the best use is made of any reduced weight.

8.1.3 The need for design management

Design management is now a recognised and respected activity but has only recently received the attention it deserves. The driving factor has been the need to produce better and more cost effective products.

The simple objective of design management is to ensure that the product meets the set parameters and is fit for the purpose intended within an accepted cost envelope. With the introduction of composite materials as the manufacturing material, this objective is brought sharply into focus because of the wide range of candidate constituent materials – fibres, resins, sandwich cores, etc. - the range of cost of these materials, the range of process techniques, assembly and quality control procedures- all of which can detract and often confuse the design team. Design management ensures that a logical and controlled interactive procedure is followed, allowing the various disciplines to achieve the best compromise for the sake of an efficient and cost effective product.

The function and necessity for design must be understood at all levels, from the corporate to the individual.

At the corporate level, the overall planning is undertaken by senior management, defining what is needed and balancing this with costs and available resources. This corporate level must also understand the importance of the design function - it is not an overhead, it is a company asset.

At the management level, project managers ensure that the particular task is properly controlled and managed. The project objectives are defined and the necessary disciplines are brought together.

At the design level, the designers use all available resources, data and facilities to design the product, within an accepted and controlled design methodology.

All this may sound fairly obvious, but the above design considerations highlight the many critical influencing factors which make management of the design so important when composite materials are involved. It is also important to understand and use a recognised design process.

8.1.4 The design process

It is necessary to have a framework in which design can function. The introduction of composite materials as the primary material enhances this necessity. An attempt to rationalise the design process for composite material has been previously made 8.1 and this is graphically illustrated in Fig. 8.1.

..\Drawings\Fig 8.1.vsd

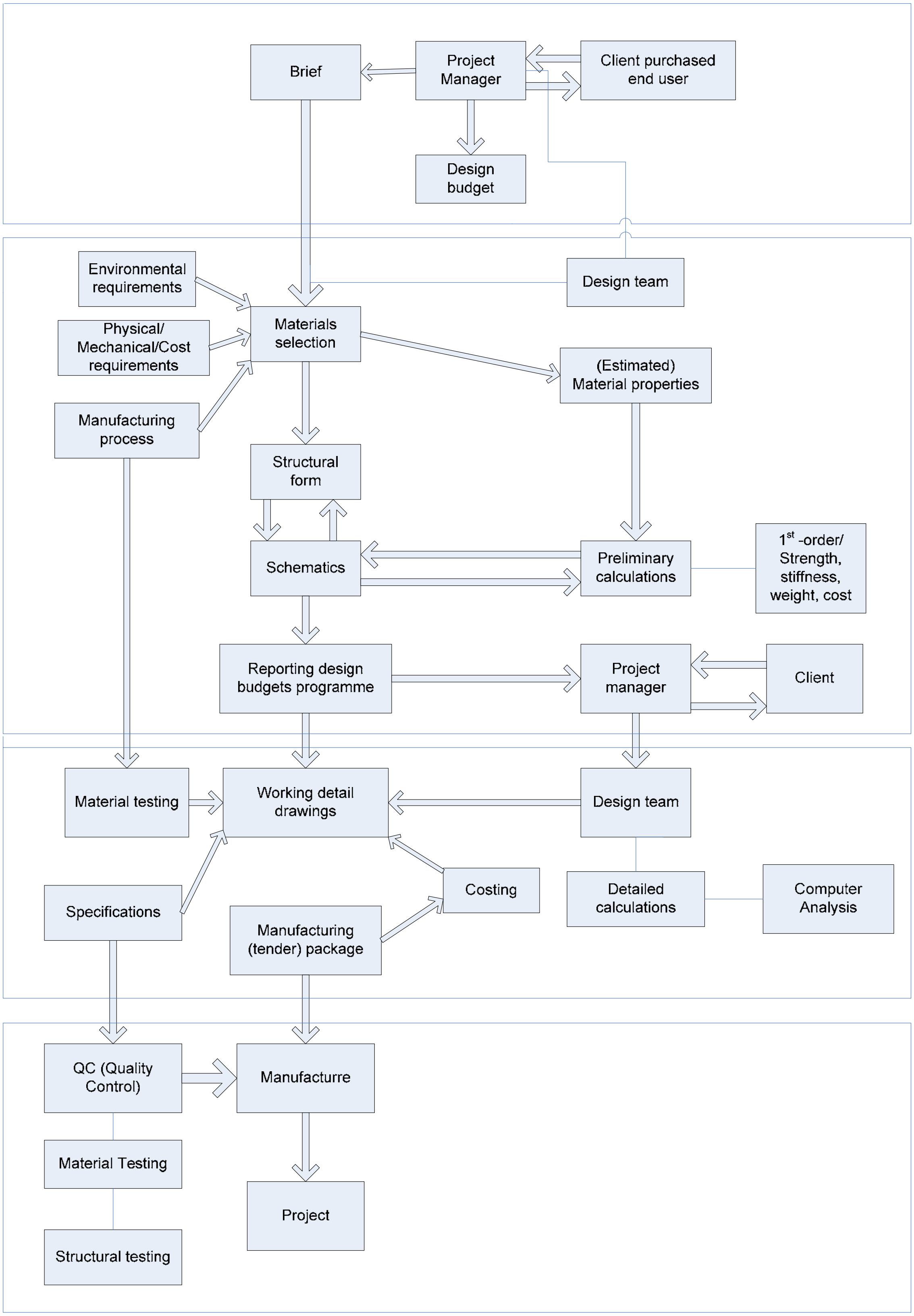


Fig 8.1: Design process for Composite Materials

The process is divided into four phases. The first is perhaps the most important: the brief. Without a well-defined brief, no product can be adequately designed. In fact, it should be argued that without a brief, no product should be commenced. The effect of the brief on composite materials is important, particularly with respect to cost. The cost of composites can range by a factor of 100. The brief therefore must contain comprehensive information on the cost envelope, including the through-life or operational costs. The required quantity is also important because this in turn will affect the cost by way of tooling, cycle times, materials used, etc.

The cost of design is also an aspect of the first phase which requires addressing carefully. As previously stated, design should not be treated as an overhead, but as an asset. Consequently, it should be costed and included in the overall costs. A design team working to a properly costed programme is one that is better working to an open budget. The associated discipline is not only good for the company but it also helps those in the design team value their own time.

The second phase involves the preliminary design. It is in this phase that the importance of design management must be appreciated. There are many disciplines involved, several activities and, with composites many different candidate materials and processes. It is extremely easy to go off in several directions when looking for an acceptable design solution, especially if those involved do not take the advice of their fellow professional disciplines.

All designers should ask themselves at the early stages of a design programme: can it be made and can it be assembled? With composites, these questions need more attention because of the many processes available, each with its own advantages and disadvantages. For instance, closed mould technology (RTM, etc.) provides a moulded surface to each face, as opposed to contact moulding or female tooling and prepregs. But closed mould technology has certain restrictions on geometry, such as draw angles, which, unless properly addressed, may lead to problems in manufacture and assembly.

Also of importance in this second phase is the question of property data. One aspect of composites not always initially appreciated by designers used to metals is that the material is often made at the point of manufacture, as opposed to buying in materials and fabricating. The material's strength and stiffness are therefore functions of the process, the quality control during the process operation, the skill of the operators and, of course, the constituent materials used. The data used in the preliminary design therefore have to be assumed or estimated theoretically. Experienced designers will have created their own data banks of material properties from previous projects and they will be able to make a selection of design properties with confidence. Less experienced designers must use published data, and care is needed in using some data, particularly those which do not reference the source or which do not fully quantify the properties, e.g. the absence of the volume fraction.

When the design concept and the manufacturing process have been frozen, the ongoing design costs have been checked and the brief reassessed, the third phase is entered: that of detail design. During this phase, the selected materials need to be used with the specified manufacturing process to make materials for testing to establish, the mechanical properties, thereby reaffirming the estimated properties from the second phase, or to revise the design for the actual values.

The interaction of skills can perhaps be appreciated when the second and third phases of the design process are studied. The composite industry is a fluid industry. It is being introduced to new materials, processes awl end uses constantly. No one person can therefore be sufficiently equipped to cope with all these factors at once. The interaction of skills is therefore essential in order to bring the best of all these factors into the design process.

This should not, and does not, stop when the final stage is entered; that of manufacture. More so than with other materials, the design process for composite materials must continue throughout the manufacturing period. The performance of the product is affected by the process, the quality control, inspection, product maintenance and handling. Feedback from this phase is important information to put back into the design envelope.

8.1.5 Design potential

Composites offer the designer unique possibilities to improve the performance of a product leading to cost effective engineering. They have excellent specific strength and stiffness properties, and through- life environmental resistance, they can be formed into complex shapes and they have the ability to be tailored to suit local and overall mechanical performance parameters.

There are, of course, some disadvantages, such as the high cost of the high performance materials and the combustibility of many of the resin systems, but perhaps the biggest disadvantage is the lack of design standards, methodologies and quality control procedures, and the lack of understanding by both management and designers of the materials themselves.

All these aspects are now being addressed and it is certain that the industry will grow as more and more applications are established, which will in turn provide the impetus for improved standards and understanding.

The designer is at the heart of this progression and the possibilities for composites are not only considerable, but also exciting. Progression must, however, be undertaken within a controlled framework and the importance of the management of design and the need for an established design process with accepted design methodologies requires constant emphasis.

8.2 Procedures for designing materials

8.2.1 The principles of design analysis

As in all structural designs the developed stress and strain levels in the polymer composite when it is under load must be determined and the material designed. The critical stress, strain and deformation values are then compared with the relevant design criteria to ensure that the component satisfies product requirements and material limitations. Polymer composites are usually macroscopically inhomogeneous and anisotropic because of the reinforcing fibres and, in addition, have viscoelastic properties derived from the polymer matrix. Owing to the differing material descriptions between composites, further material properties are required to characterise polymer composites completely, consequently, more complex analysis procedures are required to determine stress and deformation levels than are generally required for the more conventional materials.

The three main aspects of material design which will be considered are:

1. The analysis which considers the anisotropy and non-homogeneity in polymer composites (the material properties & the fibre and matrix, ply orientation, layer thicknesses, etc.).

2. The short term load condition, in which the elastic stress and analysis methods may be used, provided anisotropy is taken into account.

3. The long term load conditions, in which viscoelastic and degradation effects may be significant; in this case it would be necessary to modify the short term elastic design procedures.

8.2.2 Requirements of materials' design

Polymer composite materials generally consist of laminae of resin impregnated fibres which are **unidirectionally** or **orthogonally aligned**, **angle-ply** or **randomly orientated** systems. It is also possible to provide a mixture of fibre arrays in adjacent laminae when fabricating a composite material to meet the required loading situation. This freedom to tailor-make composite materials with specific required properties introduces an additional complexity in the design analyses of these systems over those of the conventional ones.

As the design of composite structures ideally involves the simultaneous analysis and design of the material and the structural system, this approach may be undertaken by the finite element analysis. It can be expensive for small jobs and is really relevant only to the high technology of the aerospace industry; for the medium technology applications a simpler approach is to consider the material design independently from that of the structural one. Consequently, for the latter design application, the properties of a chosen fibre/matrix array are calculated or measured and are then utilised in the structural analyses.

The majority of polymer composite structural systems are composed of relatively thin plates or shell laminates where the properties may be in terms of laminate structure and ply thickness using laminated plate theory or by commercially available PC software. [8.1-8.3]Assuming that the laminates had orthotropic symmetry and that both in-plane direct and shear loads as well as bending and twisting moments were acting on the plate, see Fig. 8.2, the element properties would require two principal tensile stiffness, shear stiffness and two principal flexural rigidities. In addition, the corresponding strength values in tension, flexure and shear would be required; the latter three values would be obtained by either mechanical tests or by undertaking a laminate analysis and thus the laminate stiffness and strength characteristics would be known. To satisfy the necessary design criteria this relatively small number of properties would then be used in the structural analysis and design for the composite.

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8.2 Schematic diagram of a composite laminate element

8.2.2.1 Short term loading considerations

A typical tensile stress-strain characteristic of a randomly orientated glass fibre-polymer composite, shown in Fig. 8.3, would indicate an approximate linear elastic relationship when a relatively low stress level is applied to the composite. This will eventually progress to a non-linear situation which indicates the onset of micro-damage (fibre debonding. resin cracking or transverse ply failure) and brittle failure; the latter is associated with fracture of the fibres.

Polymer composites may be characterised as:

- Linear-elastic for design purposes, and the relevant elastic moduli and failure stresses would then be incorporated into the calculations. If necessary, reduced values of stress would be used to take account of micro-damage failure.
- Orientated fibre composites in which the properties are highly dependent upon the direction of fibres; the design would then consider the anisotropic nature of the material.

The composite material design will be divided into two main groups, those that may be considered **quasi-isotropic** and those that are **anisotropic**.

The randomly orientated fibre polymer material is the most widely used quasi-isotropic composite in engineering applications and the mechanical properties which are required for design are the modulus of elasticity, the Poisson ratio and a failure stress. The modulus of rigidity would be obtained from the relation between E and v. Thus:

$$G=E/2(l+v) \quad \ldots\ldots\ldots\ldots\ldots\ldots.8.1$$

The an-isotropic polymer composite materials would be those with specific fibre orientations as unidirectionally aligned fibre plies or woven fibre fabric. Ills highly likely, that those composites would possess orthotropic material properties by virtue of the fact that the fibres, and hence the composite, would possess two orthogonal symmetry directions in the plane of the laminate. Four elastic constants would therefore be required to characterise the material stiffness properties. These are the moduli of elasticity of the composite in directions 1 and 2 ($E_{11}$and E_{22}), the modulus of rigidity (G_{12}) and the Poisson ratio (ν_{12}). The usual notation has been adopted here, see Fig. 5.3, where the first suffix- refers to the plane upon which the stress acts and the second suffix is the coordinate direction in which the stress acts. As laminates are two- dimensional systems, only stresses in the planes 1.2 are considered. The convention for the Poisson ratio vu is that the second suffix refers to the strain produced in direction-2 when the lamina is loaded in direction-1. The Poisson ratio ν_{12} is derived from the equation.

$$\nu_{21} = \nu_{12} E_{22}/ E_{11} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 8.2$$

The ultimate strengths σ^*11, σ^*22 and σ^*12 are also required to characterise the material. Typical tensile strengths and moduli of elasticity values are given in Table 5.1 for randomly orientated woven roving and unidirectionally aligned Kevlar and carbon fibre composites. It is important to remember that these values are only guides as the actual values will depend not only upon the type of fibre used but also upon the fibre volume fraction of each type of reinforcement and the technique used for the composite manufacture. The corresponding values for composites under compressive and flexural loads will be different from those given above owing to the non-homogeneity in polymer composites. It should be noted that the above values are those for ultimate failure; however, matrix cracking stresses may be considered the failure criteria, in which case a lower failure stress would be quoted.

The orthotropic properties of, say, woven ravings in the off-axes are much lower than those in the principal fibre directions and in design the lower stresses, particularly the shear stresses, need to be addressed.

Failure in the unidirectionally aligned composites could occur in the transverse direction as a result of low secondary stresses transverse to the main fibre direction and if this is a particular problem composites with cross-ply or angle-ply reinforcement are utilised.

Fig 8.2 Tensile stress-strain curve for typical randomly orientated fibre/ matrix laminate under short term loads.

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Fig 8.3 Design data for typical polymer composite materials

Properties	Randomly oriented glass fibre-polyester	Woven roving glass fibre-polyester	Unidirectio-nally aligned glass fiber-polyester	Unidireci-nally aligned aramid fiber-polyester	Unidirectio-nally aligned carbon fiber-polyester
ν_f	0.2	0.35	0.6	0.7	0.7
E_{11} (Gpa)	8	16	42	76	180
E_{22} (Gpa)	8	16	12	8	10
G_{12} (Gpa)	3	4	5	3	7
ν_{12}	0.3	0.15	0.3	0.34	0.28
$\sigma^*_{11\text{-ult.}}$	95	250	700	1400	1500
$\sigma^*_{11\text{dam.}\dagger}$(Mpa)	50	100	_	_	_
$\sigma^*_{22\text{-ult.}}$ (Mpa)	95	250	30	12	40
$\sigma^*_{22\text{-dam.}}$(Mpa)	50	100	_	_	_
σ^*_{12}	80	95	72	34	68

Table 8.1 Design data for typical polymer composite materials

*ultimate failure, †damage stress

8.2.2.2 Long term loading considerations

Polymer composites will not behave linearly under long term loading
- because of the viscoelastic lime, frequency and rate dependent properties of the polymer material; the creep component will be particularly significant in materials with low fibre volume fractions. Under dynamic fatigue load, complex interactions take place between fibres and matrix leading to degradation in composite mechanical properties. Both of these long term aspects of polymer composites need to be addressed by the designer.

There are particular situations where an elastic analysis may be used as the basis for design calculations. If this procedure is adopted, elastic design results are used but these may be modified to take account of the complex polymer behaviour and thus make use of the extensive design data and formulae for elastic materials derived for small strain theory. This approach would be acceptable for filled and fibre reinforced polymers which have only slight viscoelastic behaviour under short term loads. If however viscoelastic effects are significant, a pseudo-elastic design method may be applied to these materials where the elastic modulus and other elastic constants are replaced by a time or rate dependent modulus.

The basis upon which the pseudo-elastic method is formed is to approximate the viscoelastic stress-strain response to a set of pseudo- elastic stress-strain curves in which the modulus of elasticity and failure stress properties, for instance, are no longer constants but may be time, rate or frequency dependent. The pseudo-elastic material properties are then used in the normal elasticity-based design procedures to predict the behaviour of the component at a particular time, rate or frequency. This enables orthotropic elastic design formulae or-finite element analysis to be undertaken for design of long term loading situations provided that the relevant and measured material property data are used.

A set of long tent moduli (viz., E_{11}, E_{22}, G_{12}, ν_{21}) are required for a design analysis of a polymer composite unit under a long term load; these will normally be obtained from creep tests on the material. The measured stain-time function ε (t) may be used to define the time dependent modulus [$E_{11}(t) = \sigma / \varepsilon(t)$]. The creep rupture stress σ^*_{11} will be obtained from the creep rupture-time curve.

During a dynamic fatigue loading of polymer composites, resin cracking and fibre-matrix debonding could be initiated. This micro-damage could eventually lead to ultimate failure of the composite at stresses below the short term strength. In a fatigue test the results of the number of cycles to fail a specimen at different stress loads are presented on an S-N curve which shows the relationship between the failure stresses and the number of load cycles under a range of load conditions. Although there is some reduction of the modulus of the composite during the fatigue loading, generally it is not considered significant to require a modification of the stiffness characteristics of the material in the design analysis. Table 5.2 shows typical data for the magnitude of long tent load effects on three types of composites; the results are presented as percentages of short term values and demonstrate the importance of allowing for long term effects in design analyses. Knowing the long term strength and stiffness values of the composite, as a percentage of the short term, the pseudo-elastic method can be used for design analyses in the conventional short term design procedures to analyse the composite under load for time t or after a fixed load cycle N. This procedure can be formulated as partial material coefficients; this is illustrated in the limit state design method (Chapter 7). A similar approach is used in the BS 49941571 for composite tanks, by using the long term property reduction factors as design coefficients for creep and cyclic loading; analogous factors are also used to allow for the degradation due to environmental exposure.

Long term strength reduction factor	Randomly orientated glass-fibre-polyester	Woven roving polyester	Unidirectionally aligned glass-fibre epoxy
Fatigue stress ratio 10^3 - cycles	0.6—0.7	0.35-0.45	0.4—0.6
Fatigue stress ratio 10^6 -cycles	0.25—0.35	0.20—0.30	0.24.3
Creep rupture stress ratio (10^2 hours)	0.65—0.75	0.55—0.65	0.75—0.90

Table 8.2 Typical long term load reduction factors for GFRP: data refer to the ratio of long term strength/short term strength at ambient test conditions (from ref. [8.2.9]).

8.2.3 Characteristics of Materials

Many polymer composites are manufactured by stacking a series of lamina which are separated by resin-rich areas in a predetermined arrangement to ensure optimum properties and performance. This system is shown in Fig. 8.4. There are, of course, load variations in material structure which have a small effect upon the mechanical properties but when these are being determined for design analysis it is assumed that each lamina, and consequently the composite, is macroscopically homogeneous and therefore has uniform elastic properties and volume fraction throughout. It follows that the composite material properties are a smeared value of all lamina. If there is no basic **ply** data it would be necessary to determine composite properties in terms of those of the fibre and matrix. This could be undertaken by utilising theoretical formulae ranging from the simple rule of mixture to more rigorous analyses of the complete set of elastic constants as discussed in ref [8.2.7]. In addition, material property values may be estimated by feeding into microcomputer software package [8.2.1-8.2.3] basic values of fibre strength, stiffness, volume fraction and ply angle.

Fig 8.4 Composites manufactured by stacking laminates

In this discussion only especially **orthotropic laminates** (those which are symmetric about their mid-plane with balanced reinforcement) will be considered. These systems are commonly used in practice and are simpler to analyse compared with the general orthotropic lamina. Four in-plane stiffness and four flexural stiffness are required to define the properties of an especially orthotropic laminate under the general load system shown in Fig. 8.1.

Case-1: Consider the laminate behaviour with respect to the x-y plate element coordinate axes (see Fig. 8.5) where θ is equal to zero such that these axes lie in the material symmetry axes 1-2.

