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COURSE MATERIAL

SCHOOL OF MECHANICAL

DEPARTMENT OF AERONAUTICAL ENGINEERING

SAE1401 - AIRCRAFT COMPOSITE MATERIALS AND STRUCTURES

UNIT 1 INTRODUCTION ANDCOMPOSITE FUNDAMENTALS

Introduction

Composite materials are engineered materials made from two or more constituent materials with significantly different physical or chemical properties which remain separate and distinct at the macroscopic or microscopic scale within the finished structure. Only condition is that one of the materials should retain its original physical identity after processing. In composites one of the materials, called the reinforcing phase, is in the form of fibers, sheets, or particles, and is embedded in the other materials called the matrix phase. The reinforcing material and the matrix material can be metal, ceramic, or polymer.

Historical or natural examples of composites are abundant: brick made of clay reinforced with straw, mud wall with bamboo shoots, concrete, concrete reinforced with steel rebar, granite consisting of quartz, mica and feldspar, wood (cellulose fibers in lignin matrix), etc.

Advanced Composites: Advanced composite materials are refereed to those composite materials developed and used in the aerospace industries. They usually consist of high performance fibers as reinforcing phases and polymers or metals as matrices.

Matrix Phase: Polymers, Metals, Ceramics Also, continuous phase, surrounds other phase (e.g.:metal, ceramic, or polymer)

Reinforcement Phase: Fibers, Particles, or Flakes Also, dispersed phase, discontinuous phase (e.g.:metal, ceramic, or polymer)

Design of Composites

First, we must identify then numerous materials related variables that contribute to the mechanical and physical properties of the composite material. Secondly, the appropriate physical and mathematical models that describe how the properties of the individual components of the composite are combined to produce the properties of the composite material itself must be derived. So, "Yes", it is possible to design a composite material such that it has the attributes desired for a specific application. Those attributes might be as simple has having a specified stiffness and strength, a desired thermal conductivity, or have a minimum specified stiffness at the cheapest possible cost per unit volume. Whatever the specifications it should be possible to design a suitable composite material. As in all design processes, it may not be possible to meet all the specifications exactly and compromise and tradeoffs will be required, but by understanding the physical origin of the required properties and developing an appropriate mathematical description, a suitable composite can be designed. We should also keep in mind that there may be an existing conventional material that is more suitable for the application than a composite. So the composite must offer a specific advantage in terms of cost or performance than conventional alternatives. It is one of the goals of this resource to show you the logical steps needed to implement the design process

Classification of Composites

1. **Classification based on Matrix:** 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.

2.**Classification based on reinforcement**:

Fiber reinforced composites, flake composites and particulate composites. Fiber reinforced composites can be further divided into those containing discontinuous or continuous fibers.

Fibers of FRP (Fiber Reinforced Composites):

The primary function of the fibers is to carry the loads along their longitudinal directions. Common fiber reinforcing agents include:

- Aluminum, Aluminum oxide, Aluminum silica

- Asbestos
- Beryllium, Beryllium carbide, Beryllium oxide
- Carbon (Graphite)
- Glass (E-glass, S-glass, D-glass)
- Molybdenum
- Polyamide (Aromatic polyamide, Aramid), e.g., Kevlar 29 and Kevlar 49
- Polyester
- Quartz (Fused silica)
- Steel
- Tantalum
- Titanium
- Tungsten, Tungsten monocarbide

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.

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.

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 us ed 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, Aluminum 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.

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 moduli of elasticity and low tensile strain, which most ceramics possess, 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. Micro cracking can result in a composite with tensile strength lower than that of the matrix.

Classification Based on Reinforcements

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

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.

Fiber Reinforced Composites/Fiber 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.

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 possess 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.

Prepreg

Prepregs are a ready-made material made of a reinforcement form and polymer matrix. Passing reinforcing fibers or forms such as fabrics through a resin bath is used to make a prepreg. The resin is saturated (impregnated) into the fiber and then heated to advance the curing reaction to different curing stages. Thermoset or thermoplastic prepregs are available and can be either stored in a refrigerator or at room temperature depending on the constituent materials. Prepregs can be manually or mechanically applied at various directions based on the design requirements

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- Beryllium, Beryllium carbide, Beryllium oxide
- Carbon (Graphite)
- Glass (E-glass, S-glass, D-glass

- Molybdenum
- Polyamide (Aromatic polyamide, Aramid), e.g., Kevlar 29 and Kevlar 49
- Polyester
- Quartz (Fused silica)
- Steel
- Tantalum
- Titanium
- Tungsten, Tungsten monocarbide

Matrix of Fiber Reinforced Composites:

The primary functions of the matrix are to transfer stresses between the reinforcing fibers (hold fibers together) and protect the fibers from mechanical and/or environmental damages. A basic requirement for a matrix material is that its strain at break must be larger than the fibers it is holding.Most matrices are made of resins for their wide variation in properties and relatively low cost. Common resin materials include:

Resin Matrix

- Epoxy
- Phenolic
- Polyester
- Polyurethane
- Vinyl Ester

Among these resin materials, polyesters are the most widely used. Epoxies, which have higher adhesion and less shrinkage than polyesters, come in second for their higher costs.Although less common, non-resin matrices (mostly metals) can still be found in applications requiring higher performance at elevated temperatures, especially in the defense industry.

Metal Matrix

- Aluminum
- Copper
- Lead
- Magnesium
- Nickel
- Silver
- Titanium

Non-Metal Matrix

- Ceramics

Composite Constituents:

1. Resins (POLYMERS)
2. Fibers
3. Fiber Reinforcement
4. Fillers
5. Additives
6. Sandwich Panels
7. Adhesives
8. Composite Designs

Resins

Primary Function: "To transfer stress between reinforcing fibers and to protect them from mechanical and environmental damage"

Types:

- Thermoset Resin
  - Polyester
  - Vinyl Resin c. Epoxy
  - Phenolic
  - Polyurethane
- Thermoplastic
  - Acetal
  - Acryronitrile Butadiene Styrene (ABS)
  - Nylon
  - Polyenthyene (PE)
  - Polypropylene (PP)
  - Polyethylene Terephthalate (PET)

I. a. Polyesters:

- Phthalic Anhydride (GP)
- Dicyclopentadiene (DCPD) Types
- Isophthalic Acid
- Terephthalic Acid
- Polyethlyene Terephthalate (PET)

Fibers:

Primary Function: “Carry load along the length of the fiber, provides strength and or stiffness in one direction”

Can be oriented to provide properties in directions of primary loads

Fiber Types:

I. Natural

II. Man-Made

III. Many Varieties Commercially Available

Natural Fibers:

- Cellulose
- Sisal

II. Man-Made Fibers:

- Aramid
- Boron
- Carbon/Graphite
- Glass
- Nylon
- Polyester
- Polyethylene
- Polypropylene

Fiber Reinforcement:

- Glass
- Aramid
- Carbon
- Basalt

• Glass Fiber Reinforcements

- E-glass o S-glass o C-glass
- ECR-glass
- AR-glass

• Aramid (KEVLAR) Fiber Reinforcement:

    - Superior resistance to damage (energy
    - Good in tension applications (cables,
    - Moderate stiffness
    - More Expensive Than Glass

- Carbon Fiber Reinforcement:
    - Good modulus at high
    - Excellent stiffness
    - More expensive than glass
    - Brittle
    - Low electric insulating properties

Reinforcement Types:

1. Rovings (Continuous)
2. Chopped strand
3. Mat:
    a. Chopped strand
    b. Continuous strand
4. Woven roving
5. Stitched
6. Braided
7. Unidirectional
8. Veil

Reinforcement Forms: Woven Roving:

- aka – Crimped
- Plain
- Satin
- Twill
- Basket

Fillers/Additives/Modifies

Filler Types:

Types of Additives:

- Catalysts & Promoter
- Inhibitors
- Release Agent

- Pigments
- UV Absorber
- Fire Retardancy

Fillers/Additives/Modifiers of Fiber Reinforced Composites:

The primary functions of the additives (modifiers, fillers) are to reduce cost, improve workability, and/or impart desired properties. Cost Reduction: Low cost to weight ratio, may fill up to 40% (65% in some cases) of the total weight, Workability Improvement:, Reduce shrinkage, Help air release., Decrease viscosity, Control emission, Reduce coefficient of friction on surfaces, Seal molds and/or guide resin flows Initiate and/or speed up or slow down curing process, Property Enhancement:, Improve electric conductivity,Improve fire resistance, Improve corrosion resistance, Improve ultraviolet resistance, Improve surface toughness, Stabilize heat transfer, Reduce tendency of static electric charge, Add desired colors

Common materials used as additives include:

- Filler Materials:
  - Feldspar
  - Glass microspheres
  - Glass flakes
  - Glass fibers, milled
  - Mica
  - Silica
  - Talc
  - Wollastonite
  - Other microsphere products
- Modifier Materials:
  - Organic peroxide, e.g., methylethylketone peroxide (MEKP)
  - Benzoyl peroxide
  - Tertiary butyl catechol (TBC)
  - Dimethylaniline (DMA)
  - Zinc stearate, waxes, silicones
  - Fumed silica, clays

Fibres/Reinforcement materials

Introduction to Fibres

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, alumina fibers, metal fibers and wires, graphite fibers, boron fibers, aramid fibers and multi-phase fibers are used. Among the glass fibers, it is again classified into E-glass, S-glass, A- glass, R-glass etc.

