KARPAGAM ACADEMY OF HIGHER EDUCATION

(Deemed to be University)
(Established Under Section 3 of UGC Act, 1956)
EachanariPost, Coimbatore-641021.Tamilnadu,India.

FACULTY OF ENGINEERING

DEPARTMENT OF MECHANICAL ENGINEERING – AEROSPACE ENGINEERING

SUBJECT CODE: 16BTAR_E19 SEMESTER : VI

SUBJECT NAME: COMPOSITE MATERIALS AND STRUCTURES L T P C = 3 0 0 3

Course Objectives:

- To train students to be able to select composite materials, design composite structures, conduct stress analyses of selected practical applications using laminated plate theories and appropriate strength criteria.
- To train students familiar with the properties and response of composite structures subjected to mechanical loading under static and cyclic conditions.
- To identify the properties of fiber and matrix materials used in commercial composites
- To learn some common manufacturing techniques and to predict the elastic properties of both long and short fiber composites based on the constituent properties.

Course Learning Outcomes:

Students who successfully complete the course will reveal the following outcomes by tests, homework, and design project.

- ✓ An ability to identify the properties of fiber and matrix materials used in commercial composites, as well as some common manufacturing techniques.
- ✓ An ability to predict the elastic properties of both long and short fiber composites based on the constituent properties.
- ✓ A basic understanding of linear elasticity with emphasis on the difference between isotropic and anisotropic material behavior.
- ✓ An ability to analyze a laminated plate in bending, including finding laminate properties from lamina properties and find residual stresses from curing and moisture.
- ✓ An ability to predict the failure strength of a laminated composite plate.

- ✓ An exposure to recent developments in composites, including metal and ceramic matrix composites.
- ✓ An ability to use the ideas developed in the analysis of composites towards using composites in aerospace design.

UNIT - I STRESS STRAIN RELATION

Introduction to Composite Materials - Advantages and Application of composite materials, reinforcements and matrices – Generalized Hooke's Law – Elastic constants for anisotropic, orthotropic and isotropic materials.

UNIT - II METHODS OF ANALYSIS

Micro mechanics – Mechanics of materials approach, elasticity approach to determine material properties – Macro Mechanics – Stress-strain relations with respect to natural axis, arbitrary axis – Determination of material properties. Experimental characterization of lamina.

UNIT - III LAMINATED PLATES

Governing differential equation for a general laminate, angle ply and cross ply laminates. Failure criteria for composites.

UNIT - IV SANDWICH CONSTRUCTIONS

Basic design concepts of sandwich construction -Materials used for sandwich construction - Failure modes of sandwich panels.

UNIT - V FABRICATION PROCESS

Various Open and closed mould processes. Manufacture of fibers – Types of resins and properties and applications – Netting analysis.

TEXT BOOKS:

S.No.	Author(S)	Title Of The Book	Publisher	Year Of Publication
1.	Jones R.M	Mechanics of Composite Materials	McGraw-Hill, Kogakusha Ltd., Tokyo.	2015
2.	N.G.R.lyengar	Composite Materials and Structural Analysis	viva Books Pvt.Ltd; First edition. New Delhi.	2016

REFERENCES BOOKS:

S.No.	Author(S)	Title Of The Book	Publisher	Year Of Publication
1.	K.Chandrashekhara Bhagwan D.Agarwal, Lawrence J. Broutman	Analysis and Performance of Fibre Composites	John Wiley and sons.Inc., New York	2012
2.	Lubin, G	Handbook on Advanced Plastics and Fibre Glass	Von Nostrand Reinhold Co., New York.	1989
3.	AutarK.Kaw	Mechanics of Composite Materials Second Edition	CRC press, University of South Florida, Tampa, USA	2005
4.	Vasiliev & Morozov	Advanced Mechanics of Composite materials Second Edition	Elsevier Science Philadelphia, USA	2007

ESE MARKS ALLOCATION

S.No.	Particulars	Marks
1.	Section – A (20 × 1 = 20) Online Test – MCQ type	20
2.	Section – B (5 × 2 = 10)	10
3.	Section – C (5 × 14 = 70) Either ‘A’ or ‘B’ type	70
Total		**100**

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DEPARTMENT OF MECHANICAL ENGINEERING – AEROSPACE ENGINEERING

Subject Name : **Composite Materials and Structures**
Subject Code : **16BTAR_E19** **(Credits - 3)**
Name of the Faculty : **Mr.C.Nithiyapathi**
Designation : **Assistant Professor**
Year/Semester/Section : **III / VI / -**
Branch : **Aerospace Engineering**

Sl. No.	No. of Periods	Topics to be Covered	Support Materials
		UNIT – I : STRESS STRAIN RELATION	
1.	1*	Introduction to Aerospace Materials and its Properties	T[2], R[1], R[3]
2.	2	Introduction to Composite materials & its Classification	T[2], R[1], R[3]
3.	2	Advantages and Application of composite materials	T[2], R[1], R[3]
4.	2	Reinforcements and Matrices	T[2], R[1], R[3]
5.	1	Generalized Hooke’s Law	T[2], R[1], R[3]
6.	2	Elastic constants for isotropic material	T[2], R[1], R[3]
7.	1	Elastic constants for orthotropic material	T[2], R[1], R[3]
8.	1	Elastic constants for anisotropic material	T[2], R[1], R[3]
9.	1	Problem & Solution- stiffness and compliances	T[2], R[1], R[3]
10.	1	Tutorial- Problem & Solution - stiffness and compliances	T[2], R[1], R[3]
		Total No. of Hours Planned for Unit – I : 13 +1*	

(* - Fundamental Lecture)

Sl. No.	No. of Periods	Topics to be Covered	Support Materials
		UNIT – II : METHODS OF ANALYSIS	
11.	1	Introduction to Micro mechanics Analysis	T[2], R[1], R[3]
12.	2	Mechanics of materials approach to determine material properties	T[2], R[1], R[3]
13.	2	elasticity approach to determine material properties	T[2], R[1], R[3]
14.	1	Tutorial- Problem & Solution	T[2], R[1], R[3]
15.	1	Introduction to Macro mechanics Analysis	T[2], R[1], R[3]
16.	2	Stress-strain relations with respect to natural axis	T[2], R[1], R[3]
17.	1	Stress-strain relations with respect to arbitrary axis	T[2], R[1], R[3]
18.	1	Tutorial - Determination of material properties	T[2], R[1], R[3]
19.	1	Experimental characterization of lamina.	T[2], R[1], R[3]
		Total No. of Hours Planned for Unit – II : 12	

Sl. No.	No. of Periods	Topics to be Covered	Support Materials
UNIT – III : LAMINATED PLATES			
20.	2	Governing differential equation for a laminate	T[1], T[2], R[3]
21.	2	Stress – Strain relations for a laminate	T[1], T[2], R[3]
22.	1	Different types of laminates	T[1], T[2], R[3]
23.	1	Angle ply and cross ply laminates	T[1], T[2], R[3]
24.	1	Tutorial- Problem & Solution - Flexural constants	T[1], T[2], R[3]
25.	3	Failure criteria for composites	T[1], T[2], R[3]
		Total No. of Hours Planned for Unit – III: 10	

Sl. No.	No. of Periods	Topics to be Covered	Support Materials
UNIT – IV : SANDWICH CONSTRUCTIONS			
26.	2	Basic design concepts of Sandwich construction	T[2], R[2], R[3]
27.	2	Materials used for Sandwich construction	T[2], R[2], R[3]
28.	2	Failure modes of sandwich panels	T[2], R[2], R[3]
29.	1	Bending stress and shear flow in composite beams	T[2], R[2], R[3]
30.	2	Problem & Solution - Bending stress	T[2], R[2], R[3]
31.	1	Tutorial – Problem & Solution - Bending stress	T[2], R[2], R[3]
		Total No. of Hours Planned for Unit – IV: 10	

Sl. No.	No. of Periods	Topics to be Covered	Support Materials
UNIT – V : FABRICATION PROCESS			
32.	2	Various Open mould processes	T[2], R[2], R[3]
33.	2	Various closed mould processes	T[2], R[2], R[3]
34.	2	Manufacture of fibers	T[2], R[2], R[3]
35.	2	Types of resins, properties and applications	T[2], R[2], R[3]
36.	1	Netting analysis.	T[2], R[2], R[3]
37.	1	**Tutorial class - Discussion on Competitive Examination related Questions / University previous year questions**	
		Total No. of Hours Planned for Unit – V: 10	

TOTAL PERIODS : 56

TEXT BOOKS:

T [1] – Jones R.M. (1999), “Mechanics of Composite Materials”, McGraw-Hill, Kogakusha Ltd., Tokyo.

T [2] – N.G.R.lyengar.(2016), “Composite Materials and Structural Analysis”, viva Books Pvt.Ltd.; First edition., New Delhi.

REFERENCES:

R [1] - K.Chandrashekhara Bhagwan D.Agarwal, Lawrence J. Broutman (2012), “Analysis and Performance of Fibre Composites”, John Wiley and sons.Inc., New York

R [2] - Lubin, G (1989). “Handbook on Advanced Plastics and Fibre Glass”, Von Nostrand Reinhold Co., New York

R [3] - Autar K.Kaw (2005), “Mechanics of Composite Materials”, Second Edition, CRC press, University of South Florida, Tampa,USA

R [4] - Vasiliev & Morozov (2007), “Advanced Mechanics of Composite materials”, Second Edition, Elsevier Science Philadelphia, USA

WEBSITES:

W [1] - http://nptel.ac.in/
W [2] - www.ae.iitkgp.ernet.in
W [3] - www.tandfonline.com

JOURNALS:

J [1] - journals.sagepub.com
J [2] – scirp.org/journal/ojcm
J [3] – journal.sapub.org/cmaterials
J [4] – journals.elsevier.com/composite-structures
J [5] – materialstoday.com

UNIT	Total No. of Periods Planned	Lecture Periods	Tutorial Periods
I	14	13	1
II	12	10	2
III	10	09	1
IV	10	09	1
V	10	09	1
TOTAL	60	50	06

I. CONTINUOUS INTERNAL ASSESSMENT : 40 Marks

(Internal Assessment Tests: 30, Attendance: 5, Assignment / Seminar: 5)

II. END SEMESTER EXAMINATION : 60 Marks

TOTAL : 100 Marks

16BTAR_E19 COMPOSITE MATERIALS AND STRUCTURES 3 0 0 3 100

UNIT - I STRESS STRAIN RELATION

Introduction to Composite Materials - Advantages and Application of composite materials, reinforcements and matrices – Generalized Hooke’s Law – Elastic constants for anisotropic, orthotropic and isotropic materials

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TEXT BOOKS

T [1] – Jones R.M. (1999), “Mechanics of Composite Materials”, McGraw-Hill, Kogakusha Ltd., Tokyo.

T [2] – N.G.R.Iyengar.(2016), “Composite Materials and Structural Analysis”, viva Books Pvt.Ltd.; First edition., New Delhi.

REFERENCES

R [3] - Autar K.Kaw (2005), “Mechanics of Composite Materials”, Second Edition, CRC press, University of South Florida, Tampa,USA

Info:

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UNIT-I

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 trade offs 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**:

fibre reinforced composites, flake composites and particulate composites. Fibre reinforced composites can be further divided into those containing discontinuous or continuous fibres.

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 used as matrices and they require reinforcement materials which need to be stable over a range of temperature and non-reactive too. However the guiding aspect for the choice depends essentially on the matrix material. Light metals form the matrix for temperature application and the reinforcements in addition to the aforementioned reasons are characterized by high moduli.Most metals and alloys make good matrices. However, practically, the choices for low temperature applications are not many. Only light metals are responsive, with their low density proving an advantage. Titanium, Aluminium and magnesium are the popular matrix metals currently in vogue, which are particularly useful for aircraft applications. If metallic matrix materials have to offer high strength, they require high modulus reinforcements. The strength-to-weight ratios of resulting composites can be higher than most alloys.

Ceramic Matrix Materials (CMM)

Ceramics can be described as solid materials which exhibit very strong ionic bonding in general and in few cases covalent bonding. High melting points, good corrosion resistance, stability at elevated temperatures and high compressive strength, render ceramic-based matrix materials a favourite for applications requiring a structural material that doesn’t give way at temperatures above 1500ºC. Naturally, ceramic matrices are the obvious choice for high temperature applications.High modulus of elasticity and low tensile strain, which most ceramics posses, have combined to cause the failure of attempts to add reinforcements to obtain strength improvement. This is because at the stress levels at which ceramics rupture, there is insufficient elongation of the matrix which keeps composite from transferring an effective quantum of load to the reinforcement and the composite may fail unless the percentage of fiber volume is high enough. A material is reinforcement to utilize the higher tensile strength of the fiber, to produce an increase in load bearing capacity of the matrix. Addition of high-strength fiber to a weaker ceramic has not always been successful and often the resultant composite has proved to be weaker.The use of reinforcement with high modulus of elasticity may take care of the problem to some extent and presents pre-stressing of the fiber in the ceramic matrix is being increasingly resorted to as an option.When ceramics have a higher thermal expansion coefficient than reinforcement materials, the resultant composite is unlikely to have a superior level of strength. In that case, the composite will develop strength within ceramic at the time of cooling resulting in microcracks extending from fiber to fiber within the matrix. Microcracking can result in a composite with tensile strength lower than that of the matrix.

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/Fibre Reinforced Polymer (FRP) Composites

Fibers are the important class of reinforcements, as they satisfy the desired conditions and transfer strength to the matrix constituent influencing and enhancing their properties as desired.Glass fibers are the earliest known fibers used to reinforce materials. Ceramic and metal fibers were subsequently found out and put to extensive use, to render composites stiffer more resistant to heat.Fibers fall short of ideal performance due to several factors. The performance of a fiber composite is judged by its length, shape, orientation, and composition of the fibers and the mechanical properties of the matrix.The orientation of the fiber in the matrix is an indication of the strength of the composite and the strength is greatest along the longitudinal directional of fiber. This doesn’t mean the longitudinal fibers can take the same quantum of load irrespective of the direction in which it is applied. Optimum performance from longitudinal fibers can be obtained if the load is applied along its direction. The slightest shift in the angle of loading may drastically reduce the strength of the composite.Unidirectional loading is found in few structures and hence it is prudent to give a mix of orientations for fibers in composites particularly where the load is expected to be the heaviest.Monolayer tapes consisting of continuous or discontinuous fibers can be oriented unidirectional stacked into plies containing layers of filaments also oriented in the same direction. More complicated orientations are possible too and nowadays, computers are used to make projections of such variations to suit specific needs. In short, in planar composites, strength can be changed from unidirectional fiber oriented composites that result in composites with nearly isotropic properties.

Laminar Composites

Laminar composites are found in as many combinations as the number of materials. They can be described as materials comprising of layers of materials bonded together. These may be of several layers of two or more metal materials occurring alternately or in a determined order more than once, and in as many numbers as required for a specific purpose.Clad and sandwich laminates have many areas as it ought to be, although they are known to follow the rule of mixtures from the modulus and strength point of view. Other intrinsic values pertaining to metal-matrix, metal-reinforced composites are also fairly well known.Powder metallurgical processes like roll bonding, hot pressing, diffusion bonding, brazing and so on can be employed for the fabrication of different alloys of sheet, foil, powder or sprayed materials. It is not possible to achieve high strength materials unlike the fiber version. But sheets and foils can be made isotropic in two dimensions more easily than fibers. Foils and sheets are also made to exhibit high percentages of which they are put. For instance, a strong sheet may use over 92% in laminar structure, while it is difficult to make fibers of such compositions. Fiber laminates cannot over 75% strong fibers.

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

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

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

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

.**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

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:

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

- Carbon Fiber Reinforcement:

- ƒ Good modulus at high temperatures
- ƒ Excellent stiffness
- ƒ More expensive than glass
- ƒ Brittle
- ƒ 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.

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 to 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
- Epoxies
- Bismaleimide (BMI)
- Poly-ether-imide (PEI)
- Poly-ether-sulphone (PES)
- 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.

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 aileon ribs
- Airbus A340-500/600 inboard wing leading edge assemblies
- Airbus A340-500/600 inboard wing access panels
- Airbus A340-500/600 keel beam connecting angles
- Airbus A340-500/600 keel beam ribs
- AirbusA340-500/600pylon panels
- Fokker50 main landing gear door
- PEI • 737 smoke detector pans
- 737/757 galleys
- 747. stowage bins
- 767 aircraft acoustical tiles
- 767andotherBoeingaircraftbrackets
- AirbusA320 bulk cargo floor sandwich structural Panels
- Airbus A330 lower wing fairings
- A3XX main stair case (developmental)
- Beluga heavy duty entrance floor panel
- Dornier 328 landing flap ribs

- Dornier 328 ice protection plates
- Fokker 50 ice protection plates
- Fokker 50 trailing edge wing shroud skins
- Fokker 70/100 structural floor panels
- Gulfstream G-V structural floor panels
- Gulfstream IV and V rudder ribs
- Gulfstream IV and V rudder trailing edges
- Learjet air steps
- Galleys on most commercial aircraft

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

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 weatherability 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. Difficult 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

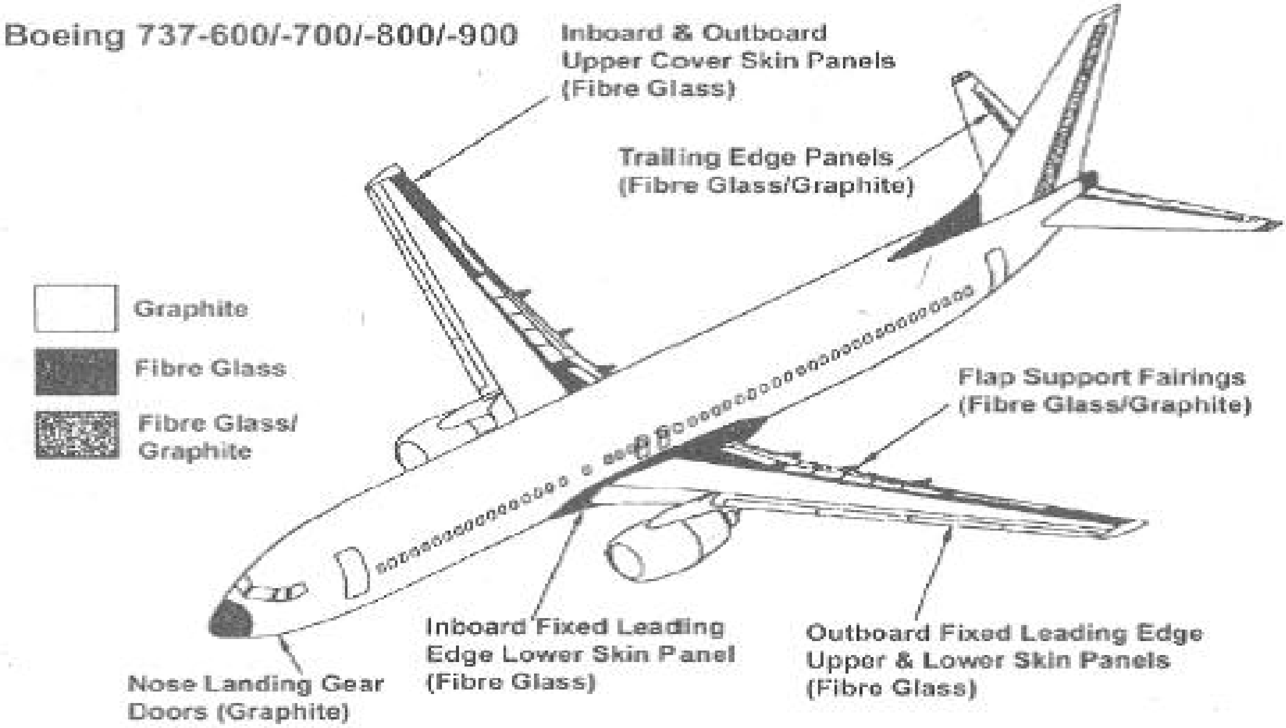
Aircraft Type	Components Made of Composite Materials
Airbus A300B2/B4	Radome, fin leading edge and tip, fin trailing edge panels, cabin and cargo hold furnishings. Fairing -pylon, wing/ fuselage rear.
Airbus A310-300	Rudder, elevator, vertical stabilizer, spoilers, cowl (inlet & fan), thrust reverser, main & nose landing gear door of wing leading & trailing edge panels, nacelles. Fairings -Ion, flap track, win fuselage.
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 gear leg.
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