The in-plane direct and shear loads N_{xx}, N_{yy} and N_{xy} are shown in Fig. 8.1 and the corresponding in-plane strains ε_{xx}, ε_{yy}, ε_{xy} for an especially orthotropic laminate are given by:

$$\begin{bmatrix} N_{xx} \\ N_{yy} \\ N_{xy} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{22} & 0 \\ A_{21} & A_{22} & 0 \\ 0 & 0 & A_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{xy} \end{bmatrix}$$

It will be seen from the above that the in-plane stiffnesses and the flexural rigidities are defined in terms of the laminate structure and ply properties.

Fig. 8.5 The material axes 1-2 and the plate axes x-y

For a generally orthotropic or anisotropic laminate the equivalent results of equations [8.4a] and [8.4b] can be written succinctly as follows:

$$\begin{bmatrix} M_{xx} \\ M_{yy} \\ M_{xy} \end{bmatrix} = \begin{bmatrix} D_{11} & D_{22} & 0 \\ D_{21} & D_{22} & 0 \\ 0 & 0 & D_{66} \end{bmatrix} \begin{bmatrix} \chi_{xx} \\ \chi_{yy} \\ \chi_{xy} \end{bmatrix}$$

where the symmetry about the leading diagonal can be noted. The [A] matrix is the extensional stiffness matrix relating the in-plane stress resultants [N] to the mid-surface strains [c] and the [Li] matrix is the flexural stiffness matrix relating the stress moments to the curvatures [χ]; these are the equations [8.4a] and [8.4b] respectively. As the [B] matrix relates [M] to [ε] and [N] to [χ] it is called the bending-extensional coupling matrix. It should be noted that a laminate structure can have bending-extensional coupling even if all the lamina are isotropic. The only time that the structure is exactly symmetric about its middle surface is when all the [B] components are equal to zero and this requires Symmetry in laminate properties, orientation and location from the middle surface. If coupling did take place between the in-plane and bending properties, other properties may be required. These are discussed in refs. [8.7] and [8.8].

Having obtained the values of laminate in-plane loads and moments from equations [8.3] and [8.4] respectively, the corresponding failure loads and bending moments under uniaxial conditions are given in terms of the relevant ultimate stress values as:

$$N^*_{xx} = h\sigma^*_{11} \qquad \mathrm{M}^*_{xx} = \frac{h^2\sigma^*_{11}}{6}$$

$$N^*_{yy} = h\sigma^*_{22} \qquad \mathrm{M}^*_{yy} = \frac{h^2\sigma^*_{22}}{6}$$

$$N^*_{xy} = h\sigma^*_{12} \qquad \mathrm{M}^*_{xy} = \frac{h^2\sigma^*_{12}}{6}$$

Case-2: If the material principal directions (the 1- and 2-directions) do not coincide with those of the co-ordinate axis, in which the application of the load lies, transformation equations must be used to relate stresses from axes 1-2 to those in the axes x-y. The derived formulae for the transformed components of [A] and [D] stiffness matrix in items of $E_{11}, E_{22}, G_{12}, \nu_{12}$, h and θ (the angle between the axes-1 and -x, see Fig. 8.4) can be found in ref. [8.2.7] and [8.2.8].

In design analysis, the modulus of elasticity and tensile strength of a laminate under a uniaxial load applied in the x-direction at an angle θ to the axis's 1-direction may be determined from the above analysis of the transformed stiffness matrix. The modulus Exx, Eyy, Gxy is given in ref [8.2.7] as:

$$\frac{1}{E_{xx}} = \frac{m^4}{E_{11}} + \frac{n^4}{E_{22}} + \left[\frac{1}{G_{12}} - \frac{2\nu_{12}}{E_{11}}\right] n^2 m^2$$

$$\frac{1}{E_{yy}} = \frac{n^4}{E_{11}} + \frac{m^4}{E_{22}} + \left[\frac{1}{G_{12}} - \frac{2\nu_{12}}{E_{11}}\right] n^2 m^2$$

$$\frac{1}{G_{xy}} = 2\left\{\frac{2}{E_{11}} + \frac{2}{E_{22}} + \frac{4\nu_{12}}{E_{11}} - \frac{1}{G_{12}}\right\} n^2 m^2 + \frac{1}{G_{12}}\left\{n^4 + m^4\right\}$$

where in = cos θ and n = sin θ.
The significance of the material anisotropy in polymer compob4tes can be seen in the relationships of E or a as a function of the orientation angle 6, shown in Fig 5.6 (a) and (b) respectively for a unidirectional fibre-polymer composite (75% fibre by weight) woven roving fibre- polymer matrix composite (50% fibre by weight) and a randomly orientated fibre-polymer matrix composite (25% by weight).

The application of a uniaxial load in the x-direction of an orthotropic material will cause tensile and shear stress components in the 1-2 axes (the fibre axis) and the tensile failure will be dependent upon the multiaxial failure criteria adopted for the material. However, currently there is no universal failure criterion valid for polymer composite materials and the two theories for failure most widely used are the maximum stress and the quadratic stress criteria.
The maximum stress theory of failure assumes that failure occurs when the stress in the principal material axis reaches a maximum value. There are three possible modes of failure and the conditions for these are:

$$\sigma_{11} = \sigma^*{}_{11}$$

$$\sigma_{22} = \sigma^*{}_{22}$$

$$\sigma_{12} = \sigma^*{}_{12}$$

where $\sigma^*_{11}$and σ^*_{22} are the ultimate tensile or compressive stress in direction-1 or -2 respectively and σ^*_{12} is the ultimate shear stress acting in plane-1 in direction-2.

5.6 Typical relationship of (a) modulus of elasticity and (b) tensile strength and line of action of load for different types of reinforcement

If the load were applied to the lamina at an angle to the principal axis's direction, then by transformation,

$$\sigma_{11} = \sigma_{xx}\cos^2\theta = \sigma_\theta \cos^2\theta$$
$$\sigma_{22} = \sigma_{xx}\sin^2\theta = \sigma_\theta \sin^2\theta$$
$$\sigma 2 = -\sigma_{xx}\sin\theta\cos\theta = -\sigma_\theta \sin\theta\cos\theta$$

The off-axis ultimate tensile strength σ_θ is the smallest value of the following stresses:

$$\sigma_u = \frac{\sigma_{11}}{\cos^2\theta}\, or \,\frac{\sigma_{22}}{\sin^2\theta}\, or \,\frac{\sigma_{12}}{\sin\theta\cos\theta}$$

One form of the quadratic stress criterion (the Tsai-Hill criterion) is based upon the strain energy in the composite, and failure occurs when the following equation is satisfied.

$$\frac{(\sigma_{11})^2}{(\sigma^*_{11})^2} - \frac{(\sigma_{11}\sigma_{22})}{(\sigma^*_{11})^2} + \frac{(\sigma_{22})^2}{(\sigma^*_{22})^2} + \frac{(\sigma_{12})^2}{(\sigma^*_{12})^2} = 1$$

This equation assumes that the composite is transversely isotropic. In most composite materials $\sigma^*_{11} >> \sigma^*_{22}$ so that the second term in the above equation tends to zero and the equation become:

$$\frac{(\sigma_{11})^2}{(\sigma^*_{11})^2} + \frac{(\sigma_{22})^2}{(\sigma^*_{22})^2} + \frac{(\sigma_{12})^2}{(\sigma^*_{12})^2} = 1$$

Using the Tsai-Hill equation [15.10] in conjunction with equation [15.9] a prediction can be made of the failure strength in direction 0 to the principal axis of an unidirectional laminae by the use of the design equation: -

$$\sigma_{\theta} = \left\{ \frac{\cos^4\theta}{\left(\sigma^*{}_{11}\right)^2} + \left[\frac{1}{\left(\sigma^*{}_{22}\right)^2} - \frac{1}{\left(\sigma^*{}_{11}\right)^2} \right] \sin^2\theta\cos^2\theta + \frac{\sin^4\theta}{\left(\sigma^*{}_{22}\right)^2} \right\}^{-1/2}$$

8.2.4 General Laminates

Polymer composites tend to be manufactured by laminating plies of polymer-fibre laminates together, as shown in Fig. 5.4, and the requirements of the composite will dictate the laminate arrangement. The continuous unidirectionally aligned and woven roving plies which carry the main load would normally be positioned symmetrically about the centre of thickness of the composite and the randomly orientated fibre-polyester with a lower fibre-matrix ratio would be positioned at the surface so that the polyester would provide a greater corrosion barrier to protect the load-bearing laminates. The randomly orientated fibre-polymer composites are also used between the woven roving composites to improve the interlaminar adhesion and strength. In laminated polymer composites it is necessary to compute the stiffness properties [A], [D] and the failure loads in terms of the composite structure, ply orientations and the component material properties.

There are several commercial software packages available (see refs [15.1-5.31] for the design of composites and they are all based upon plate theory. The programs are available in several disk versions for running on microcomputers (e.g. Macintosh. IBM PC and compatibles). The input data to the program are the material properties of the components of the composite and failure stresses. In addition, ply thickness, ply orientation and geometric values are required. The output data from the programs will contain values of elastic moduli and flexural rigidities, ply stresses and strains and any possible failure. It is also possible to compute first ply failure when the laminate is damaged and last ply failure when the laminate has failed. Analyses of various influences on the laminate can be undertaken including the effect of temperature on cooling during manufacture and moisture uptake which causes swelling.

The designer where possible, should use the commercial software packages for the analysis and design of laminates because of the complexity of the mechanical behaviour of the material. However, for widely used laminates it might be possible to employ simplified design formulae but such laminates would tend to be unidirectionally aligned fibre reinforced composites with cross-ply or angle-ply reinforcement.

8.2.4.1 Cross-ply laminates

Cross-ply laminates are fabricated with unidirectional fibres being placed at 0° and 90° to the Cartesian co-ordinate axes. If in addition the cross-ply laminate is symmetric about the mid-plane thickness it will have especially orthotropic properties. Figure 5.7(a) shows the arrangement of a cross-ply laminate and the relative positions of the axes (1, 2) and (x, y).

Using the laminate plate theory:

$$A_{11} = \left[\frac{h}{\left(1 - \nu_{12}{}^{2} \dfrac{E_{22}}{E_{11}}\right)} \right] \left[VE_{11} + (1-V)E_{22} \right]$$

$$A_{22} = \left[\frac{h}{\left(1 - \nu_{12}{}^{2} \dfrac{E_{22}}{E_{11}}\right)} \right] \left[(1-V)E_{11} + (1-V)E_{22} \right]$$

$$A_{33} = \left[\frac{\nu_{12} h E_{22}}{\left(1 - \nu_{12}{}^{2} \dfrac{E_{22}}{E_{11}}\right)} \right]$$

$$A_{33} = hG_{12}$$

where, h = thickness of laminate and V= volume fraction of 0° plies.

For the commonly used balanced laminate composed of ii plies of equal thickness (h/n) and where the volume fraction (v)in the 0° and 90° are equal, the flexural rigidities can be calculated from the following equation (from ref. [5.8]):

$$D_{11} = \left[\frac{h^3}{\left(12\left(1-\nu_{12}{}^2 \frac{E_{22}}{E_{11}}\right)\right)} \right] \left\{ \frac{1}{2}[E_{11}+E_{22}] + \frac{3}{2n}\left(E_{11}-E_{22}\right) \right\}$$

$$D_{22} = \left[\frac{h^3}{\left(12\left(1-\nu_{12}{}^2 \frac{E_{22}}{E_{11}}\right)\right)} \right] \left\{ \frac{1}{2}[E_{11}+E_{22}] + \frac{3}{2n}\left(E_{11}-E_{22}\right) \right\}$$

$$A_{33} = \left[\frac{\nu_{12} h^3 E_{22}}{\left(1-\nu_{12}{}^2 \frac{E_{22}}{E_{11}}\right)} \right]$$

$$D_{33} = \frac{h^3 G_{12}}{12}$$

It will be evident that the flexural properties in equation [5.l4] are dependent upon the number of plies; for a few plies the values of D_{11} and D_{22} are significantly different. However, as the number of plies increases, the value of the term (3/2n) becomes small, the value D_{11} tends to that for D_{22} and the cross-ply material becomes as a homogeneous material with modulus 1/2 [E_{11} + E_{22}) in both flexure and tension.

Therefore, equation [5.14] for a large number of plies, where the volume fraction V is 0.5, becomes:

$$D_{11} = D_{22} = \left[\frac{h^3}{\left(12\left(1-\nu_{12}{}^2 \frac{E_{22}}{E_{11}}\right)\right)} \right] \left\{ \frac{1}{2}[E_{11}+E_{22}] \right\}$$

Fig 5.7 Arrangement of (a) a cross-ply and (b) an angle-ply laminate

For the general orthotropic laminate the problem is much more complicated and there are no simple design formulae for accurately predicting laminate strengths. For the simplest loading condition where the laminate is under a uniaxial stress situation, the plies will generally be subjected to a multiaxial stress field. This will require a check on the stress condition of each ply as well as the introduction of a multiaxial failure criterion. As discussed earlier, this investigation is best undertaken by the utilisation of a laminate software package, although for preliminary analysis, Johnson, [5.9] has introduced some simplifying assumptions regarding the laminate stress fields and modes of failure.

Consider a cross-ply laminate under axial tensile load in the Cartesian co-ordinate direction-x in which the zero degree plies lie (see Fig. 5.7(a)).

The initial damage will usually consist of transverse ply cracking and this will occur when σ_{xx} reaches the value of the transverse ply strength σ^*_{22}. Therefore investigating the case when the laminate is balanced, symmetric and composed of a large number of plies of equal volume placed in the 0° and 90° directions (i.e. V= 0.5). Then the loads of transverse ply failure are;

$$N^*_{xx} = N^*_{yy} = h\sigma^*_{22}\left[\frac{1}{2E_{22}}\right]\left[E_{11} + E_{22}\right] \qquad [15.16]$$

If the load is increased beyond this value, ultimate failure of the laminate will occur when the longitudinal plies fail and if it is assumed that no further loa4 is taken by the cracked transverse plies then the load to failure is carried entirely by the longitudinal fibres. This is the condition assumed for the rule of mixtures values. The ultimate tensile failure of the cross-ply laminate is:

$$N^*_{xx} = N^*_{yy} = \left[\frac{1}{2h\sigma^*_{11}}\right] \qquad [5.17]$$

Considering this laminate to be under a flexural loading and that damage will take place in the surface transverse plies or the one adjacent to it, the bending moment for the balanced symmetric cross-ply laminate at first ply failure is:

$$M^*_{xx} = M^*_{yy} = h^2\sigma^*_{22}\left\{\frac{1}{12E_{22}}(E_{11} + E_{22})\right\} \qquad [5.18]$$

Because it is not possible to know the state of the transverse plies (some may still be carrying load) at the ultimate flexural load, no flexural equation can be developed. It is likely, however, that the flexural strength will be higher than that of the tensile strength. In detailed analysis it would be necessary to use the computer-based laminate analyses.

8.2.4.2 Angle-ply laminates

Figure 5.7(b) illustrates an angle-ply laminate in which the various plies are orientated at ± θ to the plate element axes, in this case the x-axis. These laminates, which have an equal member of + θ and -θ plies are balanced about their mid-plane, are orthotropic in nature. In the case where they have a large number of thin plies arranged as above they are especially orthotropic. In this case, the in-plane and bending stiffnesses are given, [5.7] as:

$$\begin{aligned}(A_{11}, A_{12}, A_{22}, A_{33}) &= h\left(\overline{Q_{11}}, \overline{Q_{12}}, \overline{Q_{22}}, \overline{Q_{33}}\right)\\ (D_{11}, D_{12}, D_{22}, D_{33}) &= (h/12)\left(\overline{Q_{11}}, \overline{Q_{12}}, \overline{Q_{22}}, \overline{Q_{33}}\right)\end{aligned} \quad [5.19]\ [5.20]$$

where the functions A and are given as:

$$\begin{aligned}\overline{Q_{11}} &= \left[\frac{1}{\left(1-\nu_{12}{}^{2}\dfrac{E_{22}}{E_{11}}\right)}\right]\left\{E_{11}m^4 + \left[2E_{22}\nu_{12} + 4G_{12}\left(1-\nu_{12}{}^{2}\frac{E_{22}}{E_{11}}\right)\right]m^2n^2 + E_{22}n^4\right\}\\ \overline{Q_{22}} &= \left[\frac{1}{\left(1-\nu_{12}{}^{2}\dfrac{E_{22}}{E_{11}}\right)}\right]\left\{E_{22}m^4 + \left[2E_{22}\nu_{12} + 4G_{12}\left(1-\nu_{12}{}^{2}\frac{E_{22}}{E_{11}}\right)\right]m^2n^2 + E_{11}n^4\right\}\\ \overline{Q_{33}} &= \left[\frac{1}{\left(1-\nu_{12}*\dfrac{E_{22}}{E_{11}}\right)}\right]\left\{\left[G_{12}\left(1-\nu_{12}{}^{2}\frac{E_{22}}{E_{11}}\right)\right](n^4+m^4) + E_{11} + E_{22} - 2G_{12}\left(1-\nu_{12}{}^{2}\frac{E_{22}}{E_{11}}\right)m^2n^2\right\}\end{aligned} \quad [5.21]$$

where m and n are cos θ and sin θ respectively and θ is the ply angle.

The failure of angle-ply laminates is complex, with the failure modes being dependent upon the angle of the ply.

If the laminate is loaded uniaxially in direction x (i.e. the plate axis, see Fig. 5.7(b)) the initial damage is likely to be shear cracking in the plies, particularly if these plies have 0<45°. The ply shear stress an in the principal axes 1-2 for a load, in the x-axis direction is obtained from the transformation relationship as:

$$\sigma_{12} = \sigma_{xx}\sin\theta\cos\theta \qquad [5.22]$$

Therefore, at first ply failure, because of shear cracking, an estimation of the in-plane load $N*_{xx}$ and an out-of-plane bending moment $M*_{xx}$ is

$$\begin{aligned}N*_{xx} &= h\sigma*_{12}\sin\theta\cos\theta\\ M*_{xx} &= \frac{1}{6}h^2\sigma*_{12}\sin\theta\cos\theta\end{aligned} \qquad [5.23]$$

where σ^*_{12} is the unidirectionally aligned ply shear strength..

The ultimate load will occur at fibre fracture and this can be estimated by netting analyses (see ref. 15.101) in which the load in the composite is assumed tote carried by the fibres. This leads to the following estimates of the ultimate loads in an angle-ply laminate, thus:

$$N^*_{xx} = h\sigma^*_{11}\cos^2\theta$$
$$M^*_{xx} = \frac{1}{6}h^2\sigma^*_{11}\cos^2\theta$$

These formulae are acceptable for small ply angles where the netting assumptions are valid.

8.2.5 Sandwich construction materials

Sandwich construction materials are used if it is necessary to increase the stiffness of the overall cross-section of the composite or the individual laminates whilst still maintaining a low weight panel. A sandwich construction material normally consists of fibre reinforced polyester laminates bonded to a low density core material; Fig. 5.8 illustrates this form of construction. The lace materials (i.e. the reinforced polyester laminates) support the flexural loads and axial forces within the composite cross-section and the core material supports the majority of the shear. The core material may be low density polymer and the four types of foam used in civil engineering (although these are not exhaustive) are:

- Rigid polyurethane,
- Phenolic,
- Polyvinyl chloride and
- Polystyrene.

The first two are thermosets and the last two are thermoplastic materials. In the high technology industries, such as the aerospace, carbon fibre-epoxy polymer composites in conjunction with aluminium honeycomb or resin-impregnated paper honeycomb are employed. In addition integral skin polyurethane foam is used in automotive panel applications. These sandwich materials allow expensive composites to be utilised simultaneously and effectively as structural and as thermal insulation units.

It is clear then that the structural sandwich beams and panels are efficient systems for flexural loading. The stiff face materials are at the plate surface where flexural stresses are high and the low stress region may consist of a lower modulus and low density material to reduce the weight of the overall panel. Sandwich panels may be classified under two main headings:

1. The low shear modulus core sandwich.
2. The shear modulus core, which is sufficiently stiff to have only limited influence on panel deflections.

Fig 5.8 Sandwich construction

8.2.5.1 Sandwich beams associated with low shear modulus cores

The first type of sandwich beam has been discussed in length in refs [5.7] and [5.11]. Section 1.5.3.4 has discussed the properties of the thin face sandwich and, consequently, this section will summarise the main design formulae and general principles of the sandwich beam and panel. Type-1 can be divided into three groups:

1. A very thin face sandwich, where the ratio d/t > 100.
2. A thin face sandwich, where the ratio 100 > d/t > 5.77 is satisfied.
3. A thick face sandwich, where the ratio d/t < 5.77 is satisfied.

The notation has, been given in Fig. 5.8.

The designer of engineering structures is not generally interested in the first group and therefore this group of sandwich systems will not be discussed. The bending stiffness for the last two groups are:

$$\begin{aligned} D_f &= E_f \frac{btd^2}{2} \\ D_f &= E_f \frac{btd^2}{2} + E_c \frac{bt^3}{6} \end{aligned} \qquad [5.25]$$

respectively, where E_f = modulus of elasticity of the face material and E_c = modulus of elasticity of the core material.

These formulae hold provided $(E_f/E_c)\,(t/c)\,(d/c)^2 > 16.7$ and $d/t > 5.77$ are fulfilled for the first relationship (equation [5.24]), and that the condition

$$(E_f/E_c)\,(t/c)\,(d/c)^2 > 16.7$$

is fulfilled for the second relationship (equation [5.25]).

