Module-1: General Introduction

M1: General Introduction

M1.1 Introduction of Composites

Historical Development / Historical overview:

Past:

After making and controlling fire and inventing the wheel, spinning of continuous yarns is probably the most important development of mankind, enabling him to survive outside the tropical climate zones and spread across the surface of the Earth. Flexible fabrics made of locally grown and spun fibres as cotton; flax and jute were a big step forward compared to animal skins. More and more natural resources were used, soon resulting in the first composites; straw reinforced walls, and bows (Figure M1.1.1 (a)) and chariots made of glued layers of wood, bone and horn. More durable materials as wood and metal soon replaced these antique composites.

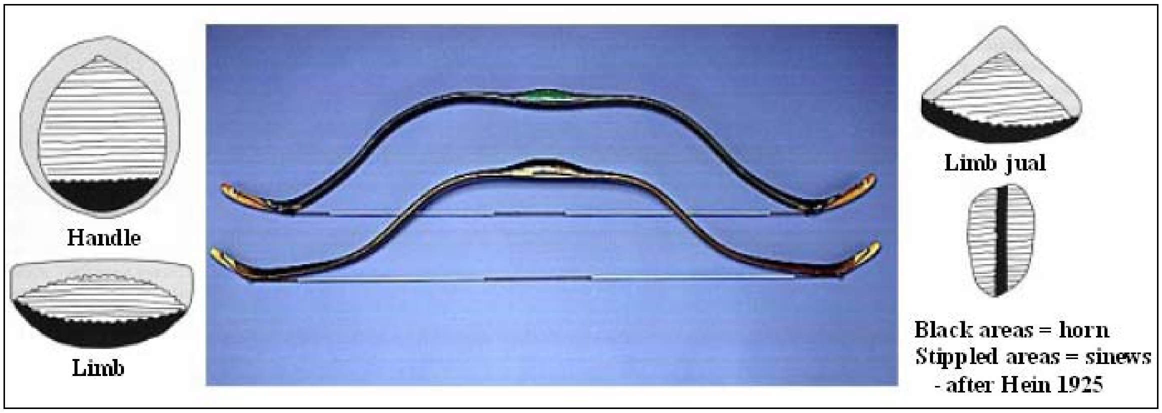

Figure M1.1.1 (a): Composite Korean bow

Present:

Originating from early agricultural societies and being almost forgotten after centuries, a true revival started of using lightweight composite structures for many technical solutions during the second half of the 20th century. After being solely used for their electromagnetic properties (insulators and radar-domes), using composites to improve the structural performance of spacecraft and military aircraft became popular in the last two decades of the previous century. First at any costs, with development of improved materials with increasing costs, nowadays cost reduction during manufacturing and operation are the main technology drivers. Latest development is the use of composites to protect man against fire and impact (Figure M1.1.1 (b)) and a tendency to a more environmental friendly design, leading to the reintroduction of natural fibres in the composite technology, see Figure M1.1.1 (c). Increasingly nowadays, the success of composites in applications, by volume and by numbers, can be ranked by accessibility and reproducibility of the applied manufacturing techniques. Some examples of use of natural fibers are shown in Figure M1.1.1 (d) and Figure M1.1.1 (e).

Figure M1.1.1 (b): Lightweight composite military helmet

Figure M1.1.1 (c): Interior part of the Mercedes A–200 (Generation of A - classes)

Figure M1.1 (d): Manufacturing of a basket using indigenous knowledge (Bangladesh)

Figure M1.1 (e): Traditional clay product/pottery in Zimbabwe

Future:

In future, composites will be manufactured even more according to an integrated design process resulting in the optimum construction according to parameters such as shape, mass, strength, stiffness, durability, costs, etc. Newly developed design tools must be able to instantaneously show customers the influence of a design change on each one of these parameters.

Concept of Composite:

Fibers or particles embedded in **matrix** of another material are 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 M1.1.1 (f) helps to classify matrices.