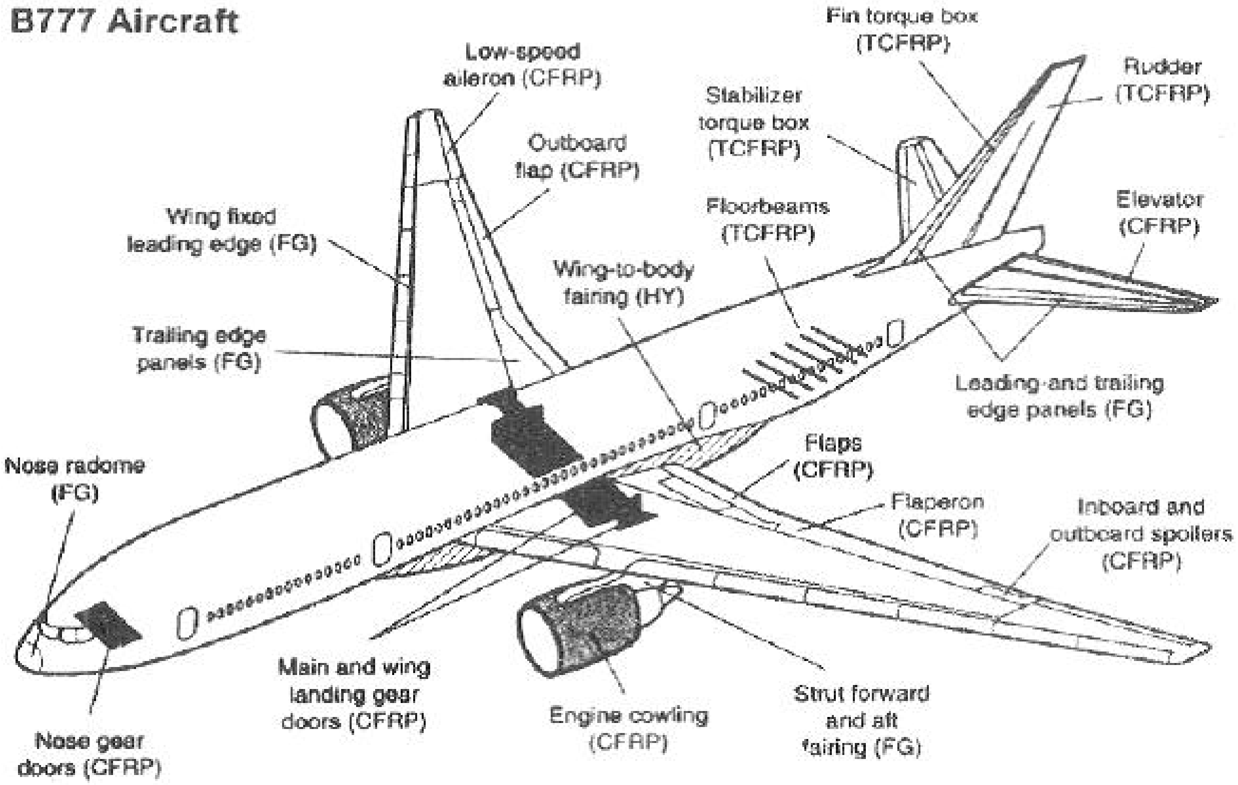
Composites account for about 15% of the structure of Airbus A320 aircraft. Although the total weight of composite structures is much higher in Airbus A330/A340 aircraft, the percentage of weight in relation to total weight of aircraft is nearly 12%.

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 nacelles.
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.

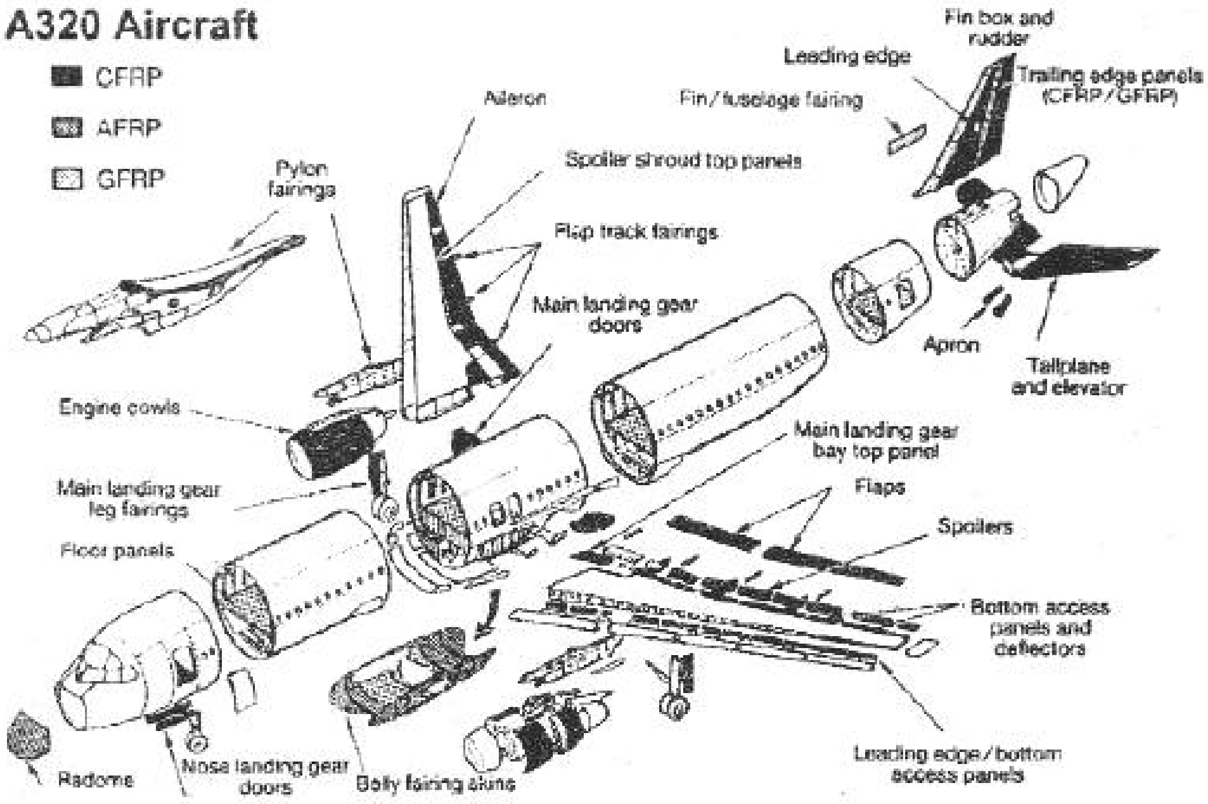
The composite components used on Boeing series of aircraft



Composite used for different part of B- 737 aircraft



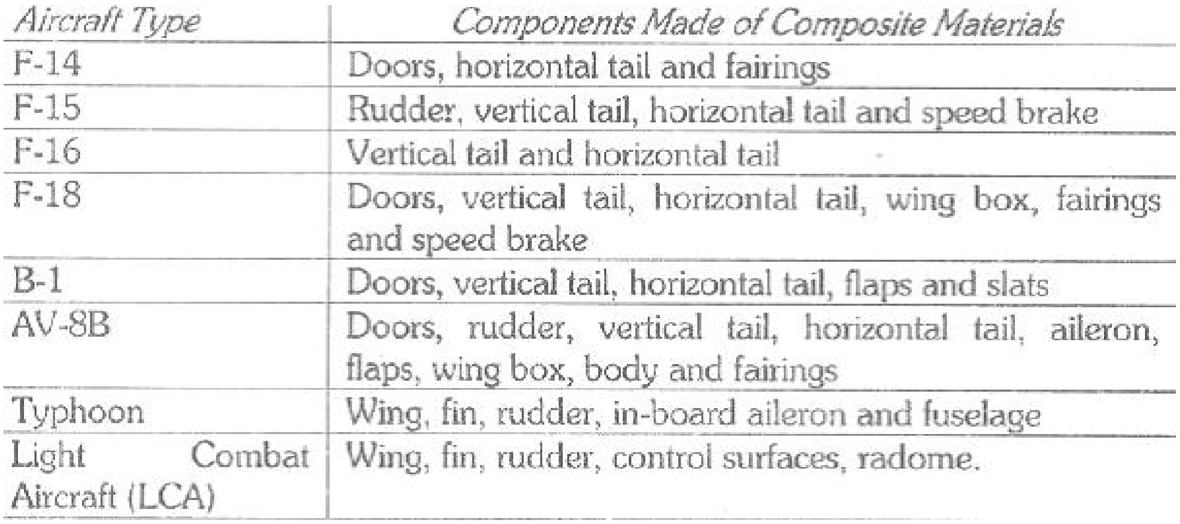
Composite used for different part of B- 777 aircraft



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

Generalised Hooke's Law

1.**Anisotropic material** There are 36 constants This can be reduced to 21 constants

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

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. **Transversly 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.

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

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.

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

Question Bank

Part-A

1. What is composite material?
2. What does the term anisotropic mean?
3. Name the three basic categories of composite materials.
4. .State Hooke's law
5. List some applications of ceramic matrix composites
6. Mention the important properties of composites
7. Write the simple definition of composite and indicate the three criteria which are supposed to be satisfied before a material called a composite
8. What are orepregs?
9. Why should the fibers are thin in diameters?
10. Compare thermoset and thermo plastic composites.
11. What are the functions of matrices
12. What is hybid composite?

PART B

1. List and explain the three general factors that determine the properties of composite materials.
2. (b) What are the major limitations on the extensive use of composite materials in engineering applications?
3. Derive the compliance matrix for an orthotropic material in terms of 9 engineering constants of it
4. Briefly, explain the application and advantages of composite materials?
5. Describe the elastic constants for an isotropic, orthotropic and isotropic material
6. Explain the properties and functions of epoxy resins.
7. How composites are classified? Briefly explain each type of composites with their merits and demerits
8. Describe the manufacturing process of Glass fiber and carbon fiber
9. Give the descibtion of various fibers and discuss their properties advantages and disadvantages.
10. Classify various resins and discuss their properties, merits and demerits.

References:

1. Robert.M.Jones, “Mechanics of Composite Materials”
2. Autar K Kaw, “Mechanics of Composite Materials”
3. Aircraft Composite materials and Structures – Study material, Sathyabama University

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UNIT - II METHODS OF ANALYSIS

Micro mechanics – Mechanics of materials approach, elasticity approach to determine material properties – Macro Mechanics – Stress-strain relations with respect to natural axis, arbitrary axis – Determination of material properties. Experimental characterization of lamina.

TEXT BOOKS

T [1] –	Jones R.M. (1999), "Mechanics of Composite Materials", McGraw-Hill, Kogakusha Ltd., Tokyo.
T [2] –	N.G.R.lyengar.(2016), "Composite Materials and Structural Analysis", viva Books Pvt.Ltd.; First edition., New Delhi.

REFERENCES

R [1] -	K.Chandrashekhara Bhagwan D.Agarwal, Lawrence J. Broutman (2012), "Analysis and Performance of Fibre Composites", John Wiley and sons.Inc., New York
R [3] -	Autar K.Kaw (2005), "Mechanics of Composite Materials", Second Edition, CRC press, University of South Florida, Tampa,USA

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Micro-mechanics of Lamina

Micromechanics deals with the study of composite material behaviour in terms of the interaction of its constituents. From the procedures of micromechanics lamina properties can be predicted. There are two basic approaches of the micromechanics of composite materials, namely (i) Mechanics of materials and (ii) Elasticity

Here, the mechanics of materials approach will be followed.

Volume Fractions:

Consider a composite material that consists of fibers and matrix material. The volume of the composite material is equal to the sum of the volume of the fibers and the volume of the matrix. Therefore,

$$v_c = v_f + v_m \qquad (3.142)$$

where, ν_c - volume of composite material

ν_f - volume of fiber

v_m - volume of matrix

Let, the fiber volume fraction V_f and the matrix volume fraction V_m be defined as

$$V_f = \frac{\nu_f}{\nu_c} \quad \text{and} \qquad (3.143)$$

$$V_m = \frac{\nu_m}{\nu_c} \qquad (3.144)$$

such that the sum of volume fractions is

$$V_f + V_m = 1 \qquad (3.145)$$

Weight Fractions:

Assuming that the composite material consists of fibers and matrix material, the weight of the composite material is equal to the sum of the weight of the fibers and the weight of the matrix. Therefore,

$$w_c = w_f + w_m \qquad (3.146)$$

where, w_c - weight of composite material

w_f - weight of fiber

w_m - weight of matrix

The weight fractions (mass fractions) of the fiber and the matrix are defined as

$$W_f = \frac{w_f}{w_c} \quad \text{and} \qquad (3.147)$$

$$W_m = \frac{w_m}{w_c} \qquad (3.148)$$

such that the sum of weight fractions is

$$W_f + W_m = 1 \qquad (3.149)$$

Density:

The density of composite material can be defined as the ratio of weight of the composite material to the volume of the composite material and is expressed as

$$\rho_c = \frac{w_c}{v_c} \qquad (3.150)$$

but, $v_c = v_f + v_m$, and $v = \dfrac{w}{\rho}$, therefore the above equation can be rewritten as

$$\frac{w_c}{\rho_c} = \frac{w_f}{\rho_f} + \frac{w_m}{\rho_m} \qquad (3.151)$$

$$\frac{w_c}{\rho_c} = \frac{w_f}{\rho_f} + \frac{w_m}{\rho_m}$$

$$\frac{1}{\rho_c} = \frac{1}{\rho_f}\left(\frac{w_f}{w_c}\right) + \frac{1}{\rho_m}\left(\frac{w_m}{w_c}\right) \qquad (3.152)$$

By writing in terms of weight fractions,

$$\frac{1}{\rho_c}=\frac{W_f}{\rho_f}+\frac{W_m}{\rho_m} \qquad (3.153)$$

$$\frac{1}{\rho_c}=\frac{W_f}{\rho_f}+\frac{W_m}{\rho_m}$$

The density of the composite material in terms of weight fractions can be written as

$$\rho_c=\frac{1}{\left(\frac{\mathbf{W_f}}{\boldsymbol{\rho}_\mathbf{f}}+\frac{\mathbf{W_m}}{\boldsymbol{\rho}_\mathbf{m}}\right)} \qquad (3.154)$$

$$\rho_c=\frac{\mathbf{1}}{\sum_{i=1}^{n}\left(\frac{\mathbf{W_i}}{\boldsymbol{\rho}_\mathbf{i}}\right)} \qquad (3.155)$$

Moreover, the equation $w_c = w_f + w_m$, in general, can be rewritten as

$$\rho_c v_c=\rho_f v_f+\rho_m v_m$$

$$\rho_c=\rho_f\left(\frac{v_f}{v_c}\right)+\rho_m\left(\frac{v_f}{v_c}\right) \qquad (3.156)$$

writing in terms of volume fractions, the density of the composite material is written as

$$\rho_c=\boldsymbol{\rho}_\mathbf{f}\mathbf{V_f}+\boldsymbol{\rho}_\mathbf{m}\mathbf{V_m} \qquad (3.157)$$

In general,

$$\rho_c=\sum_{i=1}^{n}\boldsymbol{\rho}_\mathbf{i}\mathbf{V_i} \qquad (3.158)$$

Void Content:

During the incorporation of fibers into the matrix or during the manufacturing of laminates, air or other volatiles may be trapped in the material. The trapped air or volatiles exist in the laminate as micro voids, which may significantly affect some of its mechanical properties. A high void content (over 5% by volume) usually leads to lower fatigue resistance, greater susceptibility to water diffusion, and increased variation (scatter) in mechanical properties. The void content in a composite laminate can be estimated by comparing the theoretical density with its actual density.

$$v_{\text{void}} = \left(\frac{\rho_{\text{ct}} - \rho_{\text{ce}}}{\rho_{\text{ct}}} \right) * 100 \qquad (3.159)$$

where, ρ_{ct} - theoretical density of the composite material
ρ_{ce} - experimental density of the composite material

Determination of Longitudinal Modulus:

Consider a unidirectional composite specimen as shown in Fig.3.22.

The following assumptions are made to get the basic properties:

(i) Fibers are uniform in properties and diameter.
(ii) Fibers are continuous and parallel throughout the composites.
(iii) There is a perfect bonding between the fibers and the matrix.
(iv) Strains experienced by the fiber, matrix and composites are equal. i.e.

$$\varepsilon_c = \varepsilon_f = \varepsilon_m$$

where, $\varepsilon_c, \varepsilon_f$ *and* ε_m are the longitudinal strains in fibers, matrix, and composite respectively. This condition is called iso-strain condition.

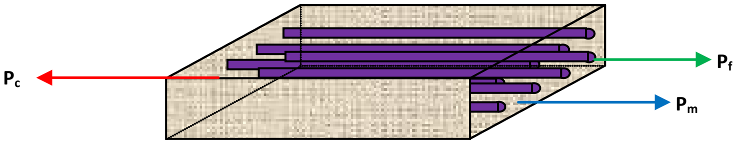


Figure 3.22 Model for longitudinal behaviour of composite material

Let, the composite be applied by a load P$_c$ which is shared between the fibers and the matrix so that

$$P_c = P_f + P_m \qquad (3.160)$$

The corresponding stress relation is

$$\sigma_c A_c = \sigma_f A_f + \sigma_m A_m \qquad (3.161)$$

Further its behaviour is assumed to be linearly elastic, and hence the modulus and stress are related. Thus,

$$E_c\,\varepsilon_c A_c = E_f \varepsilon_f A_f + E_m \varepsilon_m A_m \quad (3.162)$$

$$E_c = E_f\left(\frac{\varepsilon_f A_f}{\varepsilon_c A_c}\right) + E_m\left(\frac{\varepsilon_m A_m}{\varepsilon_c A_c}\right) \quad (3.163)$$

But, for parallel fibers the area fraction is same as the volume fraction. Thus,

$$E_c = E_f V_f + E_m V_m \quad (3.164)$$

The relationship of this form is known as ***Rule or Law of Mixtures***

$$\mathbf{E_c = E_f V_f + E_m (1 - V_f)} \quad (3.165)$$

In general

$$\mathbf{E_c = \sum_{i=1}^{n} E_i V_i} \quad (3.166)$$

Longitudinal strength:

The load is shared by the fibers and the matrix.

$$P_c = P_f + P_m \quad (3.167)$$

Thus,

$$\sigma_c A_c = \sigma_f A_f + \sigma_m A_m \quad (3.168)$$

$$\sigma_c = \sigma_f\left(\frac{A_f}{A_c}\right) + \sigma_m\left(\frac{A_m}{A_c}\right) \quad (3.169)$$

$$\sigma_c = \boldsymbol{\sigma}_\mathbf{f} \mathbf{V_f} + \boldsymbol{\sigma}_\mathbf{m} \mathbf{V_m} \quad (3.170)$$

$$\sigma_c = \sigma_f V_f + \sigma_m (1 - V_f) \quad (3.171)$$

Load carrying capacity of fibers:

The strains experienced by the composites, fibers and the matrix are equal. Thus,

$$\varepsilon_c = \varepsilon_f = \varepsilon_m \quad (3.172)$$

$$\frac{\sigma_c}{E_c} = \frac{\sigma_f}{E_f} = \frac{\sigma_m}{E_m} \quad (3.173)$$

$$\frac{\sigma_f}{\sigma_m} = \frac{E_f}{E_m} \quad \text{and} \quad \frac{\sigma_f}{\sigma_c} = \frac{E_f}{E_c} \quad (3.174)$$

$$\frac{P_f}{P_m} = \frac{\sigma_f A_f}{\sigma_m A_m} = \frac{\frac{([E_f \varepsilon_f)A]_f}{Ac}}{\frac{(E_m \varepsilon_m)A_m}{Ac}} = \frac{E_f V_f}{E_m V_m}$$

(3.175)

$$\frac{P_f}{P_c} = \frac{\sigma_f A_f}{\sigma_f A_f + \sigma_m A_m}$$

(3.176)

$$\frac{P_f}{P_c} = \frac{\sigma_f A_f \frac{\square}{Ac}}{\frac{[(\sigma]_f A_f + \sigma_m A_m)}{Ac}} = \frac{\sigma_f V_f}{\sigma_f V_f + \sigma_m V_m}$$

(3.177)

$$\frac{P_f}{P_c} = \frac{E_f \varepsilon_f V_f}{E_f \varepsilon_f V_f + E_m \varepsilon_m V_m}$$

(3.178)

$$\frac{\mathbf{P_f}}{\mathbf{P_c}} = \frac{\mathbf{E_f V_f}}{\mathbf{E_f V_f + E_m V_m}}$$

(3.179)

or,

$$\frac{\mathbf{P_f}}{\mathbf{P_c}} = \frac{\frac{\mathbf{E_f}}{\mathbf{E_m}}}{\frac{\mathbf{E_f}}{\mathbf{E_m}} + \frac{\mathbf{V_m}}{\mathbf{V_f}}}$$

(3.180)

Thus, the load sharing of the fibers depend on the modulus values and the volume fractions of fiber and matrix.