The shear stiffness of a sandwich beam is:

$$N = AG = Gbd^2/c \quad [5.26]$$

where $A = bd^2/c$ and G = shear modulus of core, and if $d/c \approx 1$ the equation may be written as

$$AG = Gbd \qquad [5.27]$$

The shear stress in the core of the sandwich beams for the last two types are:

$$\tau = \frac{Q}{bd}$$

$$\tau = \frac{Q}{bd}\left[\frac{E_f td}{2}\right]$$

respectively where Q = the shear force on the section under consideration.

The total deflections for sandwich beams are the sum of the deflections due to the bending moment and the shear deformations. This later deflection must be considered as it can be a significant percentage of the whole deflection; the two components which involve the bending and shear stiffnesses of the beam have been given above.

In considering a sandwich strut it is assumed that if the strut is narrow it will bend anti-elastically whereas if it is wide it will bend cylindrically. An approximate correction may be made by replacing the material stiffness E by: $E_f/(1-v_f^2)$ where v_f = Poisson ratio of face material and the bending stiffnesses are then:

$$D_1 = E_f\frac{btd^2}{2} \qquad \text{for the narrow strut [5.30]}$$

$$D_f = E_f \frac{btd^2}{2(1-\nu_f{}^2)}$$ for the wide strut [5.3 1]

In any analysis of the buckling of a sandwich strut the buckling stress is taken as the lower value of either (a) or (b) below where (a) is associated with the buckling stresses and (b) is associated with the wrinkling stresses.

a) The critical load of a pin-ended strut with thin faces is:

$$P = P_E\left[1+\frac{P_E}{AG}\right] \quad [5.32]$$

where $P_E = \Pi D_1/L^2$, AG is given in equation (5.26) and D_1 is given in equation (5.30).

The critical load of a pin-ended strut with thick faces is:

$$P = P_E\left[1+\frac{P_{Ef}}{P_c}-\frac{P_{Ef}}{P_c}\frac{P_{Ef}}{P_E}\right] \div \left[1+\frac{P_E}{P_c}-\frac{P_{Ef}}{P_c}\right]$$

where $P_E = \Pi D_1/L^2$, $P_{Ef} = \Pi^2 E_f I_f/L^{2,}$ $P_c = AG$ (given in equation [5.26]).

b) Wrinkling instability in sandwich struts (i.e. the compression faces of sandwich beams) occurs because of the instability associated with the short wave-length ripples on the faces. Because this is a buckling effect, the stresses may have smaller values than those predicted in formulae for struts under compression. Figure 5.9 shows the major types of wrinkling instability.

The stress in the sandwich faces at which wrinkling occurs is:

$$\sigma = B_1 E_f{}^{1/3} E_c{}^{2/3}$$

where B_1 = non-dimensionless buckling coefficient (see ref [5.11]).

If the face material of the sandwich beam has initial irregularities, then under load these irregularities are increased and tensile stresses are developed in areas between the face and the core at these positions.

Fig 5.9 Principal types of wrinkling instability

The ultimate tensile failure occurs when the bond between the faces and the core materials fails and this happens when the tensile stress reaches the value:

$$\sigma = B_2 E_f^{1/3} E_c^{2/3}$$

where B_2 = non-dimensional coefficient (see ref. [5.11]).

8.2.5.2 Sandwich beams associated with stiffer shear modulus cores

The materials used to obtain a greater shear stiffness sandwich beam compared with those discussed in Section 5.5.1 are:

1. Higher density polyurethane (PU) foam compared with that used in Section 5.5.1.
2. Higher density polyvinyl chloride (PVC) foam compared to that used in Section 5.5.1.

Section 6.4.1 discusses the greater stiffness sandwich beam and incorporates the material properties of the component parts into the design of the beam, consequently, for the design of materials reference should be made to Section 6.4.1 and subsequent sections.

8.2.6 Concluding remarks

This chapter has discussed how the material design properties of a composite element could be determined by calculation or by laboratory tests. The following chapter considers how these values for design formulation are used in composite structural design. When numerical analysis, such as finite element analysis (FEA), is used to determine the composite sizes and configurations, the material design property values are required as input data for the computer software. If orthotropic elastic material properties for the composite laminate or for the sandwich material are required, these will be obtained from analysis of the composite as discussed in Section 5.3. If composites consist of a single type of reinforcement, as discussed in Section 5.4, the material property data required for the numerical analysis will be the modulus of elasticity and the ultimate strength values as shown in Table 5.1. For the general laminates discussed in Section 5.4, the FEA would require homogeneous orthotropic properties and these would be obtained from the formulae given in Section 5.4.1 and 5.4.2 or by using a laminate software program as a preprocessor to the main FEA program.

8.3 - Structural component design techniques

8.3.1 Introduction

8.3.1.1 Preliminary design analysis

Design with composites is an iterative process (Fig. 6.1) which consists first of the selection of fibre and matrix material and laminate structure. Laminate properties obtained from measurement or from classical laminate theory (CLT) are then used as the materials data in a structural analysis, where the influence of structure geometry and loads are calculated, and structural failure criteria applied. The iterative step with composites is to change the laminate construction and to repeat the structural analysis in order to improve structural performance. In this way FRP materials are tailored for an application through the choice of fibre, matrix, fibre orientations, ply thickness, etc. Whilst this design freedom is an important factor in the success of FRP materials, it is the main reason for the increased complexity in design analysis with these materials. Materials selection and laminate analysis were described in Chapters-1 and -5, and the main objective of this chapter is to describe structural design methods for composites. It is assumed here that laminate properties have been determined from a previous laminate analysis and it is shown how the results of a structural analysis give information about the influence of fibre orientation and laminate lay-up, and may be used to optimise the laminate construction. This is achieved by paying special attention to a preliminary design analysis based on simplified geometry and loads, where the influence of laminate construction, component geometry, load conditions and failure modes can be identified. This analysis is then used for the selection of the laminate and component geometry in the iterative design process. For more detailed design this preliminary design analysis may be followed by a finite element analysis (FEA) where geometrical details, fastenings, load transfer, etc. can be studied. For many less critical applications the simplified methods described here are sufficient.

In Sections 6.2-6.5 design procedures are given for composite structural elements such as plates, thin-walled beams, sandwich plates and pressure vessels. They are based on simplified design formulae, design charts and tables which have been derived from a more detailed mathematical analysis of anisotropic structures. Examples are given to show how these procedures are used for FRP materials selection and for the design of composite structures. These procedures are given in a set of design data sheets written in note form with the minimum of explanatory text each data sheet has a diagram of the element geometry and loads; it lists the main design formulae, shows relevant design charts and concludes with some design tips and important references. This chapter is concluded in Section 6.6 with a brief discussion of detailed design of composite structures based on design software and FEA.

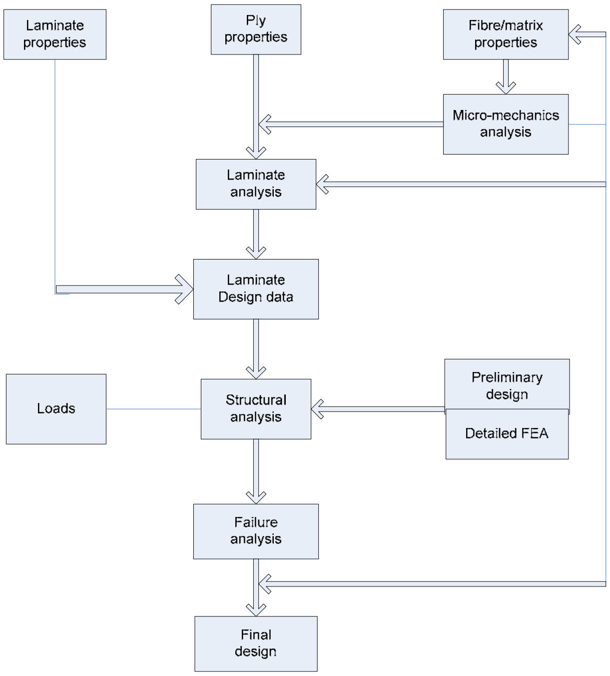


Fig.8.3.1 The design' cycle for composite materials.

The literature on composites design concentrates on laminate analysis, however refs 16.1-6.31 discuss structural design with composites, [6.4] is a valuable source of general design formulae and [6.5] includes both CLT and the structural analysis of composite elements.

8.3.1.2 Composite structural element properties

Chapter-5 described how most composite structures are composed of relatively thin plate or shell laminates so that a thin laminated plate element (Fig. 6.2) can be taken as the basic structural element. When referred to the (x, y) axes in the plane of the element the most general loading consists of in-plane direct and shear loads N_{xx}, N_{yy}, N_{xy}, bending moments M_{xx} , M_{yy} and a twisting moment M_{xy} all measured per unit width of element. Under these loads the element will stretch and bend giving rise to strains ε_{xx}, ε_{yy}, ε_{xy} and curvatures χ_{xx}, χ_{yy}, χ_{xy}. It is assumed in this chapter that the structural element is (especially) orthotropic with material symmetry axes (x, y). The general laminate load-strain and moment-curvature relations, equation [6.4c] then decouple and take the forms:

$$\begin{bmatrix} N_{xx} \\ N_{YY} \\ N_{XY} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & 0 \\ A_{12} & A_{22} & 0 \\ 0 & 0 & A_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_{XX} \\ \varepsilon_{YY} \\ \varepsilon_{XY} \end{bmatrix} \qquad [8.3.1]$$

$$\begin{bmatrix} M_{xx} \\ M_{YY} \\ M_{XY} \end{bmatrix} = \begin{bmatrix} D_{11} & D_{12} & 0 \\ D_{12} & D_{22} & 0 \\ 0 & 0 & D_{66} \end{bmatrix} \begin{bmatrix} \chi_{XX} \\ \chi_{YY} \\ \chi_{XY} \end{bmatrix} \qquad [8.3.2]$$

The laminate properties required for structural analysis are the in- plane stiffnesses [A] and flexural rigidities [D]. Especially orthotropic laminates are characterised by four in-plane stiffnesses, A_{11}, A_{22}, A_{12}, A_{66}, and four flexural rigidities, D_{11}, D_{22}, D_{12} and D_{66}. Many commonly used composite structures such as cross-ply and angle-ply laminates, unidirectional (UD) composites, fibre fabric structures which are balanced and symmetric, and composed of a reasonable number of thin plies, are especially orthotropic with stiffness matrices having the forms indicated in equations (8.3.1) and (8.3.2). The zero elements in [A] and [D] ensure that the laminate has no tension-shear and bending-torsion coupling. The coupling matrix in equation [5.4a] [B] = 0, hence there is no tension-bending coupling.

As an alternative to equation [8.3.1], the laminate in-plane strains may be characterised in terms of the averaged laminate stresses $\sigma_{xx,}$ σ_{yy}, σ_{xy} and the effective engineering elastic constants for the laminate, by the equations

$$\begin{bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{xy} \end{bmatrix} = \begin{bmatrix} \dfrac{1}{E_{xx}} & \dfrac{-\nu_{yx}}{E_{yy}} & 0 \\ \dfrac{-\nu_{yx}}{E_{yy}} & \dfrac{1}{E_{yy}} & 0 \\ 0 & 0 & \dfrac{1}{G_{xx}} \end{bmatrix} \begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{xy} \end{bmatrix} \qquad (8.3.3)$$

Fig.8.3.2 Schematic diagram of a composite laminate element

Here $E_{xx,}$ E_{yy} are laminate tensile moduli in the x- and y-directions G_{xy} the in-plane shear modulus and ν_{xy}, the lateral contraction ratio. In the convention used here, ν_{xy} is the strain in the y-direction per unit strain in the x-direction, for a load applied in the x-direction.

The following definitions and shorthand notation for the elastic constants and flexural rigidities are used extensively in this chapter and should be noted here:

$$\nu_{yx} = \nu_{xy} \frac{E_{yy}}{E_{xx}}$$

$$\mu = 1 - \nu_{xy}\nu_{yx} = 1 - \nu_{xy}{}^{2} \frac{E_{YY}}{E_{xx}}$$

$$D_1 = D_{11}$$

$$D_2 = D_{22}$$

$$D_3 = D_{12} + D_{66}$$

and for a homogeneous orthotropic plate of thickness h:

$$D_1 = \frac{E_{xx}h^3}{12\mu}; D_2 = \frac{E_{yy}h^3}{12\mu}; D_{66} = \frac{G_{xy}h^3}{12}$$

Laminate strength properties under uniaxial loads are characterised by the element in-plane tensile and shear failure loads N_{xx}*, N_{yy}* and N_{xy}* and by the bending moments at failure M_{xx}*, M_{yy}* and M_{xy}*. all measured per unit width of laminate. Alternatively under in-plane loads the averaged laminate failure stresses $\sigma_{xx}{}^{*}, \sigma_{yy}{}^{*}, \sigma_{xy}{}^{*}$ may be required. These uniaxial strength values are the simplest to use in structural analysis calculations. In practice applied loads are seldom uniaxial and laminate strength values under a multiaxial load are needed.

As input data for the composite's structural analysis, it is assumed that a laminate lay-up has been selected and the laminate stiffnesses or effective elastic constants, together with uniaxial strength values, have been calculated from CLT or measured directly for the chosen laminate. The structural analysis calculates deflections and failure loads in the composite's structure, which may be used iteratively to modify the initial laminate lay-up. Other possible refinements include the use of the structural analysis to determine the multiaxial load conditions on a laminate element (e.g. Section.6.2.2 and 6.5.2) so that an appropriate multiaxial laminate strength reserve factor can be calculated from CLT.

8.3.2 Design of composite panels

8.3.2.1 In-plane and buckling load

8.3.2.1.1 uniaxial tension or compression

See Fig. 8.3.3

Fig. 8.3.3 Panel under uniaxial compression load.

Geometry

Flat rectangular panel, sides a, b, thickness h.

Applied loads
Uniaxial tensile/compression load N_{xx}, per unit plate width, $N_{yy}= N_{xy} =0$.

Deformations
Plate strains are given in terms of the plate stiffnesses [A] by equation [3.31]:

$$\begin{aligned}\varepsilon_{xx} &= \frac{N_{xx}}{\left(A_{11}-A_{12}{}^{2}\right)/A_{22}}\\ \varepsilon_{YY} &= -\varepsilon_{XX}\frac{A_{12}}{A_{22}} \qquad [6.5]\\ \varepsilon_{XY} &= 0\end{aligned}$$

and in terms of the plate engineering constants by equation [6.3] with $\sigma_{xx} = N_{xx}/h$

$$\begin{aligned}\varepsilon_{xx} &= N_{xx}/hE_{xx}\\ \varepsilon_{yy} &= -\nu_{xy}\varepsilon_{xx} \qquad [6.6]\\ \varepsilon_{xy} &= 0\end{aligned}$$

Plate displacements follow directly from the strains, e.g. in the x-direction $u_x = a\varepsilon_{xx}$.

Failure loads

Tension: the tensile failure load is**:** $N_{XX}{}^{*} = h\sigma_{xx}{}^{*}$ [6.7]

where $\sigma_{xx}{}^{*}$ is the average laminate uniaxial failure stress as measured or as calculated from CLT with an appropriate failure criterion.

Compression: under uniaxial compression load the plate will usually buckle at a load $N_{xx}{}^{'}$, below the compressive strength load $N_{xx}{}^{*}$ in equation [6.7] .Buckling loads depend on plate geometry, edge support conditions and plate flexural properties.

For small aspect ratios 0.5< a/b <2 and for simply supported edges, the uniaxial buckling load is:

$$N_{xx}{}^{'} = \frac{\pi^2}{b^2}\left[\frac{D_1 b^2}{a^2} + \frac{D_2 a^2}{b^2} + 2D_3\right] \quad [6.8]$$

For long, simply supported plates with a/b>2, local buckling takes place which is independent of length ‘a’ at a load:

$$N_{xx}{}' = \frac{4\pi^2 D_1 K_1}{b^2}$$

$$K_1 = \frac{\left[(D_2 / D_1)^{1/2} + (D_3 / D_1)\right]}{2}$$

The plate failure bail in compression is now: $\min(N_{xx}{}^*, N_{xx}{}')$.

Plates with clamped edges will have buckling loads much higher than equations [6.8] and [6.9], which are thus conservative values for design.

Shear

See Fig. 6.4.

Geometry

Sat rectangular panel, sides ‘a’, ‘b’, thickness ‘h’.

Fig. 6.4 Panel under in-plane shear load.

Applied loads: In-plane shear load N_{xy}, per unit plate width, $N_{xx} = N_{yy} = 0$.

Deformations: Plate strains are given directly from equation [6.1] or equation [6.3]:

$$\varepsilon_{xy} = \frac{N_{xy}}{A_{66}} = \frac{N_{xy}}{hG_{xy}} \quad [6.10]$$

$$\varepsilon_{xx} = \varepsilon_{yy} = 0$$

Failure loads

For shear material failures, the failure load is: $N_{xy}{}^* = h\sigma_{xy}{}^*$ [6.11]
where a is the average laminate shear strength as measured or calculated from CLT. Thin composite plates will usually buckle in shear before this shear failure load is reached. Buckling loads depend on plate geometry, edge support conditions and plate flexural properties. For long plates with a/b>2 and simply supported edges, local buckling occurs, which is independent of length a. at a shear load N_x.

$$
\begin{aligned}
N_{xy}' &= \frac{52K_2D_1}{b^2} \\
K_2 &= \frac{(D_2D_3)^{1/2} f(c)}{D_1} \\
c &= \frac{(D_1D_2)^{1/2}}{D_3} \\
f(c) &= \begin{Bmatrix} c^{1/2}(0.62+0.38/c), c \geq 1 \\ 0.89+0.04c+0.07c^2, c<1 \end{Bmatrix}
\end{aligned}
\qquad [6.12]
$$

The plate failure load in shear is now $\min(N_{xy}^*, N_{xy}')$.

For plates with aspect ratios a/b <2, and for plates with clamped edges there are no simple formulae for the buckling load. In these cases equation [6.2] gives a conservative value for design, and can be used to estimate whether shear buckling is likely to be a possible failure mode.

8.3.2.1.3 Further references

For further general reading on panel buckling, see refs [6.1], [6.2], [6.4] and [6.6]. Specific information on rectangular orthotropic panels is given in refs [6.7]-[6.9]. PC programs for calculating panel buckling loads for different edge and load conditions are available with refs [6.7] and [6.8].

8.3.2.2 Transverse loads

See Fig. 6.5.

Geometry

Flat rectangular panel, sides ‘a’, ‘b’, thickness ‘h’. Edges, simply supported clamped or free.

Fig. 6.5 Panel under transverse load.

Applied loads

Transverse point load P or uniform pressure ‘p’ equivalent to a tram- verse load P = abp.

Design formulae

The maximum transverse deflection w in the panel is: $w = \frac{\alpha P a^2}{D_2}$ [6.13]

The maximum panel bending moments M_x, M_y are defined as:

$$M_x = \beta_1 P; M_y = \beta_2 P \qquad [6.14]$$

8.3.2.2.1 Design parameters.

Panel behaviour is governed by the dimensionless stiffness parameter 'α' and strength parameters β_1, β_2 which are functions of:

1. The plate aspect ratio a/b.
2. The material parameters $D_1 / D_2, D_3 / D_2, \nu_{xy}$.
3. The panel edge conditions.
4. The load type and load position.

Values of these parameters for different geometry, materials and load conditions are given from approximate design formulae, from graphs and tables computed from the orthotropic plate equations, or directly from PC programs. Some typical data sets for α, β_1, β_2 are given below.

8.4 Limit state design method

7.1 Introduction

Limit state design principles have become internationally recognised as the basis of codes of practice for a wide range of structural applications and materials. However, their application to design using FRP materials has been very limited, mainly because of absence of design codes using such principles but also because of the lack of familiarity with these principles among designers traditionally working with FRP materials. Nevertheless, future codes of practice on the structural application of FRP materials are likely to be based on limit state principles, particularly for codes developed internationally through such as the European Standardisation Committee (CEN). Indeed the European Community directives for European standards harmonisation recommend that all such harmonised standards be based on limit state principles for structural design. It is therefore advisable for FRP materials designers to become familiar with these principles as they apply to their materials. not only so that they can work with these codes but also so that they are able to demonstrate that products for which no design codes exist (as will often be the case) have equivalent levels of safety and reliability incorporated into their design.

The aim of this chapter is therefore to provide an introduction to the subject for those familiar with FRP materials but not with limit stale design (or vice versa). More detailed descriptions can be found in refs [7.1]-[7.3].

8.4.2 General principles of limit state design

8.4.2.1 Aims of limit state design

The document forming the basis of the development internationally of limit state design codes for various materials [7.1] defines the aim of design as:

the achievement of acceptable probabilities that the structure being designed will not become unfit for the use for which it is required during some reference period and having regard to its intended life. Thus, all structures or structural elements should be designed to sustain, with an appropriate degree of safety all loads and deformations liable to occur during construction and proper use to perform adequately in normal use and to have adequate durability during the life of the structure.

It is useful to replace the term ‘safety’ with the quantitative term ‘reliability’, which is defined as the complement to the probability of an adverse event for example, failure. One of the advantages of limit state design is that the method is readily adaptable to give the required reliability for a particular type of structure or product, and that correlation can therefore be achieved between design standards using different materials. A further advantage is that it provides a logical framework, within which the uncertainties in test data, loading, stress analysis, etc., can be quantified and understood in a consistent manner between different materials, whilst still recognising the varying characteristics of those materials. This is especially significant in the context of FRP materials which are themselves highly variable in characteristics.

8.4.2.2 Levels of sophistication

Three levels of sophistication are recognised in checking the degree of safety in structures at a given limit stage:

Level-3: an ‘exact’ probabilistic design method involving integration of the representation of the various uncertainties to derive optimum failure probabilities.