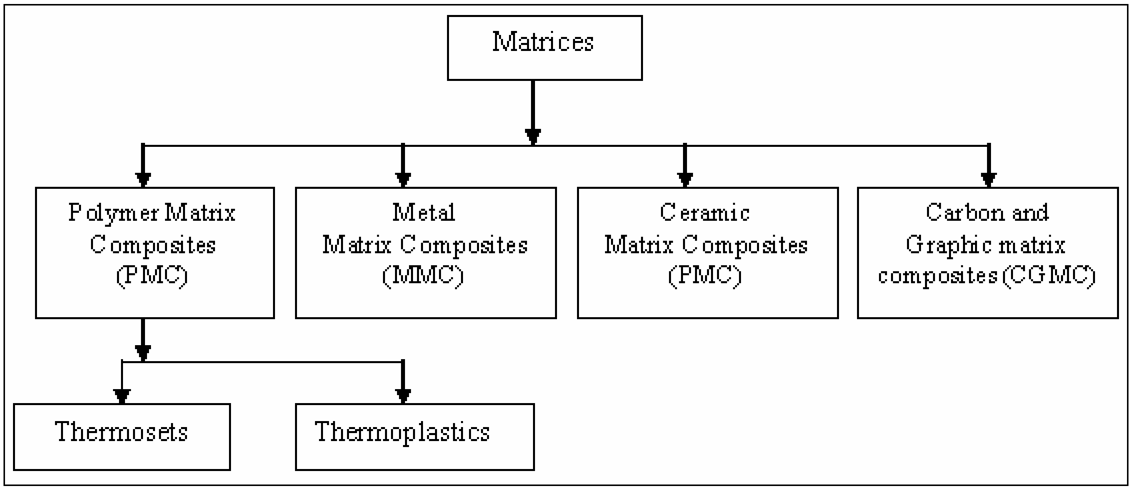

Figure M1.1 (f): Classification of Matrix Materials

M1.2 Basic Definitions and Classifications of Composites

M1.2.1 Classification of Composites

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 (FRP) 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.

M1.2.2 Organic Matrix Composites

M1.2.2.1 Polymer Matrix Composites (PMC)/Carbon Matrix Composites or Carbon-Carbon Composites

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 **creep** 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 M1.2.1 shows kinds of thermoplastics.

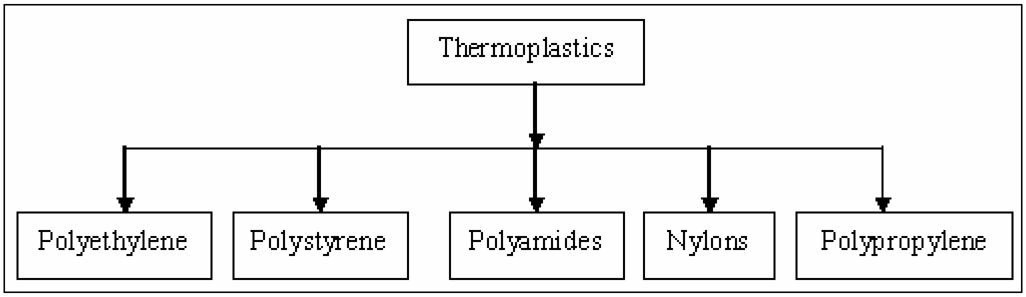

Figure M1.2.1: Thermoplastics

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 M1.2.2 shows some kinds of thermosets.

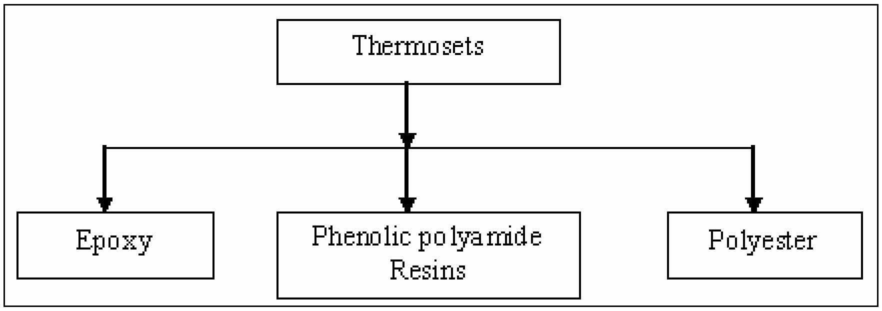

Figure M1.2.2: Thermoset Materials

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 accoutrey.

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 .

M1.2.2.2 Metal Matrix Composites (MMC)

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.