Determination of Transverse Modulus:

Consider unidirectional composites. The following assumptions are made

(i) Fibers are uniform in properties and diameter.

(ii) Fibers are continuous and parallel throughout the composite.

(iii)There is a perfect bonding between the fibers and the matrix.

(iv)The fibers and the matrix are made up of layers and each layer will carry the same load. Therefore the fiber and matrix layers will experience equal stress. i.e.

$$\sigma_c = \sigma_f = \sigma_m$$

(3.181)

where, $\sigma_c, \sigma_f,$ **and** σ_m are the stresses in the composites, fibers and matrix respectively, in the loading direction (transverse direction).

(v) the thickness of the composite material is equal to the sum of the thickness of fibers and matrix. i.e.

$$t_c = t_f + t_m$$

(3.182)

where, t_c, t_f, and t_m are the thicknesses of composites, fibers, and matrix respectively

Let, the load be applied in the transverse direction, i.e. the direction perpendicular to the parallel fibers.

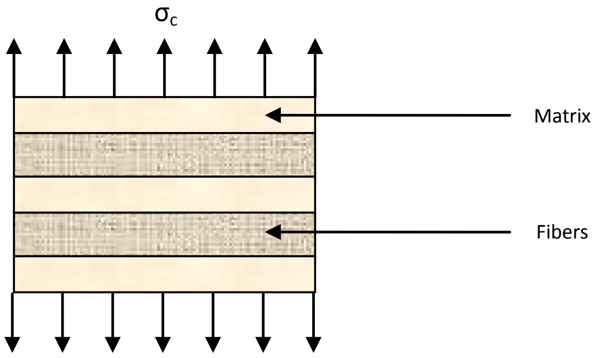


Figure 3.23 Model for transverse behaviour of composite material

Under the applied transverse load, the elongation of composite material δ_c in the direction of the load is the sum of the fiber elongation and the matrix elongation. i.e.

$$\delta_c = \delta_f + \delta_m \tag{3.183}$$

where, δ_c, δ_f, *and* δ_m are the elongations of composite, fibers, and matrix respectively

but , strain, $\varepsilon = \delta / t$, (3.184)

and it gives $\delta = \varepsilon * t$ (3.185)

therefore, the above equation can be rewritten as

$$\varepsilon_c t_c = \varepsilon_f t_f + \varepsilon_m t_m \tag{3.186}$$

$$\varepsilon_c = \varepsilon_f \left(\frac{t_f}{t_c}\right) + \varepsilon_m \left(\frac{t_m}{c}\right) \tag{3.187}$$

$$\varepsilon_c = \varepsilon_f V_f + \varepsilon_m V_m$$

$$\frac{\sigma_c}{E_c} = \frac{\sigma_f}{E_f} V_f + \frac{\sigma_m}{E_m} V_m \tag{3.188}$$

but, $\sigma_c = \sigma_f = \sigma_m$ (3.189)

therefore,

$$\frac{1}{E_{cT}} = \frac{V_f}{E_f} + \frac{V_m}{E_m} \tag{3.190}$$

$$E_{cT} = \frac{E_f * E_m}{E_f V_m + E_m V_f} \qquad (3.191)$$

or

$$E_{cT} = \frac{1}{\Sigma_{i=1}^{n} \frac{V_i}{E_i}} \qquad (3.192)$$

Exercise Problems:

1) Find the weight fraction and volume fraction of fibers in the glass/epoxy composites . The following data is obtained from the burnout test.

weight of the empty crucible = 46.5401 gm

weight of crucible and composite piece = 49.1201 gm

weight of crucible and glass fiber = 48.3420 gm.

The density of glass fiber is 2600 kg/m ^{3}

and 1300 kg/m ^{3}

2.) Calculate the ratio of fiber stress to matrix stress and matrix stress to composite stress for V_f = 15%, 30 %, 45 % and 70 %. Take E_f =250 G Pa and E_m = 15 G Pa.

References:

1) "Analysis and Performance of Fiber composites", BD Agarwal, L J Broughtman and K Chandrashekhara, John Wiley and sons.

2) " Principles of Composite Material Mechanics, Ronald R Gibson, CRC Press.

Theories of stress transfer in short fibers:

Tensile load applied to a discontinuous fiber lamina is transferred to the fibers by a shearing mechanism between fibers and matrix. Since, the matrix has low modulus, the longitudinal strain in the matrix is higher than that in the adjacent fibers. If a perfect bond is assumed between the two constituents, the difference in longitudinal strains creates a shear stress distribution across the fiber–matrix interface. Ignoring the stress transfer at the fiber end cross sections and the interaction between the neighboring fibers, we can calculate the normal stress distribution in a discontinuous fiber by a simple force equilibrium analysis.

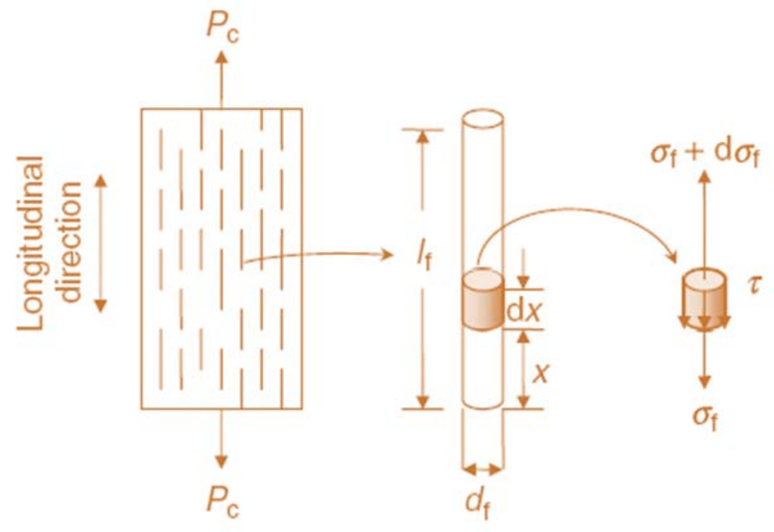


Figure 3.24 stress distribution on short fiber

Consider an infinitesimal length dx at a distance x from one of the fiber ends. The force equilibrium equation for this length is

$$(\pi r^2)\sigma_f + (2\pi r\ dz)\tau = (\pi r^2)(\sigma_f + d\sigma_f) \qquad (3.193)$$

which on simplification gives

$$\frac{d\sigma_f}{dz} = \frac{2\tau}{r} \qquad (3.194)$$

where,

σ_f is the fiber stress in the axial direction

τ is the shear stress on the cylindrical fiber-matrix interface

r is the fiber radius

$$\sigma_f = \sigma_{fo} + \frac{2}{r}\int_0^z \tau \, dz \qquad (3.195)$$

where, σ_{fo} is the stress on the fiber end. In many analyses σ_{fo} is neglected because of yielding of the matrix adjacent to the fiber end or separation of the fiber end from the matrix as a result of large stress concentrations. Therefore,

$$\sigma_f = \frac{2}{r}\int_0^z \tau \, dz = \frac{2\tau_z}{r} \qquad (3.196)$$

The maximum fiber stress occurs at the midfiber length, *i.e.*, at $z = \frac{l}{2}$

$$(\sigma_f)_{\max} = \frac{\tau l}{r} \qquad (3.197)$$

Based on the assumption that the strains in fibers, matrix and composite are equal, the maximum fiber stress $(\sigma_f)_{\max}$ is limited as given below.

$$\varepsilon_c = \varepsilon_f \qquad (3.198)$$

$$\frac{(\sigma_f)_{\max}}{E_f} = \frac{\sigma_c}{E_c} \qquad (3.199)$$

$$(\sigma_f)_{\max} = \frac{E_f}{E_c}\sigma_c \qquad (3.200)$$

The minimum fiber length may be defined as a load-transfer length in which the maximum fiber stress, $\sigma_{f,\max}$ can be achieved on the application of the external load, σ_c .

The minimum fiber length, $l_t = \frac{\sigma_{f,\max}}{\tau}\frac{d}{2} = \frac{\left(E_f/(E_c)\sigma c^d\right)}{2\tau}$ (3.201)

where, ‘d’ is the diameter of the fiber

The critical fiber length may be defined as the minimum fiber length in which the maximum allowable fiber stress or the fiber ultimate strength, σ_u can be achieved.

The critical fiber length, $l_c = \frac{\sigma_f u}{\tau}\frac{d}{2}$ (3.202)

Thus the minimum fiber length, l_t, is based on the applied stress, σ_c, whereas the critical fiber length, l_c, is independent of applied stress, σ_c.

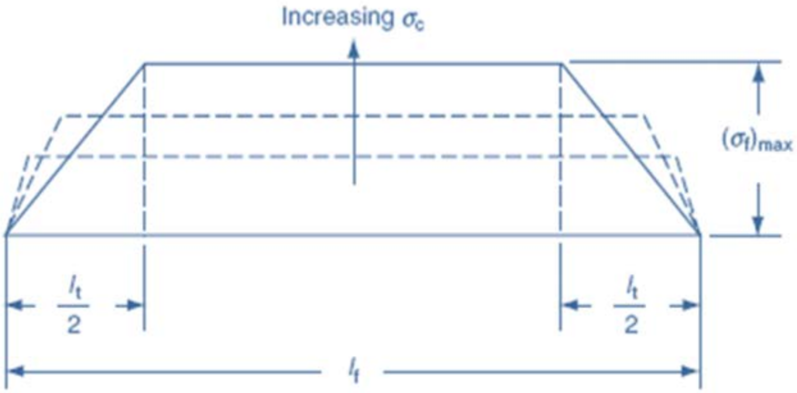


Figure 3.25a stress on short fiber

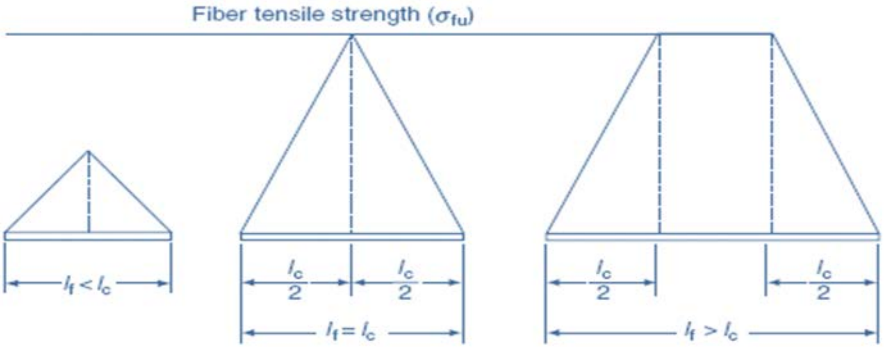


Figure 3.25b Variations of fiber stress for different fiber lengths

From the figure 3.25, the following points are deduced.

(i) For $l_f < l_c$, the maximum fiber stress may never reach the ultimate fiber strength. In this case, either the fiber–matrix interfacial bond or the matrix may fail before fibers achieve their ultimate strength.

(ii) For $l_f > l_c$, the maximum fiber stress may reach the ultimate fiber strength over much of its length. However, over a distance equal to l_c /2 from each end, the fiber remains less effective.

(iii) For effective fiber reinforcement, that is, for using the fiber to its ultimate strength, one must select $l_f >> l_c$.

(iv) For a given fiber diameter and strength, l_c can be controlled by increasing or decreasing τ. For example, a matrix-compatible coupling agent may increase τ, which in turn decreases l_c. If l_c can be reduced relative to l_f through proper fiber surface treatments, effective reinforcement can be achieved without changing the fiber length.

Prediction of Modulus of short fibers:

The Halpin-Tsai equations provide the way to calculate various moduli of aligned short-fiber composites.

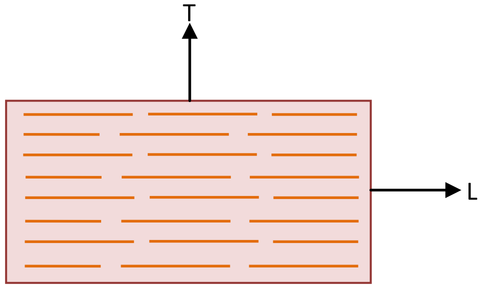


Figure 3.26 Model of an aligned short-fiber compsite

$$E_L = \frac{1+2\left(\frac{l_f}{d_f}\right)\eta_L V_f}{1-\eta_L V_f} E_m \qquad (3.203)$$

$$E_T = \frac{1+2\eta_T V_f}{1-\eta_T V_f} E_m \qquad (3.204)$$

$$G_{LT} = \frac{1+\eta_G V_f}{1-\eta_G V_f} G_m \qquad (3.205)$$

$$\nu_{LT} = V_f \nu_f + V_m \nu_m \qquad (3.206)$$

where,

$$\eta_L = \frac{E_f / E_m - 1}{\frac{E_f}{E_m} + 2\left(\frac{l_f}{d_f}\right)} \qquad (3.207)$$

$$\eta_T = \frac{E_f / E_m - 1}{E_f / E_m + 2} \qquad (3.208)$$

$$\eta_G = \frac{G_f / G_m - 1}{G_f / G_m + 1} \qquad (3.209)$$

The short fiber composite with random orientation produces the composite with isotropic behaviour in a plane. To predict the elastic moduli of such randomly oriented composites, the empirical formulae given below are used.

$$E_{random} = \frac{3}{8}E_L + \frac{5}{8}E_T \tag{3.210}$$

$$G_{random} = \frac{1}{8}E_L + \frac{1}{4}E_T \tag{3.211}$$

$$\nu_{random} = \frac{E_{random}}{G_{random}} - 1 \tag{3.212}$$

Lecture 21 and 22

Problems (Module III):

Problem 3.1: Calculate the fraction of load carried by the fibers of glass-epoxy composites with 30% fibers by volume. Elastic moduli of glass fibers and epoxy resin are 70 and 3.5 GPa respectively.

Solution:

The formula for the load shared by fibers is given by,

$$\frac{P_f}{P_c} = \frac{E_f / E_m}{\left(E_f / E_m + \left(\frac{V_m}{V_f}\right)\right)} \tag{3.213}$$

V_f (given) = 0.30

V_m = 1 - V_f = 1 - 0.30

= 0.70

E_f (given) = 70 GPa

E_m(given) = 3.5 GPa

$$\frac{P_f}{P_c} = \frac{70/3.5}{\left(70/3.5 + (0.7/0.3)\right)} \tag{3.214}$$

$$= 0.90$$

Therefore, the fiber carries 90 % of the total load applied to the composite. If the volume fraction of fiber is increased, then the composite will carry more load. But, there is a limit for the maximum volume fraction of fiber, practically around 70%. If the volume fraction of fiber is more, then the entire fibers could not be wetted properly due to less amount of matrix.

Problem 3.2 : Calculate the elastic constants for the composite that consists of randomly distributed short glass fibers 60% by weight. The diameter and the length of the fiber used are 2.5 mm and 25 mm respectively. The Epoxy resin is used as matrix. Assume the necessary data if not given.

<u>Solution:</u>

As the fibers are short and distributed randomly, the Halpin-Tsai equations will be used to determine the young's modulus, shear modulus and Poisson's ratio.