There is a greater market and higher degree of commercial movement of organic fibers.The potential of fibers of graphite, silicon carbide and boron are also exercising the scientific mind due to their applications in advanced composites.

Types of fibers

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.. 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 such loads for many months or years continuously.

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

Metal Fibers

As reinforcements, 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 with each other through alloying mechanisms are major disadvantages. Steel wire is the most extensively used reinforcement in most large-scale metal filament applications. Wire is used for its capacity to enhance the tensile strength of concrete and continuous metal fibers are the reinforcing constituents in metal and ceramic composite materials.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 temperatures and the resultant steep variation of thermal expansion coefficient with the resins are a discouragement that limits their application.

Alumina Fibers

Alumina or 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 is important property is it is high melting point of about 2000°C and the composite can be successfully used at temperatures up to about 1000°C. Magnesium and aluminium matrices frequently use alumina fiber reinforced composites as they do not damage the fiber even in the liquid state.

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 is continued until the desired 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 times that of glass. Boron coated carbons are much cheaper to make than boron tungsten fiber. But its low modulus of elasticity often works against it.

Silicon Carbide Fibers

Silicon carbide can be coated over a few metals and their room temperature tensile strengths and tensile moduli are like those of boron-tungsten. The advantages of silicon carbide-tungsten are several and they are more desirable than uncoated boron tungsten fibers. Elevated temperature performance and the fact that they reported only a 35% loss of strength at 1350°C are their best qualities. Silicon carbide-tungsten and silicon carbide-carbon have both been seen to have very high stress-rupture strength at 1100°C and 1300°C. Uncoated boron-tungsten fibers tend to lose all their strength at temperatures over 680°C. Silicon carbide fibers do not react with molten aluminium, 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 diameter. They are prone to surface damage and need careful, delicate handling, especially during fabrication of the composite. Further, above 930°C, weakening reactions occur between tungsten and silicon carbide, making it difficult 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.

Aramid Fibers

Aramid fibers are made from aromatic polyamides which are long polymeric .chains and aromatic rings. They are structures in which six carbon 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. Aramid have high tensile strength, high modulus and low weight. Impact- resistant structures can be produced from aramid. 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 also unaffected by organic solvents and 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 the failure of aramid fibers is unique. When they fail, the fibers break into small fibrils, which are like fibers within the fibers. This unique failure mechanism is responsible for high strength.

Quartz and Silica Fibers

The glass-types typically contain about 50 to 78% 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 ontains 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 diameters. Roving or yarns and other forms of fibers can be made from high silica as well as quartz. All matrix materials that accept fiberglass are amenable to high silica and 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 insulating properties and do not melt at temperatures up to 1600°C. In addition, they have low thermal expansion coefficients which make them withstand high temperatures.

Graphite Fibers

While use of the term carbon for graphite is permissible, there is one basic difference between the two. Elemental 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 1320°C, while graphite fibers and cloth are graphitized at 1950 to 3000°C. The properties of graphite remain unchanged even at very 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 stiffest 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 graphitization are time-consuming, apart from demanding excessive energy, materials and close controls throughout the process. Cheaper pitch base fibers are now being developed, with greater performance potential and there are possibilities of the increased use of graphite fibers.

Multiphase Fibers

Spoolable filaments made by chemical vapour deposition processes are usually the multi-phase 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. poly-phase fiber is a core-sheath fiber consisting of a poly-crystalline core.

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UNIT – II - MECHANICS OF COMPOSITE LAMINA

Mechanical Properties of fibers

Composite materials are not homogeneous. Their properties are dependent on many factors, the most important of which are the type of fibre, quantity of fibre (as volume fraction) and the configuration of the reinforcement. They are generally completely elastic up to failure and exhibit neither a yield point nor a region of plasticity. They tend to have low strain to failure(less than 3%). The resulting area under the stress/strain curve, which represents the work done to failure, is relatively small when compared to many metals.

The properties of composites are dependent on the properties of the fibre and the matrix, the proportion of each and the configuration of the fibres. If all the fibres are aligned in one direction then the composite relatively stiff and strong in that direction, but in the transverse direction it has low modulus and low strength. When a unidirectional composite is tested at a small angle from the fibre axis, there is a considerable reduction in strength. Theoretical variation in tensile modulus with the angle of load relative to the principal fibre direction (unidirectional carbon fibre reinforced plastic (UD CFRP), fibre volume fraction Vf = 0.5).

Fibers Strength and stiffness

Glass fibre reinforced polymer (GFRP)

E glass fibres, which have a modulus of about 70GPa, produce composites with modest moduli. In the case of unidirectional fibres and the highest typical fibre volume fraction of 0.65, a composite has a modulus of about45GPa and strength of around 1300MPa. At right angles to this, in the transverse direction, the modulus approaches that of the resin itself at about4GPa and the strength would be 50–100MPa. The unidirectional compo-sites used in the ROBUST Project, manufactured using the vacuum process with prepreg material in an epoxy matrix, had the following properties:

- Longitudinal tensile modulus: 36GPa
- Longitudinal tensile strength: 750MPa
- Elongation at break: 3.1%.

Bidirectional E glass laminates have a typical fibre volume fraction of about 0.4 and a tensile modulus at that volume fraction of about 14GPa.Random laminates (e.g. chopped strand mat) have a typical fibre volume fraction of about 0.2 and a tensile modulus at that volume fraction of about9GPa. The use of S2 or R glass improves the composite modulus to about60GPa for unidirectional and 20GPa for woven fabric (bidirectional) constructions. This is at some monetary disadvantage. They are both more expensive than E glass and they are only available in a fairly limited range of material types and resin compatibilities. Probably the most important virtue of S2 and R glass is their high strength, which is considerably higher than E glass.

Carbon and graphite fibers

Carbon fibre reinforced plastic (CFRP)The dominant carbon fibres in current use (typically Toray T700) have a tensile modulus of about 230GPa, a tensile strength of around 5000MPaand a strain-to-failure of 2%. Unidirectional composites produced from them in either an epoxy or vinyl-ester matrix have the following typical properties:

- Longitudinal tensile modulus: 155–165GPa
- Longitudinal tensile strength: 2500–3000MPa
- Elongation at break: 1.2–1.3%

Carbon fibres are available which will give a tensile modulus of about250GPa in a unidirectional composite, comparing very favourably with steel at about 210GPa. However, as this composite is unidirectional, it has extremely low modulus in the transverse direction. The principal attributes of carbon fibre composites are their very high specific stiffness (the ratio of modulus/density), excellent fatigue and environmental resistance.Currently there are various pultruded CFRP plates available commercially for plate bonding applications. The pultruded plates used in the ROBUST Project, as well as the plates manufactured with prepreg materials, possessed a modulus of about 130GPa and a strength of 1500MPa.Pultruded plates now available from other sources typically exploit fibers with superior properties such as Toray T700, resulting in composites with the properties shown above. A financial penalty has to be paid for materials exhibiting properties significantly in excess of these; the strain-to-failure of composites made with them will also be reduced significantly.

Carbon and graphite have substantial capability as reinforcing fibers, with great flexibility in the properties that can be provided. Primary characteristics for reinforcing fibers in polymer matrix composites are high stiffness and strength. The fibers must maintain these characteristics in hostile environments such as elevated temperatures, exposure to common solvents and fluids, and environmental moisture. To be used as part of a primary structure material it should also be available as continuous fiber. These characteristics and requirements have substantial implications for the physical, chemical and mechanical properties of the fiber, which in turn implies processing and acceptance parameters.