M1.2.2.3 Ceramic Matrix Materials (CMM)

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.

M1.2.3 Classification Based on Reinforcements

M1.2.3: Introduction to 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 M1.2.3 shows types of reinforcements in composites.

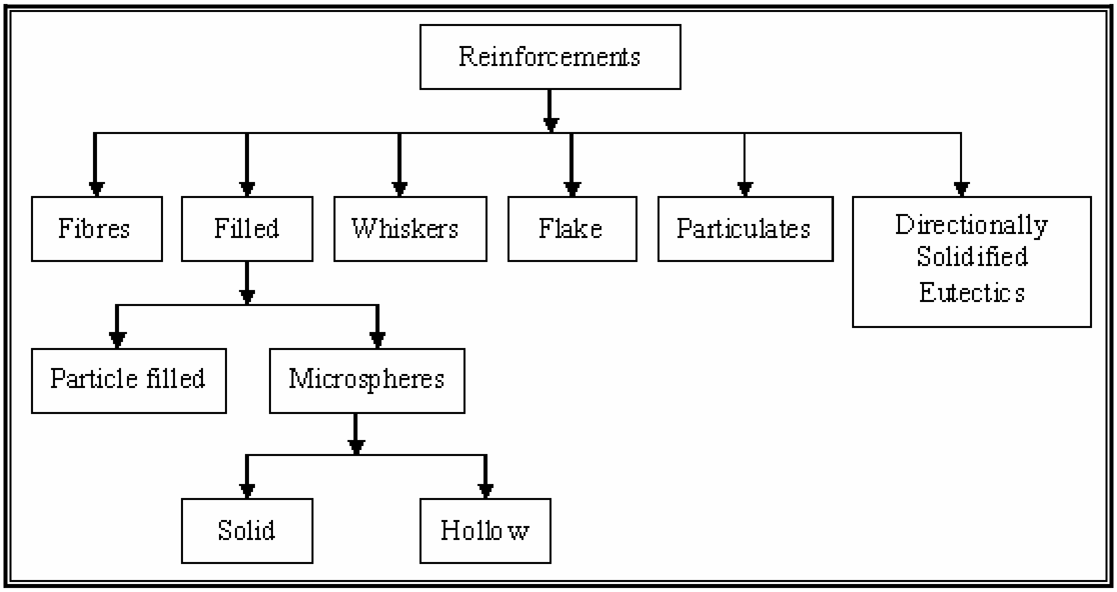

Figure M1.2.3: Reinforcements

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 minimal or even nil the composite must behave as brittle as possible.

M1.2.3.1 Fiber Reinforced Composites/Fibre Reinforced Polymer (FRP) Composites

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, and 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 achieve 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 a 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 fibers.

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.

M1.2.3.2 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**.

M1.2.3.3 Particulate Reinforced Composites (PRC)

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.

Note: In this module text in "Italic" indicates advanced concepts.

[Give hyperlink as advanced/reference material]

M1.2.4 Classification Based on Reinforcements and Matrices

There are two types of constituent materials: matrix and reinforcement. At least one portion (fraction) of each type is required. The matrix material surrounds and supports the reinforcement materials by maintaining their relative positions. The reinforcements impart special physical (mechanical and electrical) properties to enhance the matrix properties.

M1.2.4.1 Classification Based On Matrices

The matrix is the monolithic material into which the reinforcement is embedded, and is completely continuous. This means that there is a path through the matrix to any point in the material, unlike two materials sandwiched together. In structural applications, the matrix is usually a lighter metal such as aluminum, magnesium, or titanium, and provides a compliant support for the reinforcement. In high temperature applications, cobalt and cobalt-nickel alloy matrices are common.

The composite materials are commonly classified based on 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.

These three types of matrixes produce three common types of composites.