<u>Data given</u>

E_f = 70 GPa (assumed)
E_m = 3.5 GPa (assumed)
ρ_f = 2.5 g/cm^3 (assumed)
ρ_m = 1.2 g/cm^3 (assumed)
l_f = 25 mm (given)
d_f = 2.5 mm (given)
w_f = 0.60 (given)

The equations used for determining young's modulus for a unidirectional lamina is given by

$$E_{11} = \frac{1+2\left(l_f / d_f\right)\eta_L V_f}{1-\eta_L V_f} E_m \qquad (3.215)$$

$$E_{22} = \frac{1+2\eta_T V_f}{1-\eta_T V_f} E_m \qquad (3.216)$$

Therefore, it is necessary to calculate the volume fraction of fibers, V_f , the coefficients η_L and η_T.

$$V_f = \frac{\dfrac{W_f}{\rho_f}}{\left(\dfrac{W_f}{\rho_f}\right)+\left(\dfrac{W_m}{\rho_m}\right)} \quad (3.217)$$

$$W_m = 1 - W_f = 1 - 0.60 \quad (3.218)$$

$$= 0.40$$

$$V_f = \frac{\dfrac{0.6}{2.5}}{\left(\dfrac{0.6}{2.5}\right)+\left(\dfrac{0.4}{1.2}\right)} \quad (3.219)$$

$$= 0.42$$

$$\eta_L = \frac{\left(E_f / E_m\right)-1}{\left(E_f / E_m\right)+2\left(l_f / d_f\right)} \quad (3.220)$$

$$= \frac{\left({}^{70}/_{3.5}\right)-1}{\left({}^{70}/_{3.5}\right)+2\left({}^{25}/_{2.5}\right)}$$

$$= 0.475$$

$$\eta_T = \frac{\left(E_f / E_m\right)-1}{\left(E_f / E_m\right)+2} \quad (3.221)$$

$$= \frac{\left({}^{70}/_{3.5}\right)-1}{\left({}^{70}/_{3.5}\right)+2}$$

$$= 0.864$$

Therefore,

$$E_{11} = \frac{1+2\left(25/2.5\right)*0.475*0.42}{1-0.475*0.42}*3.5 \quad (3.222)$$

$$= 21.82 \text{ GPa}$$

$$E_{22} = \frac{1+2*0.864*0.42}{1-0.864*0.42}*3.5 \quad (3.223)$$

$$= 9.48 \text{ GPa}$$

The equations of elastic constants for randomly oriented short fibers are given by:

$$E_{random} = \frac{3}{8}E_{11} + \frac{5}{8}E_{22} \quad (3.224)$$

$$G_{random} = \frac{1}{8}E_{11} + \frac{1}{4}E_{22} \quad (3.225)$$

$$\nu_{random} = \frac{E_{random}}{2G_{random}} - 1 \quad (3.226)$$

Therefore,

$$E_{random} = \frac{3}{8}*21.82 + \frac{5}{8}*9.48 \quad (3.227)$$

= 14.11 GPa

$$G_{random} = \frac{1}{8}*21.82 + \frac{1}{4}*9.48 \quad (3.228)$$

= 5.10 GPa

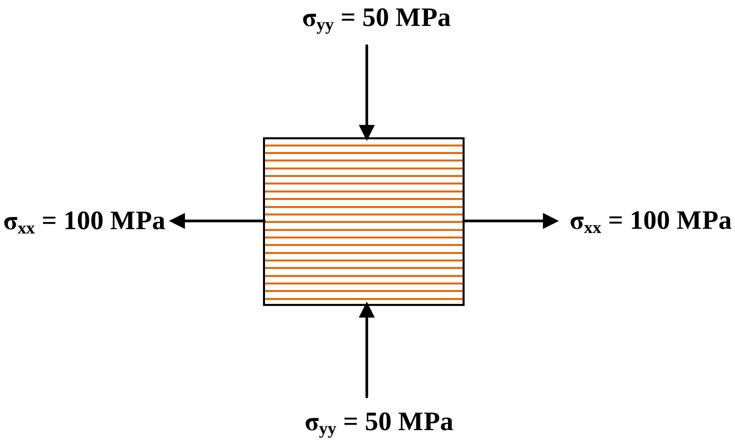
$$\nu_{random} = \frac{14.11}{2*5.10} - 1 \quad (3.229)$$

= 0.383

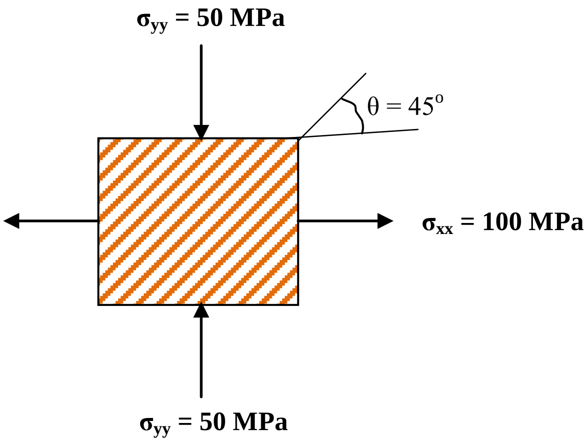
Problem 3.3 : Calculate the strains in the xy directions for the composite subjected to the loading as shown in the figure. The composite is made of boron-epoxy. Take the data given for 0^o unidirectional E-glass-epoxy as:

E_{11} = 200 GPa; E_{22} = 20 GPa;

G_{12} = 6.5 GPa; ν_{12} = 0.2;



case (a)



case (b)

Solution:

case (a): It is a 0^o unidirectional composite. Therefore, it is a specially orthotropic lamina.

The strains experienced by the composite are given by,

$$\varepsilon_{XX} = \varepsilon_{11} = \frac{\sigma_{XX}}{E_{11}} - \nu_{21}\frac{\sigma_{yy}}{E_{22}} \quad (3.230)$$

$$\varepsilon_{yy} = \varepsilon_{22} = \frac{\sigma_{yy}}{E_{22}} - \nu_{12}\frac{\sigma_{XX}}{E_{11}} \quad (3.231)$$

$$\gamma_{Xy} = \gamma_{yx} = \gamma_{12} = \gamma_{21} = \frac{\tau_{Xy}}{G_{12}} \quad (3.232)$$

Data given:

σ_{xx} = 100 MPa (3.233)

σ_{yy} = - 50 MPa (Compression) (3.234)

τ_{xy} = 0

ν_{21} may be calculated from,

$$\nu_{21} = \nu_{12}\frac{E_{22}}{E_{11}} \quad (3.235)$$

$$\nu_{21} = 0.2 * \frac{20}{200}$$

$$= 0.02$$

Therefore, $$\varepsilon_{Xx} = \frac{100\times10^{-3}}{200} - 0.02*\frac{-50\times10^{-3}}{20} \qquad (3.236)$$

$$= 0.55 \times 10^{-3}$$

$$\varepsilon_{yy} = \frac{-50\times10^{-3}}{20} - 0.2*\frac{100\times10^{-3}}{200} \qquad (3.237)$$

$$= -2.6 \times 10^{-3}$$

$$\gamma_{Xy} = \frac{0}{G_{12}} \qquad (3.238)$$

$$= 0$$

<u>case (b):</u> It is a 45° unidirectional composite loaded in the x and y direction, not along the principal material directions. Therefore, it is a generally orthotropic case.

The elastic constants are calculated first using,

$$\frac{1}{E_x} = \frac{\cos^4\theta}{E_L} + \frac{\sin^4\theta}{E_T} + \frac{1}{4}\left(\frac{1}{G_{LT}} - \frac{2\nu_{LT}}{E_L}\right)\sin^2 2\theta \qquad (3.239)$$

$$\frac{1}{E_y} = \frac{\sin^4\theta}{E_L} + \frac{\cos^4\theta}{E_T} + \frac{1}{4}\left(\frac{1}{G_{LT}} - \frac{2\nu_{LT}}{E_L}\right)\sin^2 2\theta \qquad (3.240)$$

$$\frac{\nu_{xy}}{E_x} = \frac{\nu_{LT}}{E_L} - \frac{1}{4}\left(\frac{1}{E_L} + \frac{1}{E_T} + \frac{2\nu_{LT}}{E_L} - \frac{1}{G_{LT}}\right)\sin^2 2\theta \qquad (3.241)$$

$$\frac{\nu_{yx}}{E_y} = \frac{\nu_{TL}}{E_T} - \frac{1}{4}\left(\frac{1}{E_L} + \frac{1}{E_T} + \frac{2\nu_{LT}}{E_L} - \frac{1}{G_{LT}}\right)\sin^2 2\theta \qquad (3.242)$$

Therefore, $E_x = 10.34$ GPa

$E_y = 10.34$ GPa (3.243)

$\nu_{xy} = \nu_{yx} = 0.26$

The coefficients of mutual influence are calculated using,

$$m_x = \sin 2\theta\left[\nu_{LT} + \frac{E_L}{E_T} - \frac{E_L}{2G_{LT}} - \cos^2\theta\left(1 + 2\nu_{LT} + \frac{E_L}{E_T} - \frac{E_L}{G_{LT}}\right)\right] \qquad (3.244)$$

$$m_y = \sin 2\theta\left[\nu_{LT} + \frac{E_L}{E_T} - \frac{E_L}{2G_{LT}} - \sin^2\theta\left(1 + 2\nu_{LT} + \frac{E_L}{E_T} - \frac{E_L}{G_{LT}}\right)\right] \qquad (3.245)$$

$m_x = m_y = 4.5$

The strains are calculated using the equations:

$$\varepsilon_x = \frac{\sigma_x}{E_x} - \nu_{yx}\frac{\sigma_y}{E_y} - m_x\frac{\tau_{xy}}{E_L} \qquad (3.246)$$

$$\varepsilon_y = \frac{\sigma_y}{E_y} - \nu_{xy}\frac{\sigma_x}{E_x} - m_y\frac{\tau_{xy}}{E_L} \qquad (3.247)$$

$$\gamma_{xy} = \frac{\tau_{xy}}{G_{xy}} - m_x\frac{\sigma_x}{E_L} - m_y\frac{\sigma_y}{E_L} \qquad (3.248)$$

$$\varepsilon_x = \frac{100\times10^{-3}}{10.34} - 0.02 * \frac{-50\times10^{-3}}{10.34} - m_x\frac{0}{E_L} \qquad (3.249)$$

$= 9.768 \text{ x } 10^{-3}$

$$\varepsilon_y = \frac{-50\times10^{-3}}{10.34} - 0.2 * \frac{100\times10^{-3}}{10.34} - m_y\frac{0}{E_L} \qquad (3.250)$$

$= - 6.770 \text{ x } 10^{-3}$

$$\gamma_{xy} = \frac{0}{G_{xy}} - 4.5 * \frac{100\times10^{-3}}{10.34} - 4.5 * \frac{-50\times10^{-3}}{10.34} \qquad (3.251)$$

$= - 43.30 \text{ x } 10^{-3}$

Problem 3.4: Determine the stiffness matrix for an angle-ply graphite-epoxy lamina containing 50% volume of fibers. Take the following engineering constants for the composite. Consider the fiber orientation angles of both 0^o and 45^o.

E_f = 230 GPa E_m =3.5 GPa ν_f = 0.2 ν_m = 0.3

Solution:

As the engineering constants of the composite are not directly given, they are to be determined using the rule of mixtures.

V_f = 0.50 (given)

$$E_c = E_{11} = E_f{*}V_f + E_m{*}V_m \qquad (3.252)$$

$= 230{*}0.5 + 3.5{*}(1 - 0.5)$

= 116.75 GPa

$$E_{22} = \frac{E_f * E_m}{E_f * V_m + E_m * V_f} \tag{3.253}$$

$$= \frac{230 * 3.5}{230 * (1 - 0.5) + 3.5 * 0.5}$$

= 6.90 GPa

$$\nu_{12} = \nu_f * V_f + \nu_m * V_m \tag{3.254}$$

= 0.2 * 0.5 + 0.3 * (1- 0.5)

= 0.25

$$\nu_{21} = \frac{E_{22}}{E_{11}} \nu_{12} \tag{3.255}$$

$$= \frac{6.90}{116.75} * 0.25$$

= 0.015

As the values of G_f and G_m are not given, in order to calculate G_{12}, G_f and G_m are determined based isotropic relationship as follows:

$$G_f = \frac{E_f}{2(1+\nu_f)} \tag{3.256}$$

$$= \frac{230}{2(1 + 0.2)}$$

= 95.83 GPa

$$G_m = \frac{E_m}{2(1+\nu_m)} \tag{3.257}$$

$$G_m = \frac{3.5}{2(1+0.3)}$$

= 1.35 GPa

Therefore, $$G_{12} = \frac{G_f * G_m}{G_f * V_m + G_m * V_f} \qquad (3.258)$$

$$= \frac{95.83 * 1.35}{95.83 * (1 - 0.5) + 1.35 * 0.5}$$

= 2.66 GPa

Case (a) 0^o lamina

As the fiber orientation angle is 0^o, it is a specially orthotropic case. Elements of the stiffness matrix are obtained from,

$$Q_{11} = \frac{E_{11}}{1 - \nu_{12}\nu_{21}} \qquad (3.259)$$

$$= \frac{116.75}{1 - 0.25 * 0.015}$$

= 117.19 GPa

$$Q_{22} = \frac{E_{22}}{1 - \nu_{12}\nu_{21}} \qquad (3.260)$$

$$= \frac{6.90}{1 - 0.25 * 0.015}$$

= 6.93 GPa

$$Q_{12} = \frac{\nu_{12} E_{22}}{1 - \nu_{12}\nu_{21}} = \frac{\nu_{21} E_{11}}{1 - \nu_{12}\nu_{21}} \qquad (3.261)$$

$$= \frac{0.25 * 6.90}{1 - 0.25 * 0.015}$$

= 1.73 GPa

$$Q_{66} = G_{LT} \qquad (3.262)$$

= 2.66 GPa

The stiffness matrix for 0^o lamina is given by

$$[Q] = \begin{bmatrix} 117.19 & 1.73 & 0 \\ 1.73 & 6.93 & 0 \\ 0 & 0 & 2.66 \end{bmatrix} \text{GPa}$$

The compliance matrix can be obtained by inversing the stiffness matrix,

$$[S] = [Q]^{-1} = \begin{pmatrix} 8.5 & -2.125 & 0 \\ -2.125 & 144.83 & 0 \\ 0 & 0 & 375.94 \end{pmatrix} \times 10^{-3} \ \text{GPa -1}$$

Case (b) 45^o lamina

As the fiber orientation angle is 45^o, the lamina will experience the generally orthotropic behaviour. The elements of the transformed reduced stiffness matrix are obtained as,

$$\begin{aligned}
\bar{Q}_{11} &= Q_{11}\cos^4\theta + Q_{22}\sin^4\theta + 2(Q_{12} + 2Q_{66})\sin^2\theta\cos^2\theta \\
\bar{Q}_{22} &= Q_{11}\sin^4\theta + Q_{22}\cos^4\theta + 2(Q_{12} + 2Q_{66})\sin^2\theta\cos^2\theta \\
\bar{Q}_{12} &= (Q_{11} + Q_{22} - 4Q_{66})\sin^2\theta\cos^2\theta + Q_{12}\left(\sin^4\theta + \cos^4\theta\right) \\
\bar{Q}_{16} &= (Q_{11} - Q_{12} - 2Q_{66})\sin\theta\cos^2\theta - (Q_{22} - Q_{12} - 2Q_{66})\sin^2\theta\cos\theta \\
\bar{Q}_{26} &= (Q_{11} - Q_{12} - 2Q_{66})\sin^2\theta\cos\theta - (Q_{22} - Q_{12} - 2Q_{66})\sin\theta\cos^2\theta \\
\bar{Q}_{66} &= (Q_{11} + Q_{22} - 2Q_{12} - 2Q_{66})\sin^2\theta\cos^2\theta + Q_{66}\left(\sin^4\theta + \cos^4\theta\right)
\end{aligned} \qquad (3.263)$$

Therefore,

$$\bar{Q}_{11} = 117.19 * \cos^4 45^\circ + 6.93\sin^4 45^\circ + 2(1.73 + 2*2.66)\sin^2 45^\circ \cos^2 45^\circ$$

$$= 34.56 \text{ GPa}$$

$$\bar{Q}_{22} = 117.19*\sin^4 45^\circ + 6.93\cos^4 45^\circ + 2(1.73 + 2*2.66)\sin^2 45^\circ \cos^2 45^\circ$$

$$= 34.56 \text{ GPa}$$

$$\overline{Q_{12}} = (117.19 + 6.93 - 4*2.66)\sin^2 45^\circ \cos^2 45^\circ + 1.73\left(\sin^4 45^\circ + \cos^4 45^\circ\right)$$

$$= 29.24 \text{ GPa}$$

$$\overline{Q}_{16} = \left(117.19 - 1.73 - 2*2.66\right)\sin 45^\circ \cos^2 45^\circ$$

$$-\left(6.93 - 1.73 - 2*2.66\right)\sin^3 45^\circ \cos 45^\circ$$

$$= 27.57 \text{ GPa}$$

$$\overline{Q_{26}} = \left(117.19 - 1.73 - 2*2.66\right)\sin^3 45^\circ \cos 45^\circ$$
$$-\left(6.93 - 1.73 - 2*2.66\right)\sin 45^\circ \cos^3 45^\circ$$

$$= 27.57 \text{ GPa}$$

$$\overline{Q}_{66} = \left(117.19 + 6.93 - 2*1.73 - 2*2.66\right)\sin^2 45^\circ \cos^2 45^\circ$$

$$+2.66\left(\sin^4 45^\circ + \cos^4 45^\circ\right) \qquad (3.264)$$

$$= 31.50 \text{ GPa}$$

The transformed reduced stiffness matrix for 45^o lamina is given by

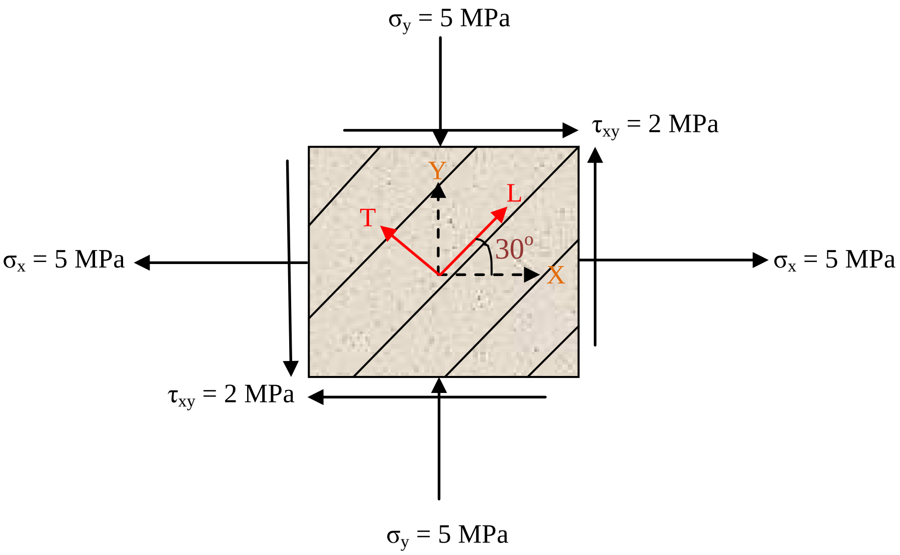
$$[\bar{Q}] = \begin{bmatrix} 34.56 & 29.24 & 27.57 \\ 29.24 & 34.56 & 27.57 \\ 27.57 & 27.57 & 31.50 \end{bmatrix} \text{GPa}$$

As expected the stiffness matrix for 45^o lamina contains all non-zero elements.

Problem 3.5: Find the stresses and strains in both the principal material directions and the reference directions (xy) for the lamina shown in the figure. The engineering constants for the lamina may be taken as:

E_L = 13.8 GPa E_T = 3.35 GPa G_{LT} = 4.12 GPa

ν_{LT} = 0.36 ν_{TL} = 0.087



Solution:

Data given:

$\sigma_x = 5$ MPa

$\sigma_y = -5$ MPa

$\tau_{xy} = 2$ MPa

The stresses along the principal material directions can be determined using stress transformation formula given by,

$$\begin{Bmatrix} \sigma_L \\ \sigma_T \\ \tau_{LT} \end{Bmatrix} = \begin{bmatrix} \cos^2\theta & \sin^2\theta & 2\sin\theta\cos\theta \\ \sin^2\theta & \cos^2\theta & -2\sin\theta\cos\theta \\ -\sin\theta\cos\theta & \sin\theta\cos\theta & \cos^2\theta - \sin^2\theta \end{bmatrix} \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} \tag{3.265}$$

For $\theta = 30^o$

$$\begin{Bmatrix} \sigma_L \\ \sigma_T \\ \tau_{LT} \end{Bmatrix} = \begin{bmatrix} 0.75 & 0.25 & 0.866 \\ 0.25 & 0.75 & -0.866 \\ -0.433 & 0.433 & 0.5 \end{bmatrix} \begin{Bmatrix} 5 \\ -5 \\ 2 \end{Bmatrix}$$

$\sigma_L = 4.23$ MPa

$\sigma_T = -4.23$ MPa

$\tau_{LT} = -3.33$ MPa

The strains along the principal material directions can be determined from the strain-stress relations:

$$\varepsilon_L = \frac{\sigma_L}{E_L} - \nu_{TL}\frac{\sigma_T}{E_T} \tag{3.266}$$

$$= \frac{4.23}{13.8\times10^3} - 0.087*\frac{-4.23}{3.35\times10^3}$$

$$= 4.164 \text{ x } 10^{-4}$$

$$\varepsilon_T = \frac{\sigma_T}{E_T} - \nu_{\mathbf{LT}}\frac{\sigma_L}{E_L} \tag{3.267}$$

$$\varepsilon_T = \frac{-4.23}{3.35\times10^3} - 0.36*\frac{4.23}{13.8\times10^3}$$

$$= -13.73 \text{ x } 10^{-4}$$

$$\gamma_{LT} = \frac{\tau_{LT}}{G_{LT}} \tag{3.268}$$

$$\gamma_{LT} = \frac{-3.33}{4.12\times10^3}$$

$$= -8.083 \text{ x } 10^{-4}$$

Now, the strains along the xy directions can be calculated from the strain transformation law.

$$\begin{Bmatrix}\varepsilon_x\\ \varepsilon_y\\ \gamma_{xy}\end{Bmatrix} = \begin{bmatrix}\cos^2\theta & \sin^2\theta & -\sin\theta\cos\theta\\ \sin^2\theta & \cos^2\theta & \sin\theta\cos\theta\\ 2\sin\theta\cos\theta & -2\sin\theta\cos\theta & \cos^2\theta - \sin^2\theta\end{bmatrix}\begin{Bmatrix}\varepsilon_L\\ \varepsilon_T\\ \gamma_{LT}\end{Bmatrix} \tag{3.269}$$

For θ = 30^o

$$\begin{Bmatrix}\varepsilon_x\\ \varepsilon_y\\ \gamma_{xy}\end{Bmatrix} = \begin{bmatrix}0.75 & 0.25 & -0.433\\ 0.25 & 0.75 & 0.433\\ 0.866 & -0.866 & 0.5\end{bmatrix}\begin{Bmatrix}4.164\times10^{-4}\\ -13.73\times10^{-4}\\ -8.083\times10^{-4}\end{Bmatrix}$$

$$\varepsilon_x = 3.19 \text{ x } 10^{-4}$$

$$\varepsilon_y = -12.76 \text{ x } 10^{-4}$$

$$\gamma_{xy} = 11.45 \text{ x } 10^{-4}$$

Problem 3.6: A shear stress τ_{xy} = -15 MPa is applied on a unidirectional angle-ply lamina. The fibers are at 45^o to the x-axis. Calculate the stresses in the principal material directions.