Interest in carbon fibers for structural materials was initiated in the late 1950s when synthesized rayons in textile form were carbonized to produce carbon fibers for high temperature missile applications. One of the first distinctions to be made is the difference between carbon and graphite fibers, although the terms are frequently used interchangeably. Background information for these differences is contained in the following sections. The primary purpose of making this distinction here is to alert the reader that users may mean different things when referring to graphite versus carbon fibers.

Carbon and graphite fibers are both based on graphene (hexagonal) layer networks present in carbon. If the graphene layers or planes stack with three dimensional orders the material is defined as graphite. Usually extended time and temperature processing is required to form this order, making graphite fibers more expensive. Because the bonding between planes is weak, disorder frequently occurs such that only the two dimensional ordering within the layers is present. This material is defined as carbon. With this distinction made, it should be understood that while some differences are implied, there is not a single condition which strictly separates carbon from graphite fibers, and even graphite fibers retain some disorder in their structure.

General material description Three different precursor materials are commonly used at present to produce carbon fibers: rayon, Polyacrylonitrile (PAN), and isotropic and liquid crystalline pitches. Carbon fibers are made predominately from carbonization of Polyacrylonitrile (PAN). The fibers consist of intermingled fibrils of turbostratic graphite with basal planes tending to align along the fiber axis. This forms an internal structure reminiscent of an onion skin. Pitch fibers may have a different internal structure, more like sheafs or spokes. The highly anisotropic morphology gives rise to moduli in the range of 200-750 GPa parallel to the fiber long axis, and around 20 GPa in the normal direction. For comparison, single crystal (whisker) of graphite is about 1060 and 3 GPa, respectively, but these properties are not attainable in fiber form. Ultra high modulus fibers can be prepared from liquid-crystalline mesophase pitch; the higher degree of orientation in the precursor translates through to the final carbonized fiber leading to larger and more oriented graphite crystallites.

Manufacture

The manufacturing process for carbon fiber described below is for the Polyacrylonitrile (PAN) variant, which is one of the most common. Some differences between Polyacrylonitrile (PAN) processing and the pitch and rayon precursors are then described afterwards. The manufacture of Polyacrylonitrile (PAN) based carbon fiber can be broken down into the white fiber and black fiber stages. Most manufacturers consider the details of these processes proprietary.

White fiber

Production of Polyacrylonitrile (PAN) precursor, or white fiber, is a technology in itself. Fairly conventional fiber processes are performed: polymerization, spinning, drawing, and washing. Additional drawing stages may be added in the process. Characteristics of the white fiber influence the processing and results for the black fiber processing.

Black fiber

The black fiber process consists of several steps: oxidation (or thermosetting), pyrolysis (or carbonizing), surface treatment, and sizing. In the oxidation process the Polyacrylonitrile (PAN) fiber is converted to a thermoset from a thermoplastic. For this oxidation process the fiber diameter is limited by waste gas diffusion. In the pyrolysis process, which is performed under an inert atmosphere, most of the non-carbon material is expelled, forming ribbons of carbon aligned with the fiber axis. In the surface treatment step the fiber may be etched in either gas or liquid phase by oxidizing agents such as chlorine, bromine, nitric acid or chlorates. This improves the wettability for the resin and encourages formation of a strong, durable bond. Some additional improvement through removal of surface flaws may also be realized. This process can be electrolytic. The carbon fibers are often treated with solution of unmodified epoxy resin and/or other products as a size. The sizing prevents fiber abrasion, improves handling, and can provide an epoxy matrix compatible surface.Carbon fiber differences due to pitch/ Polyacrylonitrile (PAN)/rayon precursors

As a rule PAN precursor can provide higher strength carbon fibers, while pitch can provide higher moduli. Rayon based fibers tend to be less expensive but lower performance. Pitch fiber composites have been prepared with elastic moduli superior to steel and electrical conductivity higher than copper conductor. The shear strengths and impact resistance are degraded, however. Yield for PAN is approximately 50%, but for pitch can be as high as 90%.

Typical properties of Carbon and Graphite fibers

Typically limitations on the end use for carbon fibers in composite structure depend more on the resin matrix than the fiber. Some exceptions to this are present, however, in which case the oxidative stability, thermal conductivity, coefficient of thermal expansion, or other properties of the fiber must be taken into account. Some. While some carbon fiber properties are fairly universal, different products from different manufacturers can have substantially different properties. Three of the major manufacturers for the US are Amoco, Hercules and Toray. It should be noted that translation of fiber properties to composite properties is dependent on many factors in addition to rule of mixtures.

Aramid fibers

Aramid fibre reinforced plastic (AFRP)

Unidirectional aramid composites have high tensile strength (1200–1400MPa) and a very low density. This high specific tensile strength is an important attribute which makes them particularly suited to use as tension members. Some aramids exhibit relatively low compressive yield strength of about 230MPa. Thus composites using these fibres must be carefully designed, particularly for compression or bending. This makes them particularly suited to use in tension member applications, but often not suited to bending applications. It is usually the high modulus variants of aramids (e.g. Kevlar 49) which are most commonly used as composite reinforcement, conferring a tensile modulus for unidirectional composites of about 75GPa. This is very similar to aluminium; however, as this is a unidirectional composite the associated transverse modulus is only about 5GPa.The tensile modulus of unidirectional and bidirectional aramid compo-sites represents a reasonable compromise between the low modulus glass-fibre composites and the much higher carbon fibre composites. Similarly the tensile strength of aramid composites is a compromise between E glass and carbon fibre composites. In the early 1970's, Du Pont Company introduced Kevlar™ aramid, an organic fiber with high specific tensile modulus and strength. This was the first organic fiber to be used as reinforcement in advanced composites. Today this fiber is used in various structural parts including reinforced plastics, ballistics, tires, ropes, cables, asbestos replacement, coated fabrics, and protective apparel. Aramid fiber is manufactured by extruding a polymer solution through a spinneret. Major forms available from Du Pont are continuous filament yarns, rovings, chopped fiber, pulp, spun-laced sheet, wet-laid papers, thermoplastic impregnated tows, and thermoformable composite sheets. Important generic properties of aramid fibers are: low density, high tensile strength, high tensile stiffness, low compressive properties (nonlinear), and exceptional toughness characteristics. The density of aramid is 0.052 lb/in3 (1.44 gm/cm3). This is about 40% lower than glass and about 20% lower than commonly used carbon. Aramids do not melt and they decompose at about 900°F (500°C). Tensile strength of yarn, measured in twisted configuration, can be varied from 500 - 600 ksi (3.4 - 4.1 GPa) by choosing different types of aramids. The nominal coefficient of thermal expansion is 3x10-6 in/in/F° (-5x10-6 m/m/C°) in the axial direction. Aramid fibers, being aromatic polyamide polymers, have high thermal stability and dielectric and chemical properties. Excellent ballistic performance and general damage tolerance is derived from fiber toughness. Aramid is used, in fabric or composite form, to achieve ballistic protection for humans, armored tanks, military aircraft, and so on.

Composite systems, reinforced with aramid, have excellent vibration-damping characteristics. They resist shattering upon impact. Temperature of use, in composite form with polymer matrix, range from -33 to 390°F (-36 - 200°C), the nominal tensile properties of composites reinforced with aramid are listed in Table M2.2.2 (a) - in thermoset and thermoplastic resin matrix. At 60% fiber volume fraction, composites of epoxy reinforced with aramid fibers have nominal tensile strength (room temperature) of 200 ksi (1.4 GPa) and nominal tensile modulus of 11 Msi (76 GPa). These composites are ductile under compression and flexure. Ultimate strength, under compression or flexure, is lower than glass or carbon composites. Composite systems, reinforced with aramid, are resistant to fatigue and stress rupture. In the system of epoxy reinforced with aramid, under tension/tension fatigue, unidirectional specimens (Vf ~ 60%) survive 3,000,000 cycles at 50% of their ultimate stress. Recently, thermoplastic resin composites reinforced with aramid have been developed. These thermoplastic composite systems have exhibited equivalent mechanical properties compared to similar thermoset systems. In addition, thermoplastic systems provide potential advantages in economical processing, bonding, and repair. A unique thermoformable sheet product, in thermoplastic matrix reinforced with aramid fibers, is available.