1. ***Polymer matrix composites** (PMCs), of which GRP is the best-known example, use ceramic fibers in a plastic matrix.*
2. ***Metal-matrix composites** (MMCs) typically use silicon carbide fibers embedded in a matrix made from an alloy of aluminum and magnesium, but other matrix materials such as titanium, copper, and iron are increasingly being used. Typical applications of MMCs include bicycles, golf clubs, and missile guidance systems; an MMC made from silicon-carbide fibers in a titanium matrix is currently being developed for use as the skin (fuselage material) of the US National Aerospace Plane.*
3. ***Ceramic-matrix composites** (CMCs) are the third major type and examples include silicon carbide fibers fixed in a matrix made from a borosilicate glass. The ceramic matrix makes them particularly suitable for use in lightweight, high-temperature components, such as parts for airplane jet engines.*

M1.2.4.1.1 Polymer Matrix Composites (PMC)/Carbon Matrix Composites/Carbon-Carbon Composites (CCC)

*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.*

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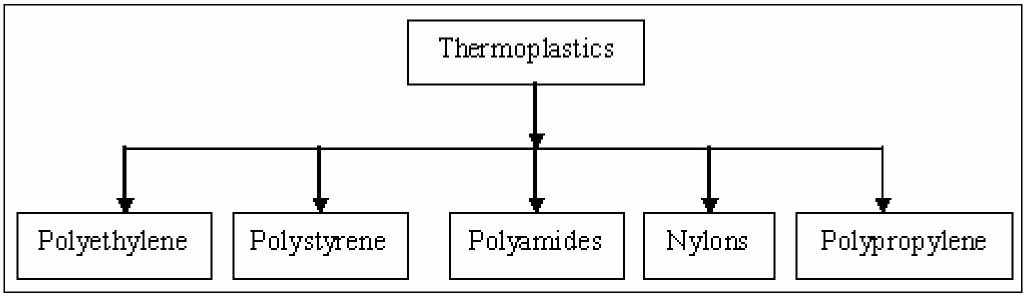

Figure M1.2.4.1: Thermoplastics

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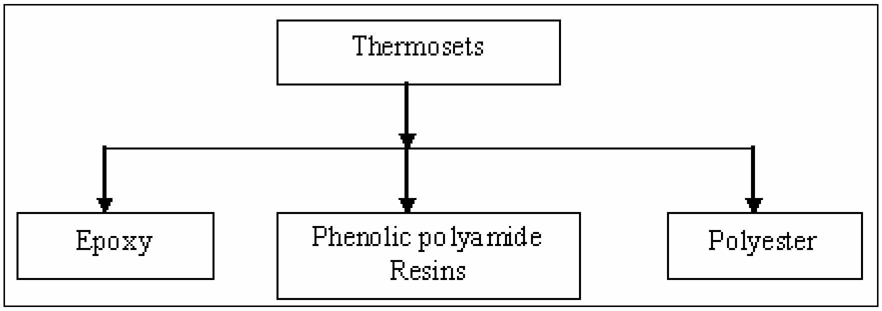

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Polyester resins *on the other hand are quite easily accessible, cheap and find use in a wide range of fields.* ***Liquid polyesters*** *are stored at room temperature for months, sometimes for years and the mere addition of a catalyst can cure the 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 accoutrey.*

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 .*

M1.2.4.1.2 Metal Matrix Composites (MMC)

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.

M1.2.4.1.3 Ceramic Matrix Materials (CMM)

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.*

M1.2.4.2 Classification Based On Reinforcements

Introduction to Reinforcement

Reinforcements: *A strong, inert woven and nonwoven fibrous material incorporated into the matrix to improve its metal glass and physical properties. Typical reinforcements are asbestos, boron, carbon, metal glass and ceramic fibers, flock, graphite, jute, sisal and whiskers, as well as chopped paper, macerated fabrics, and synthetic fibers. The primary difference between reinforcement and filler is the reinforcement markedly improves tensile and flexural strength, whereas filler usually does not. Also to be effective, reinforcement must form a strong adhesive bond with the resin.*

The role of the reinforcement in a composite material is fundamentally one of increasing the mechanical properties of the neat resin system. All of the different fibres used in composites have different properties and so affect the properties of the composite in different ways.

However, individual fibres or fibre bundles can only be used on their own in a few processes such as filament winding. For most other applications, the fibres need to be arranged into some form of sheet, known as a fabric, to make handling possible. Different ways for assembling fibres into sheets and the variety of fibre orientations possible lead to there being many different types of fabrics, each of which has its own characteristics.