Level-2: a probabilistic design method in which the basic variables are represented by their known or postulated distributions and a defined reliability level is accepted. The distributions are assumed to be uncorrelated.

Level-1: a semi-probabilistic design method iii which appropriate levels of reliability are provided by the specification of a number of partial safety factors related to nominal values of the basic variables.

Level-3 concepts are used primarily in research. Design codes generally adopt a Level-1 approach, although Level-2 concepts will normally have been used in the design of the code itself Level-2 methods may be used directly in design if sufficient statistical data for the basic variables are available (or can be obtained) and the required level of reliability justifies the cost. However, it is envisaged that for the majority of FRP applications Level-1 design methods will be the most appropriate, once appropriate codes of practice have been developed, and it is this method which is described in more detail here.

8.4.2.3 Limit states

The performance of all or part of an FRP structure or structural com, ponent can be described with reference to a limited set of limit states beyond which the design requirements are no longer satisfied. Limit states can be placed into three categories:

- The ultimate limit states (ULS), corresponding to the maximum toad-carrying capacity.
- The serviceability limit states (SLS), relating to the criteria governing normal use.
- The conditional limit states, corresponding to an infrequent major random event, e.g. fire. Conditional limit states are frequently placed in one of the other categories (ULS or SLS).

Examples of the ultimate limit states include loss of stability (buckling) and rupture of critical sections due to the material strength being exceeded (strength may be reduced by environmental effects or by repeated loading). Serviceability limit states may include excessive deformation, excessive vibration and local damage which reduces durability or affects efficiency or appearance.

8.4.2.4 Design

All the relevant limit states need to be considered in the design of an FRP structure, although it is generally acceptable to design on the basis of the limit state judged to be critical and then to check that the remaining limit states are not reached.

The consideration of each limit state requires the setting up of a calculation model incorporating the appropriate basic variables allowing for the influence of direct and indirect loads, the response of the structure and the behaviour of the material. The uncertainties associated with the variables and with the calculation model itself are allowed for either by a method of partial coefficients (Level-1 approach) or by a probabilistic method (Level-2). The basic variables are considered to be independent, random variables.

8.4.2.5 The method of partial coefficients (Level-1)

In the method of partial coefficients the variability of these basic variables are taken into account by the selection of characteristic values for each of them. The uncertainties associated with the characteristic values and the calculation models are taken into account by the application of partial coefficients to the variables or their effects. Where the necessary data are available, the characteristic value for a variable is normally based on a statistical interpretation of that data. Thus for a varying load the characteristic value is defined as that value that has a prescribed probability of not being exceeded within the reference period. When characteristic values for loads cannot be established from statistical data, they could be estimated on the basis of available information, and, possibly, forecasts of future developments.

The variation of strength and other properties of the materials are treated by defining characteristic properties which would be related to standard test specimens and procedures. Standardised test procedures would be vital for the successful application of the method. The characteristic value of a material property is normally defined as that value that has a prescribed probability of not being reached in a hypothetical unlimited test series.

Two types of partial coefficient are used, one type for the loads or load effects and the other for the strength of materials or elements. The partial coefficients vary depending on the load type, the material, the type of FRP structure or component, the importance of the application, and the safety and economic consequences of the limit state under consideration being exceeded. When partial coefficients are applied to a characteristic value, the resulting value is termed a design value. The design value for a particular variable might vary for different limit states (whereas the characteristic value is normally constant). Thus, for a particular limit state, the design value of the different types of variable would be given by:

$$F_d = \gamma_f F_k$$

$$f_d = \frac{f_k}{\gamma_m}$$

where F_d is the design value of a load, F_k is the characteristic value of the load, y is the partial coefficient for the load, f_d is the design material property (e.g. strength), f_k is the characteristic property and Tm is the partial material coefficient for the property.

The partial coefficients can be further subdivided to enable rational and consistent values for the individual coefficients to be defined. Thus the partial coefficient y can be considered as a function of three coefficients, γ_{f1}, γ_{f2} and γ_{f3}, where: takes account of the possible unfavourable deviation of the loads from (he characteristic values: y takes account of the reduced probability that combinations of loads will simultaneously reach their characteristic value: and y takes account of possible inaccurate assessment of the load effects.

The partial material coefficient γ_m can also be broken down, and can be considered as a function of two coefficients γ_{m1} and γ_{m2}, where: γ_{m1} takes account of unfavourable deviations of the material properties from the specified characteristic values, and the possible differences between the material property in the structure or element and that derived from test specimens: and γ_{m2} takes account of possible local weaknesses arising from the manufacturing process, and unfavourable geometric deviations resulting from manufacturing tolerances. A greater number of subdivisions can be chosen if necessary.

A further coefficient, γ_n can be introduced to adjust either γ_f or γ_m. γ_n In can be considered as a function of two coefficients, γ_{n1}, and γ_{n2}, where: γ_{n1} takes account of the nature of the failure associated with the limit state, e.g. whether ductile or brittle and whether collapse can occur without warning; and γ_{n2} takes account of the consequences of failure, from economic considerations as well as those of human safety. However, γ_n is normally used simply as a modifying factor to the other factors rather than explicitly as a separate factor.

Fabrication tolerances are recognised as a problem to both moulders and designers. In certain cases where the variability of a geometric parameter could have a significant effect on the strength of an element, for example the thickness of a thin composite skin, it would be appropriate to apply a coefficient explicitly rather than by inclusion in γ_m. The design values a_d of geometrical parameters would be obtained from the characteristic values a_k (normally the nominal specified values) and an additive element Δ_a, since additive elements would generally be more suitable than factors for geometric parameters, i.e. $a_d = a_k + \Delta_{\mathbf{a}}$ where 'Δ_a' takes account of the importance of variations in a, and the given tolerance limits for a.

8.4.2.6 Choice of values for -the partial coefficients

The values of the partial coefficients depend on the limit state under consideration and should be based on statistical data when available. Where such data are not available the coefficients are derived by calibration with pre-existing practice or judgment.

Where a limit state design Code of Practice covers the material and application being considered, this would of course normally specify the partial coefficients to be used for each limit state (the above process having been carried out by the authors of the Code).

8.4.2.7 Summary of the partial coefficient method

The object of the partial coefficient method outlined above for FRP structures is to achieve, by means of suitably derived partial coefficients applied to the characteristic values of **the relevant basic variables,** acceptable probabilities that for each limit state the resistance of the structure or element would exceed the load effects. This is illustrated in simple form in Fig. 7.1, where a typical resistance function, *f* and a typical load function *f*, are plotted.

Fig.7.1 Load and resistance distributions

8.4.3 Characteristics of FRP materials

8.4.3.1 General

The great variety of polymers, additives and modifiers means that there are no universal methods describing the behaviour of all polymer materials. Nevertheless, polymers do exhibit many similar characteristics, with differences only in magnitude, and for the most part it is these characteristics that distinguish the structural behaviour of polymers from those of conventional materials. The more pronounced viscoelastic behaviour and influence of temperature and environmental factors are examples of this. The many types of fibre reinforcement would appear to introduce further complexity. However, in some respects the behaviour of FRP is less complex than unreinforced and short-fibre plastics, because typically both the fibre reinforcement and the polymer matrix are more elastic (i.e. less viscous) than thermoplastics, resulting in lesser dependence of properties on temperature and duration of loading. In other respects, of course, the behaviour is more complex, arising from the wide disparity in properties of the constituents and the possible variations in the arrangement of the fibres, All of these factors need to be embraced by the limit state design method.

In the following sections the main characteristics of FRP materials are described, drawing particular attention to where these differ from conventional structural materials e.g., concrete, metals, masonry, wood) so that those aspects that need to be covered by the design method are summarised. In this context the definition of FRPs excludes randomly oriented isotropic short-FRP materials.

8.4.3.2 Structural characteristics of FRP materials

8.4.3.2.1 Fibres

Fibre reinforcement not only comes in a variety of materials with different strengths and stiffnesses, but also in a variety of forms, e.g. mats, straight rovings, woven fabrics. In some forms the fibres are grossly kinked to conform to a weave pattern and this can reduce the strength of the composite material. Unlike most conventional materials, the strength and stiffness of the material can be varied by adjusting the fibre content.

8.4.3.2.2 Matrices

The wide variety of polymers with different characteristics is further complicated by the addition of fillers and Plasticisers which can significantly alter the composite properties. This can result in published properties being of little value because the exact composition is not stated or cannot be reproduced. Some matrices may exhibit poor bonding with the fibre reinforcement and are thus unable to develop the full strength capacity of the fibres.

8.4.3.2.3 Processes

The characteristics of materials with identical constituents can be influenced by the process used in their production. Factors such as unplanned fibre orientation, insufficient compaction, inadequate curing, inaccurate fibre placement and lap joints in preformed reinforcement can all adversely affect the material properties.

8.4.3.2.4 Short term stress-strain relationships

Provided fibres are orientated in the stress direction most FRP materials exhibit mainly linear elastic behaviour to failure. Characteristic stress- strain curves are shown in Fig.7.2: Type I is the most typical for materials with fibres aligned in more than one direction, with the '**knee**' indicating the onset of first damage, i.e. crazing or micro-cracking at the transverse fibres. Type-II is typical for unidirectional laminates stressed parallel to the fibres and Type-III is typical for cases where the influence of the matrix is significant, i.e. random in-plane reinforced laminates or aligned fibre laminates stressed off the principal fibre axes.

Fig.7.2 Characteristic stress-strain curves for reinforced plastics

Unlike most structural materials; FRP materials do not exhibit yielding (except for aramid fibre composites in compression) and therefore are not ductile. However, they do not generally display the other characteristics of classic brittle materials, i.e. low tensile strength and sensitivity to impact and stress concentrations. This is because the fibres act as crack inhibitors, although where there are no fibres to limit the spread of cracks, e.g. transverse to a unidirectionally reinforced laminate or in interlaminar layers, the material behaves in a brittle manner.

8.4.3.2.5 Directional properties

FRP materials are neither homogeneous nor, generally, isotropic. Depending on the fibre alignment, an FRP laminate can exhibit in- plane elastic properties which are planar-isotropic, orthotropic or anisotropic. In aligned fibre laminates properties can alter significantly when the direction of applied stress departs from a principal fibre direction. Unbafanced and asymmetric multi-ply laminates show even more complex behaviour.

8.4.3.2.6 Long term loading

Under sustained stress, the strain in FRP continues to increase and he magnitude of stress needed to produce rupture diminishes with time. These phenomena are referred to as creep and creep rupture respectively. The behaviour is complex and is influenced by temperature and environment. Although the effect in FRP is less pronounced than with unreinforced polymers, it is generally more significant than with other structural materials.

8.4.3.2.7. Fatigue

As with static loading, fatigue behaviour under repeated or cyclic loading is highly directional. Unlike most conventional structural materials, some FRP materials, notably glass reinforced materials; do not have a fatigue limit. High frequency stress variations can generate internal heat in the material.

8.4.3.2.8 Environmental factors

The interaction of time, temperature, stress and environment can have a profound effect on the structural performance of FRP materials, to a far greater extent than with any other major structural material except possibly wood. Even normally occurring agents such as water (or water vapour) and ultraviolet rays from the sun can seriously affect FRP materials.

8.4.1.2.9 Characterisation of FRP materials

Other structural materials, such as wood and concrete, display widely varying properties and characteristics. However, design in these materials is facilitated by classification of the materials, related to established specifications in the case of concrete, and by generally accepted, simplifications of the overall behaviour. No such characterisation exists in FRP materials.

8.4.4 Application of partial coefficient method

8.4.4.1 General

When it comes to applying limit state methodology to an actual FRP design exercise, the ideal situation would be one where there existed an accepted national or international Code of Practice, based on limit state philosophy and covering the intended materials and application. Such a code would normally set out the limit states to be considered and specify characteristic values and partial coefficient values to be used. However, few such codes exist at present and it will be found necessary in most cases to develop the design criteria from genera) principles (as must be done for other design methodologies where no code exists).

The broad range of applications of FRP materials makes it inadvisable to attempt to develop a single set of design criteria to treat all possible applications. A similar approach is adopted for other materials, e.g. there are different design criteria for steel buildings and steel offshore structures. Design methods and national codes will tend to be application-orientated and the following paragraphs endeavour to set out the general principles on which limit state design criteria for FRP structures could be based.

It is not proposed to discuss criteria for loads since these are essentially independent of the structural material.

8.4.4.2 Limit states

For the design of any structure or component it is necessary to select all the relevant limit states for consideration. The actual limit states selected obviously depend on the nature of the FRP structure and its intended use, and the following is intended only as an indication of those limit states that have to be considered in view of the particular characteristics of FRP described previously.

8.4.4.2.2 Serviceability limit states (SLS)

1. Deflection/deformation: this is to be a critical limit state in many applications because of the generally lower magnitude and directional nature of FRP stiffness compared with conventional structural materials such as steel and concrete.
2. Residual deformation: the viscoelastic behaviour of some FRP materials may result in excessive permanent deformation under sustained loading.
3. First damage: crazing or microcracking of the material may constitute a limit state for various reasons, e.g. it accelerates environmental degradation or causes leakage from a fluid container.
4. Buckling or wrinkling (local): this may be a serviceability or ultimate limit state depending on the nature of the application and the post-buckling behaviour of the material.
5. Vibration.
6. Environmental damage, i.e. effect on performance (reduced properties) or appearance without causing failure.
7. Impact damage: as (6).

8.4.4.2.3 Ultimate limit states (ULS)

1. Collapse, i.e. loss of equilibrium of whole or part of structure.
2. Rupture of section: causing failure of structure or element of structure. This may take several forms, e.g. tension, shear4 flexure or interlaminar shear, and may require definition of failure criteria for the material. Rupture may be influenced by the interaction of time, temperature, stress and environment.
3. Buckling, i.e. loss of stability. May be critical owing to lower stiffness and directional nature of properties.

4. Fatigue.

5. Resonance.

6. Fire resistance.

8.4.4.3 Methods of analysis (ULS)

Methods of analysis at ultimate loads have to take account of the lack of ductility in most FRP materials in contrast to most conventional structural materials. This has two main effects:

1. Non-linear structural analysis involving redistribution of stresses in redundant structures is not valid.

2. Internal redistribution of the stresses in a cross-section cannot take place. This means that load effects such as temperature gradients and shear lag have to be considered at the ultimate limit state (unlike ductile materials where these effects need only be considered at the serviceability limit state).

However, the almost linear stress-strain curves to failure of most FRP materials means that elastic methods of analysis are adequate for most applications.

8.4.4.4 Material parameters

8.4.4.4.1 Characteristic material properties

The required characteristic material properties for FRP materials differ in many respects from those required for most conventional structural materials. Firstly, standard grades of material are not available. Steel, for example, is produced under stringent quality control to a characteristic strength in limit state design, and the modulus and the Poisson’s ratio vary little, whatever the composition. The material is homogeneous and isotropic, so no other elastic constants are required and environmental conditions.

By contrast, standard data on FRP composites is generally either not available or cannot be relied upon except for preliminary design. UP to 21 elastic constants may be required for a rigorous analysis of a complex laminates, stiffness as well as strength varies with the composition, and the properties vary with temperature and production process and may degrade with time. Material design data are therefore normally derived from the testing of specimens. For maximum reliability the specimens and test conditions should represent as closely as possible the material and conditions of use of the final product.

Derivation of characteristic design properties from test data is a specialist subject and is dealt with elsewhere, for example refs [6.4] and [6.5]. In the construction industry characteristic material properties are commonly taken as the lower 5% fractile, but other values may be appropriate for different applications. The quoted characteristic values, which for FRP materials will include stiffness, strengths and possibly first damage as well as ultimate strengths, should be associated with the governing limitations, e.g. constituent materials, production process, limits of temperature and environmental conditions. This implies, of course, that separate characteristic values should be used when any of the conditions is changed, e.g. a different temperature range. An alternate method would to be use a single characteristic value for each property, for a given set of conditions, and to use factors to derive representative values for other conditions. These would not be true partial coefficients, however, since they do not represent uncertainties.

8.4.4.4.2 Partial material coefficients

The partial material coefficient γ_m allows fro uncertainties in the assumed properties of the material in the final structure. Ideally it should be derived from statistical data but this requires specialist techniques [6.4] and sufficient data are rarely available (since specimen testing does not deal with all the uncertainties). The coefficient is normally derived by a combination of statistical methods and calibration with pre-existing practice, or simply by judgment where there is not relevant pre-existing practice.

Most existing limit state design codes do not subdivide the γ_m factor, although different values are frequently given for different limit states, indicating that the derivation involved subdivision. FRP material properties used in design tend to have uncertainties not associated with more conventional material. For the properties of multi-ply laminates, for example, there are three different methods of deriving the laminate characteristics, with reducing level of uncertainty:

- Properties of constituent materials (fibre, matrix) derived from test specimen data; properties of individual plies derived from theory; properties of laminate derived from theory.
- Properties of individual plies derived from test specimen data; properties of individual plies derived from theory.
- Properties of laminate derived from test specimen data (not always practical).

Clearly different partial coefficient values should be applied to the characteristic value depending on which derivation method is used, and this may justify a further subdivision of the partial material coefficient values (in addition to different characteristic values) in view of the different level of uncertainty associated with each process. Materials produced by automated processes generally demonstrate a lower spread of test results and are produced to smaller dimensional tolerances than manual processes, and this can be reflected in lower partial coefficient values and a resulting economy in design.

8.4.4.4.3 Brittle failure modes

Higher values of the partial material factor are normally applied when the failure mode is brittle. Thus tensile failure of a unidirectional composite, failure by interlaminar shear or tension, and a failure of certain bonded connections are examples of limit state where higher values would apply.

8.4.4.5 Buckling instability

Two distinct methods of dealing with buckling instability can be found in existing limit state design codes. In those dealing with concrete structures, slender compression members must be designed for an additional eccentricity of load, the magnitude on the slenderness ratio of the member. In those dealing with metal structures, local plate buckling and overall buckling instability are dealt with by strength reduction factors dependent on slenderness ratios, and this would appear to be the more appropriate method for PEP structures. Additionally, for FRP structures and plates in compression, uncertainties in the stiffness parameters need to be allowed for by the partial material coefficient.

8.4.4.6 Fatigue

Again, two distinct methods have been formulated in other limit state codes. In one draft code it is proposed that the calculated fatigue life should exceed the design life factored by a partial coefficient. However, a more rational approach is to use characteristic S-N curves (i.e. curves joining lower fractile points rather than the mean values) to calculate fatigue life, which is then required to exceed the design life.

For FRP materials, fatigue behaviour is influenced by temperature, environment and direction of stress (for non-isotropic laminates), and characteristic S-N curves should be associated with governing limitations as suggested for other material properties, Section 7.4.1.

8.4.4.7 Summary

The preceding paragraphs demonstrate that limit state design philosophy can be applied to the design of FRP structures. Those difficulties which may occur in representing the complex behaviour of FRP would occur whichever design philosophy is used, and the benefits of using a logical and rational approach consistent with other structural materials are considerable.

7.5 Example

The following fictitious example has been selected to give a simple illustration of the application of limit state design principles to an FRP component. The characteristic and partial coefficient values have not been derived by statistical or any other methods, and should not be regarded as proposed values.

An electronic scoreboard is to be suspended from the roof of a covered stadium by a number of hangar rods. The design criteria for each rod are listed below:
Length: 8.0 meters
Diameter: to be determined
Loading: 110 kN dead load;
15 kN live load (occasional maintenance);
33 kN (30% DL) accidental overload due to failure of one other hangar.
Deflection: 15 mm maximum during design life (due to dead load).
Design life: 10 years.

The selected material is graphite-epoxy composite with protection against environmental degradation. The characteristic short term material properties (from tests) are:
Longitudinal modulus, E = 180 GPa

Ultimate tensile strength, $\sigma_{\mu} = 1500$ MPa

Sustained loading tests indicate that rupture occurs at 80% of ultimate tensile strength after 10 hours (11.4 years).

8.4.5.1 Limit states

The following limit states will be considered:
Ultimate (ULS):

1. Creep rupture
2. Accidental collapse

Serviceability (SLS):

3. Deflection
4. First damage

The rod will be designed for the creep rupture limit state and then checked against the remaining limit states.

8.4.5.2 Partial coefficients

Partial coefficients are given in Table 7.1.

8.4.5.3 Material property reduction factors

Creep: graphite-epoxy composites exhibit little creep deformation, but a stiffness reduction factor of 1.1 will be used to allow for what may occur within the design life.

Table 7.1 Partial coefficients

		ULS	SLS
Partial load coefficient γ_f	Dead load	1.5	1.2
	Live load	2.0	1.5
	Accidental	1.2	-
Partial material coefficient γ_m	Strength	3.0	-
	Stiffness	-	1.1

Creep rupture: strength reduction factor of 1.25 will be used to allow for the reduction in strength due to sustained loading over the reference period.

Module 9: Manufacturing Processes

Learning Unit-1:

9.1 Fabrication/Manufacturing Techniques

9.1.1 Tooling of Composites

The manufacture of composite detailed parts and assemblies requires that some kind of accurate repeatable tool surface be provided, which is capable of withstanding repeated exposures to the cure cycle environment of high temperature sand pressures. Individual composite parts or details will require a variety of support tooling-beyond the initial cure tool, which are as follows:

- Master model reference patterns,
- Trim or router tools,
- Precision hole location drill tools,
- Assembly fixtures,
- Ply locating templates, and
- Associated shop aids.