These composite systems are also used to achieve low coefficient of thermal expansion or high wear resistance. They are non-conductive and exhibit no galvanic reaction with metals. Aramid fibers are available in several forms with different fiber modulus (Table M2.2.2 (b)). Kevlar™29 has the lowest modulus and highest toughness (strain to failure ~ 4%). These fibers are used mostly in ballistics and other soft composite systems such as cut- and slash- resistance protective apparel, ropes, coated fabric, asbestos replacement, pneumatic tires, etc. These are also used for composites where maximum impact and damage tolerance is critical and stiffness is less important. Kevlar™49 is predominantly used in reinforced plastics - both in thermoplastic and thermoset resin systems. It is also used in soft composites like core of fiber optic cable and mechanical rubber good systems (e.g., high pressure flexible hose, radiator hose, power transmission belts, conveyor belts, etc.). An ultra-high modulus Type 149 has been made available recently. It has 40% higher modulus than Kevlar™49. Kevlar™29 is available in fiber yarn sizes and two rovings sizes. Kevlar™49 is available in six yarn and two rovings sizes.

Kevlar™149 is available in three yarn sizes. Yarn sizes range from the very fine 55 denier (30 filaments) to 3000 denier (1300 filaments). Rovings are 4560 denier (3072 filaments) and 7100 denier (5000 filaments). Composite thermoplastic tows, several types of melt-impregnated thermoplastic reinforced with different Kevlar ™ yarns and deniers, are also available.Aramid composites were first adopted in applications where weight savings were critical - for example, aircraft components, helicopters, space vehicles, and missiles. Armor applications resulted from the superior ballistic and structural performance. In marine recreational industries, light weight, stiffness, vibration damping, and damage tolerance are valued. Composites reinforced with aramids are used in the hulls of canoes, kayaks, and sail and power boats. These same composite attributes have led to use in sports equipment. Composite applications of aramid continue to grow as systems are developed t o capitalize on other properties. The stability and frictional properties of aramids at high temperatures have led to brake, clutch, and gasket uses; low coefficient of thermal expansion is being used in printed wiring boards; and exceptional wear resistance is being engineered into injection-molded thermoplastic industrial parts. Melt- impregnated thermoplastic composites, reinforced with aramids, offer unique processing advantages - e.g., in-situ consolidation of filament-wound parts. These can be used for manufacturing thick parts where processing is otherwise very difficult.

Aramid fiber is relatively flexible and tough. Thus it can be combined with resins and processed into composites by most of the methods established for glass. Yarns and rovings are used in filament winding, prepreg tape, and in pultrusion. Woven fabric prepreg is the major form used in thermoset composites. Aramid fiber is available in various weights, weave patterns, and constructions; from very thin (0.0002 in., 0.005mm) lightweight (275 gm/m2) to thick (0.026 in., 0.66 mm) heavy (2.8 gm/m2) woven roving. Thermoplastic-impregnated tows can be woven into various types of fabrics to form prepregs. These composites demonstrate good property retention under hot and humid conditions. Chopped aramid fiber is available in lengths from 6 mm to 100 mm. The shorter lengths are used to reinforce thermoset, thermoplastic, and elastomeric resins in automotive brake and clutch linings, gaskets, and electrical parts. Needle-punched felts and spun yarns for asbestos replacement applications are made from longer fiber staple. A unique very short fiber (0.08 - 0.16 in., 2 - 4 mm) with many attached fibrils is available (aramid pulp). It can provide efficient reinforcement in asbestos replacement uses. Aramid short fibers can be processed into spun-laced and wet-laid papers. These are useful for surfacing veil, thin-printed wiring boards, and gasket material. Uniform dispersion of aramid short fiber in resin formulations is achieved through special mixing methods and equipment. Inherent fiber toughness necessitates special types of tools for cutting fabrics and machining aramid composites.

Glass fibres

Glass in the forms used in commerce has been produced by many cultures since the early Etruscan civilization. Glass as a structural material was introduced early in the seventeenth century and became widely used during the twentieth century as the technology for flat pane was perfected. Glass fibrous usage for reinforcement was pioneered in replacement of metals and used for both commercial and military uses with the advent of formulation control and molten material which is die or bushing pulled into continuous filaments. These events lead to a wide range of aerospace and commercial high performance structural applications still in use today.

Common manufacture methods

Most often raw products (and/additives) are mixed and are premelted into marbles. This form facilitates sampling for analysis but, more important, presents a raw product form for automated feeding to the individual melt furnaces. Another method is to feed, via hoppers, dried raw products directly to batch cans. Regardless of the raw form, the material is fed into furnaces to become molten at approximately 2800°F (1500°C). The molten mass flows onto plates which contain many bushings with small orifices from which the individual filaments are drawn. In some cases the individual bushings are heat controlled within <1F° (0.6C°). The diameter of the filaments is controlled by the viscosity of the glass melt and the rate of extrusion. Cooling or solidification occurs rapidly as the glass leaves the bushings in filament form under ambient conditions. Cooling is often added by water spray and/or application of the binders. The individual untwisted filaments are gathered and high speed wound on tubes or "cakes". Sometimes finishes are applied after the strands are wound on the tubes then conditioned (dried). For products common to this document the strands are "C" (continuous) filaments--not "S" (staple) filament. To produce rovings the strands are then creeled, unwound and gathered again to form ends or multiple untwisted strands. This process of gathering or combining is again repeated to form rovings of desired yields (yards per pound). For weaving of fabrics and braiding, the strands are twisted to form yarns. Single yarns are composed of single strands twisted by itself. Two (etc.) strand construction is two strands twisted to produce a single yarn. Plied yarns are made from twisting two or more yarns together. Twisting and plying is often referred to as "throwing". A variable in processing "C" filament products is the repeated tensioning required during the numerous product forms fabrication. Tensioning devices are used--such as: disc-type or "whirls", gate-type, tension bars or "S" bars, and compensating rolls in the delivery from the creels. Humidity is another controlled variable in thetwisting, plying, braiding, warping, slashing, gulling and weaving areas. These operations are facilitated to maintain a relative humidity of 60 to 70 percent range. During the glass processing operations surface abrasion is a factor which must be monitored. The many devices such as: guide eyes, spacer bars, rollers and such are subject to wear and must be maintained. Wear could also affect tensioning. These contact devices are manufactured from materials including: stainless steel, chromium plating, and ceramics.

Advantages and disadvantages

For many years glass composites have had a distinct strength to weight advantage. Although the rapid evolution of carbon and aramid fibers has gained advantages, glass composite products have still prevailed in certain applications. Cost per weight or volume, certain armament applications, chemical or galvanic corrosion resistance, electrical properties, and availability of many product forms remain as examples of advantage. Coefficient of thermal expansion and modulus properties compared to carbon composites may be considered as typical disadvantages. When compared to aramid composites, glass has a disadvantage as to tensile properties but an advantage as to ultimate compression, shear properties, and moisture pick-up. Commercial uses for glass products are many-fold. These include filtration devices, thermal and electrical insulation, pressure and fluid vessels, and structural products for automotive and recreation vehicles. Many uses are applicable to military and aerospace products as well. A partial listing would include: asbestos replacement, circuitry, optical devices, radomes, helicopter rotor blades, and ballistic applications. Because of the many product forms, structural applications are limitless to fabricate. If there are limitations, compared to other fibers, they may include low thermal and electrical conductivity or perhaps melting temperatures when compared to carbon fibers.

Boron

Elemental boron fiber is formed as a deposition reaction on a hot tungsten wire which is continuously drawn through a reactor containing BCl3 and H3. The tungsten wire substrate also reacts to form tungsten boride in the core. The crystalline structure of the deposited boron is considered amorphous due to its small size (20Å). Boron is available as a cylindrical fiber in two nominal diameters, 4- and 5.6-mil (0.10 and 0.14 mm), which have a density of 2.57 and 2.49 g/cm3 (0.0929 and 0.0900 lb/in3), respectively. Chemical etching of the fiber surface produces a higher strength, but the process is not used commercially.Boron fiber is unmatched for its combination of strength, stiffness, and density. The tensile modulus and strength of boron fiber are 60 x 106 psi and 0.52 x 106 psi (40 GPa and 3600 MPa). Thermal conductivity and thermal expansion are both low, with a coefficient of thermal expansion of 2.5-3.0 x 10-6/F° (4.5-5.4 x 10-6/C°).