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 M1.2.4.3 shows types of reinforcements in composites.*

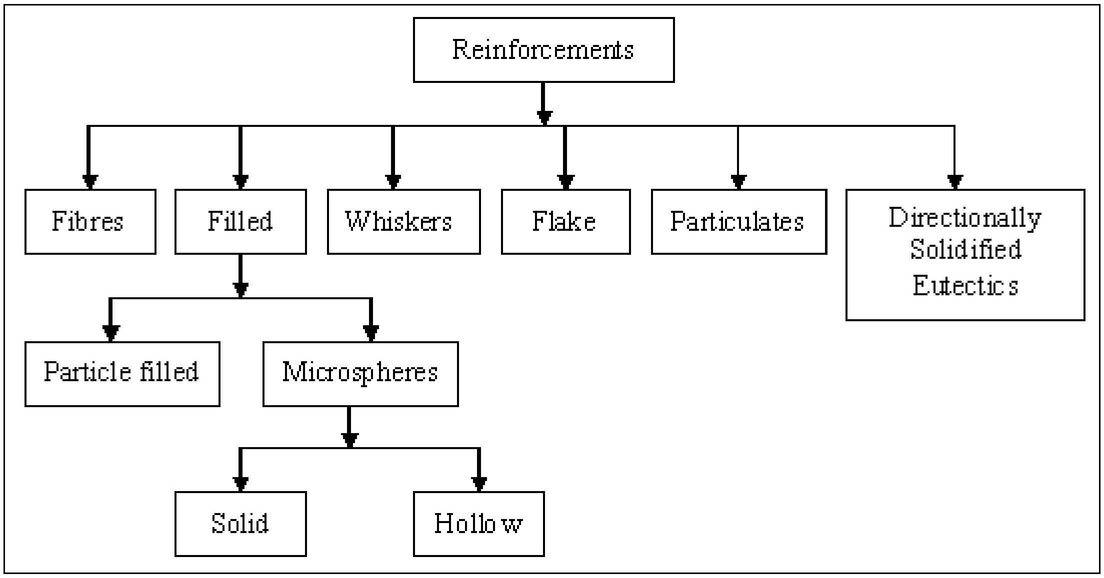

Figure M1.2.4.3 Reinforcements

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 minimal or even nil the composite must behave as brittle as possible.

M1.2.4.2.1 Fiber Reinforced Composites/Fibre Reinforced Polymer (FRP) Composites

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, and 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 achieve 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 fibers.

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.*

M1.2.4.2.2 Fibre Reinforcements

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.

M1.2.4.2.3 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.

M1.2.4.2.4 Laminar Composites/Laminate Reinforced 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****.*

M1.2.4.2.5 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.

M1.2.4.2.6 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.

M1.2.4.2.6.1 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 it's 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 minimal (smallest). In resin-rich surfaces of reinforced systems, the Microspheres which are free of orientation and sharp edges are capable of producing smooth surfaces.

M1.2.4.2.7 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.*

M1.2.4.2.8 Cermets/Ceramal

The Cermet is an abbreviation for the "'ceramic" and "metal." A CerMet is a composite material composed of ceramic (Cer) and metallic (Met) materials. A Cermet is ideally designed to have the optimal properties of both a ceramic, such as high temperature resistance and hardness, and those of a metal, such as the ability to undergo plastic deformation. The metal is used as a binder for an oxide, boride, carbide, or alumina. Generally, the metallic elements used are nickel, molybdenum, and cobalt. Depending on the physical structure of the material, cermets can also be metal matrix composites, but cermets are usually less than 20% metal by volume.

It is used in the manufacture of resistors (especially potentiometers), capacitors, and other electronic components which may experience high temperatures.

Some types of cermet are also being considered for use as spacecraft shielding as they resist the high velocity impacts of micrometeoroids and orbital debris much more effectively than more traditional spacecraft materials such as aluminum and other metals.

One application of these materials is their use in vacuum tube coatings, which are key to solar hot water systems.

Cermets are also used in dentistry as a material for fillings and prostheses. Also it used in machining on cutting tools.