The primary objective of any tool for composite fabrication is to make an accurate repeatable part within the confines of the process parameters defined by the manufacturer/designer and the detail performance characteristics meeting the requirements of the end user. Design of the initial tool becomes the most pressing initial issue of tooling for composites. Factors, which govern the basic tool design, are as follows:

- Coefficient of thermal expansion (CTE). One of the most critical parameters in the design of tooling for composites is the difference between the CTE of the problems. The greater the difference between the CTE of the composite detail and the tool, the more pronounced the effect would be. One of the effects that occurs as a function of these dimensional differences is called spring back Composite details, when cured, hold the specific molded shape, as defined by the tool, as a result of the cured combination of resin and reinforcement. The spring back, or more accurately defined as a warpage condition, occurs when the composite detail is cured into a tool, that at a specific temperature has one definite dimensional tolerance and then upon cooling to ambient temperature, contracts to its original ambient dimensions. Warpage occurs when stresses are induced to the composite as the tool begins to return to the ambient dimensions. This condition will become predominant as the temperature difference between ambient and cure temperature increases and the dimensional size of tool increases. A common method of minimising the effect of spring back or warpage of a composite detail during and after cure cycle is to determine the CTE of the composite part being fabricated and the CTE of the tooling material selected. During the design of tooling, CTE of the tooling material should be matched to that of the composite detail. Another condition leading to warpage of the laminate includes an unbalanced laminate orientation where the numbers of plies of material are more dominant in one direction than other.
- Using CTE in the design of tooling for composites. Following two methods are commonly used to minimise the effect of CTE when designing tooling for the fabrication of composite details:

    - Careful selection of the appropriate tooling material. Difference between CTE of tooling material and composite detail to be fabricated should be as close as possible.
    - Use of shrink factors in calculation of dimensions prior to tool fabrication.
- Choice of material in the design of tooling. Careful selection of the appropriate material for tool use must include review of the following criteria:
    - Anticipated tool usage i.e. expected life of tool. The life expectancy of any tool fabricated for the lay-up and cure of composite details is dependent on a variety of factors. Material selection, shop handling procedures and cure cycle time all affect the ability of tool to withstand long usage.
    - Cost available for tool fabrication. Cost of tool fabrication is difficult to quantify due to variable factors such as material and manpower cost.
    - Material available for tool construction.
    - Available methods for tool fabrication. Methods of manufacturing vary depending on equipment and personnel resources available. Plaster type master models and wet lay-up type molds take minimum facility requirements and basic shop skills. Use of prepreg materials requires additional skill levels and expenditure on account of sophisticated ovens and autoclaves.
    - Level of dimensional tolerances required from composite details. Based on the type of manufacturing method and the type of material selected, different levels of dimensional tolerances are possible. Initially, the dimensional tolerance for the composite detail to be fabricated is determined. Compliance to this tolerance is critical in meeting structural demands and conformance to any form, fit or functional requirements.
- Designing tools for resistance to failure. Due to the abusive environment experienced by tooling during the fabrication of composite details, life expectancy of the tooling is always short of anticipated value. Repetitive cycling from ambient to over 177°C (350°F),inadequate care and handling procedures, incorrect fabrication techniques have lead to a variety of defects resulting in premature, temporary or permanent failure of the tool. Failure modes common to composite lay-up tools fabricated by both wet lay-up and prepreg methods generally involve fibre separation and delamination. This is due to a variation in CTE between the resin matrix and the fibre. Possible solution to the problem of delamination between layers of prepreg tooling is the use of resin systems with glass transition temperature values at or slightly above the maximum usable temperature. For example, if the tool is intended to be cycled repeatedly at 177°C (350°F), glass transition temperature value of the resin system in the 220°C (425°F) range will allow more cycles.

9.1.1.1 Master Models

A master model is a master source identified with holes, scribe lines, trim lines or any other feature of the part that requires duplicating to other tools. The master model is a physical representation of the design or a point of reference to which all supporting tooling, both for fabrication and inspection, would be indexed. Since this surface will provide the reference pattern for all subsequent operations beyond initial fabrication, extreme care must always be taken to protect the master model. Master models may be fabricated from a variety of materials such as plaster, machined urethane or epoxy board stock, monolithic graphite or ferrous and non-ferrous metals. Each material offers distinct advantages and disadvantages. To determine which material is the most feasible, the entire tooling philosophy must be reviewed. Master models are generally stored indefinitely so that they may be referred to over the life cycle of the manufactured parts. Due to hygroscopic nature of plaster, care must be taken to protect the master model from the environment to maintain accuracy. Adequate storage conditions should be utilized for complete protection of master model throughout the life expectancy.

9.1.1.1.1 Plaster Masters

One of the oldest methods of producing a master is from plaster. Plaster is made from the mineral called gypsum ($CaSO_4$) which is finely ground and dehydrated to produce a fine powder with uniform properties. With the addition of water to form workable slurry, a reaction occur which produces heat and the inert gypsum gets dried. Plaster is manufactured in various textures or grades. Coarse grades are used to buildup the master model surface and then followed by fine grades which allow precise details such as trim lines or other identifications to be scribed into the surface. Depending on grade being used, plaster has a setting expansion of approximately 0.080% and a thermal expansion in the dried state of a maximum of 0.027ºC (0.0156ºF).

9.1.1.1.2Template Method

There are several techniques of building a plaster master determined by the shape of the part. If the part is not symmetrical and does not have a constant cross-section or the size is large, the master model is made from a series of templates secured to a flat base to form a 3D full-scale model of the part. Space between the templates is relative to the degree of abruptness of the contour. For normal gentle contours, a space of 15-20mm is common. Templates are usually made of aluminium to prevent corrosion. For temporary masters, steel is some times used, however, because of the amount of moisture present during mixing and application of the plaster, steel templates may rust. A schematic of typical template plaster master is shown in Fig9.1.

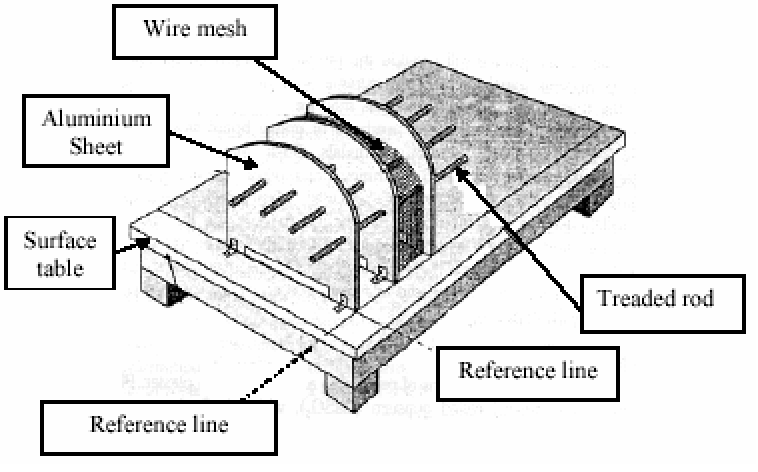


Fig 9.1

If electronic data is available, the templates can be NC-machined or cut with water or laser jet directly from the flat pattern generated by the data. Except for NC-method, deburring is generally required to remove spurs or sharp edges from the templates prior to use. Holes are drilled to the templates for threaded rod spacer sand screen support rods. For large models, air passages are cut into the bottom of the template to allow for even curing of the plaster. Once sufficient templates have been prepared, bluing is applied to a flat-ridged steel table and scribed with a pointed tool to denote the location of each template. Flatness of the table is critical and should be within0.127mm. Tooling balls, which indicate the x-, y- and z-direction are some times placed on the table corners as reference points for the system. Each template is attached 90° to the base table with angles. Threaded rods are secured with nuts on each side of the template to provide rigidity to the template face. Wire mesh is placed between the templates and secured to the threaded rod. This is used to hold plaster in place. Slurry of plaster is poured between the templates; surface is made even and left to dry to forma smooth and accurate surface. Because of the tendency of plaster to absorb moisture, it should be sealed after the surface has had adequate time to cure. Commercially available lacquers can be used to seal the surface and provide a suitable protection within the shop environment.

9.1.1.1.3 Follow Board Method

A method widely used when a constant cross-section is required to be built is the follow board. A flat surface is required with an accurate side surface to act as a guide rail. A template of the contour is prepared from sheet of aluminium or steel and attached to a wooden guide support. Plaster is mixed and built up on the surface to within 3mm of the final contour. Partial drying is recommended before the final plaster mix is applied. This will prevent shrinking and cracking of the plaster surface which otherwise would affect accuracy. Using the template and guide support, the plaster contour is formed by pushing the template evenly over the surface (Fig 9.2).

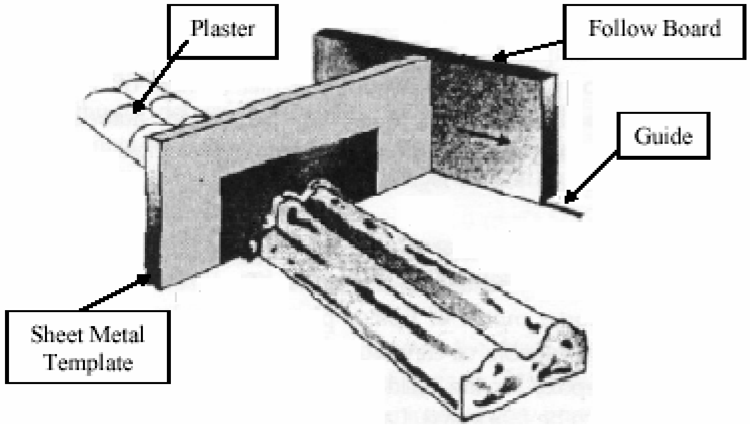


Fig 9.2

9.1.1.1.4 Sweep Method

Sweep method is used when a symmetrical surface such as cone or hemispherical shape is involved. As with the follow board method, a flat surface is required from which a frame of desired shape can be constructed. For large shapes, intermediate templates should be placed to provide adequate support.

The sweep itself is made from sheet metal of 3 mm minimum thickness and supported by a wooden guide or other mechanical guides. Plaster can be reinforced to form the desired shapes. All master models fabricated from plaster require, in addition to sealing with commercial grade lacquer, suitable storage, if the model is required to be stored for any period of time outside the shop environment. .

9.1.1.1.5 Lay-up Molds

Lay-up molds are used to form the shape of the part to be produced and have the part periphery scribed on the surface. Tools can be made directly from a NC machined master model or from a plastic faced plaster splash taken from a master model not capable of elevated temperature and pressures. The choice of glass or carbon/epoxy for the mold is generally governed by the complexity and CTE of the part to be fabricated. Lay-up molds must be capable of maintaining a vacuum tight environment while being subjected to high temperatures and pressures.

NC-Machining

Due to the widespread use of CAD systems, a great deal of accuracy can be transferred into the master model through the NC machining operations.

Composite Materials

Composite tools are usually made from epoxy resin matrix and either E-glass or carbon fibres as reinforcements. Depending on the life cycle required, tools could be made from prepreg or by wet lay-up procedures. Prepregs generally require curing within an autoclave because of the elevated pressures. Because of the increased compaction available while curing in an autoclave, tooling fabricated from prepregs ate capable of a greater number of cure cycles than the wet lay-up method. In addition to greater compaction, autoclave curing offers better control of resin content and uniformity of reinforcement.

9.1.1.1.6 Prepreg Method

There is considerable number of prepregs available as epoxy 'B' staged glass or carbon reinforced cloth. The first step prior to prepreg application on the master surface is to ensure that the prepreg and the master surface are absolutely clean and free from debris and that the surface is smooth and without pin holes. A quick vacuum check is always a good idea at a minimum of 6.2 kPa. A loss of 500 Pa within 5 minutes with the pump non-operating is acceptable. Apply masking tape around the tool periphery for later application of the sealant tape. It is absolutely necessary that the, master surface can be released with a suitable hard wax or other release agents. After the cleaning and releasing processes have been completed, release coated tooling pins should be placed into the holes of the master. Series of steps followed after the above processes are:

- Carefully lay each ply onto the surface and work out wrinkles or air bubbles and maintain the warp direction of each ply in the 0ºdirection.
- An overlap between the plies should be preferably 3-6 mills.
- Debulking should be done to ensure that no air is entrapped at the interface and the smooth surface on the tool. It is accomplished by application of a peel ply net to the edge of the laminate and working out wrinkles and air bubbles.
- Sealant tape should be placed around the periphery to prevent resin flow. Adequate precautions should be taken to allow for resin bleed.
- The orientation for each ply should be such that a balanced system is maintained to minimise stress build up in the laminate.
- As a rule of thumb, debulking should be done after every 4-5 plies. Final build up of the laminate should be at least 9.5 mm.
- Final vacuum bagging is performed with a layer of peel ply, perforated Teflon, polyester breather and vacuum bag.
- Recommended heat up rate and cure temperature should be followed. Most systems can be initially cured at up to 63°C (145°F) and 586-689 kPa of pressure for 14 hours.
- After the autoclave cycle, carefully remove the bag and films .from the laminate to avoid lift up from the master surface. Attachment of support or back up structure (e.g. egg crate) to the laminate is very important to minimise any

potential residual stresses built into the laminate. Support structure details are shown in Fig. 9.3.

- Separation of the tool from the master should be done carefully to avoid damage to the master or the tool itself. Tooling pins should be removed prior to separation. Once the tool is separated, the surface should be inspected for pin holes or -roughness. Pin holes can be filled with resin and the roughness can be smoothened with fine grit sandpaper. Care must be taken that no fibres are lifted by sanding along1he length of the fibres.

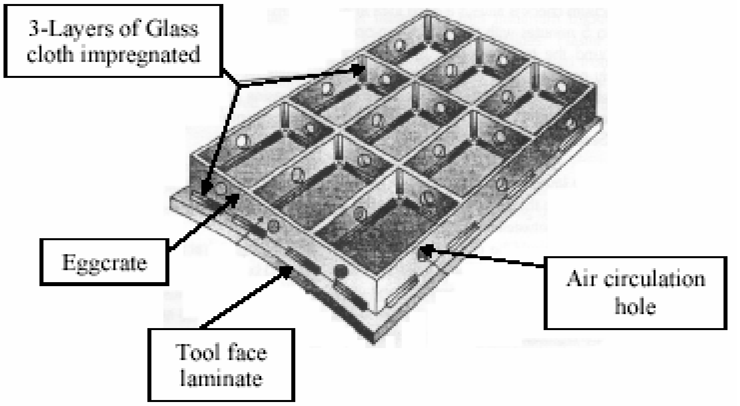


Fig 9.3

Once, the tool has been cleaned up, the required check for vacuum integrity is accomplished by placing a layer of polyester breather cloth on the surface and a vacuum bag over it. The acceptance criterion is generally that there is no loss greater that 500 Pa in 5 minutes at a minimum of 6.2 kPa at the start of the test. If possible, depending on the complexity of the tool, place the tool back onto the master and check for any warp or out of contour problems.

9.1.1.1.7 Wet Lay-up Method

Wet lay-up of composite tools can be for room or elevated temperatures use. The difference is only in the resin selection. Procedurally, the process is the same except for the cure cycles. Initial steps in wet lay-up method are same as are described in prepreg method namely, cleaning of master surface, checking for vacuum integrity, placing of masking tape around the periphery, releasing with a suitable wax or release agent, placing of tooling pins into the holes of master, etc. For wet lay-up two resins are used, one for the gel or face coat and one for laminating. The gel coat is generally the same as the laminating resin but with additives to thicken it to make it adhere to the contour of the master. Excessive buildup should be avoided incomers or at the bottom of contours while applying the gel coat. Too much resin will result in cracking and crazing later in the tool life cycle. It should also be ensured that air bubbles are removed. Air that remains entrapped either on the tool surface or within the layers of cloth could result in possible blisters and delamination later during tool usage. Application of first few plies should be done carefully to avoid pushing through the gel coat surface. It should be ensured that the plies are completely wet. All wrinkles and entrapped air should be worked out before another ply is added. Overlaps of 6.35 mm between plies should be maintained but the seam should never be placed over a seam from a previous ply. After each ply, additional resin should be added to cover the surface. After the fourth ply, or prior to the resin curing, apply a peel ply to the surface for compaction cycle. Debulking should be performed after every 6-ply or before resin begins to cure. Final laminate thickness should be 9.5 mm. After the final ply has been applied, the compaction step is repeated

with the peel ply, mold release film, bleeder and the vacuum bag. Fabricate a support or backup structure of similar material to the laminate to avoid stresses caused by the difference in CTE between the support structure and the laminate. Allow the tool to stand at ambient temperature for a minimum of 24 hours prior to post cure.
After the final 177°C (350°F) post cure, inspect the surface for pinholes and repair any blemishes with gel coat resin. A final vacuum check at 635 mm Hg with a loss of no more than 51 mm is acceptable.

9.1.1.2 Plastic Faced Plaster

Plastic faced plasters (PFP) are tooling aids that minimise the wear and tear on masters by duplicating the master surface with a suitable unit that can be used for variety of purposes. PFP sallow for tooling to be directly fabricated from the master surface without exposing the master model to adverse environmental conditions, such as autoclave temperatures and pressures. If taken directly from the mater surface, the PFP is the reverse of the master contour. An intermediate plaster splash is required to get back to the master contour with a PFP. If the surface required is directly from the master model, the PFP will be taken directly from the master surface. If the surface is above or below the master surface, appropriate steps must be taken by either taking additional splashes with or without layers of tooling wax to achieve the appropriate dimension. PFPs can be used in an autoclave (with vacuum integrity) up to approximately 105°C (220°F), however, a limit of one or two runs is all that can be expected. PFPs provide tooling aids for a variety of other room temperature shop applications.

Drill Templates

Drill templates or fixtures are used primarily to drill and locate precision holes in the production composite parts. Drill fixtures are fabricated using a room temperature fibre glass/epoxy system. Because the tool is used in the shop environment at ambient conditions, no vacuum integrity or elevated temperature requirements are needed.

Trim and Router Templates

Trim and router templates are used to trim and rout cured composite parts to a specific dimensional tolerance. Accuracy is required for these tools in order for the composite detail to fit precisely with adjacent details. Trim and router templates can be fabricated directly from the master model, composite tool or tooling aids such as PFP. They are generally fabricated using room temperature cured fibre glass/epoxy system. Since 'trim and routing operations are always carried out at room temperature, CTE is not considered in the design of this type of tooling.

Ply Locating Templates

Ply locating templates are used during the lay-up of the production part and designate locations for the plies and indexing of detail parts. In addition, these templates may also show individual ply orientation.

9.1.2 Manufacturing Processes

9.1.2.0 Introduction

Manufacturing of composite materials involves distinct operations that may vary depending upon available technology, existing facilities and personnel skill. The manufacturing process may also vary due to wide variety of composite materials and their application. Each of the fabrication processes has characteristics that define the type of products to be produced. This is advantageous because this expertise allows the manufacturer to provide the best solution for the customer. *Factors considered for selection of most efficient manufacturing process* are as follows:

- User needs
- Total production volume
- Performai1ce requirements
- Economic targets
- Size of the product
- Labour
- Surface complexity
- Materials
- Appearance
- Tooling/assembly
- Production rate
- Equipment

The goals of the composite manufacturing process are to:

- Achieve a consistent product by controlling
    - Fibre thickness
    - Fibre volume
    - Fibre direction
- Minimise voids
- Reduce internal residual stresses
- Process in the least costly manner

The procedure to achieve these goals involves series of actions to select the three key components, viz.

- Composite material and its configuration
- Tooling
- Process

As reinforcement for composite material, the choice between unidirectional tape and woven fabric is made on the basis of the greater strength and modulus attainable with the tape particularly in applications in which compression strength is important. Salient advantages and disadvantages of tape and fabric for their selection are given below:

Tape Advantages

- Best modulus and strength efficiency
- High fibre volume achievable
- Low scrap rate
- Less tendency to trap volatiles
- Automated lay-up possible
- No discontinuities

- Available in thin plies

Tape Disadvantages

- Poor drape on complex shapes
- Cured composite more difficult to machine
- Lower impact resistance
- Multiple plies required for balance and symmetry
- Higher labour cost for-hand lay-up

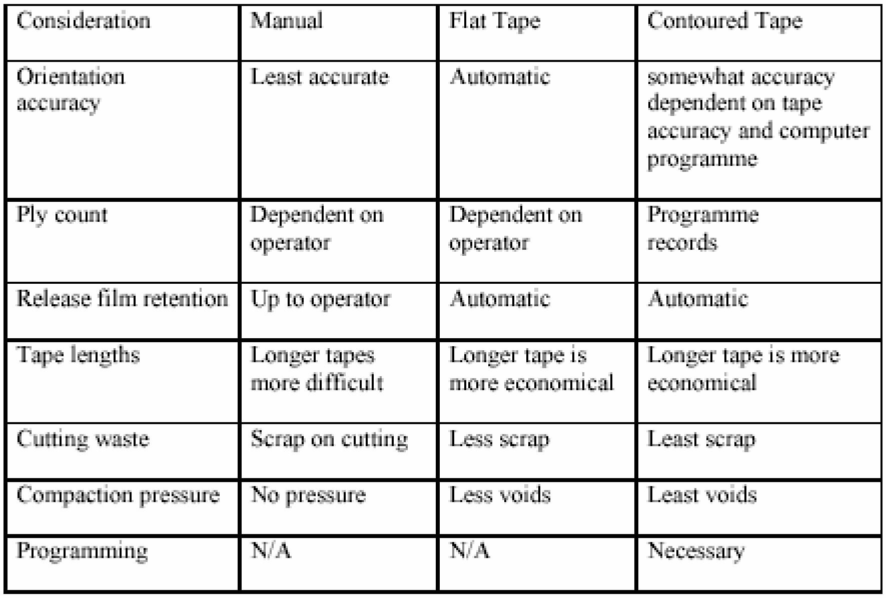
Fabric Advantages

- Better drape for complex shapes
- Single ply is balanced and may be essentially symmetric
- Can be laid up without resin
- Plies stay in line better during cure
- Cured parts easier to machine
- Better impact resistance
- Many forms available

Fabric Disadvantages

- Fibre discontinuities (splices)
- Less strength and modulus
- Lower fibre volume than tape
- More costly than tape
- Greater scrap rates
- Warp and fill properties differ
- Fabric distortion can cause part warping

Another aspect considered important for composite fabrication is appropriate lay-up techniques along with composite cure control. Some of the considerations for choosing lay-up techniques are given below:



Consideration	Manual	Flat Tape	Contoured Tape
Orientation accuracy	Least accurate	Automatic	somewhat accuracy dependent on tape accuracy and computer programme
Ply count	Dependent on operator	Dependent on operator	Programme records
Release film retention	Up to operator	Automatic	Automatic
Tape lengths	Longer tapes more difficult	Longer tape is more economical	Longer tape is more economical
Cutting waste	Scrap on cutting	Less scrap	Least scrap
Compaction pressure	No pressure	Less voids	Least voids
Programming	N/A	N/A	Necessary

Consideration	Manual	Flat Tape	Contoured Tape

Orientation accuracy	Least accurate	Automatic	somewhat accuracy dependent on tape accuracy and computer programme
Ply count	Dependent on operator	Dependent on operator	Programme records
Release film retention	Up to operator	Automatic	Automatic
Tape lengths	Longer tapes more difficult	Longer tape is more economical	Longer tape is more economical
Cutting waste	Scrap on cutting	Less scrap	Least scrap
Compaction pressure	No pressure	Less voids	Least voids
Programming	N/A	N/A	Necessary

9.1.2.1 Classification of Manufacturing Processes

Most widely used manufacturing methods for laminated fibre composites are as follows:

9.1.2.1.1 Open Mold Process

- Spray lay-up - Chopped roving and resin sprayed simultaneously, rolled.
- Hand lay-up - Lay-up of fibres or woven cloth, impregnate, no heat or pressure.
- Filament winding.
- Sheet molding compound.
- Expansion tool molding.
- Contact molding.