Solution:

As $\sigma_x = \sigma_y = 0$, the stress transformation equations become,

$$\sigma_L = \sigma_x \cos^2\theta + \sigma_y \sin 2\theta + 2\tau_{\mathrm{Xy}} \sin\theta\cos\theta \qquad (3.270)$$

$$\therefore \sigma_L = 2\tau_{\mathrm{Xy}} \sin\theta\cos\theta \qquad (3.271)$$

$$= 2*(-15)\sin 45^\circ \cos 45^\circ$$

$$= -15\ MPa$$

$$\sigma_T = \sigma_x \sin^2\theta + \sigma_y \cos 2\theta - 2\tau_{X\,y} \sin\theta\cos\theta \qquad (3.272)$$

$$\therefore \sigma_T = -2\tau_{Xy} \sin\theta\cos\theta \qquad (3.273)$$

$$= -2*(-15)\sin 45^\circ \cos 45^\circ$$

$$= 15\ M$$

$$\tau_{LT} = -\sigma_x \sin\theta\cos\theta + \sigma_y \sin\theta\cos\theta + \tau_{xy}(\cos 2\theta - \sin 2\theta) \qquad (3.274)$$

$$\therefore \tau_{LT} = \tau_{Xy}(\cos 2\theta - \sin 2\theta) \qquad (3.275)$$

$$= (-15)\left(\cos 90^\circ - \sin 90^\circ\right)$$

$$= 15$$

From the values found, it is clear that the principal material directions will be the principal stress axes under these loading condition.

References:

1. Robert.M.Jones, “Mechanics of Composite Materials”
2. Autar K Kaw, “Mechanics of Composite Materials”
3. Aircraft Composite materials and Structures – Study material, Sathyabama University

16BTAR_E19 COMPOSITE MATERIALS AND STRUCTURES 3 0 0 3 100

UNIT - III LAMINATED PLATES

Governing differential equation for a general laminate, angle ply and cross ply laminates. Failure criteria for composites.

TEXT BOOKS

T [1] – Jones R.M. (1999), “Mechanics of Composite Materials”, McGraw-Hill, Kogakusha Ltd., Tokyo.

T [2] – N.G.R.Iyengar.(2016), “Composite Materials and Structural Analysis”, viva Books Pvt.Ltd.; First edition., New Delhi.

REFERENCES

R [3] - Autar K.Kaw (2005), “Mechanics of Composite Materials”, Second Edition, CRC press, University of South Florida, Tampa,USA

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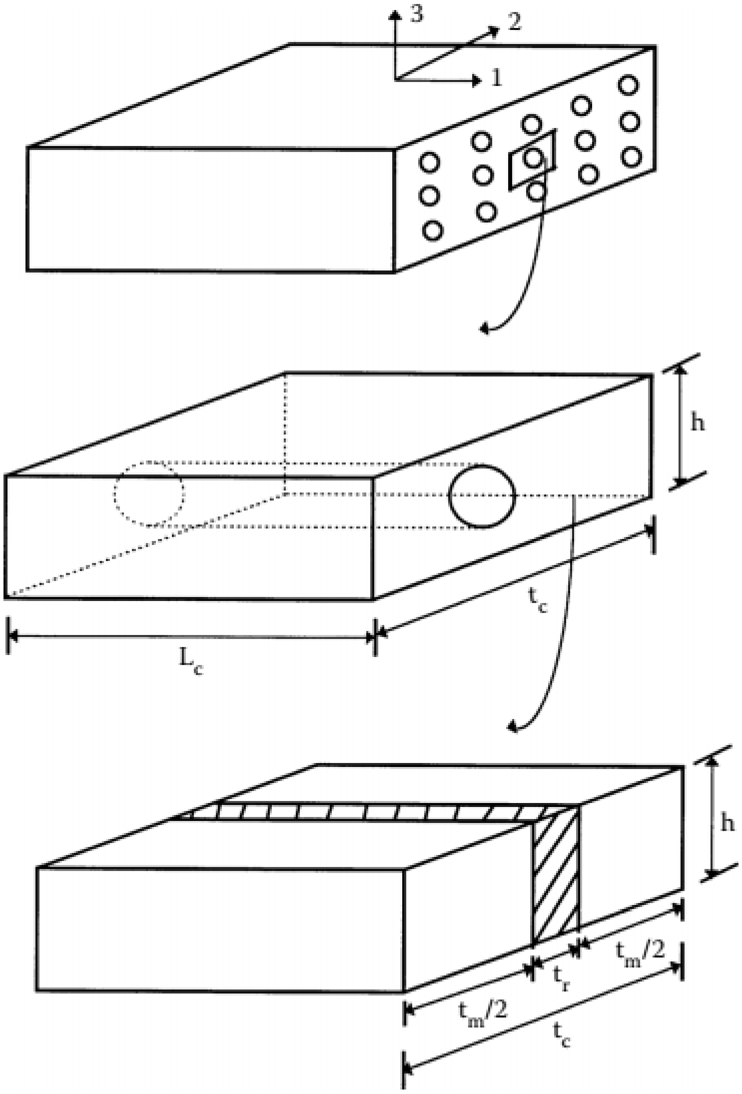
Introduction

The design of a laminated composite structure, such as a flat floor panel or a pressure vessel, starts with the building block of laminae, in which fiber and matrix are combined in a manufacturing process such as filament winding or prepregs. The material of the fiber and matrix, processing factors such as packing arrangements, and fiber volume fraction determine the stiffness, strength, and hygrothermal response of a single lamina. These properties can be found by using the properties of the individual constituents of the lamina or by experiments, Then the laminate can have variations in material systems and in stacking sequence of plies to tailor a composite for a particular application.



First, special cases of laminates that are important in the design of laminated structures will be introduced. Then the failure criterion analysis will be shown for a laminate. Eventually, we will be designing laminates mainly on the basis of optimizing for cost, weight, strength, and stiffness. Other mechanical design issues are briefly introduced at the end of the chapter.

Special Cases of Laminates

Based on angle, material, and thickness of plies, the symmetry or antisymmetry of a laminate may zero out some elements of the three stiffness matrices [*A*], [*B*], and [*D*]. These are important to study because they may result in reducing or zeroing out the coupling of forces and bending moments, normal and shear forces, or bending and twisting moments. This not only simplifies the mechanical analysis of composites, but also gives desired mechanical performance. For example the analysis of a symmetric laminate is simplified due to the zero coupling matrix [*B*]. Mechanically, symmetric laminates result in no warpage in a flat panel due to temperature changes in processing.

Symmetric Laminates

A laminate is called symmetric if the material, angle, and thickness of plies are the same above and below the midplane. An example of symmetric laminates is $[0/30/60]_s$:

0
30
60
30
0

For symmetric laminates from the definition of [*B*] matrix, it can be proved that [*B*] = 0. Thus, Equation (4.29) can be decoupled to give

$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} \\ A_{12} & A_{22} & A_{26} \\ A_{16} & A_{26} & A_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \end{bmatrix} \tag{5.1a}$$

$$\begin{bmatrix} M_x \\ M_y \\ M_{xy} \end{bmatrix} = \begin{bmatrix} D_{11} & D_{12} & D_{16} \\ D_{12} & D_{22} & D_{26} \\ D_{16} & D_{26} & D_{66} \end{bmatrix} \begin{bmatrix} \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{bmatrix}. \qquad (5.1b)$$

This shows that the force and moment terms are uncoupled. Thus, if a laminate is subjected only to forces, it will have zero midplane curvatures. Similarly, if it is subjected only to moments, it will have zero midplane strains.

The uncoupling between extension and bending in symmetric laminates makes analyzing such laminates simpler. It also prevents a laminate from twisting due to thermal loads, such as cooling down from processing temperatures and temperature fluctuations during use such as in a space shuttle, etc.

Cross-Ply Laminates

A laminate is called a cross-ply laminate (also called laminates with specially orthotropic layers) if only 0 and 90° plies were used to make a laminate. An example of a cross ply laminate is a $[0/90_2/0/90]$ laminate:

0
90
90
0
90

For cross-ply laminates, $A_{16} = 0$, $A_{26} = 0$, $B_{16} = 0$, $B_{26} = 0$, $D_{16} = 0$, and $D_{26} = 0$; thus, Equation (4.29) can be written as

$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \\ M_x \\ M_y \\ M_{xy} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & 0 & B_{11} & B_{12} & 0 \\ A_{12} & A_{22} & 0 & B_{12} & B_{22} & 0 \\ 0 & 0 & A_{66} & 0 & 0 & B_{66} \\ B_{11} & B_{12} & 0 & D_{11} & D_{12} & 0 \\ B_{12} & B_{22} & 0 & D_{12} & D_{22} & 0 \\ 0 & 0 & B_{66} & 0 & 0 & D_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \\ \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{bmatrix}. \qquad (5.2)$$

In these cases, uncoupling occurs between the normal and shear forces, as well as between the bending and twisting moments. If a cross-ply laminate is also symmetric, then in addition to the preceding uncoupling, the coupling matrix $[B] = 0$ and no coupling takes place between the force and moment terms.

Angle Ply Laminates

A laminate is called an angle ply laminate if it has plies of the same material and thickness and only oriented at +θ and –θ directions. An example of an angle ply laminate is [–40/40/–40/40]:

–40
40
–40
40

If a laminate has an even number of plies, then $A_{16} = A_{26} = 0$. However, if the number of plies is odd and it consists of alternating +θ and –θ plies, then it is symmetric, giving $[B] = 0$, and A_{16}, A_{26}, D_{16}, and D_{26} also become small as the number of layers increases for the same laminate thickness. This behavior is similar to the symmetric cross-ply laminates. However, these angle ply laminates have higher shear stiffness and shear strength properties than cross-ply laminates.

ntisymmetric Laminates

A laminate is called antisymmetric if the material and thickness of the plies are the same above and below the midplane, but the ply orientations at the same distance above and below the midplane are negative of each other. An example of an antisymmetric laminate is:

45
60
–60
–45

From Equation (4.28a) and Equation (4.28c), the coupling terms of the extensional stiffness matrix, $A_{16} = A_{26} = 0$, and the coupling terms of the bending stiffness matrix, $D_{16} = D_{26} = 0$:

$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \\ M_x \\ M_y \\ M_{xy} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & 0 & B_{11} & B_{12} & B_{16} \\ A_{12} & A_{22} & 0 & B_{12} & B_{22} & B_{26} \\ 0 & 0 & A_{66} & B_{16} & B_{26} & B_{66} \\ B_{11} & B_{22} & B_{16} & D_{11} & D_{12} & 0 \\ B_{12} & B_{22} & B_{26} & D_{12} & D_{22} & 0 \\ B_{16} & B_{26} & B_{66} & 0 & 0 & D_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \\ \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{bmatrix}. \qquad (5.3)$$

Balanced Laminate

A laminate is balanced if layers at angles other than 0 and 90° occur only as plus and minus pairs of $+\theta$ and $-\theta$. The plus and minus pairs do not need to be adjacent to each other, but the thickness and material of the plus and minus pairs need to be the same. Here, the terms $A_{16} = A_{26} = 0$. An example of a balanced laminate is [30/40/–30/30/–30/–40]:

30
40
–30
30
–30
–40

From Equation (4.28a),

$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \\ M_x \\ M_y \\ M_{xy} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & 0 & B_{11} & B_{12} & B_{16} \\ A_{12} & A_{22} & 0 & B_{12} & B_{22} & B_{26} \\ 0 & 0 & A_{26} & B_{16} & B_{26} & B_{66} \\ B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & D_{16} \\ B_{12} & B_{22} & B_{26} & D_{12} & D_{22} & D_{26} \\ B_{16} & B_{26} & B_{66} & D_{16} & D_{26} & D_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \\ \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{bmatrix}. \qquad (5.4)$$

Quasi-Isotropic Laminates

For a plate of isotropic material with Young's modulus, E, Poisson's ratio, ν, and thickness, h, the three stiffness matrices are

$$[A] = \begin{bmatrix} \dfrac{E}{1-\nu^2} & \dfrac{\nu E}{1-\nu^2} & 0 \\ \dfrac{\nu E}{1-\nu^2} & \dfrac{E}{1-\nu^2} & 0 \\ 0 & 0 & \dfrac{E}{2(1+\nu)} \end{bmatrix} h\,, \qquad (5.5)$$

$$[B] = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \qquad (5.6)$$

$$[D] = \begin{bmatrix} \frac{E}{12(1-\nu^2)} & \frac{\nu E}{12(1-\nu^2)} & 0 \\ \frac{\nu E}{12(1-\nu^2)} & \frac{E}{12(1-\nu^2)} & 0 \\ 0 & 0 & \frac{E}{24(1+\nu)} \end{bmatrix} h^3 . \tag{5.7}$$

A laminate is called quasi-isotropic if its extensional stiffness matrix [A] behaves like that of an isotropic material. This implies not only that $A_{11} = A_{22}$, $A_{16} = A_{26} = 0$, and $A_{66} = \frac{A_{11} - A_{12}}{2}$, but also that these stiffnesses are independent of the angle of rotation of the laminate. The reason for calling such a laminate quasi-isotropic and not isotropic is that the other stiffness matrices, [B] and [D], may not behave like isotropic materials. Examples of quasi-isotropic laminates include [0/±60], $[0/\pm45/90]_s$, and [0/36/72/–36/–72].

Example

A [0/±60] graphite/epoxy laminate is quasi-isotropic. Find the three stiffness matrices [A], [B], and [D] and show that

1. $A_{11} = A_{22}$; $A_{16} = A_{26} = 0$; $A_{66} = \frac{A_{11} - A_{12}}{2}$.
2. $[B] \neq 0$, unlike isotropic materials.
3. [D] matrix is unlike isotropic materials.

Use properties of unidirectional graphite/epoxy lamina from Table 2.1. Each lamina has a thickness of 5 mm.

Solution

From Example 2.6, the reduced stiffness matrix [Q] for the 0° graphite/epoxy lamina is

$$[Q] = \begin{bmatrix} 181.8 & 2.897 & 0 \\ 2.897 & 10.35 & 0 \\ 0 & 0 & 7.17 \end{bmatrix} (10^9)\ Pa .$$

From Equation (2.104), the transformed reduced stiffness matrices for the three plies are

$$[\bar{Q}]_0 = \begin{bmatrix} 181.8 & 2.897 & 0 \\ 2.897 & 10.35 & 0 \\ 0 & 0 & 7.17 \end{bmatrix} (10^9)\ Pa\ ,$$

$$[\bar{Q}]_{60} = \begin{bmatrix} 23.65 & 32.46 & 20.05 \\ 32.46 & 109.4 & 54.19 \\ 20.05 & 54.19 & 36.74 \end{bmatrix} (10^9)\ Pa\ ,$$

$$[\bar{Q}]_{-60} = \begin{bmatrix} 23.65 & 32.46 & -20.05 \\ 32.46 & 109.4 & -54.19 \\ -20.05 & -54.19 & 36.74 \end{bmatrix} (10^9)\ Pa.$$

The total thickness of the laminate is $h = (0.005)(3) = 0.015$ m.

The midplane is 0.0075 m from the top and bottom of the laminate. Thus, using Equation (4.20),

$$h_0 = -0.0075 \text{ m}$$

$$h_1 = -0.0025 \text{ m}$$

$$h_2 = 0.0025 \text{ m}$$

$$h_3 = 0.0075 \text{ m}$$

Using Equation (4.28a) to Equation (4.28c), one can now calculate the stiffness matrices [*A*], [*B*], and [*D*], respectively, as shown in Example 4.2:

$$[A] = \begin{bmatrix} 1.146 & 0.3391 & 0 \\ 0.3391 & 1.146 & 0 \\ 0 & 0 & 0.4032 \end{bmatrix} (10^9)\ Pa\text{-}m\ ,$$

$$[B] = \begin{bmatrix} -3.954 & 0.7391 & -0.5013 \\ 0.7391 & 2.476 & -1.355 \\ -0.5013 & -1.355 & 0.7391 \end{bmatrix} (10^6)\ Pa\text{-}m^2\ ,$$

$$[D] = \begin{bmatrix} 28.07 & 5.126 & -2.507 \\ 5.126 & 17.35 & -6.774 \\ -2.507 & -6.774 & 6.328 \end{bmatrix} (10^3)\ Pa\text{-}m^3 .$$

1. From the extensional stiffness matrix $[A]$,

$$A_{11} = A_{22} = 1.146 \times 10^9\ \ Pa\text{-}m$$

$$A_{16} = A_{26} = 0$$

$$\frac{A_{11} - A_{12}}{2} = \frac{1.146 - 0.3391}{2} \times 10^9$$

$$= 0.4032 \times 10^9\ Pa\text{-}m$$

$$= A_{66}.$$

   This behavior is similar to that of an isotropic material. However, a quasi-isotropic laminate should give the same $[A]$ matrix, if a constant angle is added to each of the layers of the laminate. For example, adding 30° to each ply angle of the [0/±60] laminate gives a [30/90/–30] laminate, which has the same $[A]$ matrix as the [0/±60] laminate.
2. Unlike isotropic materials, the coupling stiffness matrix $[B]$ of the [0/±60] laminate is nonzero.
3. In an isotropic material,

$$D_{11} = D_{22}\ ,$$

$$D_{16} = D_{26} = 0\ ,$$

   and

$$D_{66} = \frac{D_{11} - D_{12}}{2}\ .$$

   In this example, unlike isotropic materials, $D_{11} \neq D_{22}$ because

$$D_{11} = 28.07 \times 10^3\ Pa\text{-}m^3$$

$$D_{22} = 17.35 \times 10^3 \ Pa\text{-}m^3$$

$$D_{16} \neq 0, \ D_{26} \neq 0 \text{ as}$$

$$D_{16} = -2.507 \times 10^3 \ Pa\text{-}m^3$$

$$D_{26} = -6.774 \times 10^3 \ Pa\text{-}m^3$$

$$\frac{D_{11} - D_{12}}{2} \neq D_{66}$$

because

$$\frac{D_{11} - D_{12}}{2} = \frac{28.07 \times 10^3 - 5.126 \times 10^3}{2}$$

$$= 11.47 \times 10^3 \ Pa\text{-}m^3$$

$$D_{66} = 6.328 \times 10^3 \ Pa\text{-}m^3.$$

One can make a quasi-isotropic laminate by having a laminate with N ($N \geq 3$) lamina of the same material and thickness, where each lamina is oriented at an angle of 180°/N between each other. For example, a three-ply laminate will require the laminae to be oriented at 180°/3 = 60° to each other. Thus, [0/60/–60], [30/90/–30], and [45/–75/–15] are all quasi-isotropic laminates. One can make the preceding combinations symmetric or repeated to give quasi-isotropic laminates, such as $[0/\pm60]_s$, $[0/\pm60]_s$, and $[0/\pm60]_{2s}$ laminates. The symmetry of the laminates zeros out the coupling matrix [B] and makes its behavior closer (not same) to that of an isotropic material.