Available almost exclusively in filament or epoxy matrix prepreg form, boron fiber has been used for aerospace applications requiring high strength and/or stiffness, and for selective reinforcement in sporting goods. The most notable use of this fiber is the stabilizer sections of the F-14 and F-15 military aircraft, dorsal longerons of the B-1B bomber, and the repair of metallic airframe structures. High modulus (HM) or high strength (HS) carbon/epoxy composites can match either the tensile modulus or strength of boron composites at a more economical price, but boron/epoxy composites offer twice the composite strength.

Alumina

Continuous polycrystalline alumina fiber is ideally suited for the reinforcement of a variety of materials including plastics, metals, and ceramics. Alumina is prepared in the form of continuous yarn containing a nominal 200 filaments. It is supplied in bobbins containing continuous filament yarn, and alumina/ aluminum and alumina/magnesium plates. Alumina staple is also available for short fiber reinforcement.Fibers that are more than 99% purity α alumina have excellent chemical resistance, and have higher modulus and temperature capabilities than ceramic fibers containing silica. The high modulus of 55 Msi (380 GPa) is comparable to that of boron and carbon. The average filament tensile strength is 200 ksi (1.4 GPa) minimum. Since alumina is a good insulator, it can be used in applications where conducting fibers cannot. Nominal properties of alumina are listed in Table M2.2.6 (a). Cost projections for alumina are competitive with carbon. Alumina, in continuous form, offers many advantages for composite fabrication including ease of handling, the ability to align fibers in desired directions, and filament winding capability. The fact that alumina is an electrical insulator combined with its high modulus and compressive strength makes it of interest for polymer matrix composite applications. For example, alumina/epoxy and aramid/epoxy hybrid composites reinforced with alumina and aramid fibers have been fabricated and are of potential interest for radar transparent structures, circuit boards, and antenna supports.

Quartz

Quartz fiber is very pure (99.95%) fused silica glass fiber. Typical fiber properties are shown in Table M2.2.8 (a). Quartz is produced as continuous strands consisting of 120 or 240 individual filaments of 9 micron nominal diameter. These single strands are twisted and plied into heavier yarns. Quartz fibers are generally coated with an organic binder containing a silane coupling agent which is compatible with many resin systems. Strands for rovings are combined into multiple ends without applied twist. These strands are coated with a "direct size" which is compatible with many resins. Woven fabrics may be used as woven or may be "scoured" (washed) to remove the nonfunctional components of the binder and some, but not all, of the silane coupling agent. Following scouring, the fabric may be finished with a variety of silane coupling agent finishes having specific resin compatibility.Quartz fiber nomenclature is the same as that for E or S glass fibers except that the glass composition is designated by the letter Q as shown in Table M2.2.8 (b). Commonly used quartz fabrics are listed in Table M2.2.8 (c). Quartz rovings are continuous reinforcements formed by combining a number of 300 2/0 zero twist strands. End counts of 8, 12, and 20 are available having yields from 750 to 1875 yards per pound (660 to 264 g/km). Quartz fibers are also available in the form of chopped fiber in cut lengths from 1/8 inch to 2 inches (3 to 50 mm). Quartz fibers with a filament tensile strength of 850 ksi (5,900 MPa) have the highest strength-to weight ratio, virtually exceeding all other high temperature materials. The quartz fibers can be used at temperatures much higher than "E" glass or "S" glass fiber with service temperatures up to 1920°F (1050°C) possible. Quartz fibers do not melt or vaporize until the temperature exceeds 3000°F (1650°C), providing potential in ablative applications. Additionally, these fibers retain virtually all of the characteristics and properties of solid quartz. The quartz fibers are chemically stable. They are not affected by halogens or common acids in the liquid or gaseous state with the exception of hydrofluoric and hot phosphoric acids. Quartz fibers should not be used in environments where strong concentrations of alkalies are present. Quartz fibers, when combined with certain matrix systems, offer potential advantages in stealth application due to their high electrical resistively properties. Quartz does not form paramagnetic centers, nor does it capture neutrons in high energy applications. These fibers offer a low dielectric constant and loss tangent providing excellent properties as electrical insulators. Typical properties for quartz fibers combined with three different polymer matrix systems are shown in Table M2.2.8 (d) to Table M2.2.8 (f). Quartz products are relatively expensive compared to "E" or "S-2" glass products.

Ultrahigh molecular weight polyethylene (UHMWPE) Material Description

Ultrahigh molecular weight polyethylene fiber (UHMWPE) is the generic name for a high performance fiber which is more widely known today by the trade name Spectra, assigned by the major marketer of UHMWPE fiber, Allied Signal Inc. Non-oriented UHMWPE was first synthesized in the mid 1950s. A number of academic and commercial institutions in the United States and Europe worked to develop oriented UHMWPE fiber.The generally accepted definition of what constitutes "ultrahigh molecular weight" is a molecular weight greater than 3,000,000. The properties of polyethylene depend strongly on the molecular weight and the degree of branching. UHMWPE fiber is a linear polymer and its molecular weight typically varies between 3,000,000 and 6,000,000. This fiber is highly oriented axially and the chains form a highly crystalline structure, between 95-99%, but the crystallinity is not in the form of folded chains as is typically found in thermoplastics. Instead, the chains are fully extended (Figure M2.2.2). The fiber is formed by a gel-spinning process where the polymer is dissolved in order to disentangle the polymer chains. From solution the fibers are then drawn and the molecules become axially aligned to an extremely high degree. The resulting fiber diameter is rather large at 27 microns (for Spectra 1000) compared to other high performance fibers (typical aramid fiber diameter is 12 microns; S-2 glass, 7; carbon fibers, 7). Resin is a generic term used to designate the polymer, polymer precursor material, and/or mixture or formulation thereof with various additives or chemically reactive components. The resin, its chemical composition and physical properties, fundamentally affect the processing, fabrication and ultimate properties of composite materials. Variations in the composition, physical state, or morphology of a resin and the presence of impurities or contaminants in a resin may affect handleability and processability, lamina/ laminate properties, and composite material performance and long-term durability. This section describes resin materials used in polymer matrix composites and adhesives, and considers possible sources and consequences of variations in resin chemistry and composition, as well as the effects of impurities and contaminants, on resin processing characteristics and on resin and composite properties.

RESINS

Epoxy The term epoxy is a general description of a family of polymers which are based on molecules that contain epoxide groups. An epoxide group is an oxirane structure, a three-member ring with one oxygen and two carbon atoms. Epoxies are polymerizable thermosetting resins containing one or more epoxide groups curable by reaction with amines, acids, amides, alcohols, phenols, acid anhydrides, or mercaptans. The polymers are available in a variety of viscosities from liquid to solid. Epoxies are used widely in resins for prepregs and structural adhesives. The advantages of epoxies are high strength and modulus, low levels of volatiles, excellent adhesion, low shrinkage, good chemical resistance, and ease of processing. Their major disadvantages are brittleness and the reduction of properties in the presence of moisture. The processing or curing of epoxies is slower than polyester resins. The cost of the resin is also higher than the polyesters. Processing techniques include autoclave molding, filament winding, press molding, vacuum bag molding, resin transfer molding, and pultrusion. Curing temperatures vary from room temperature to approximately 350°F (180°C). The most common cure temperatures range between 250° and 350°F (120° and 180°C). The use temperatures of the cured structure will also vary with the cure temperature. Higher temperature cures generally yield greater temperature resistance. Cure pressures are generally considered as low pressure molding from vacuum to approximately 100 psi (700 kPa).

Polyester (thermosetting)

The term thermosetting polyester resin is a general term used for orthophthalic polyester resin or isophthalic polyester resin. Polyester resins are relatively inexpensive and fast processing resins used generally for low-cost applications. In combination with certain fillers, they can exhibit resistance to breakdown under electrical arc and tracking conditions. Isophthalic polyester resins exhibit higher thermal stability, dimensional stability, and creep resistance. In general, for a fiber-reinforced resin system, the advantage of polyester is its low cost and its ability to be processed quickly.