9.1.2.1.2 Closed Mold Process

- Compression molding – Load with raw material, press into shape.
- Vacuum bag, pressure bag, autoclave - Prepreg laid up, bagged, cured.
- Injection molding – Mold injected under pressure.
- Resin Transfer – Fibres in place, resin injected at low temperature.

9.1.2.1.3 Continuous Process

- Pultrusion.
- Braiding.

All the methods described above are discussed in detail in the following paras.

9.1.2.1.1 Open Mold Processes

Open molding offers a number of process and product advantage over other high volume and complex application methods. These include:.

- Freedom of design
- Easy to change design
- Low mold and/or tooling cost

- Tailored properties possible
- High strength large parts possible
- On-site production possible

Disadvantages associated with the open molding process include:

- Low to medium number of parts
- Long cycle times per molding
- Not the cleanest application process
- Only one surface has aesthetic appearance
- Operator skill dependent

9.1.2.1.1.1 Spray Lay-up

In a spray lay-up method, the fibre is chopped in a hand held gun and fed into a spray of catalysed liquid resin directed at the mold (Fig 10.1). The sprayed, catalysed liquid resin will wet the reinforcement fibres, which are simultaneously chopped in the same spray gun. The deposited materials are left to cure under standard atmospheric conditions.

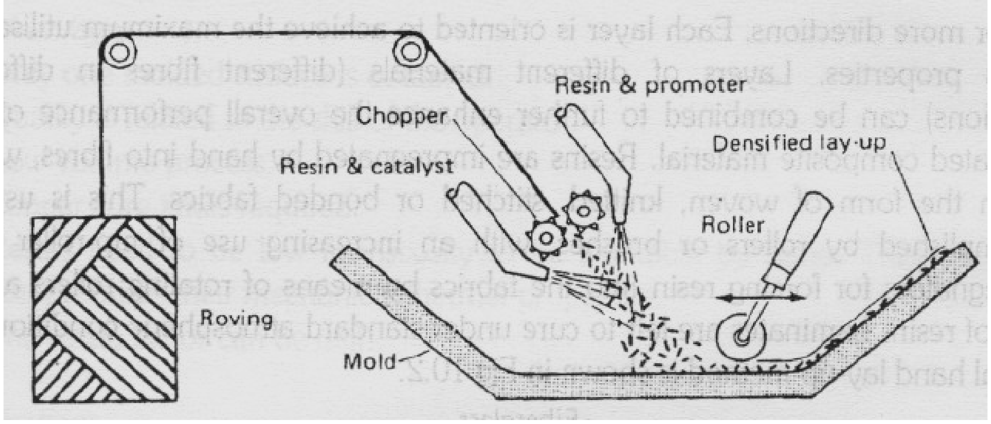


Fig 10.1

Advantages

- Widely used form any years.
- Low cost way of quickly depositing fibre and resin.
- Low cost tooling.

Disadvantages

- Laminates tend to be very resin-rich and, therefore, excessively heavy.
- Only short fibres are incorporated, which severely limits the mechanical properties of the laminate.
- Resins need to be low in viscosity to be sprayable. This generally compromises their mechanical/thermal properties.
- The high styrene content of spray lay-up resins generally means that they have the potential to be more harmful and their lower viscosity means that they have an increased tendency to penetrate clothing etc.

Applications

Simple enclosures, lightly loaded structural panels, e.g. caravan bodies, truck fairings, bathtubs, shower trays, some small dinghies.

9.1.2.1.1.2 Wet Lay-up/Hand Lay-up

The hand (wet) lay-up is one of the oldest and most commonly used methods for manufacture of composite parts. Hand lay-up composites are a case of continuous fibre reinforced composites. Layers of unidirectional or woven composites are combined to result in a material exhibiting desirable properties in one or more directions. Each layer is oriented to achieve the maximum utilisation of its properties. Layers of different materials (different fibres in different directions) can be combined to further enhance the overall performance of the laminated composite material. Resins are impregnated by hand into fibres, which are in the form of woven, knitted, stitched or bonded fabrics. This is usually accomplished by rollers or brushes, with an increasing use of nip-roller type impregnators for forcing resin into the fabrics by means of rotating rollers and a bath of resin. Laminates are left to cure under standard atmospheric conditions. A typical hand lay-up method is shown in Fig10.2.

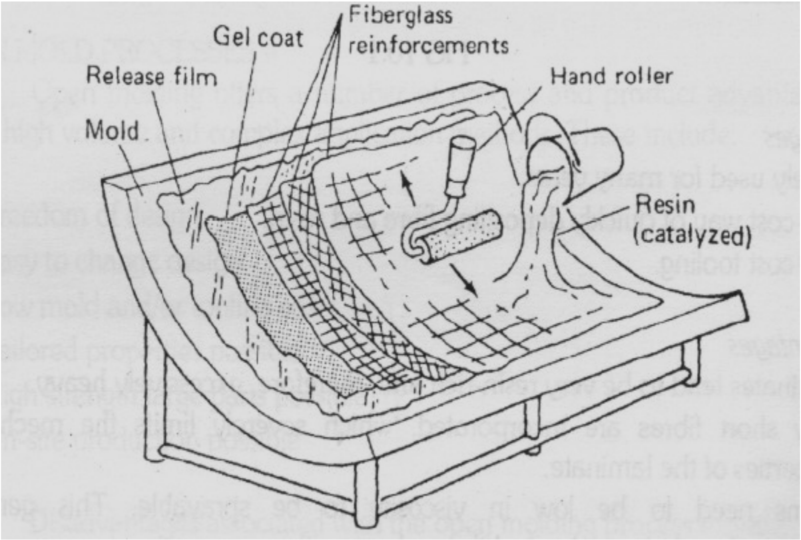


Fig 10.2

Some of the advantages and disadvantages of hand lay-up of composite structures are as follows:

Advantages

- Design flexibility.
- Large and complex items can be produced.
- Tooling cost is low.
- Design changes are easily effected.
- Sandwich constructions are possible.
- Semi-skilled workers are needed.
- Higher fibre content and longer fibres than with spray lay-up.

Disadvantages

- Only one molded surface is obtained.
- Quality is related to the skill of the operator.
- Low volume process.
- Longer cure times required.
- Resins need to be low in viscosity to be workable by hand. This generally compromises their mechanical/thermal properties.
- The waste factor can be high.

Applications

- Standard wind-turbine blades, production boats, architectural moldings.

9.1.2.1.1.3 Filament Winding

Filament winding is automated processes for creating parts of simple geometry wherein continuous resin impregnated fibres are wound over a rotating male tool called mandrel. Fig 10.3 depicts a filament winding process where a continuous fibre roving passes through a shuttle, which rotates and the roving is wrapped around a revolving or stationary mandrel. Two basic types of filament winding are in use - (i) the polar or planer method, and (ii) the high helical pattern winding.

The polar or planer method of winding utilizes a fixed mandrel and a shuttle that revolves around the longitudinal axis of the part to form longitudinal winding patterns. This type of winding is used if the longitudinal fibres are required with angle less than 25° to the mandrel axis. The polar winding schematic is shown in Fig 10.4.

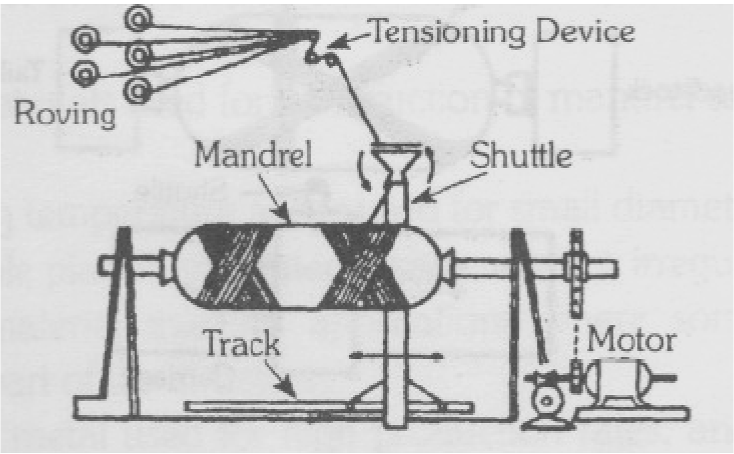


Fig10.3

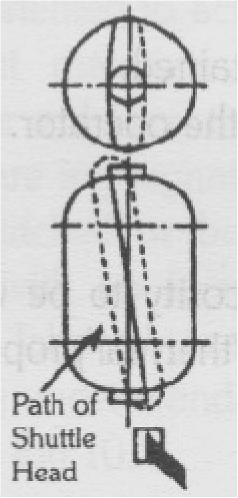
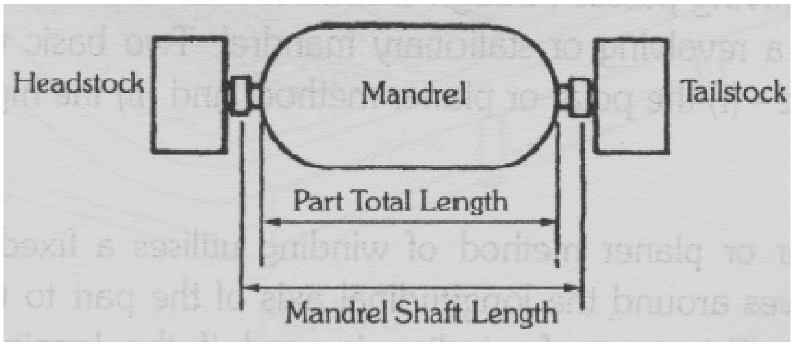


Fig 10.4

In the high helical pattern winding, the mandrel rotates while the shuttle transverses back and forth. Both the mandrel rotation and shuttle movement are in the horizontal plane. By controlling the mandrel rotation and shuttle speed, the fibre angle can be controlled. Angles of 25°-85° to the mandrel rotation axis are possible. The helical winding schematic is shown in Fig 10.5.



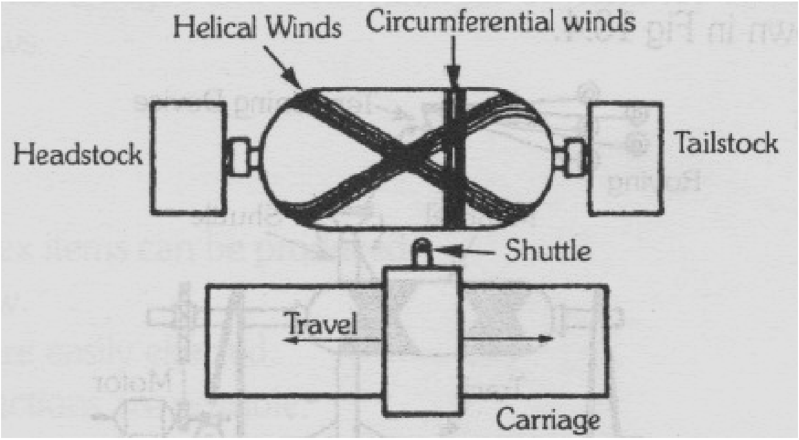


Fig 10.5

After completion of the winding, the filament wound structure is cured at room temperature or in an oven. The mandrel is removed after the curing. The mandrel, which determines accurate internal geometry for the component, is generally the only major tool. Low cost mandrel materials such as cardboard or wood can be used for winding low cost routine parts. For critical parts requiring close tolerances, expensive mandrels designed for long term use may be required. For high temperature cure 315°C (600°F), graphite mandrels with low thermal expansion may be advantageous. However, attention should be paid for potential difficulties for mandrel removal.

Mandrels are either removable or non-removable. Removable mandrels are classified according to the removal techniques as:

- Entirely removed.
- Collapsible.
- Breakable or soluble.

The selection of mandrel involves several considerations. These include part size and complexity, size of openings, resin system and its curing and the number of components to be fabricated. The requirements for a mandrel are:

- It must be stiff and strong enough to support its own weight and the weight of the applied composite while resisting the fibre tension pressure from winding and curing.
- It must be dimensionally stable and should have thermal coefficient of expansion greater than the transverse coefficient of the composite structure.

Different materials used for construction of mandrel are:

- Low melting temperature alloys used for small diameter applications.
- Sand, soluble plaster and eutectic salts used for irregular shapes.
- Inflatable material used in applications where sometimes the mandrel remains a part of the structure.
- Segmented metal used for high production rates, and where the mandrel can be withdrawn through a small hole in the part.

Of the above, segmented metal and inflatable mandrel are the reusable mandrels.

Advantages

- . Excellent mechanical properties due to use of continuous fibres.

- High degree of design flexibility due to controlled fibre orientation and lower cost of large number of composites.
- This is a very fast and economic method of laying down material.
- Resin content can be controlled by metering the resin onto each fibre tow through nips or dies.

Disadvantages

- Difficulty to wind complex shapes, which may require complex equipment.
- Poor external finish.
- The process is limited to convex shaped components.
- Fibre cannot easily be laid exactly along the length of a component.
- Mandrel costs for large components can be high.
- Low viscosity resins usually need to be used with lower mechanical properties.

9.1.2.1.1.4 Sheet Molding Compound

Sheet molding compound (SMC) refers to both a material and a process for producing glass fibre reinforced polyester resin items. The material is typically composed of a filled, thermosetting resin and a chopped or continuous strand reinforcement of glass fibre. A SMC processing machine, (Fig 10.6) produces molding compound in sheet form. The glass fibre is added to a resin mixture that is carried onto a plastic carrier film. After partial cure, the carrier films are removed. The sheet molding material is cut into lengths and placed onto matched metal dies under heat and pressure. Salient advantages of SMC molding process are as follows:

- High volume production.
- Excellent part reproducibility.
- Minimum material scrap.
- Excellent design flexibility.
- Parts consolidation.

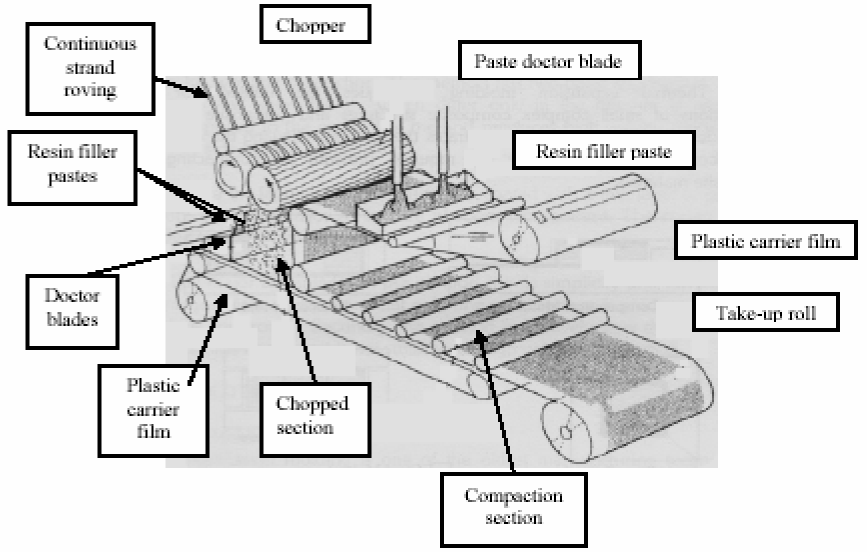


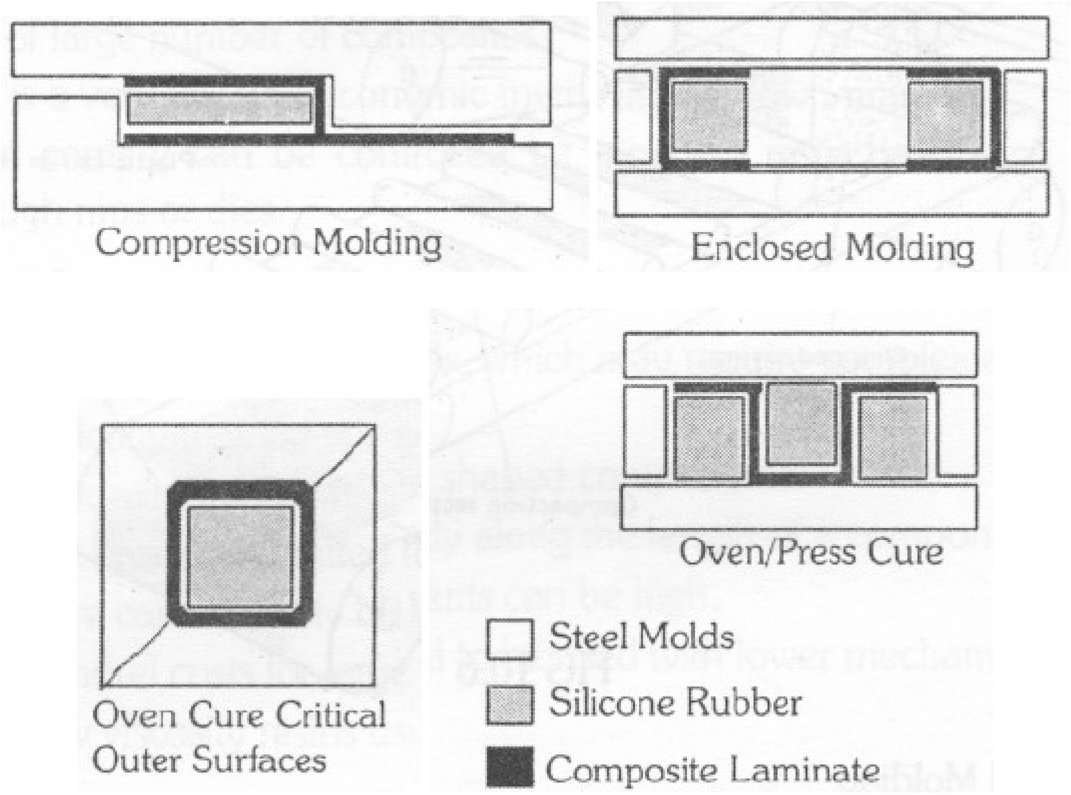
Fig 10.6

9.1.2.1.1.5 Expansion Tool Molding

Expansion tool molding makes use of rubber inserts in a metal or epoxy tool that expands when heated to provide the molding pressure. The advantage of expansion tool molding is its ability to fabricate parts without an autoclave. The method is dependent upon materials with high coefficients of thermal expansion. It is designed to utilize the difference in thermal expansion between rubber and the tooling material. The female areas of the mold are made of a material with a low coefficient of thermal expansion. The male plug is made of a silicon rubber or other rubber type tool material having comparatively high coefficient of thermal expansion. When the tool is heated, the rubber male plug expands at a much greater rate than the surrounding female tool.

Pressure up to 14 MPa (2000 psi) can be achieved at 175°C (350°F), which acts in all directions. The molding pressure can be controlled by controlling the temperature, rubber composition, rubber thickness and the ratio of rubber volume to the female mold volume.

Thermal expansion molding techniques are utilised for special applications of small complex composite structures and composite tubing with critical outside surfaces. Fig 10.7 illustrates the methods allowing the expansion of the silicone rubber to provide the required pressure for compacting of the composite materials.


Compression Molding

Enclosed Molding

Oven Cure Critical Outer Surfaces

Oven/Press Cure

Fig 10.7

The linear thermal coefficient of most silicone rubbers fall in the range of 1-2.1x10^5. This range is consistent over a 23-246°C (75-480°F) temperature range. The rubbers have a linear expansion of approximately17 times that of carbon steels due' to which they are used to mold composites by thermal expansion molding techniques. Silicone rubber is very slow to cool down and extra time must be allowed because the rubber is impossible to remove from the composite part until it has shrunk back to its original size..