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.*

M1.2.4.2.9 Solidification of Composites/Directionally Solidified Eutectics

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.*

M1.2.5 Common Categories of Composite Materials based on fibre length:

Based on the form of reinforcement, common composite materials can be classified as follows:

1. *Fibers as the reinforcement (Fibrous Composites):*
    a. *Random fiber (short fiber) reinforced composites*

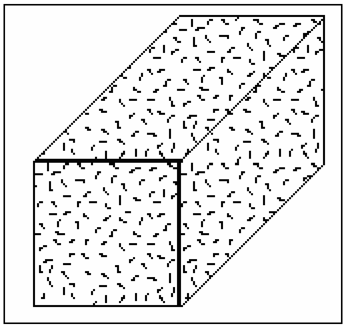

Figure M1.2.5.1: Short-fibre reinforced composites

    b. *Continuous fiber (long fiber) reinforced composites*

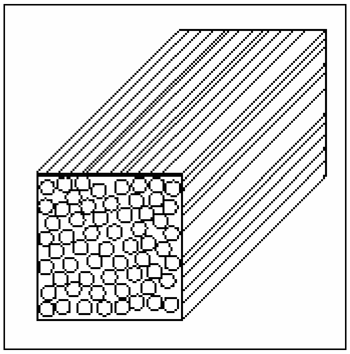

Figure M1.2.5.2: Long- fibre reinforced composites

2. *Particles as the reinforcement (Particulate composites):*

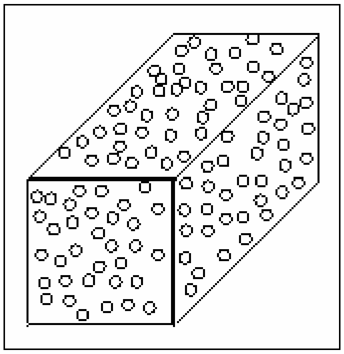

Figure M1.2.5.3: Particulate Composites

3. *Flat flakes as the reinforcement (Flake composites):*

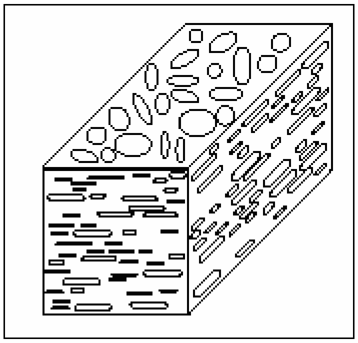

Figure M1.2.5.4: Flake Composites

4. *Fillers as the reinforcement (Filler composites):*

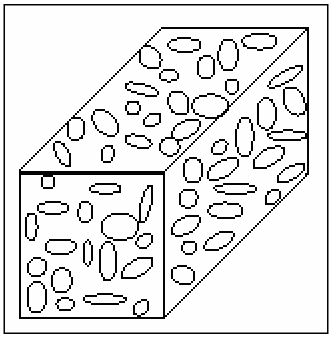

Figure M1.2.5.5: Filler Composites

M1.2.5 Examples for composite materials:

- Fibre reinforced plastics:
    - Classified by type of fiber:
        - Wood (**cellulose fibers** in a lignin and hemicellulose matrix)
        - **Carbon-fibre reinforced plastic (CRP)**
        - **Glass-fibre reinforced plastic (GRP)** (informally, "fiberglass")
    - Classified by matrix:
        - **Thermoplastic Composites**
            - short fiber thermoplastics
            - long fiber thermoplastics or long fiber reinforced thermoplastics
            - glass mat thermoplastics
            - continuous fiber reinforced thermoplastics
        - Thermoset Composites
- **Reinforced carbon-carbon** (carbon fibre in a graphite matrix)
- **Metal matrix composites (MMCs)**:
    - White cast iron
    - Hardmetal (carbide in metal matrix)
    - Metal-intermetallic laminate
- **Ceramic matrix composites**:
    - Bone (hydroxyapatite reinforced with collagen fibers)
    - Cermet (ceramic and metal)
    - Concrete
- **Organic matrix/ceramic aggregate composites**
    - Asphalt concrete
    - Dental composite
    - Syntactic foam
    - Mother of Pearl
- **Chobham armour** (see **composite armour**)
- **Engineered wood**
    - Plywood
    - Oriented strand board
    - Wood plastic composite (recycled wood fiber in polyethylene matrix)
    - Pykrete (sawdust in ice matrix)

- **Plastic-impregnated or laminated paper or textiles**
    - Arborite
    - Formica (plastic)

M1.2.6 Role and Selection of fibers

The points to be noted in selecting the reinforcements include **compatibility** with matrix material, **thermal stability**, density, melting temperature etc. The efficiency of discontinuously reinforced composites is dependent on tensile strength and density of reinforcing phases. The compatibility, density, chemical and thermal stability of the reinforcement with matrix material is important for material fabrication as well as end application. The thermal discord strain between the matrix and reinforcement is an important parameter for composites used in thermal cycling application. It is a function of difference between the **coefficients of thermal expansion** of the matrix and reinforcement. The manufacturing process selected and the reinforcement affects the crystal structure.