Design of a Laminated Composite

Because we have developed the laminated plate theory for composites subjected to in-plane mechanical loads, temperature, and moisture, the designs in this chapter are also limited to such loads and simple shapes. Factors not covered in this section include stability; out-of plane loads; and fracture, impact, and fatigue resistance; interlaminar strength; damping characteristics; vibration control; and complex shapes. These factors are introduced briefly

Design of laminated composites includes constraints on optimizing and constraining factors such as

- Cost
- Mass as related to aerospace and automotive industry to reduce energy cost
- Stiffness (to limit deformations) as related to aircraft skins to avoid buckling
- Thermal and moisture expansion coefficients as related to space antennas to maintain dimensional stability

These factors are similar to those used with designing with monolithic materials; thus, the main issue with designing with composites as opposed to monolithic materials involves understanding the orthotropic nature of composite plies.

The possibility of different fiber-matrix systems combined with the variables such as fiber volume fraction first dictate the properties of a lamina. Then, laminae can be placed at angles and at particular distances from the midplane in the laminate. The material systems and the stacking sequence then determine the stresses and strains in the laminate. The failure of the composite may be based on the first ply failure (FPF) or the last ply failure (LPF). Although one may think that all plies failing at the same time is an ideal laminate, others may argue that differences between the two give time for detection and repair or replacement of the part.

Laminate selection is a computationally intensive and repetitive task due to the many possibilities of fiber-matrix combinations, material systems, and stacking sequence. Computer programs have made these calculations easy and the reader is directed to use the PROMAL[2] program included in this book or any other equivalent program of choice to fully appreciate designing with composites. A more scientific approach to optimization of laminated composites is out of scope of this book, and the reader is referred to Gurdal et al.[3]

Example

1. An electronic device uses an aluminum plate of cross-section 4 in. × 4 in. to take a pure bending moment of 13,000 lb-in. The factor of safety is 2. Using the properties of aluminum given in Table 3.4, find the thickness of the plate.

Solution

1. The maximum normal stress in a plate under bending is given by

$$\sigma = \pm \frac{M\frac{t}{2}}{I}, \tag{5.20}$$

where

M = bending moment (lb-in.)
t = thickness of plate (in.)
I = second moment of area (in.^{4})

For a rectangular cross-section, the second moment of area is

$$I = \frac{bt^3}{12}, \tag{5.21}$$

where b = width of plate (in.).

Using the given factor of safety, $F_s = 2$, and given $b = 4$ in., the thickness of the plate using the maximum stress criterion is

$$t = \sqrt{\frac{6MF_s}{b\sigma_{ult}}}, \tag{5.22}$$

where σ_{ult} = 40.02 Ksi from Table 3.4

$$t = \sqrt{\frac{6(13000)2}{4(40.02)10^3}}$$

$$= 0.9872 \ in.$$

2. The designer wants at least to halve the thickness of the plate to make room for additional hardware on the electronic device. The choices include unidirectional laminates of graphite/epoxy, glass/epoxy, or their combination (hybrid laminates). The ply thickness is 0.125 mm (0.0049213 in.). Design a plate with the lowest cost if the manufacturing cost per ply of graphite/epoxy and glass/epoxy is ten and four units, respectively. Use the properties of unidirectional graphite/epoxy and glass/epoxy laminae from Table 2.2.

   Now the designer wants to replace the 0.9872 in. thick aluminum plate by a plate of maximum thickness of 0.4936 in. (half that of aluminum) made of laminated composites. The bending moment per unit width is

$$M_{xx} = \frac{13,000}{4}$$

$$= 3,250 \ lb\text{-}in./in.$$

Using the factor of safety of two, the plate is designed to take a bending moment per unit width of

$$M_{xx} = 3,250 \times 2$$

$$= 6,500 \ lb\text{-}in./in.$$

The simplest choices are to replace the aluminum plate by an all graphite/epoxy laminate or an all glass/epoxy laminate. Using the procedure described in Example 5.3 or using the PROMAL[2] program, the strength ratio for using a single 0° ply for the previous load for glass/epoxy ply is

$$SR = 5.494 \times 10^{-5}.$$

The bending moment per unit width is inversely proportional to the square of the thickness of the plate, so the minimum number of plies required would be

$$N_{Gl/Ep} = \sqrt{\frac{1}{5.494 \times 10^{-5}}}$$

$$= 135 \text{ plies.}$$

This gives the thickness of the all-glass/epoxy laminate as

$$t_{Gl/Ep} = 135 \times 0.0049213 \text{ in.}$$

$$= 0.6643 \text{ in.}$$

The thickness of an all-glass/epoxy laminate is more than 0.4935 in. and is thus not acceptable.

Similarly, for an all graphite/epoxy laminate made of only 0° plies, the minimum number of plies required is

$$N_{Gr/Ep} = 87 \text{ plies.}$$

This gives the thickness of the plate as

$$t_{Gr/Ep} = 87 \times 0.0049213$$

$$= 0.4282 \text{ in.}$$

The thickness of an all-graphite/epoxy laminate is less than 0.4936 in. and is acceptable.

Even if an all-graphite/epoxy laminate is acceptable, because graphite/epoxy is 2.5 times more costly than glass/epoxy, one would suggest the use of a hybrid laminate. The question that arises now concerns the sequence in which the unidirectional plies should be stacked. In a plate under a bending moment, the magnitude of ply stresses is maximum on the top and bottom face. Because the longitudinal tensile and compressive strengths are larger in the graphite/epoxy lamina than in a glass/epoxy lamina, one would put the former as the facing material and the latter in the core.

e maximum number of plies allowed in the hybrid laminate is

$$N_{\max} = \frac{\textit{Maximum Allowable Thickness}}{\textit{Thickness of each ply}}$$

$$= \frac{0.4936}{0.0049213}$$

$$= 100 \text{ plies.}$$

Several combinations of 100-ply symmetric hybrid laminates of the form $[0_n^{Gr}/0_m^{Gl}/0_n^{Gr}]$ are now subjected to the applied bending moment. Minimum strength ratios in each laminate stacking sequence are found. Only if the strength ratios are greater than one — that is, the laminate is safe — is the cost of the stacking sequence determined. A summary of these results is given in Table 5.8.

From Table 5.8, an acceptable hybrid laminate with the lowest cost is case VI, $[0_{16}^{Gr}/0_{68}^{Gl}/0_{16}^{Gr}]$.

TABLE 5.8

Cost of Various Glass/Epoxy–Graphite/Epoxy Hybrid Laminates

	Number of plies			
Case	**Glass/epoxy (m)**	**Graphite/epoxy (2n)**	**Minimum SR**	**Cost**
I	0	87	1.023	870
II	20	80	1.342	880
III	60	40	1.127	640
IV	80	20	0.8032	—
V	70	30	0.9836	—
VI	68	32	1.014	592
VII	66	34	1.043	604

3. Did your choice of the laminate composite design decrease the mass? If so, by how much?

3. The volume of the aluminum plate is

$$V_{Al} = 4 \times 4 \times 0.9871$$

$$= 15.7936 \text{ in.}^3$$

The mass of the aluminum plate is (specific gravity = 2.7 from Table 3.2),

$$M_{Al} = V_{Al}\, \rho_{Al}$$

$$= 15.793 \times [(2.7)\,(3.6127 \times 10^{-2})]$$

$$= 1.540 \text{ lbm.}$$

The volume of the glass/epoxy in the hybrid laminate is

$$V_{Gl/Ep} = 4 \times 4 \times 0.0049213 \times 68$$

$$= 5.354 \text{ in.}^3$$

The volume of graphite/epoxy in the hybrid laminate is

$$V_{Gr/Ep} = 4 \times 4 \times 0.0049213 \times 32$$

$$= 2.520 \text{ in.}^3$$

Using the specific gravities of glass, graphite, and epoxy given in Table 3.1 and Table 3.2 and considering that the density of water is 3.6127×10^{-2} lbm/in.^{3}:

$$\rho_{Gl} = 2.5 \times (3.6127 \times 10^{-2}) = 0.9032 \times 10^{-1} \text{ lbm/in.}^3$$

$$\rho_{Gr} = 1.8 \times (3.6127 \times 10^{-2}) = 0.6503 \times 10^{-1} \text{ lbm/in.}^3$$

$$\rho_{Ep} = 1.2 \times (3.6127 \times 10^{-2}) = 0.4335 \times 10^{-1} \text{ lbm/in.}^3$$

The fiber volume fraction is given in Table 2.1 and, substituting in Equation (3.8), the density of glass/epoxy and graphite/epoxy laminae is

$$\rho_{Gl/Ep} = (0.9032 \times 10^{-1})\,(0.45) + (0.4335 \times 10^{-1})\,(0.55)$$

$$= 0.6449 \times 10^{-1} \text{ lbm/in.}^3$$

$$\rho_{Gr/Ep} = (0.6503 \times 10^{-1})\,(0.70) + (0.4335 \times 10^{-1})\,(0.30)$$

$$= 0.5853 \times 10^{-1} \text{ lbm/in.}^3$$

The mass of the hybrid laminate then is

$$M_h = (5.354)\,(0.6449 \times 10^{-1}) + (2.520)(0.5853 \times 10^{-1})$$

$$= 0.4928 \text{ lbm.}$$

The percentage savings using the composite laminate over aluminum is

$$= \frac{1.540 - 0.4928}{1.540} \times 100$$

$$= 68\%.$$

This example dictated the use of unidirectional laminates. How will the design change if multiple loads are present? Examples of multiple loads include a leaf spring subjected to bending moment as well as torsion or a thin pressure vessel subjected to an internal pressure to yield a biaxial state of stress. In such cases, one may have a choice not only of material systems and their combination, but also of orientation of plies. Combinations of angle plies can be infinite, so attention may be focused on angle plies of 0°, 90°, 45°, and –45° and their combinations. This reduces the possibilities to a finite number for a limited number of material systems; however, but the number of combinations can still be quite large to handle.

Example

An electronic device uses an aluminum plate of 1-in. thickness and a top cross–sectional area of 4 in. × 4 in. to take a pure bending moment. The designer wants to replace the aluminum plate with graphite/epoxy unidirectional laminate. The ply thickness of graphite/epoxy is 0.125 mm (0.0049213 in.).

1. Use the properties of aluminum and unidirectional graphite/epoxy as given in Table 3.4 and Table 2.2, respectively, to design a plate of graphite/epoxy with the same bending stiffness in the needed direction of load as that of the aluminum beam.
2. Does the laminate design decrease the mass? If so, by how much?

Solution

1. The bending stiffness, E_b, of the aluminum plate is given by:

$$E_b = EI \qquad (5.2$$

$$= E\left(\frac{1}{12}bh^3\right),$$

where

E = Young's modulus of aluminum
b = width of beam
h = thickness of beam

$$E_b = 10.3 \times 10^6 \left(\frac{1}{2}(4)(1)^3\right)$$

$$= 3.433 \times 10^6 \text{ lb–in.}^2$$

To find the thickness of a graphite/epoxy laminate with unidirectional plies and the same flexural rigidity, let us look at the bending stiffness of a laminate of thickness, h:

$$E_b = E_x I$$

$$= E_x \frac{1}{12} bh^3,$$

where E_x = Young's modulus in direction of fibers.

Because $E_x = E_1 = 26.25$ Msi for a 0° ply from Table 2.2,

$$3.433 \times 10^6 = 26.25 \times 10^6 \left(\frac{1}{2}\, 4h^3\right),$$

giving

$$h = 0.732 \text{ in.}$$

Thus, a 1-in. thick aluminum beam can be replaced with a graphite/epoxy laminate of 0.732 in. thickness. Note that, although the Young's modulus of graphite /epoxy is approximately 2.5 times that of aluminum, the thickness of aluminum plate is approximately only

1.4 times that of the graphite /epoxy of laminate because the bending stiffness of a beam is proportional to the cube of the thickness. Thus, the lightest beam for such bending would be influenced by the cube root of the Young's moduli. From the thickness of 0.732 in. of the laminate and a thickness of 0.0049312 in. of the lamina, the number of 0° graphite/epoxy plies needed is

$$n = \frac{0.732}{0.0049213} = 149\ .$$

The resulting graphite/epoxy laminate then is $[0_{149}]$.

2. The volume of the aluminum plate V_{Al} is

$$V_{Al} = 4 \times 4 \times 1.0$$

$$= 16 \text{ in.}^3$$

The mass of the aluminum plate is (specific gravity = 2.7 from Table 3.2; density of water is 3.6127×10^{-2} lbm/in.^{3}):

$$M_{Al} = V_{Al}\, \rho_{Al}$$

$$= 16 \times (2.7 \times 3.6127 \times 10^{-2})$$

$$= 1.561 \text{ lbm.}$$

The volume of a $[0_{149}]$ graphite/epoxy laminate is

$$V_{Gr/Ep} = 4 \times 4 \times 0.0049213 \times 149$$

$$= 11.73 \text{ in.}^3$$

The density of a graphite/epoxy from Example 5.5 is

$$\rho_{Gr/Ep} = 0.5853 \times 10^{-1}\, \frac{lbm}{in^3}\ .$$

The mass of the graphite/epoxy laminate beam is

$$M_{Gr/Ep} = (0.5853 \times 10^{-1})\ (11.73)$$

$$= 0.6866 \text{ lbm.}$$

Therefore, the percentage saving in using graphite/epoxy composite laminate over aluminum is

$$\frac{M_{Al} - M_{Gr/Ep}}{M_{Al}}$$

$$= \frac{1.561 - 0.6866}{1.561} \times 100$$

$$= 56\%.$$

UNIT-3 Part-2

STRENGTH AND FAILURE THEORIES

Introduction Failure:Every material has certain strength, expressed in terms of stress or strain, beyond which it fractures or fails to carry the load. Failure Criterion: A criterion used to hypothesize the failure. Failure Theory: A Theory behind a failure criterion.

Need of Failure Theories:

(a) To design structural components and calculate margin of safety.
(b) To guide in materials development.
(c) To determine weak and strong directions.

Failure Theories for Isotropic Materials: Strength and stiffness are independent of the direction. Failure in metallic materials is characterized by Yield Strength.

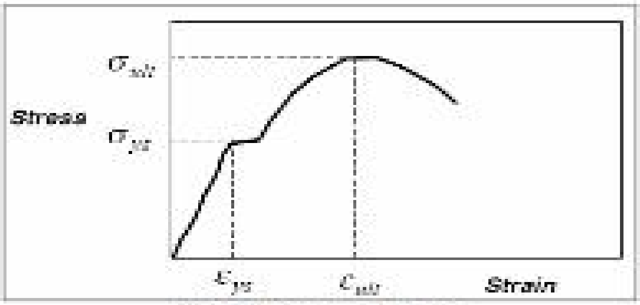


Figure: Stress-strain curve

Macromechanical Failure Theories in Composite Materials:

- Maximum Stress Theory
- Maximum Strain Theory
- Tsai-Hill Theory (Deviatoric strain energy theory)
- Tsai-Wu Theory (Interactive tensor polynomial theory)

Application of Failure Theory

First step is to calculate the stresses/strains in the material principal directions. This can be done by transformation of stresses from the global coordinates to local material coordinates of the ply.

Ply Stresses:

$$\{\sigma\}_{x,y} = [T_\sigma]\{\sigma\}_{1,2} \quad \text{or} \quad \{\sigma\}_{1,2} = [T_\sigma]^{-1}\{\sigma\}_{x,y}$$

Ply strains:

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

----------1

Now apply the failure criteria in the material coordinate system.

We can use the constitutive equations (stress-strain relationships for an individual lamina/ply or hence laminate) to calculate the stresses in each ply when we know the values of the loads acting on the laminate. By comparing these stresses with a corresponding limiting value we can decide whether, or not, the laminate will fail when subjected to the service loads.

There are several ways to define failure. The obvious one is when we have complete separation, or fracture; clearly, then, the component can no longer support the loads acting on it. However, a more general definition would be 'when the component can no longer fulfill the function for which it was designed'.

Such a definition includes total fracture but could also include excessive deflection as seen when a laminate buckles (basically a stiffness rather than a strength limit), or even just matrix cracking. The latter could constitute failure for a container because any contents would be able to leak through the matrix cracks in the container's walls.

As for isotropic materials, a failure criterion can be used to predict failure. A large number of such criteria exist, no one criterion being universally satisfactory. We shall start by considering a single ply before moving on to discuss laminates.

The lamina to be a regular array of parallel continuous fibres perfectly bonded to the matrix. We know that, there are five basic modes of failure of such a ply: longitudinal tensile or compressive, transverse tensile or compressive, or shear. Each of these modes would involve detailed failure mechanisms associated with fibre, matrix or interface failure.

We can regard the strengths in the principal material axes (parallel and transverse to the fibres) as the fundamental parameters defining failure. When a ply is loaded at an angle to the fibres, as it is when it is part of a multidirectional laminate, we have to determine the stresses in the principal directions and compare them with the fundamental values.

Strength can be determined by the application of failure criteria, which are usually grouped into three classes: limit criteria, the simplest; interactive criteria which attempt to allow for the interaction of multiaxial stresses; and hybrid criteria which combine selected aspects of limit and interactive methods. In this text we shall only discuss criteria that fit into the first two classes.

Limit criteria

(a) Maximum stress criterion

The maximum stress criterion consists of five sub-criteria, or limits, one corresponding to the strength in each of the five fundamental failure modes. If any one of these limits is exceeded, by the corresponding stress expressed in the principal material axes, the material is deemed to have failed.

$$\sigma_1 \geqslant \hat{\sigma}_{1T} \quad \text{or} \quad \sigma_1 \leqslant \hat{\sigma}_{1C} \quad \text{or} \quad \sigma_2 \geqslant \hat{\sigma}_{2T} \quad \text{or} \quad \sigma_2 \leqslant \hat{\sigma}_{2C} \quad \text{or} \quad \tau_{12} \geqslant \hat{\tau}_{12}. \qquad (7.1.1)$$

In mathematical terms we say that failure has occurred if or,
(Recalling that a compressive stress is taken as negative so, for example, failure would occur if $\sigma_2 = 0$ MPa and $\sigma_{2T} = -150$ MPa).