9.1.2.1.1.6 Contact Molding

Contact molding involves the application of molding material to an open mold where it is allowed to cure. The process has been basically developed for the manufacture of large fibre glass components such as boats, automotive parts, etc. The process requires minimal tooling and equipment cost and thus is ideally suited for low volume production. The method has two basic approaches, namely hand lay-up and spray lay-up, which differ only in the manner in which. The material is applied to the mold. The method produces high quality surface finish on only one side of the final product.

Before the lay-up, the mold surface is coated with a thin layer of gel. After the lay-up, the part is allowed to cure at room temperature. The curing can be accelerated by using heat lamps.

The major advantages of the method are its simplicity and low cost. The disadvantages of the method are that only one good surface is produced while the other side is very rough. Secondly, the method is relatively slow due to long lay-up and cure time and thus it is not suitable for high volume production.

9.1.2.1.2 Closed Mold Processes

9.1.2.1.2.1 Compression Molding

Compression molding is one of the oldest manufacturing techniques in the composites industry. The recent development of high strength, fast cure, sheet molding compounds bulk molding compounds and advancement in press technology is making the compression molding process very popular for mass production of composite parts. Fully formed parts are molded in matched metal compression molds that give the final part shape. In comparison with the injection molding process, better physical and mechanical properties can be obtained in compression molding.

This process utilises large tonnage presses wherein the part is cured between two matched steel dies under pressure and high temperature. The moving platen is heated either by steam or electricity to promote thermal curing. Curing of the part is affected by the following factors:

- Size of platen, which determines the length and width of the part, which can be cured.
- Total tonnage of the press, which determines the pressure to be exerted on the projected surface area of the part.

After placing the laminate to be cured called the 'charge' in the core of the mold, the cavity is then closed at a rate of usually 4-12 mm/sec. In most cases the mold is heated to 150°C (302°F), which causes the charge viscosity to be reduced. With increasing mold pressure as the mold is closed, the charge flows towards the cavity extremities, forcing air out of the cavity. The molding pressure based on projected part area ranges from 0.7 to 9 MPa (100 to 1200 psi). Higher molding pressure causes sink marks, while lower pressure cause scumming of the mold and porosity. The curing time is usually between 25 sec to 3 minutes depending on several factors including' resin-initiator-inhibitor reactivity, part thickness, component complexity and mold temperature.

The exertion of high pressure eliminates the problem of development of voids. The primary advantage of the compression molding is its ability of producing large number of parts with little dimensional variations, if any, from part to part. A wide variety of shapes, sizes and complexity can be produced by compression molding. An important factor to be considered before deciding to use compression molding is the high tooling cost and the need for large heated presses. Thus, this method is not practical for low volume production.

Cure time is very critical. If the resin cure exotherm is not properly controlled, cracking, blistering or warping may occur. Fig 10.8 shows a typical compression mold.

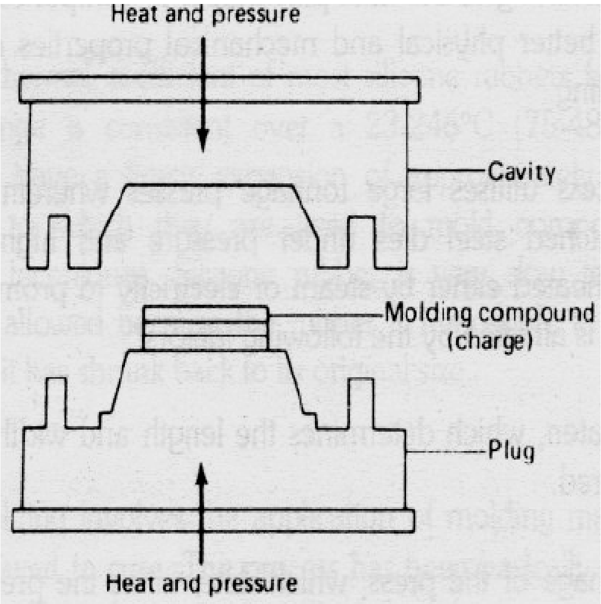


Fig 10.8

9.1.2.1.2.2 Vacuum Bag Molding

Today bag molded (vacuum and pressure) composites provide higher performance that results from optimisation of process controls, design refinements and improved materials.

Vacuum bagging techniques have been developed for fabricating a variety of aerospace components and structures. The process is principally suited to prepreg materials. This method utilises a flexible film or rubber bag that covers the part lay-up. The bag permits evacuation of the air to apply atmospheric pressure. The primary limitation of this method is the limited pressure that can be applied.

The bag used in this method has two fold objectives:

- It provides a means for removing volatile products during cure; and
- It provides a means for the application of a pressure of one atom which is adequate for some materials.

The essential steps in the process are the lay-up, preparation of bleeder system and the bagging operation. The required number of plies are cut to size and positioned in a mold. When individual plies of a prepreg material are formed to the lay-up tool, certain amount of voids exists between layers. The lay-up is covered with a flexible membrane or vacuum bag, which is sealed around the edges of the mold by a sealant. An edge bleeder is also placed near the edges of the lay-up. Its function is to absorb excess resin, which may flow during curing.

Requirement for proper bagging are:

- Bag to be impervious to air pressure,
- Bag to uniformly apply the cure pressure,
- Bag not to leak under over-pressure, and

- Good and high capacity vacuum path to be provided to evacuate air from between the bag and the tool.

A vacuum is drawn on the lay-up, which helps in eliminating entrapped air. A maximum pressure of about 104 kPa (15 psi) is achieved in this method. The removal of excess resin results in higher fibre content and improved mechanical properties. The lay-up is usually allowed to cool at room temperature. To reduce the cure time, oven is preferred. A typical vacuum bag molding is shown in Fig 10.9.

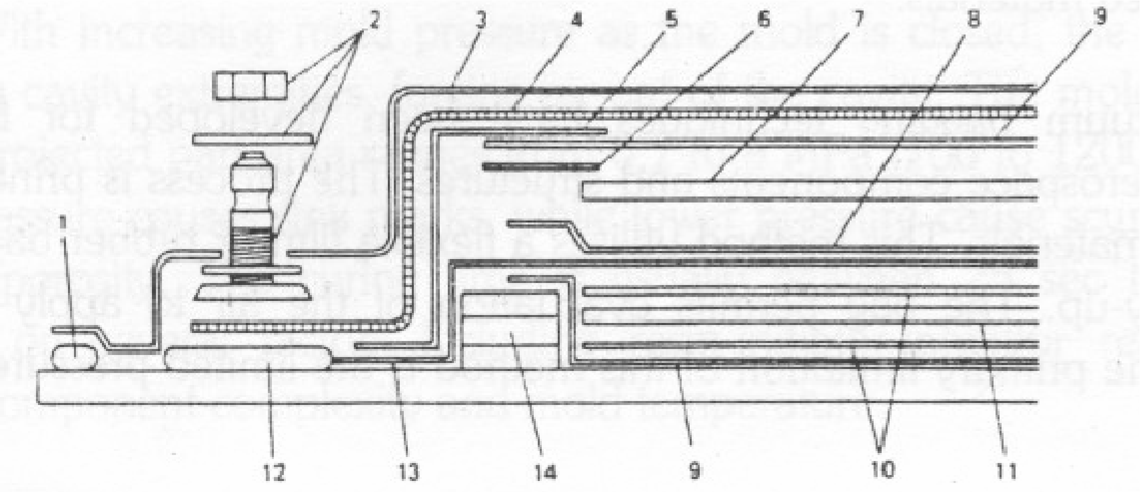


Fig 10.9

Functions of vacuum bag components are as follows:

No.	Component	Functions
1	Bag sealant	Temporarily bonds vacuum bag to tool
2	Vacuum fitting and hardware	Exhausts air, provides convenient connection to vacuum pump
3	Bagging film	Encloses part, allows for vacuum and pressure
4	Open weave breather mat	Allows air or vacuum transfer to all of part
5	Polyester tape (wide)	Holds other components of bag in place
6	Polyester tape (narrow)	Holds components in place
7	Caul sheet	Imparts desired contour and surface finish to composites
8	Perforated release film	Allows flow of resin or air without adhesion
9	Non-perforated release	Prevents adhesion of laminate film resin to tool surface
10	Peel ply	Imparts a bondable surface to cured laminate
11	Laminate	
12	Glass breather manifold	Allows transfer of air or vacuum.
13	Glass bleeder ply	Soaks up excess resin
14	Stacked silicon edge dam	Forces excess resin to flow vertically, increasing fluid pressure

Two types of vacuum bags commonly used are - (1) expandable bagging, or (2) reusable bagging.

9.1.2.1.2.2.1 Expendable Vacuum Bagging

Bleed-out systems are devised to maintain reduced pressures within the bags contents. The bagged lay-up includes the bleed-out system designed for the composite part. Bagged lay-ups can be bled in two ways, namely vertically or edge bled. The basic difference between the two methods is shown in Fig 10.10 (a) & (b).

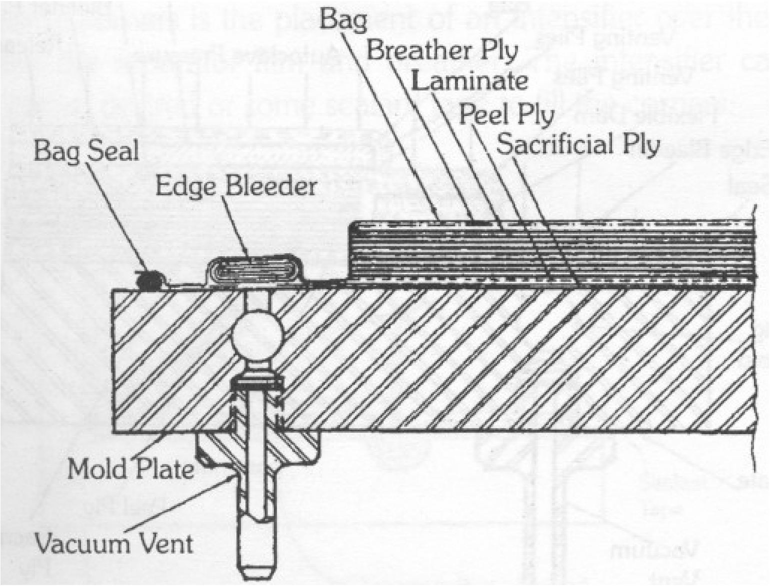


Fig 10.10(a)

Many of today's resin systems are mostly net resin and do not require any resin bleed during cure. This allows for better control of the resin content of the composite structures. If a resin bleed sequence is preferred, the following sequence can be used as a general guide:

- The surface of the mold is prepared with the release agent.
- The composite plies are applied and rubbed out to remove the entrapped air.
- A perforated release film is applied over the composite laminate and extended approximately 3.2mm beyond all edges.
- A predetermined number of bleeder plies are applied over the release film and extended to the perimeter of the lay-up.
- A perforated release film is applied over the bleeders and extended 3.2 mm from edge.
- One or two layers of a non-woven breather is placed over the lay-up and extended over the release film.
- Sealant tape is applied around the perimeter of the bleeder.
- The vacuum bag is positioned and sealed.
- The contents are evacuated and the bag is checked and sealed against leaks.
- The bagged lay-up is ready for curing.

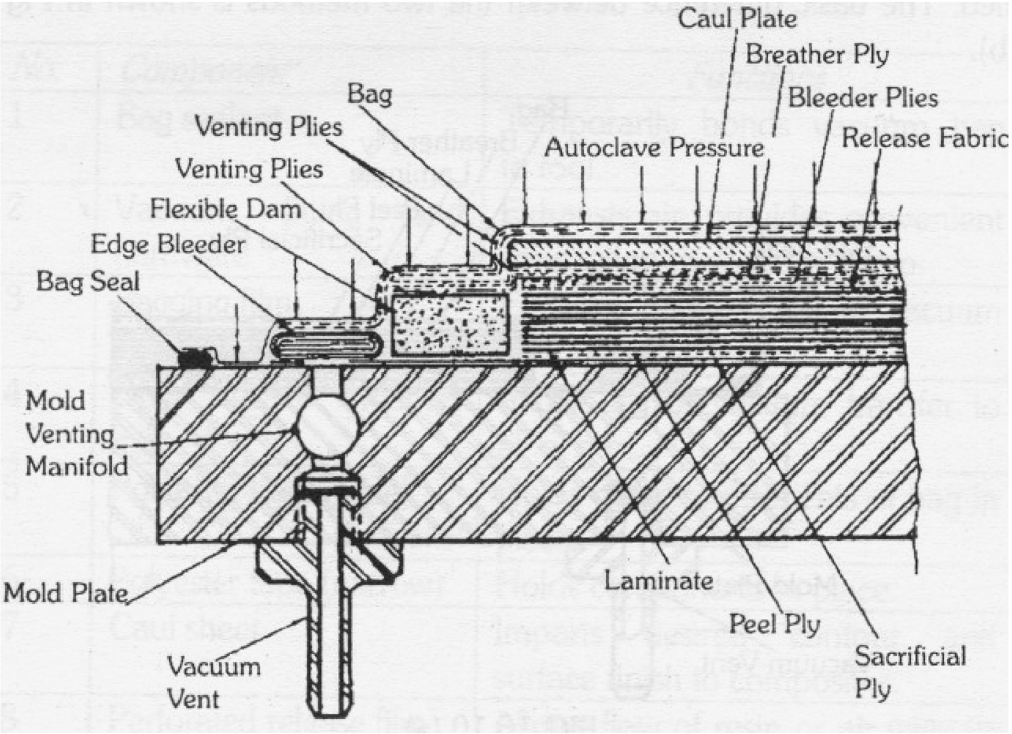


Fig 10.10(b)

Vacuum bag bridging is one of the leading causes of resin rich and excessive voids in corners of composite laminates. Fig 10.11 illustrates this common problem.

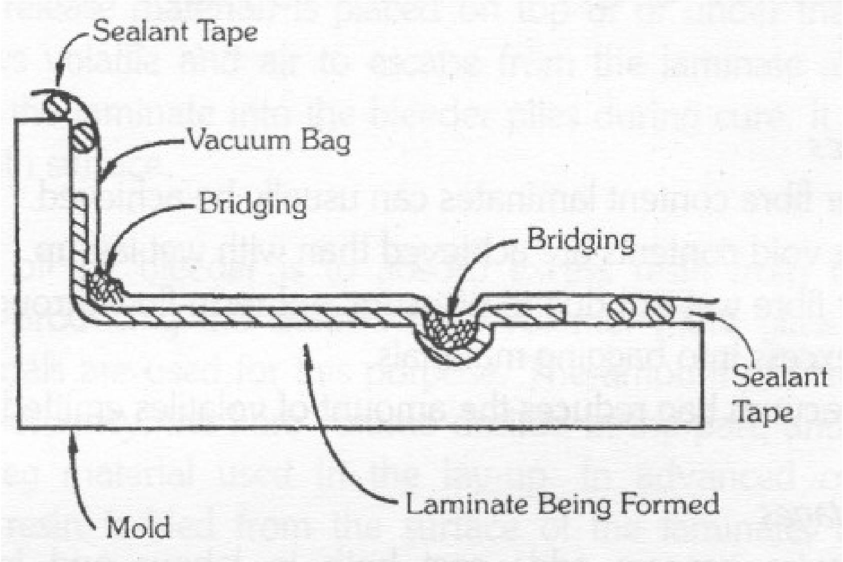


Fig 10.11

One method of eliminating bridging of the vacuum bag is presented in Fig 10.12 by means of 'ears' in the bag. Another method to help reduce resin rich and excessive voids in corners is the placement of an intensifier over the area, usually placed between the separator film and breather. The intensifier can be molded rubber in the radius desired or some sealant tape to fill the corners.

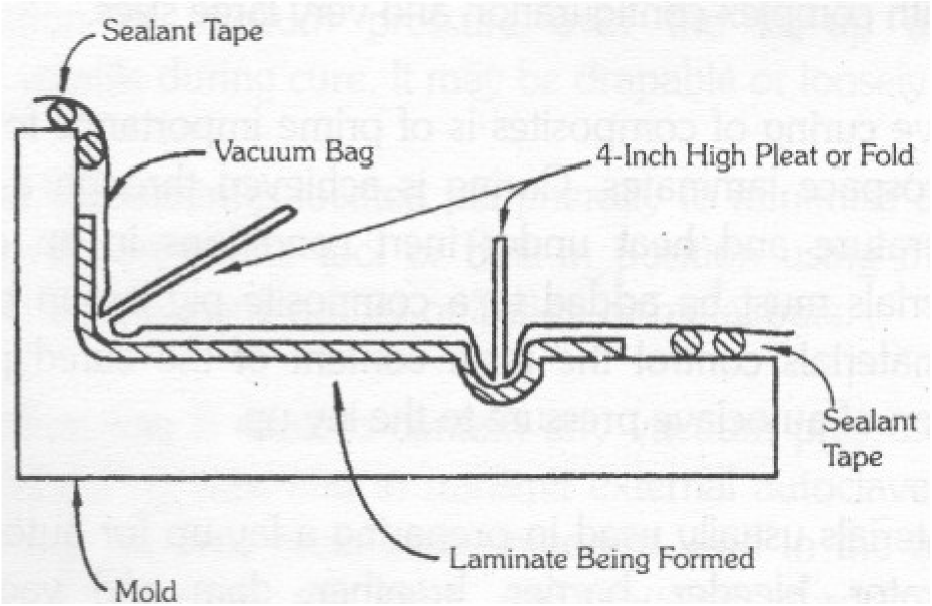


Fig 10.12

9.1.2.1.2.2.2 Reusable Vacuum Bagging

Due to material and recurring cost associated with the use of expendable vacuum bags, use of silicone rubber reusable bags are the solution.

Salient advantages and disadvantages of the vacuum bagging method are as follows:

Advantages

- Higher fibre content laminates can usually be achieved.
- Lower void contents are achieved than with wet lay-up.
- Better fibre wet-out due to pressure and resin flow throughout structural fibres, with excess into bagging materials.
- The vacuum bag reduces the amount of volatiles emitted during cure.

Disadvantages

- The extra process adds cost both in labour and in disposable bagging materials.
- A higher level of skills required by the operators.
- Mixing and control of resin contents till largely determined by operator skill.

9.1.2.1.2.3 Autoclave Molding

Autoclave molding is similar to vacuum bag process except that the lay-up is subjected to greater pressures and compact parts are produced. Primary disadvantage is high initial and recurring operating cost. The advantage is to produce parts with complex configuration and very large sizes.

Autoclave curing of composites is of prime importance for manufacturing high quality aerospace laminates. Curing is achieved through a combination of pressure, temperature and heat under inert conditions in an enclosed vessel. Processing materials must be added to a composite ply lay-up before autoclave curing. These materials control the resin content of the cured part and ensure proper application of autoclave pressure to the lay-up.

The materials usually used in preparing a lay-up for autoclave curing are peel ply, separator, bleeder, barrier, breather, dam and vacuum bag. The materials are compatible with the maximum cure temperature and pressures required for the matrix system being cured. The peel ply if used is placed immediately on top of or under the composite laminate. It is ultimately removed just before bonding or painting operations so that a clean, bondable surface is available.

A separator (release material) is placed on top of or under the laminate and peel ply. It allows volatile and air to escape from the laminate and excess resin to be bled from the laminate into the bleeder plies during cure. It also gives the cured part a smooth surface.

The purpose of the bleeder is to absorb excess resin from the lay-up during cure, thereby producing the desired fibre volume. Fibre glass fabric or other absorbent materials are used for this purpose. The amount of bleeder used is a function of its absorbency, the fibre volume desired in the part, and the resin content of the prepreg material used in the lay-up. In advanced composites essentially all excess resin is bled from the surface of the laminate, with edge bleeding being minimised by properly damming the lay-up edges.

The barrier is commonly placed between the bleeder plies, and breather plies. In the case of epoxy resin, unperforated film is used so that resin removal from the part can be controlled. For resins that produce volatile by-products during cure, a film with small perforations and large spacing is used to prevent the breather materials from becoming clogged with resin.

The breather is a material placed on top of the barrier film to allow uniform application of vacuum pressure over the lay-up and removal of entrapped air or volatile during cure. It may be drapable or loosely woven fabric.

The dam is sometimes located peripherally to minimise edge bleeding. It maybe an integral part of the tool or built-in position using materials such as pressure-sensitive tape, silicone rubber or Teflon or metal bars.

The vacuum bag is used to contain any vacuum pressure applied to the lay-up before and during cure and to transmit external autoclave pressure to the part. It prevents any gaseous pressurizing medium used in the autoclave (air or inert gas) from permeating the part and causing porosity and poor or unacceptable part quality.

Major components of autoclave are - a vessel to contain pressure; sources to heat the gas stream and circulate it uniformly within the vessel; a sub-system to pressurize the gas stream; a sub-system to apply vacuum to parts covered by a vacuum bag; a sub-system to control operating parameters; and a sub-system to load the models into the autoclaves.

The materials, which can be processed in the autoclave, are metal bonding adhesives, reinforced epoxy laminates, thermoplastic laminates, ceramics, carbon matrix materials; and many other applications.