Also the role of the reinforcement depends upon its type in structural Composites. In particulate and whisker reinforced Composites, the matrix are the major load bearing constituent. The role of the reinforcement is to strengthen and stiffen the composite through prevention of matrix deformation by **mechanical restraint**. This restraint is generally a function of the ratio of inter-particle spacing to particle diameter. In continuous fiber reinforced Composites, the reinforcement is the principal load-bearing constituent. The metallic matrix serves to hold the reinforcing fibers together and transfer as well as distribute the load. Discontinuous fiber reinforced Composites display characteristics between those of continuous fiber and particulate reinforced composites. Typically, the addition of reinforcement increases the strength, stiffness and temperature capability while reducing the thermal expansion coefficient of the resulting MMC. When combined with a metallic matrix of higher density, the reinforcement also serves to reduce the density of the composite, thus enhancing properties such as specific strength.

M1.2.7 Matrix Materials

M1.2.7.1 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.

M1.2.7.1.1 Matrix Selection

Thermodynamically stable dispersoids are essential for the use of metal matrix composites for high temperature applications. This can be done by using an alloy dispersoid system in which **solid state diffusivity**, **interfacial energies** and **elemental solubility** are minimized, in turn reducing coarsening and interfacial reactions. Aluminium and magnesium alloys are regarded as widely used matrices due to low density and high thermal conductivity. Composites with low matrix alloying additions result in attractive combinations of ductility, toughness and strength. In discontinuous reinforced metal matrix composites minor alloying elements, used in wrought alloys as grain refiners, are not required. These additions should be avoided since coarse inter-metallic compounds get formed during consolidation, thus, reducing the tensile ductility of the composite.

M1.2.7.1.2 Role of matrix materials

The choice of a matrix alloy for an MMC is dictated by several considerations. Of particular importance is whether the composite is to be continuously or discontinuously reinforced. The use of continuous fibers as reinforcements may result in transfer of most of the load to the reinforcing filaments and hence composite strength will be governed primarily by the fiber strength. The primary roles of the matrix alloy then are to provide efficient transfer of load to the fibers and to blunt cracks in the event that fiber failure occurs and so the matrix alloy for continuously reinforced composites may be chosen more for toughness than for strength. On this basis, lower strength, more ductile, and tougher matrix alloys may be utilized in continuously reinforced composites. For discontinuously reinforced composites, the matrix may govern composite strength. Then, the choice of matrix will be influenced by consideration of the required composite strength and higher strength matrix alloys may be required.

Additional considerations in the choice of the matrix include potential reinforcement/matrix reactions, either during processing or in service, which might result in degraded composite performance; thermal stresses due to thermal expansion mismatch between the reinforcements and the matrix; and the influence of matrix fatigue behavior on the cyclic response of the composite. Indeed, the behavior of composites under cyclic loading conditions is an area requiring special consideration. In composites intended for use at elevated temperatures, an additional consideration is the difference in melting temperatures between the matrix and the reinforcements. A large melting temperature difference may result in matrix creep while the reinforcements remain elastic, even at temperatures approaching the matrix melting point. However, creep in both the matrix and reinforcement must be considered when there is a small melting point difference in the composite.

M1.2.7.2 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.

M1.2.7.3 Desired 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**.

M1.2.7.4 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 chemical 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.

M1.3 Advantages and Limitations of Composites Materials

M1.3.1 Advantages of Composites

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.

M1.3.2 Limitations of Composites

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

- High cost of raw materials and fabrication.
- Composites are more brittle than wrought metals and thus are more easily damaged.
- Transverse properties may be weak.
- Matrix is weak, therefore, low toughness.
- Reuse and disposal may be difficult.
- Difficult to attach.
- 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.

- Analysis is difficult.
- 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.

M1.3.3 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.