Fiber-reinforced polyesters (FRP) can be processed by many methods. Common processing methods include matched metal molding, wet lay-up, press (vacuum bag) molding, injection molding, filament winding, pultrusion, and autoclaving. Polyesters can be formulated to cure more rapidly than do phenolics during the thermoset molding process. While phenolic processing, for example, is dependent on a time/temperature relationship, polyester processing is primarily dependent on temperature. Depending on the formulation, polyesters can be processed from room temperature to 350°F (180°C). If the proper temperature is applied, a quick cure will occur. Without sufficient heat, the resin/catalyst system will remain plasticized. Compared to epoxies, polyesters process more easily and are much tougher, **whereas phenolics are more difficult to process and brittle, but have higher service temperatures.**

Phenolic

Phenol-formaldehyde resins and their direct precursors were first produced commercially in the early 1900's for use in the commercial market. Urea formaldehyde and melamine-formaldehyde appeared in the 1920 - 1930's as a less expensive alternative for lower temperature use. Phenolics, in general, cure by a condensation route with the off-gassing of water. The resulting matrix is characterized by both chemical and thermal resistance as well as hardness, and low smoke and toxic degradation products. The phenolic polymers, often called either phenolic resole or novolacs resins are condensation polymers based upon either a reaction of excess formaldehyde with a base catalyst and phenol (resole), or a reaction of excess phenol with an acidic catalyst and formaldehyde (novolac). The basic difference between resoles and novolacs consist of no methylol groups in the novolacs and the resulting need for an extension agent of paraformaldehyde, hexamethylenetetraamine, or additional formaldehyde as a curative. These resins have higher molecular weights and viscosities than either parent material. Consequently, they are optimal for processing parts of unusual conformations and complex curvature. The resins allow either press or autoclave cure and allow relatively high temperature free-standing postcures.

Polyimides

The polyimide resin family comprises a diverse number of polymers all of which contain an aromatic heterocyclic ring structure.Other polyimides are synthesized from a variety of cyclic anhydrides or their diacid derivatives through reaction with a diamine. This reaction forms a polyamic acid which then undergoes condensation by the removal of water and/or alcohol. Polyimide matrix composites excel in high temperature environments where their thermal resistance, oxidative stability, low coefficient of thermal expansion and solvent resistance benefit the design. Their primary uses are circuit boards and hot engine and aerospace structures. A polyimide may be either a thermoset resin or a thermoplastic. Thermosetting polyimides characteristically have crosslinkable end-caps and/or a rigid polymer backbone. A few thermoplastic polyimides can become thermoset polymers if a sufficiently high Postcure temperature is employed during part processing. Alternately, partially cured thermoset polyimides containing residual plasticizing solvents can exhibit thermoplastic behavior. Thus, it is difficult to state with certainty that a particular polyimide is indeed a thermoset or thermoplastic. Polyimides, therefore, represent a transition between these two polymer classifications. Polyimide properties, such as toughness and thermal resistance, are influenced by the degree of crosslinking and chain extension. Molecular weight and crosslink density are determined by the specific end cap group and by the stoichiometry of the anhydride: amine mixture which produces the polyamic acid by stepwise chain growth, after which the polyamic acid is recyclized by continued thermal cure to form the final polymer structure. The choice of solvent employed in the resin formulation has a significant impact on crosslinking and chain extension. Solvents such as N-methyl 2-pyrrolidone (NMP), promote chain extension by increasing resin flow, chain mobility and molecular weight prior to formation of a substantial crosslink network. From a practical standpoint, these solvents are beneficial to polymerization, but they are detrimental to part manufacture because of their tendency to cause ply delaminations. Most polyimide resin monomers are powders. Some bismaleimides are an exception. As a result, solvents are also added to the resin to enable impregnation of unidirectional fiber and woven fabrics. Commonly, a 50:50 by weight mixture is used for fabrics and a 90:10 by weight high solids mixture is used to produce a film for unidirectional fiber and low areal weight fabric prepregs. Solvents are further used to control prepreg handling qualities, such as tack and drape. Most of the solvents are removed in a drying process during impregnation, but total prepreg volatiles contents typically range between 2 and 8% by weight. This includes all volatiles, including those produced by the condensation cure reactions. Polyimides require high cure temperatures, usually in excess of 550°F (~90°C). Consequently, normal epoxy composite consumable materials are not usable, and steel tooling becomes a necessity. Polyimide bagging and release films, such as Kapton and Upilex, replace the lower cost nylon bagging and polytetrafluoroethylene (PTFE) release films common to epoxy composite processing. Fiberglass fabrics must be used for bleeder and breather materials instead of polyester mat materials.

Difference between Thermosets and Thermoplastic Resins

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)

Typical Properties of Thermosetting Materials

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

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.

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.

Vinyl Ester

- Vinyl ester combines inherent toughness with outstanding heat and chemical resistance,
- Corrosion-resistance, and
- Possesses low ester content and low instauration 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.

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.

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.

UNIT – III - MECHANICS OF COMPOSITE LAMINA AND SANDWICH PANELS

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SCHOOL OF MECHANICAL

DEPARTMENT OF AERONAUTICAL ENGINEERING

SAE1401 - AIRCRAFT COMPOSITE MATERIALS AND STRUCTURES

UNIT – IV - MECHANICAL BEHAVIOUR OF COMPOSITE LAMINATES

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.

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 to400°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 M3.2.3 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 stabilizer

Poly- phenylene –sulphide

- Airbus A320-200 rudder nose ribs
- Airbus A340 aileron 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

Properties of PEEK 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 reactor.

M2.3.3.3 Carbon matrices

Carbon fibre reinforced carbon is a high strength composite material, which is also resistant to high temperature in a non-oxidizing 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 oxidizing 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 carbonization 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 summarized 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.

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. 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).

Role of Matrices in Composites

1. Transfer stresses between the fibers.
2. Provide a barrier against an adverse environment.
3. Protect the surface of the fibers from mechanical abrasion.
4. Determine inter-laminar shear strength.
5. Determine damage tolerance of composites.
6. Determine in-plane shear strength.
7. Determine the processibility of composites.
8. Determine heat resistance of composites

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SAE1401 - AIRCRAFT COMPOSITE MATERIALS AND STRUCTURES

UNIT – V - BENDING, BUCKLING AND VIBRATIONS OF LAMINATED BEAMS AND PLATES

Functions of Matrix

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

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

Advantages of Composites

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

1. High resistance to fatigue and corrosion degradation.
2. High 'strength or stiffness to weight' ratio. As enumerated above, weight savings are ignificant ranging from 25-45% of the weight of conventional metallic designs.
3. Due to greater reliability, there are fewer inspections and structural repairs.
4. Directional tailoring capabilities to meet the design requirements. The 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.

5. Improved dent resistance is normally achieved. Composite panels do not sustain damage as easily as thin gage sheet metals.
6. 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.
7. 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.
8. High resistance to impact damage.
9. Like metals, thermoplastics have indefinite shelf life. 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.
10. 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 broadrange of thermal expansion design requirements and to minimize thermal stresses.
11. Manufacture and assembly are simplified because of part integration (joint/fastener reduction)thereby reducing cost.
12. The improved weather ability of composites in a marine environment as well as their corrosion resistance and durability reduce the down time for maintenance.

Composites as Unique Materials

Advantages:

1. Specific tensile strength is 4 to 6 times greater than steel or aluminum
2. Specific modulus is 3 to 5 times that of steel or aluminum

3. Specific thermal conductivity 40 times that of copper
4. Greater fatigue resistance than steel or aluminum
5. Greater design flexibility than homogeneous materials
6. Potential for corrosion is significantly reduced
7. Minimize part count and simplified fastening methods

Disadvantages:

1. Raw material cost
2. Lack of clear-cut design rules
3. Lack of high productivity manufacturing methods
4. High cost of raw materials and fabrication.
5. Composites are more brittle than wrought metals and thusare more easily damaged.
6. Transverse properties may be weak.
7. Matrix is weak, therefore, low toughness.
8. Reuse and disposal may be difficult.
9. ifficult to attach.

APPLICATIONS OF COMPOSITES

Application of Composites in Aircraft Industry

The use of fibre reinforced composites has become increasingly attractive alternative to the conventional metals for many aircraft components mainly due to their increased strength, durability, corrosion resistance, resistance to fatigue and damage tolerance characteristics. Composites also provide greater flexibility because the material can be tailored to meet the design requirements and they also offer significant weight advantages. Carefully designed individual composite parts, at present, are about 20-30% lighter than their conventional metal counterparts. Although all-composite airplanes are now available in the world market, yet advances in the practical use of composite materials should enable further reduction in the structural weight of airplane. The composite materials used in aircraft industry are generally reinforced fibres or filaments embedded in a resin matrix. The most common fibres are carbon, aramid, glass and their hybrid. The resin matrix is generally an epoxy based system requiring curing temperatures between 120° and 180°C (250° and 350°F).