An autoclave system allows a complex chemical reaction to occur inside a pressure vessel according to a specified schedule in order to process a variety of materials. The pressure and temperature requirements are governed by the type of material to be cured. The evolution of materials and processes has taken autoclave operating conditions from 120°C (248°F) and 276 kPa (40 psi) pressure to well over 760°C (1400°F) and 69 MPa (10000 psi). Epoxy matrix composites, in general, use autoclave cure cycles, which involve487-690 kPa (85-100 psi) pressure and 175°C (350°F) temperature. The materials processed in autoclaves range from metal bonding adhesives, reinforced epoxy laminates, thermoplastic laminates, metal, ceramic and carbon matrix materials, to many other aerospace and electronic components. Autoclave is generally provided with automatic programmable controllers, which monitor and maintain the required heat up and cool down cycles. The vacuum surrounding the part lay-up is also controlled and is discontinued after initial temperature increase to prevent excess resin flow. Brief functioning of various parts of autoclave is discussed in the following paras.

Pressure Vessel

It provides the means to retain pressure inside the work space. Typically, the pressure vessel is fabricated from pressure vessel quality carbon steel. It is thermally insulated. All autoclave vessels and closures are required to be inspected at regular interval. This will reveal any potentially dangerous situation.

Gas Stream Heating

Several heating methods are available for autoclave systems. Most common method for large autoclaves is indirect gas firing in which products of combustion are passed from external chamber to an internal coil. Gas heating is regularly used in autoclaves with maximum operating temperature of 450°-540°C (8500-1000°F).

Earlier, hot oil was used as a heating medium in which oil was circulated from an external heater to an internal coil. This system became obsolete due to contamination problems of bonding area leading to improper processing of parts. Steam heating is often used for autoclaves operating in the 150°-175°C (3000-350°F) range. The superheated steam is passed through a coil in the autoclave to heat the circulating gas. Most small autoclaves are electrically heated.

Gas circulation, within the autoclave, is essential to provide temperature uniformity and proper heat transfer to the loaded part. The gas circulation is maintained at 1 to 3 m/s (250to 300 ft/min) in the workspace.

Gas Stream Pressurisation

The three pressurizing gases typically used for autoclaves are (a) air (b) nitrogen and (c) carbon dioxide.

Air is used for most of the 120°C (250°F) cures. However, disadvantage of air is that it sustains combustion and maybe hazardous at temperatures above 150°C (300°F). Nitrogen is commonly used in the autoclaves. Liquid Nitrogen is stored in cryogenic form and then vaporised at approximately 1380 to 1552 kPa (200 to 225 psi). Carbon dioxide is the second most commonly used gas. It is stored as refrigerated liquid at approximately 2070 kPa (300 psi). Disadvantages of carbon dioxide are its high density, hazards to personnel, etc.

Vacuum Systems

Most parts processed in autoclaves are covered with vacuum bags, which are used primarily for compaction of laminates and to provide vacuum for removal of volatile products. The bag allows the part to be subjected to differential pressure in the autoclave without being directly exposed to the autoclave atmosphere. The vacuum bag is also used to apply varying levels of vacuum to the part. The ability to provide pressure on the part under the bag by means of vacuum results in reduced void content.

Control System

Control system means ability to monitor and control cure cycles. The cure cycle is controlled by feedback from thermocouples, transducers and sensors, which are provided at different locations in the autoclave.

Loading System

Carts or trolleys help in placing the parts horizontally and vertically in the autoclave. The parts are loaded s~ that they are accessible to enable repair of bag leaks. All vacuum sources and vacuum sensor lines are connected to the part when loaded on cart and desired vacuum maintained. The cart must be gently rolled into the autoclave.

At present, computer controlled autoclaves with facility for storage of up to 60 different curing cycles programmes are available in the world market.

In industry, autoclave curing of composites is used to improve cured product quality and reduce fabrication costs by providing:

- Process optimization.
- Reduced process inconsistencies and product rejections. Accurate, real-time quality assurance with rapid error detection and correction.
- Verification of process reaction behaviour kinetics.
- Non-destructive verification of cured properties.
- Accurate, permanent process documentation.
- Flexibility in adapting to new or modified processes.

9.1.2.1.2.4 Injection Molding

Injection molding refers to a process that generally involves forcing or injecting a fluid plastic material into a closed mold. It is differentiated from compression molding, in which plastic materials in a soft but not fluid condition are formed by transferring them into an open mold, which is then forcibly closed. This method is not normally used in polymeric matrix compound processes due to fibre damage in the barrel.

The molding compound is fed into injection chamber through the feed hopper. The molding compound is heated in the injection chamber wherein it changes into liquid form. It is forced into the injection mold by the plunger. A typical injection mold is shown in Fig 10.13.

The injection molding process generally has the following advantages over the compression molding:

- More readily automated process,
- Permits finer part detail.

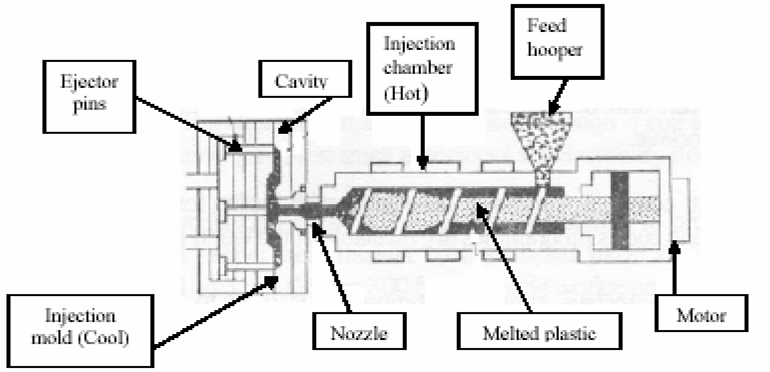


Fig 10.13

The part and the mold can often be designed in a manner so that no subsequent trimming or machining operations are required. However, all plastic materials cannot be injection molded successfully. There are two basic categories of plastic injection molding (a) thermoplastic and (b) thermoset. In the former, a thermoplastic material is melted and forced through an orifice into the mold, which is kept relatively cool. The material solidifies in the mold from which it can then be removed. In thermoset injection molding, the solidification occurs at high temperature. Therefore, a reaction material is forced into a generally warm mold in which the material further polymerises into a solid part.

This method is normally used for high-volume and low-cost component manufacturing. The disadvantage of the method is that it is limited to materials with very short fibre lengths. Also, since there is large amount of flow during the process, material non-uniformities do exist.

9.1.2.1.2.5 Resin Transfer Molding (RTM)

Resin transfer molding is a closed mold low pressure process that allows the fabrication of composites ranging in complexity from simple, low performance to complex, high performance parts and in size from small to large (Fig10.14). The process is differentiated from other molding processes in that the dry reinforcement and the resin are combined within the mold to form the composite component. The fibre reinforcement, which may be pre-shaped, is placed into a tool cavity, which is then closed. A tube connects the closed tool cavity with a supply of liquid resin, which is pumped or transferred into the tool to impregnate the reinforcement for subsequent curing. Injection pressure is normally less than 690 kPa (100 psi). The displaced air is allowed to escape through vents to avoid dry spots. Cure cycle is dependent on part thickness, type of resin system and the temperature of the mold and resin system. The part cures in the mold, normally heated by controllers.

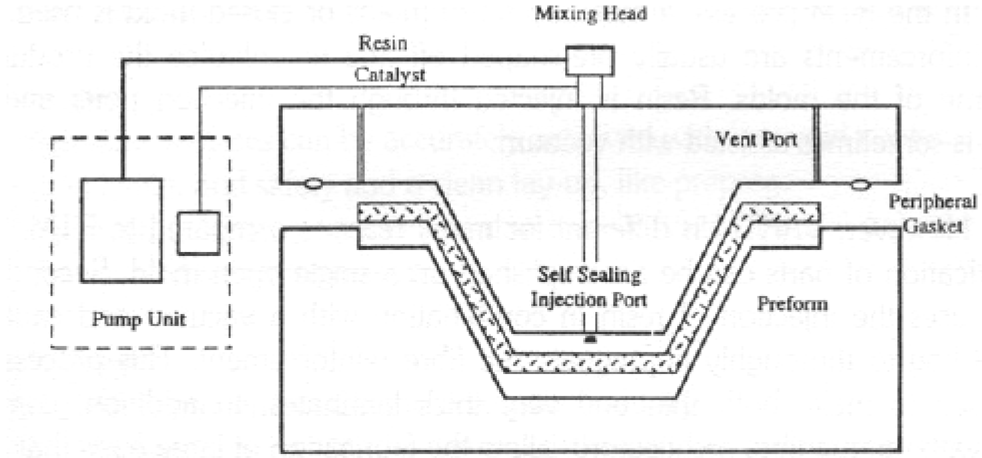


Fig10.14

The advantages and associated disadvantages of the RTM process are given below:

Advantages

- Parts can be made with better reproducibility than with wet lay-up.

- Reinforcement and combination of reinforcements can be used to meet specific properties.
- Production cycles are much faster than with wet lay-up.
- Using matched tools for the mold, one can improve the finish of all the surfaces.
- Mechanical properties of molded parts are comparable to other composite fabrication processes.
- Large and complex shapes can be made efficiently.
- Volatile emissions are low because RTM is a closed mold process.
- The skill level of operator is less critical.
- Mold surfaces can be gel coated to improve surface performance.

Disadvantages

- The mold design is critical and requires good tools or great skill.
- Reinforcement movement during resin injection is sometimes a problem.
- Control of flow pattern or resin uniformity is difficult. Radii and edges tend to be resin rich.

Vacuum Assisted Resin Transfer Molding (VARTM)

In the RTM process, a matched set of molds or closed mold is used. The fibre reinforcements are usually pre-shaped off line to enhance the production cycle time of the molds. Resin is injected through the injection ports and the process is sometimes assisted with vacuum.

However, VARTM is different for many reasons compared to RTM. First, the fabrication of parts can be accomplished on a single open mold. Second, the process uses the injection of resin in combination with a vacuum and captured under a bag to thoroughly impregnate the fibre reinforcement. This process has been used to make both thin and very thick laminates. In addition, complex shapes with unique fibre architectures allow the fabrication of large parts that have a high structural performance.

Fabrics are laid up as a dry stack of materials as in RTM and covered with peel ply and a knitted type of non-structural fabric. The whole dry stack is then vacuum bagged, and once bag leaks have been eliminated, resin is allowed to flow into the laminate. The resin distribution over the whole laminate is aided by resin flowing easily through the non structural fabric, and wetting the fabric.

Advantages

- Much lower tooling cost due to one half of the tool being a vacuum bag.
- Large components can be fabricated.
- Standard wet lay-up tools may be modified for this process.
- Cored structures can be produce din one operation.

Disadvantages

- Relatively complex process to perform well.
- Resins must be very low in viscosity, properties, thus compromising mechanical
- Unimpregnated areas can occur resulting in very expensive scrap parts.

Resin Film Infusion (RFI)

In resin film infusion process, dry fabrics are laid up interleaved with layers of semi-solid resin film supplied on a release paper. The lay-up is vacuum bagged to remove air through the dry fabrics, and then heated to allow the resin to first melt and flow into the air-free fabrics, and then after a certain time, to cure. The main attraction of resin film infusion is probably for parts of high surface area.

Advantages

- High fibre volumes can be accurately achieved with low void contents.
- Good health and safety and a clean lay-up, like prepreg.
- High resin mechanical properties due to solid state of initial polymer material and elevated temperature cure.

Disadvantages

- Not widely proven outside the aerospace industry.
- Tooling needs to be able to withstand the process temperatures of the resin film.
- Core materials need to withstand the process temperatures and pressures.

9.1.2.1.3. Continuous Processes

9.1.2.1.3.1 Pultrusion

Pultrusion is an automated process used to create shapes by pulling rovings through a shaped and heated die. The use of pultruded parts in aircraft is limited to specialized applications. Practical applications are limited to constant cross-section parts. Pultrusion is used to manufacture constant cross-section shapes, viz., I-beam, box, channels, tubings, etc.

The Pultrusion process machine consists of six different parts namely, the creel, the resin bath, the forming die, the heated curing die, the pullers and the cut-off saw. The creel is the beginning of the Pultrusion process and is the material storage system from which the fibres and mat or fabric are drawn in the correct sequence to match the design requirements of the structural shape. Virtually all Pultrusion processes utilise a resin impregnation bath to facilitate the impregnation of the resin into the fibre structure. The use of pre-impregnated fibres eliminates the resin bath.

Two types of dies are used in Pultrusion process, namely, the forming and the heating or curing die. Forming is done immediately after the impregnation process. Forming dies are normally attached to the heating or curing die in order to provide the correct relationship between the forming and the heated curing step. The rovings go through a heated die that represents the cross-section of finished part. Curing is accomplished by heating the die. The product continuously pulled out and as it comes out of the puller mechanism, it is cu the desired length by an automatic saw.

The process is continuous and can be used to manufacture extremely long sections. At typical continuous Pultrusion process is shown in Fig10.15.

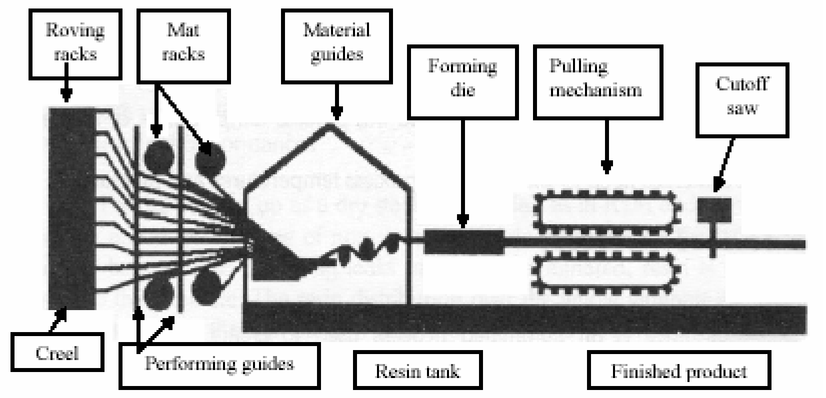


Fig 10.15

There are two categories of Pultrusion products. The first category consist of solid rod and bar stock produced from axial fibre glass reinforcements and polyester resins. These are used to make fishing rods and electrical insulator rods which require high axial tensile strength. The second category consists of structural profiles, which uses a combination of axial fibres and multi-directional fibre mats to create a set of properties that meet the requirements of the application in the transverse and longitudinal directions.

More than 90% of all pultruded products are fibre glass reinforced polyester. When better corrosion resistance is required, vinyl ester resins are used. When a combination of superior mechanical and electrical properties is required, epoxy resin is used. Higher temperature resistance and superior mechanical properties generally dictate the use of epoxy resins reinforced with aramid or carbon fibres.

The major limitation of this method for aircraft use is the constant cross section requirement. Also, more complex geometries are not feasible by this technique. The chief advantage of the method is the ability to produce consistent parts at very low cost in a short period of time. Pultruded composite parts exhibit all the features produced by other composite processes, such as, high strength to weight ratio, corrosion resistance, dimensional stability, etc.

Advantages

- Production is continuous.
- Material scrap rate is low.
- The requirement for support material is eliminated i.e., breathers. bleeder, cloth, separator film, bagging film, edge tape, etc.
- Labour requirements are low.

Disadvantages

- Limited to constant or near constant cross-section components.
- Heated die costs can be high.

9.1.2.1.3.2 Braiding

The braiding process involves the weaving of fibres into shape by repeatedly crossing them back and forth over a mandrel. The use of braiding process in the aircraft industry is generally restricted to non-structural applications. The braiding process has been utilised extensively for covering of the electrical wires and fuel lines. The primary advantage that braiding offers is a rapid, automated method for forming an interwoven structure. The method is a product of textile technology and usually utilises equipment adapted from the textile industry. The braiding carriers follow a zigzag path in a large circle surrounding the mandrel. The surface of the mandrel is tightly woven with the fibres in a helical pattern.

Due to high level of conformability and the damage resistance capability of braided structures, the composite industry had found structural applications of braided composites ranging from rocket launchers to automotive parts to aircraft structures.

2-D braided structures are inter-twined fibrous structures capable of forming structures with 0° and ±θ fibre orientation. Although 2-D braids can be fabricated in tape form, the majority of braided structures are fabricated with tubular geometry. Thickness is built up by over braiding previously braided layers similar to a ply lay-up process. Braiding can take place vertically or horizontally. A schematic of a horizontal braider is shown in Fig 10.16. Although braiding is similar to filament winding, the major difference between braiding and filament winding is that braids are interlaced structures having as many as 144 or more interlacing per braiding cycle.

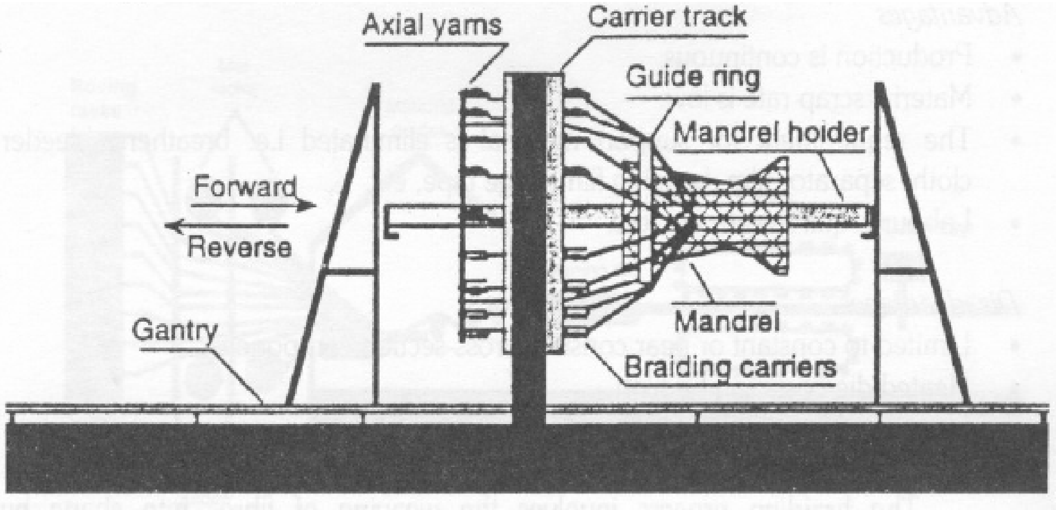


Fig 10.16

3-D braiding technology is an extension of 2-D braiding in which the fabric is constructed by the inter-twining or orthogonal interlacing of yarns to form an integral structure through position displacement. A unique feature of 3-D braids is their ability to provide through the thickness reinforcement of composites as well as their ready adaptability to the fabrication of a wide range of complex shapes ranging from solid rods to I-beams to thick walled rocket nozzles. A generalized schematic of a 3-D braiding process is shown in Fig10.17.

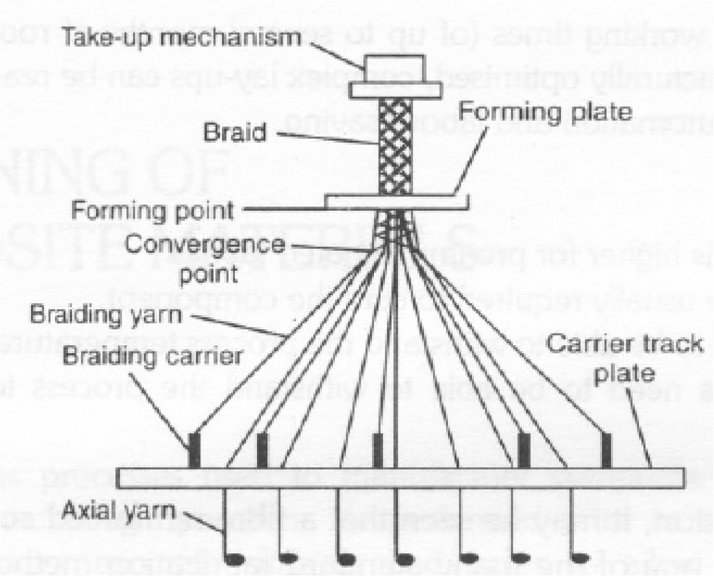


Fig 10.17

*Prepreg Molding

In prepreg molding, fabrics and fibres are pre-impregnated under heat and pressure or with solvent, or a pre-catalysed resin. The catalyst is largely latent at ambient temperatures giving the material useful life when defrosted. The resin is usually a near solid at ambient temperatures, and so the pre-impregnated materials (prepregs) have a light sticky feel, such as that of adhesive tape. The prepregs are laid up by hand or machine onto a mold surface, vacuum bagged and then heated to typically120-180°C (248-356°F). This allows the resin to flow followed by curing. Additional pressure for the molding is usually provided in an autoclave.

Advantages

- Resin/catalyst levels and the resin content in the fibre are accurately set by the materials manufacturer. High fibre contents can be safely achieved.
- The materials have excellent health and safety characteristics and are clean to work with.
- Fibre cost is minimised in unidirectional tapes since there is no secondary process to convert fibre into fabric prior to use.
- Resin chemistry can be optimised for mechanical and thermal performance, with the high viscosity resins being impregnable due to the manufacturing process.
- The extended working times (of up to several months at room temperatures) means that structurally optimised, complex lay-up scan be readily made.
- Potential for automation and labour saving. .

Disadvantages

- Materials cost is higher for pre-impregnated fabrics.
- Autoclaves are usually required to cure the component.
- Tooling needs to be able to withstand the process temperatures involved.
- Core materials need to be able to withstand the process temperatures and pressures.

In conclusion, it may be seen that a fibre reinforced composite may be manufactured by one of the many standard fabrication methods as explained above. The selection of the best method for a given application requires the consideration of numerous factors. The selection process must determine the appropriate constituent materials, the actual part design, the required tooling, the fabrication process and the necessary inspection and testing requirements to assure part quality.