(b) Maximum strain criterion The maximum strain criterion merely substitutes strain for stress in the five sub-criteria. We now say that failure has occurred if

$$\varepsilon_1 \geqslant \hat{\varepsilon}_{1T} \quad \text{or} \quad \varepsilon_1 \leqslant \hat{\varepsilon}_{1C} \quad \text{or} \quad \varepsilon_2 \geqslant \hat{\varepsilon}_{2T} \quad \text{or} \quad \varepsilon_2 \leqslant \hat{\varepsilon}_{2C} \quad \text{or} \quad \gamma_{12} \geqslant \hat{\gamma}_{12} \qquad (7.1.2)$$

As when calculating stiffness, it is important that we can deal with the situation in which the fibres are not aligned with the applied stresses. We illustrate this by considering the simple case of a single stress σ_x , inclined at an angle θ to the fibres (Figure M7.1.1). We now use equations $\sigma_{12} = T\sigma_{xy}$ and $\varepsilon_{12} = T\varepsilon_{xy}$ to obtain the stresses in the principal material directions. Putting $\sigma_y = \tau_{xy} = 0$ in those equations we obtain

$$\sigma_1 = \sigma_x \cos^2\theta, \quad \sigma_2 = \sigma_x \sin^2\theta, \quad \tau_{12} = -\sigma_x \sin\theta\cos\theta. \qquad (7.1.3)$$

We then apply equations (7.1.1) to determine whether failure has occurred. We are seeking the value of ax to cause failure and we see from equation (7.1.3) that there are three possible results, i.e. clearly the smallest value of σ_x will be the failure stress.

$$\sigma_x = \hat{\sigma}_{1T}/\cos^2\theta \text{ – fibre failure, } \sigma_x = \hat{\sigma}_{2T}/\sin^2\theta \text{ – transverse failure}$$

$$\sigma_x = -\hat{\tau}_{12}/\sin\theta\cos\theta \text{ – shear failure;}$$

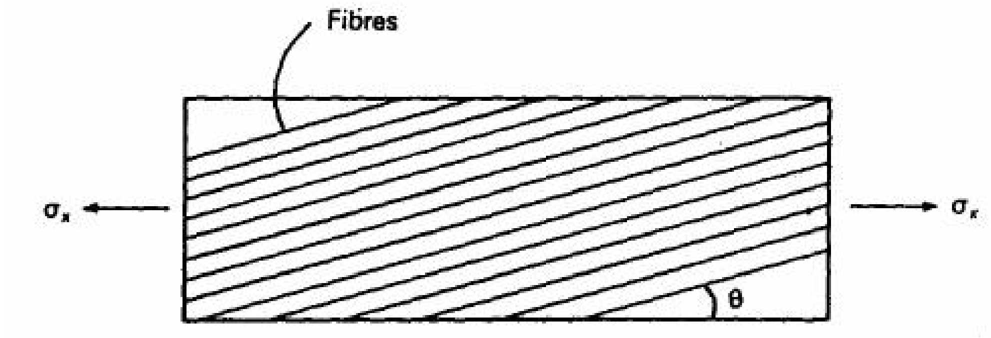


Figure M7.1.1 Uniaxial stresses, σ inclined at an angle ⎝ to the fibres of unidirectional composites.

The effect on the value of σ xat failure as θ is varied as illustrated in Figure M7.1.2. We see that each mode of failure is represented by a separate curve. Fibre failure is most likely when θ is small, transverse (either matrix or interface) failure is when θ approaches 90 °, and shear failure at intermediate angles.

Available Failure Criteria for Composite Materials

Within the Laminate drop-down menu, Helius:CompositePro provides the user with four different procedures for performing failure analysis of laminates. The four laminate failure analysis procedures are: First Ply Failure, First Ply Failure Survey, Progressive Failure, and Failure Envelop. Within each of these four laminate failure analysis procedures, Helius:CompositePro provides the user with a choice of eight different failure criteria for composite materials: Max Strain, Max Stress, Tsai-Wu, Tsai-Hill, Hashin, Christensen, Puck, and MCT. Each of these eight failure criteria is briefly described below.

1) Max Strain Criterion:

The Max Strain Criterion identifies three possible modes of failure: Longitudinal Failure, Transverse Failure, or Shear Failure.

$\varepsilon_{11}^{\max+}$ ≡ Value of ε_{11} at longitudinal tensile failure, $\varepsilon_{11}^{\max+} = S_{11}^{+}/E_{11}$
$\varepsilon_{11}^{\max-}$ ≡ Value of ε_{11} at longitudinal compressive failure, $\varepsilon_{11}^{\max-} = S_{11}^{-}/E_{11}$
$\varepsilon_{22}^{\max+}$ ≡ Value of ε_{22} at transverse tensile failure, $\varepsilon_{22}^{\max+} = S_{22}^{+}/E_{22}$
$\varepsilon_{22}^{\max-}$ ≡ Value of ε_{22} at transverse compressive failure, $\varepsilon_{22}^{\max-} = S_{22}^{-}/E_{22}$
$\varepsilon_{22}^{\max}$ ≡ Absolute value of ε_{12} at longitudinal shear failure, $\varepsilon_{12}^{\max} = S_{12}/G_{12}$

Longitudinal Failure occurs whenever $\varepsilon_{11} \geq \varepsilon_{11}^{\max+}$ or $\varepsilon_{11} \leq \varepsilon_{11}^{\max-}$
Transverse Failure occurs whenever $\varepsilon_{22} \geq \varepsilon_{22}^{\max+}$ or $\varepsilon_{22} \leq \varepsilon_{22}^{\max-}$
Longitudinal Shear Failure occurs whenever $|\varepsilon_{12}| \geq |\varepsilon_{12}^{\max}|$

Failure Index = Max. Absolute Value of $\left(\frac{\varepsilon_{11}}{\varepsilon_{11}^{\max+}}, \frac{\varepsilon_{11}}{\varepsilon_{11}^{\max-}}, \frac{\varepsilon_{22}}{\varepsilon_{22}^{\max+}}, \frac{\varepsilon_{22}}{\varepsilon_{22}^{\max-}}, \frac{\varepsilon_{12}}{\varepsilon_{12}^{\max-}} \right)$

Since the failure index is a simple ratio of strains, the failure load can be computed by simply dividing the applied load by the failure index. For example, consider a composite material that is subjected to a transverse normal stress of 1 psi. If the computed failure index is 0.0002, then the transverse normal stress at failure is (1 psi)/0.0002 = 5000 psi.

2) Max Stress Criterion:

The Max Stress Criterion identifies three possible modes of failure: Longitudinal Failure, Transverse Failure, or Shear Failure.

S_{11}^{+} ≡ Value of σ_{11} at longitudinal tensile failure
S_{11}^{-} ≡ Value of σ_{11} at longitudinal compressive failure
S_{22}^{+} ≡ Value of σ_{22} at transverse tensile failure
S_{22}^{-} ≡ Value of σ_{22} at transverse compressive failure
S_{12} ≡ Absolute value of σ_{12} at longitudinal shear failure

Longitudinal Failure occurs whenever $\sigma_{11} \geq S_{11}^{+}$ or $\sigma_{11} \leq S_{11}^{-}$

Transverse Failure occurs whenever $\sigma_{22} \geq S_{22}^{+}$ or $\sigma_{22} \leq S_{22}^{-}$

Longitudinal Shear Failure occurs whenever $|\sigma_{12}| \geq |\sigma_{12}^{\max}|$

Failure Index = Max. Absolute Value of $\left(\frac{\sigma_{11}}{S_{11}^{+}}, \frac{\sigma_{11}}{S_{11}^{-}}, \frac{\sigma_{22}}{S_{22}^{+}}, \frac{\sigma_{22}}{S_{22}^{-}}, \frac{\sigma_{12}}{S_{12}^{-}} \right)$

Since the failure index is a simple ratio of stresses, the failure load can be computed by simply dividing the applied load by the failure index. For example, consider a composite material that is subjected to a transverse normal stress of 1 psi. If the computed failure index is 0.0002, then the transverse normal stress at failure is (1 psi)/0.0002 = 5000 psi.

3) **Tsai-Wu Criterion:**

The Tsai-Wu Criterion is a quadratic, interactive stress-based criterion that identifies failure, but does not distinguish between different modes of failure (Ref. 38).

Failure occurs whenever the following condition is satisfied.

$$F_1\sigma_{11} + F_2\sigma_{22} + F_{11}\sigma_{11}^2 + F_{22}\sigma_{22}^2 + F_{66}\sigma_{12}^2 + 2F_{12}\sigma_{11}\sigma_{22} \geq 1.0$$

The various coefficients F_i and F_{ij} of the Tsai-Wu criterion are defined in terms of known/measured strengths of the composite material.

S_{11}^{+} ≡ Value of σ_{11} at longitudinal tensile failure

S_{11}^{-} ≡ Value of σ_{11} at longitudinal compressive failure

S_{22}^{+} ≡ Value of σ_{22} at transverse tensile failure

S_{22}^{-} ≡ Value of σ_{22} at transverse compressive failure

S_{12} ≡ Absolute value of σ_{12} at longitudinal shear failure

$$F_1 \equiv \frac{1}{S_{11}^{+}} + \frac{1}{S_{11}^{-}}$$

$$F_2 \equiv \frac{1}{S_{22}^{+}} + \frac{1}{S_{22}^{-}}$$

$$F_{11} \equiv -\frac{1}{S_{11}^{+}S_{11}^{-}}$$

$$F_{22} \equiv -\frac{1}{S_{22}^{+}S_{22}^{-}}$$

$$F_{66} \equiv \frac{1}{S_{12}S_{12}}$$

The interaction coefficient F_{12} can be defined in one of two different ways. If a biaxial failure stress ($\sigma_{11} = \sigma_{22} = \sigma_{\text{biax}}$) is used, then F_{12} is computed as

$$F_{12} \equiv \frac{1}{2\sigma_{biax}^{2}}\left[1 - \left(\frac{1}{S_{11}^{+}} + \frac{1}{S_{11}^{+}} + \frac{1}{S_{22}^{+}} + \frac{1}{S_{22}^{+}}\right)\sigma_{biax} + \left(\frac{1}{S_{11}^{+}S_{11}^{+}} + \frac{1}{S_{22}^{+}S_{22}^{+}}\right)\sigma_{biax}^{2}\right]$$

Otherwise, the interaction coefficient F_{12} is computed as

$F_{12} = f^{*}\sqrt{F_{11}F_{22}}$ where f^{*} is a user-specified constant, $-0.5 \leq f^{*} \leq 0$.

If the Tsai-Wu criterion is selected for analysis in Helius:CompositePro, the user must specify the coefficient f^{*}.

The failure index reported for the Tsai-Wu criterion is

$$\text{Failure Index} \equiv F_1\sigma_{11} + F_2\sigma_{22} + F_{11}\sigma_{11}^{2} + F_{22}\sigma_{22}^{2} + F_{66}\sigma_{12}^{2} + 2F_{12}\sigma_{11}\sigma_{22} .$$

4) **Tsai-Hill Criterion:**

The Tsai-Hill criterion is a quadratic, interactive stress-based criterion that identifies failure, but does not distinguish between different modes of failure.

Failure occurs whenever the following condition is satisfied.

$$\frac{\sigma_{11}^{2}}{S_{11}^{2}} - \frac{\sigma_{11}\sigma_{22}}{S_{11}^{2}} + \frac{\sigma_{22}^{2}}{S_{22}^{2}} + \frac{\sigma_{12}^{2}}{S_{12}^{2}} \geq 1.0$$

The coefficients S_{ij} of the Tsai-Hill criterion are computed as follows:

S_{11}^{+} ≡ Value of σ_{11} at longitudinal tensile failure

S_{11}^{-} ≡ Value of σ_{11} at longitudinal compressive failure
S_{22}^{+} ≡ Value of σ_{22} at transverse tensile failure
S_{22}^{-} ≡ Value of σ_{22} at transverse compressive failure
S_{12} ≡ Absolute value of σ_{12} at longitudinal shear failure

If $\sigma_{11} \geq 0$, then $S_{11} = S_{11}^{+}$
If $\sigma_{11} < 0$, then $S_{11} = S_{11}^{-}$
If $\sigma_{22} \geq 0$, then $S_{22} = S_{22}^{+}$
If $\sigma_{22} < 0$, then $S_{22} = S_{22}^{-}$

The failure index reported for the Tsai-Hill criterion is

$$\text{Failure Index} = \frac{\sigma_{11}^2}{S_{11}^2} - \frac{\sigma_{11}\sigma_{22}}{S_{11}^2} + \frac{\sigma_{22}^2}{S_{22}^2} + \frac{\sigma_{12}^2}{S_{12}^2} .$$

5) **Hashin Criterion:**

The Hashin criterion identifies four different modes of failure for the composite material: tensile fiber failure, compressive fiber failure, tensile matrix failure, compressive matrix failure.

S_{11}^{+} ≡ Value of σ_{11} at longitudinal tensile failure
S_{11}^{-} ≡ Value of σ_{11} at longitudinal compressive failure
S_{22}^{+} ≡ Value of σ_{22} at transverse tensile failure
S_{22}^{-} ≡ Value of σ_{22} at transverse compressive failure
S_{12} ≡ Absolute value of σ_{12} at longitudinal shear failure
S_{23} ≡ Absolute value of σ_{23} at transverse shear failure

If $\sigma_{11} \geq 0$, then the Tensile **Fiber** Failure Criterion is:

$$F_f^{+} \equiv \left(\frac{\sigma_{11}}{S_{11}^{+}}\right)^2 + \alpha\left(\frac{\sigma_{12}}{S_{12}}\right)^2 \geq 1.0.$$

If $\sigma_{11} < 0$, then the Compressive **Fiber** Failure Criterion is:

$$F_f^{-} \equiv \left(\frac{\sigma_{11}}{S_{11}^{-}}\right)^2 \geq 1.0.$$

If $\sigma_{22} \geq 0$, then the Tensile **Matrix** Failure Criterion is:

$$F_m^{+} \equiv \left(\frac{\sigma_{22}}{S_{22}^{+}}\right)^2 + \alpha\left(\frac{\sigma_{12}}{S_{12}}\right)^2 \geq 1.0.$$

If $\sigma_{22} < 0$, then the Compressive **Matrix** Failure Criterion is:

$$F_m^- \equiv \left(\frac{\sigma_{22}}{2S_{23}}\right)^2 + \left[\left(\frac{S_{22}^-}{2S_{23}}\right)^2 - 1\right]\frac{\sigma_{22}}{S_{22}^-} + \left(\frac{\sigma_{12}}{S_{12}}\right)^2 \geq 1.0.$$

Note that the Hashin equations include two user-specified parameters: α and S_{23}.

- α: User-specified coefficient that determines the contribution of the longitudinal shear stress to fiber tensile failure. Allowable range is $0.0 \leq \alpha \leq 1.0$, and the default value is $\alpha=0$.

- S23: Transverse shear strength of the composite material in the 23 plane.

6) **Christensen Criterion:**

The Christensen criterion utilizes the following six fundamental strengths of the composite material to identify two different failure modes: matrix failure and fiber failure.

S_{11}^+ ≡ Value of σ_{11} at longitudinal tensile failure
S_{11}^- ≡ Value of σ_{11} at longitudinal compressive failure
S_{22}^+ ≡ Value of σ_{22} at transverse tensile failure
S_{22}^- ≡ Value of σ_{22} at transverse compressive failure
S_{12} ≡ Absolute value of σ_{12} at longitudinal shear failure
S_{23} ≡ Absolute value of σ_{23} at transverse shear failure

The matrix failure criterion is

$$\left(\frac{1}{S_{22}^+} - \frac{1}{S_{22}^-}\right)(\sigma_{22} + \sigma_{33}) + \frac{1}{S_{22}^+ S_{22}^-}(\sigma_{22} + \sigma_{33})^2 + \frac{1}{S_{23}^2}(\sigma_{23}^2 - \sigma_{22}\sigma_{33}) + \frac{1}{S_{12}^2}(\sigma_{12}^2 + \sigma_{13}^2) \geq 1.0$$

where the transverse shear strength S23 is required to satisfy $S_{23} \geq \frac{1}{2}\sqrt{S_{22}^+ S_{22}^-}$.

The fiber failure criterion is

$$\left(\frac{1}{S_{22}^+} - \frac{1}{S_{22}^-}\right)\sigma_{11} + \frac{\sigma_{11}^2}{S_{22}^+ S_{22}^-} \geq 1.0$$

7) **Puck Criterion:**

The Puck criterion (Ref. 6 and 7) identifies fiber failure and inter-fiber failure in a unidirectional composite, but further separates inter-fiber failure into three different physical modes and further separates fiber failure into two different physical modes. The general form of the Puck criterion utilizes the full 3-D state of stress and strain, but Helius:CompositePro's implementation considers only in-plane stresses and strains consistent with Classical Laminate Theory.

To use the Puck failure criterion, the user must specify two pieces of information:

- Composite Material Type: Either a carbon fiber reinforced polymer (CFRP) or a glass fiber reinforced polymer (GFRP) must be specified.

- Fiber Material Type: For lamina materials that were not defined using CompositePro's micromechanics module (Section 4.2), the user must identify the fiber material used in the composite lamina.

Fiber Failure

The Puck criterion recognizes two different modes of fiber failure, the first being a tensile failure, and the second being a compressive "fiber kinking" failure. The tensile fiber failure criterion is

$$\frac{1}{\epsilon_{1T}}\left(\epsilon_1 + \frac{\nu_{f12}}{E_{f1}} m_{\sigma f}\sigma_2\right) = 1 \quad ,$$

and the compressive "fiber kinking" failure is

$$\frac{1}{\epsilon_{1C}}\left|\left(\epsilon_1 + \frac{\nu_{f12}}{E_{f1}} m_{\sigma f}\sigma_2\right)\right| = 1 - (10\gamma_{21})^2 \quad .$$

In the above fiber failure criteria, ϵ_{1T} and ϵ_{1C} are the composite strains corresponding to composite longitudinal tensile and compressive failure, respectively, ϵ_1 is the uniaxial strain in the composite, ν_{f12} is the longitudinal Poisson ratio of the fiber, E_{f1} is the longitudinal tensile modulus of the fiber, σ_2 is the transverse stress of the composite, γ_{21} is the longitudinal shear strain in the composite, and $m_{\sigma f}$ is intended to capture the differences in the transverse stresses in the fiber and matrix. For carbon fibers $m_{\sigma f} \approx 1.1$, and for glass fibers $m_{\sigma f} \approx 1.3$. In the above equations, the tensile equation is evaluated if $\left(\epsilon_1 + \frac{\nu_{f12}}{E_{f1}} m_{\sigma f}\sigma_2\right) > 0$, and the compressive criterion is evaluated if $\left(\epsilon_1 + \frac{\nu_{f12}}{E_{f1}} m_{\sigma f}\sigma_2\right) < 0$.

Inter-Fiber Failure (Matrix Cracking)

In the Puck criterion, inter-fiber failure encompasses any matrix cracking or fiber/matrix debonding. The Puck criterion recognizes three different inter-fiber failure modes, referred to as modes A, B, and C. These inter-fiber failure modes are distinguished by the orientation of the fracture planes relative to the reinforcing fibers.