The first structural composite aircraft components, which were introduced during 1950-60, were made from glass fibre reinforced plastics. These components included the fin and the rudder of Grumman E-2A, helicopter canopies, frames, radomes, fairings, rotor blades, etc. Due to high strength and stiffness combined with low density, composites like Boron Fibre Reinforced Plastics (BFRP) and Carbon Fibre Reinforced Plastics (CFRP) .were preferred instead of aluminium for high performance aircraft structures. For lightly loaded structures, Aramid Fibre Reinforced Plastics (AFRP) which possess low density, have been used. The use of AFRPcontinues to be restricted to the lightly loaded structures due to the fact that although these fibres possess high tensile strength, they have very low compressive strength. For light aircraft and lightly loaded structural components, Glass Fibre Reinforced Plastics (GFRP) has become one of the standard materials. Over the years, use of composite materials has also increased from few small access panels and canopy frames to almost complete airframe surfaces thereby providing weight savings leading to improved performance, reduced drag and also improved durability and corrosion resistance. Consequently, now-a-days, composite materials like GFRP, CFRP and AFRP have become standard materials for flight control surfaces, engine cowlings, fairings, radomes, landing gear doors, floor panels, fan ducts, etc. in aircraft application .

In 1979, the in-service evaluation of Airbus A300 aircraft led to further use of composite components on Airbus A300 aircraft namely CFRP spoilers and rudders, air brakes, CFRP landing gear doors, etc. Use of composites was extended to Airbus A310 aircraft during 1980-85, and thereafter to Airbus A320 aircraft in 1987.

Various composite components used on Airbus series of aircraft are given in the Table

Aircraft Type	Components Made of Composite Materials
Airbus A300B2/B4	Radome, fin leading edge and tip, fin trailing edge panels, cabin and cargo
Airbus A310-300	Rudder, elevator, vertical stabilizer, spoilers, cowl (inlet & fan), thrust reverser, main & nose landing gear door of wing leading & trailing edge panels, nacelles.
Airbus A320/A319 & A321	Aileron, horizontal and vertical stabilizer, elevator, rudder, spoilers, flaps, engine cowl, radome, landing gear doors (main & nose), floor panels, wing panels (leading & trailing edge), other access panels, nacelles.Fairings -flap track, wing/fuselage (forward & rear), and main landing
Airbus A330	Ailerons, rudder, flaps, spoilers, elevator, horizontal and vertical stabilizer, wing panels (leading & trailing edge), landing gear doors (main & nose), nacelles.Fairings -flap track, wing/fuselage (forward & rear).
Airbus 340	Ailerons, rudder, flaps, spoilers, elevator, horizontal and vertical stabilizer,wing panels (leading & trailing edge), landing gear doors (main & nose), nacelles.Fairings -flap track, wing/fuselage (forward & rear).

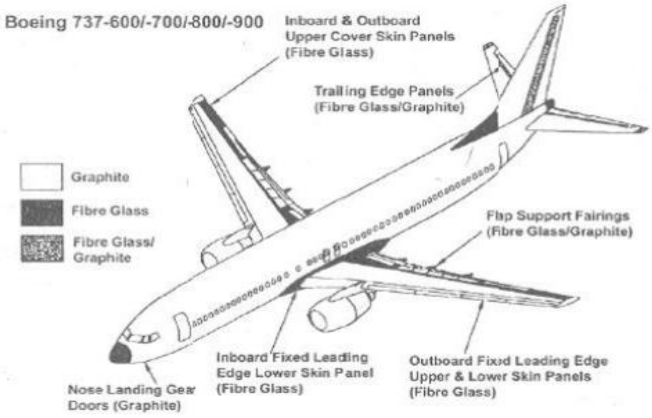
The components used on Airbus series of aircraft

Composites account for about 15% of the structure of Airbus A320 aircraft. Although the total weight of composite structures is much higher in Airbus A330/A340 aircraft, the percentage of weight in relation to total weight of aircraft is nearly 12%.

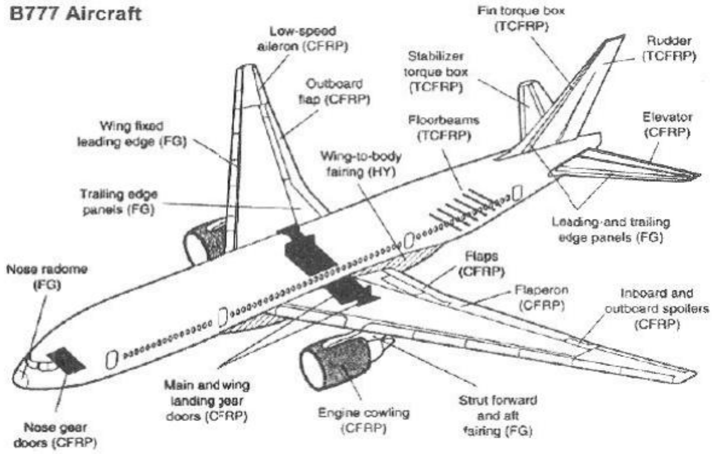
Aircraft Type	Components Made of Composite Materials
Boeing 737 -200-300-400	Spoilers and horizontal stabilizer (both limited production), trailing edge flaps. Aileron, elevator, rudder, nacelles. Aileron, elevator, rudder, nacelles.
Boeing 747-400	CFRP winglets and main deck floor panels. CFRP and AFRP used in cabin fittings engine

Boeing 757	Aileron, elevator, rudder, spoilers, flaps (in-board & outboard), fairings and nacelles.
Boeing 767	Ailerons, elevator, rudder, spoilers, landing gear doors (nose & main), fairings and nacelles.
Boeing 777	Ailerons, elevator, rudder, spoilers, flaps (in-board & outboard), floor beams, landing gear doors (nose & main), fairings and nacelles.

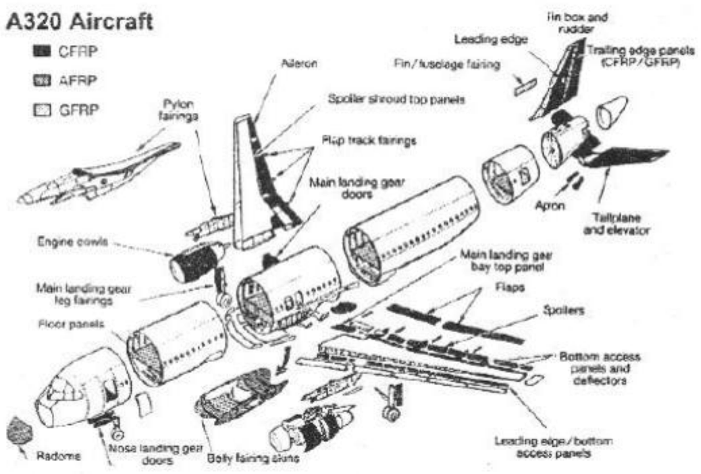
The composite components used on Boeing series of aircraft



Composite used for different part of B- 737 aircraft



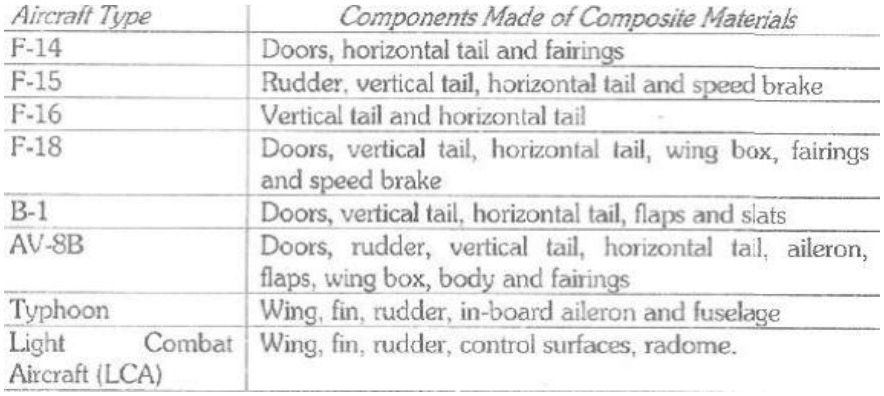
Composite used for different part of B- 777 aircraft



Composite used for different part of A-320 aircraft

Military Aircraft Applications

Most military aircraft applications use carbon fibre reinforced epoxy composites. About 26% of the structural weight of AV-8B aircraft of carbon fibre reinforced composite comprises the wing box, forward fuselage, horizontal stabilizer, elevators, rudder and other control surfaces. Various composite components used on different military aircraft are given in the Table



Aircraft Type	*Components Made of Composite Materials*
F-14	Doors, horizontal tail and fairings
F-15	Rudder, vertical tail, horizontal tail and speed brake
F-16	Vertical tail and horizontal tail
F-18	Doors, vertical tail, horizontal tail, wing box, fairings and speed brake
B-1	Doors, vertical tail, horizontal tail, flaps and slats
AV-8B	Doors, rudder, vertical tail, horizontal tail, aileron, flaps, wing box, body and fairings
Typhoon	Wing, fin, rudder, in-board aileron and fuselage
Light Combat Aircraft (LCA)	Wing, fin, rudder, control surfaces, radome.

Various composite components used on significant helicopter types are given in the Table

Helicopter Type	**Components Made of Composite Materials**
MBB BK 117	Main rotor blades, tail rotor blades, horizontal stabilizer, vertical stabilizer.
Bell 206L	Vertical stabilizer.
Bell 402	Main rotor blades
Dauphin	Main rotor blades, vertical stabilizer.
McDonnell Douglas MD 520N	Main rotor blades, tail boom.
McDonnell Douglas MD 900	Main rotor blades, fuselage mid section, tail boom, canopy frame, internal fuselage, horizontal stabilizer, vertical stabilizer.
Advanced Light Helicopter (ALH)	Main & tail rotor blades, rotor hub, nose cone, crew & passenger doors, cowling, most of the tail unit, lower rear tail boom, cock it section.

The composite components used on significant helicopter types

Generalized Hooke’s Law

1. **Anisotropic** material there are 36 constants this can be reduced to 21 constants

$$\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{Bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \\ C_{21} & C_{22} & C_{23} & C_{24} & C_{25} & C_{26} \\ C_{31} & C_{32} & C_{33} & C_{34} & C_{35} & C_{36} \\ C_{41} & C_{42} & C_{43} & C_{44} & C_{45} & C_{46} \\ C_{51} & C_{52} & C_{53} & C_{54} & C_{55} & C_{56} \\ C_{61} & C_{62} & C_{63} & C_{64} & C_{65} & C_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \varepsilon_4 \\ \varepsilon_5 \\ \varepsilon_6 \end{Bmatrix}$$

Symmetry

$$C_{ij} = C_{ji}$$

and

$$S_{ij} = S_{ji}$$

Apply symmetric conditions the 36 constants reduces to 21 independent constants

$$\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{Bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \\ M & C_{22} & C_{23} & C_{24} & C_{25} & C_{26} \\ M & \Lambda & C_{33} & C_{34} & C_{35} & C_{36} \\ M & \Lambda & \Lambda & C_{44} & C_{45} & C_{46} \\ M & \mathrm{SYM} & \Lambda & \Lambda & C_{55} & C_{56} \\ M & \Lambda & \Lambda & \Lambda & \Lambda & C_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \varepsilon_4 \\ \varepsilon_5 \\ \varepsilon_6 \end{Bmatrix}$$

2. Mono clinic Materials: There is one plane of symmetry. It has only 13 constants

$$\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{Bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & C_{16} \\ M & C_{22} & C_{23} & 0 & 0 & C_{26} \\ M & \Lambda & C_{33} & 0 & 0 & C_{36} \\ M & \Lambda & \Lambda & C_{44} & C_{45} & 0 \\ M & \mathrm{SYM} & \Lambda & \Lambda & C_{55} & 0 \\ M & \Lambda & \Lambda & 0 & 0 & C_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \varepsilon_4 \\ \varepsilon_5 \\ \varepsilon_6 \end{Bmatrix}$$

3. Orthotrpic Materials: Some engineering materials, including certain piezoelectric materials (e.g. Rochelle salt) and 2- ply fiber-reinforced composites, are orthotropic. By definition, an orthotropic material has at least 2-orthogonal planes of symmetry, where material properties are independent of direction within each plane. Such materials require 9- independent variables (i.e. elastic constants) in their constitutive matrices. In contrast, a material without any planes of symmetry is fully anisotropic and requires 21-elastic constants, whereas a material with an infinite number of symmetry planes (i. e. every plane is a plane of symmetry) is isotropic, and requires only 2 -elastic constants.

$$\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{Bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ M & C_{22} & C_{23} & 0 & 0 & 0 \\ M & \Lambda & C_{33} & 0 & 0 & 0 \\ M & \Lambda & \Lambda & C_{44} & 0 & 0 \\ M & \mathrm{SYM} & \Lambda & \Lambda & C_{55} & 0 \\ M & \Lambda & \Lambda & \Lambda & \Lambda & C_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \varepsilon_4 \\ \varepsilon_5 \\ \varepsilon_6 \end{Bmatrix}$$

4. Transversely Isotropic Materials: A special class of orthotropic materials is those that have the same properties in one plane (e.g. the x-y plane) and different properties in the direction normal to this plane (e.g. the z-axis). Such materials are called transverse isotropic, and they are described by 5 -independent elastic constants, instead of 9 for fully orthotropic. Examples of transversely isotropic materials include some piezoelectric materials (e.g. PZT-4, barium titanate) and fiber-reinforced composites where all fibers are in parallel.

$$\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{Bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{12} & 0 & 0 & 0 \\ M & C_{22} & C_{23} & 0 & 0 & 0 \\ M & \Lambda & C_{22} & 0 & 0 & 0 \\ M & \Lambda & \Lambda & \dfrac{(C_{22}-C_{23})}{2} & 0 & 0 \\ M & \mathrm{SYM} & \Lambda & \Lambda & C_{66} & 0 \\ M & \Lambda & \Lambda & \Lambda & \Lambda & C_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \varepsilon_4 \\ \varepsilon_5 \\ \varepsilon_6 \end{Bmatrix}$$

5. Isotropic Material: Most metallic alloys and thermoset polymers are considered isotropic, where by definition the material properties are independent of direction. Such materials have only 2 independent variables (i.e. elastic constants) in their stiffness and compliance matrices, as opposed to the 21 elastic constants in the general anisotropic case.The two elastic constants are usually expressed as the Young's modulus E and the Poisson's ratio η (or ‘n’). However, the alternative elastic constants bulk modulus (K) and/or shear modulus (G) can also be used. For isotropic materials, G and K can be found from E and n by a set of equations, and vice-versa.

$$\begin{Bmatrix}\sigma_1\\ \sigma_2\\ \sigma_3\\ \sigma_4\\ \sigma_5\\ \sigma_6\end{Bmatrix}=\begin{vmatrix} \mathbf{C_{11}} & \mathbf{C_{12}} & \mathbf{C_{12}} & \mathbf{0} & \mathbf{0} & \mathbf{0}\\ \mathrm{M} & \mathbf{C_{11}} & \mathbf{C_{12}} & \mathbf{0} & \mathbf{0} & \mathbf{0}\\ \mathrm{M} & \Lambda & \mathbf{C_{11}} & \mathbf{0} & \mathbf{0} & \mathbf{0}\\ \mathrm{M} & \Lambda & \Lambda & \dfrac{(\mathbf{C_{11}}-\mathbf{C_{12}})}{\mathbf{2}} & \mathbf{0} & \mathbf{0}\\ \mathrm{M} & \mathbf{SYM} & \Lambda & \Lambda & \dfrac{(\mathbf{C_{11}}-\mathbf{C_{12}})}{\mathbf{2}} & \mathbf{0}\\ \mathrm{M} & \Lambda & \Lambda & \Lambda & \Lambda & \dfrac{(\mathbf{C_{11}}-\mathbf{C_{12}})}{\mathbf{2}} \end{vmatrix}\begin{Bmatrix}\varepsilon_1\\ \varepsilon_2\\ \varepsilon_3\\ \varepsilon_4\\ \varepsilon_5\\ \varepsilon_6\end{Bmatrix}$$