Inter-Fiber Failure Mode A:

Mode A corresponds to a fracture angle of 0°. The criterion is invoked if the transverse stress in the composite is greater than 0 (thus indicating a transverse crack perpendicular to the transverse loading).

$$\sqrt{\left(\frac{\tau_{21}}{S_{21}}\right)^2 + \left(1 - p_{\perp\parallel}^{(+)}\frac{Y_T}{S_{21}}\right)^2 \left(\frac{\sigma_2}{Y_T}\right)^2} + p_{\perp\parallel}^{(+)}\frac{\sigma_2}{S_{21}} = 1 - \left|\frac{\sigma_1}{\sigma_{1D}}\right| \quad .$$

Inter-Fiber Failure Mode B:

Mode C corresponds to a transverse compressive stress (inhibiting crack formation) with a longitudinal shear stress which is below a fracture resistance (coupled with empirical constants).

$$\frac{1}{S_{21}}\left(\sqrt{{\tau_{21}}^{2}+\left(p_{\perp\parallel}^{(-)}\sigma_2\right)^{2}}+p_{\perp\parallel}^{(-)}\frac{\sigma_2}{S_{21}}\right)=1-\left|\frac{\sigma_1}{\sigma_{1D}}\right| .$$

The above criterion is evaluated if

$$\sigma_2<0 \; and \; 0\leq\left|\frac{\sigma_2}{\tau_{21}}\right|\leq\frac{R_{\perp\perp}^{A}}{|\tau_{21c}|} .$$

Inter-Fiber Failure Mode C:

Mode C corresponds to a transverse compressive stress (inhibiting crack formation) with a longitudinal shear stress which is significantly large enough to cause fracture on an inclined plane to fiber axis. Within the context of Classical Laminate Theory, we do not need to define the fracture angle, as it is irrelevant for failure predictions involving only in-plane stresses and strains (and no degradation of material properties). The failure criterion for Mode C is

$$\frac{1}{\left(2\left(1+p_{\perp\perp}^{(-)}\right)\right)}\left(\left(\frac{\tau_{21}}{S_{21}}\right)^{2}+\left(\frac{\sigma_2}{R_{\perp\perp}^{A}}\right)^{2}\right)\frac{R_{\perp\perp}^{A}}{(-\sigma_2)}=1-\left|\frac{\sigma_1}{\sigma_{1D}}\right| .$$

The above criterion is evaluated if

$$\sigma_2<0 \; and \; 0\leq\left|\frac{\tau_{21}}{\sigma_2}\right|\leq\frac{|\tau_{21c}|}{R_{\perp\perp}^{A}} .$$

Description of Coefficients and Terms used in the Inter-Fiber Failure criteria

We will make use of commonly accepted notation, e.g., τ_{21} is the composite longitudinal shear stress, σ_1 is the composite longitudinal normal stress, σ_2 is the composite transverse normal stress, Y_T is the composite transverse tensile strength, and Y_C is the transverse compressive strength. $p_{\perp\parallel}^{(-)}$ and $p_{\perp\parallel}^{(+)}$ are the slopes of the (σ_2, τ_{21}) fracture envelope. To establish the connection between $p_{\perp\perp}^{(-)}$ and $p_{\perp\parallel}^{(-)}$, Puck assumes that the following relationship holds

$$\frac{p_{\perp\perp}^{(-)}}{R_{\perp\perp}^{A}}=\frac{p_{\perp\parallel}^{(-)}}{R_{\perp\parallel}^{A}}=\left(\frac{p}{R}\right)=const .$$

Therefore, $p_{\perp\perp}^{(-)}$ is given by

$$p_{\perp\perp}^{(-)} = R_{\perp\perp}^{A} \frac{p_{\perp\parallel}^{(-)}}{R_{\perp\parallel}^{A}} \ .$$

Within the context of the in-plane stresses and strains of the Classical Laminate Theory, $R_{\perp\parallel}^{A}$ can be defined as $R_{\perp\parallel}^{A} = S_{21}$ which allows Puck to express $R_{\perp\perp}^{A}$ as

$$R_{\perp\perp}^{A} = \frac{S_{21}}{2p_{\perp\parallel}^{(-)}}\left(\sqrt{1 + 2p_{\perp\parallel}^{(-)}\frac{Y_C}{S_{21}}} - 1\right) .$$

Now we must define the values for $p_{\perp\parallel}^{(-)}$ and $p_{\perp\parallel}^{(+)}$. Puck and Mannigal (2007) provide the following recommended values for $p_{\perp\parallel}^{(-)}$ and $p_{\perp\parallel}^{(+)}$.

Reinforcement Type	$p_{\perp\parallel}^{(-)}$	$p_{\perp\parallel}^{(+)}$
Glass Fiber	0.25	0.3
Carbon Fiber	0.3	0.35

Puck also defines τ_{21c} as

$$\tau_{21c} = S_{21}\sqrt{1 + 2p_{\perp\perp}^{(-)}} \ .$$

Finally, we must define σ_{1D}. This is a "degraded" stress in the composite allowing for pre-fiber failure breakage of individual fibers, which causes localized damage in these areas in the form of microcracking and debonding. To account for this weakening effect, Puck degrades the fracture resistances (R) by a weakening factor f_w. Puck defines two equations for this. The first is for the generalized weakening factor.

$$f_w = 1 - \left(\frac{\sigma_1}{\sigma_{1d}}\right)^n .$$

The second is to give another expression of the weakening factor in order to keep the fracture conditions homogeneous and of first degree with respect to the stresses.

$$f_w = 1 - \frac{\sigma_1}{\sigma_{1D}} \ .$$

For the in-plane stress states considered by Helius:CompositePro, these two should be equal since there are no iterative calculations on fracture planes being performed. Therefore,

$$\sigma_{1D} = \frac{\sigma_1}{\left(\frac{\sigma_1}{\sigma_{1d}}\right)^n} \quad .$$

Based on the recommendations of Puck, Helius:CompositePro uses n=6 for the exponent and empirically computes σ_{1d} as $1.1X_T$ $or - 1.1X_C$ depending on the sign of σ_1.

References:

1. Robert.M.Jones, “Mechanics of Composite Materials”
2. Autar K Kaw, “Mechanics of Composite Materials”
3. Aircraft Composite materials and Structures – Study material, Sathyabama University

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UNIT - IV SANDWICH CONSTRUCTIONS

Basic design concepts of sandwich construction -Materials used for sandwich construction - Failure modes of sandwich panels.

TEXT BOOKS

T [1] –	Jones R.M. (1999), “Mechanics of Composite Materials”, McGraw-Hill, Kogakusha Ltd., Tokyo.
T [2] –	N.G.R.Iyengar.(2016), “Composite Materials and Structural Analysis”, viva Books Pvt.Ltd.; First edition., New Delhi.

REFERENCES

R [2] -	Lubin, G (1989). “Handbook on Advanced Plastics and Fibre Glass”, Von Nostrand Reinhold Co., New York
R [3] -	Autar K.Kaw (2005), “Mechanics of Composite Materials”, Second Edition, CRC press, University of South Florida, Tampa,USA

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Unit IV

Sandwich construction

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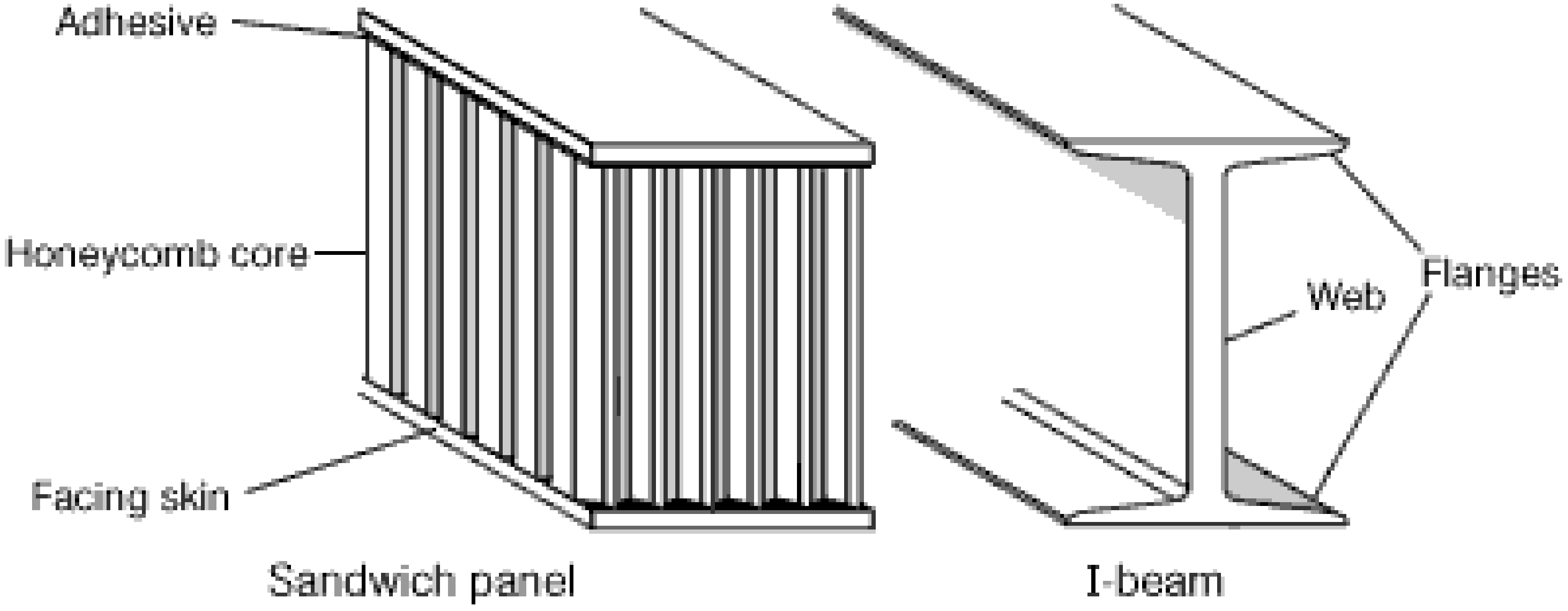
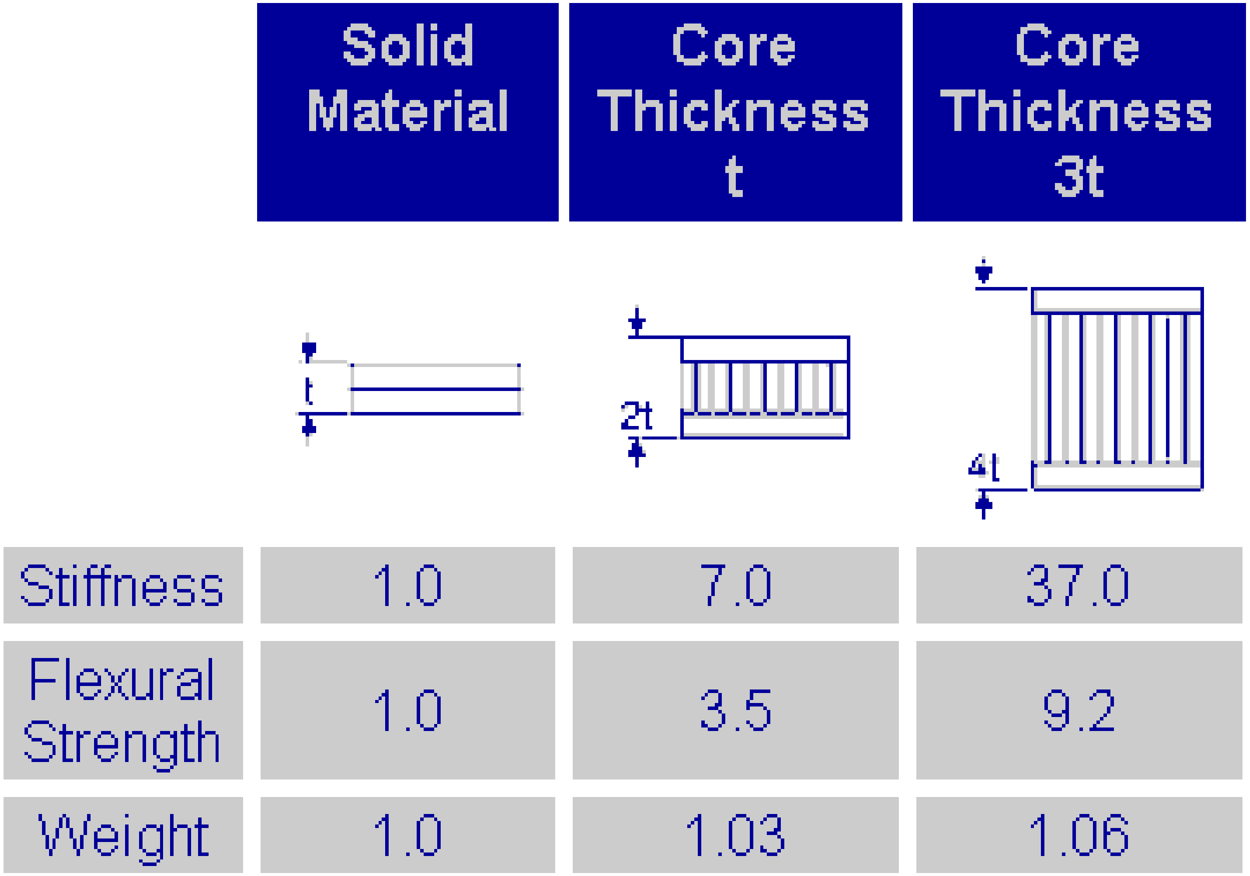
Sandwich Construction

- Thin composite skins bonded to thicker, lightweight core.
- Large increase in second moment of area without weight penalty.
- Core needs good shear stiffness and strength.
- Skins carry tension and compression loads.

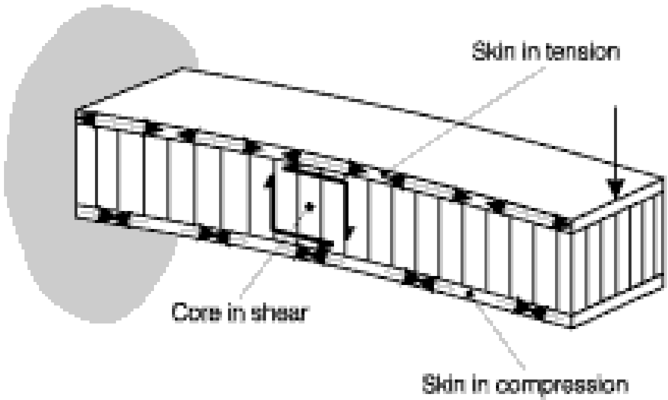
Sandwich panels are a very efficient way of providing high bending stiffness at low weight. The stiff, strong facing skins carry the bending loads, while the core resists shear loads. The principle is the same as a traditional ‘I’ beam:



Bending stiffness is increased by making beams or panel thicker - with sandwich construction this can be achieved with very little increase in weight:

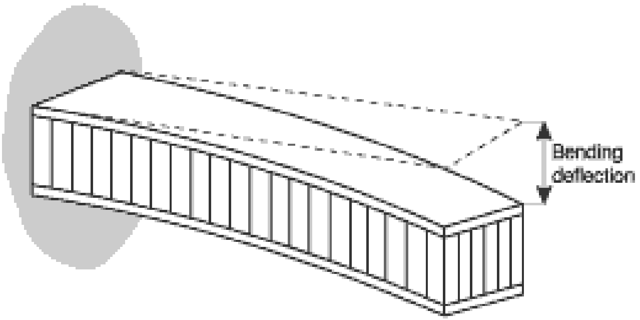


	Solid Material	Core Thickness t	Core Thickness 3t
Stiffness	1.0	7.0	37.0
Flexural Strength	1.0	3.5	9.2
Weight	1.0	1.03	1.06

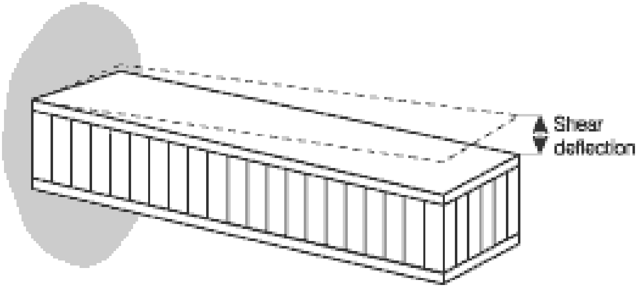


The stiff, strong facing skins carry the bending loads, while the core resists shear loads.

Total deflection = bending + shear



Bending depends on the skin properties; shear depends on the core



Foam core comparison

PVC (closed cell)

- *'linear' – high ductility, low properties*
- *'cross-linked' – high strength and stiffness, but brittle*
- *~ 50% reduction of properties at 40-60*^{o}*C*
- *chemical breakdown (HCl vapour) at 200*^{o}*C*

Foam core comparison

PU

- *inferior to PVC at ambient temperatures*
- *better property retention (max. 100^{o}C)*

Phenolic

- *poor mechanical properties*
- *good fire resistance*
- *strength retention to 150^{o}C*

Foam core comparison

Syntactic foam

- *glass or polymer microspheres*
- *used as sandwich core or buoyant filler*
- *high compressive strength*

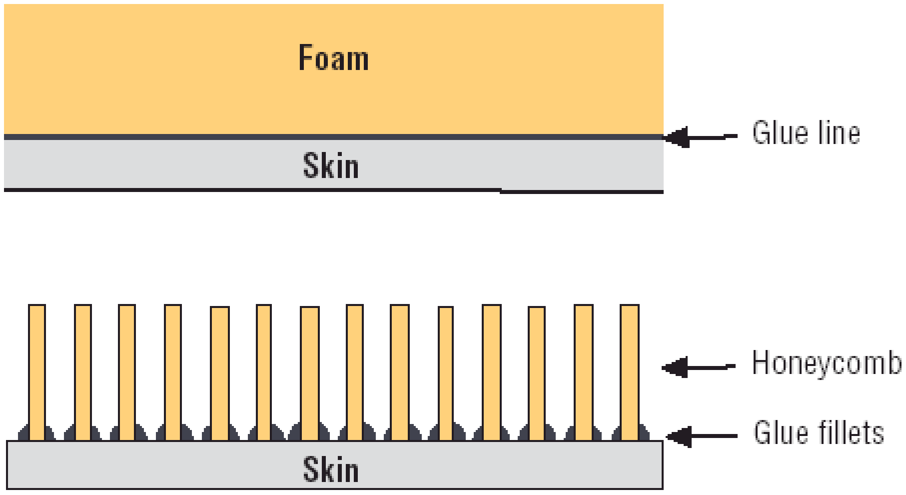
Balsa

- *efficient and low cost*
- *absorbs water (swelling and rot)*
- *not advisable for primary hull and deck structures; OK for internal bulkheads, etc?*

Material	Property	Honeycomb Advantages
Foam includes – polyvinyl chloride (PVC) – polymethacrylimide – polyurethane – polystyrene – phenolic – polyethersulfone (PES)	Relatively low crush strength and stiffness Increasing stress with increasing strain Friable Limited strength Fatigue Cannot be formed around curvatures	Excellent crush strength and stiffness Constant crush strength Structural integrity Exceptionally high strengths available High fatigue resistance OX-Core and Flex-Core cell configurations for curvatures
Wood-based includes – plywood – balsa – particleboard	Very heavy density Subject to moisture degradation Flammable	Excellent strength-to-weight ratio Excellent moisture resistance Self-extinguishing, low smoke versions available

Sandwich constructions made with other core materials (balsa, foam, etc) have a large surface are available for bonding the skins.

In honeycomb core, we rely on a small fillet of adhesive at the edge of the cell walls:

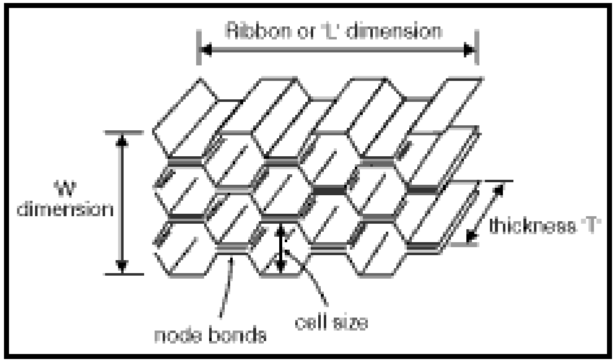


Core/Laminate Bond for Foams and Honeycombs

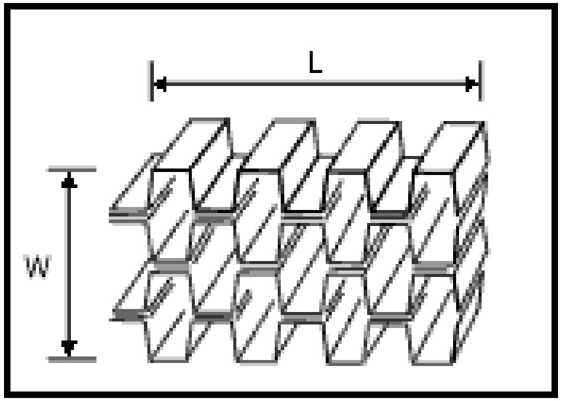
The fillet is crucial to the performance of the sandwich, yet it is very dependent on manufacturing factors (resin viscosity, temperature, vacuum, etc).

Honeycomb is available in polymer, carbon, aramid and GRP. The two commonest types in aerospace applications are based on aluminium and Nomex (aramid fibre-paper impregnated with phenolic resin).

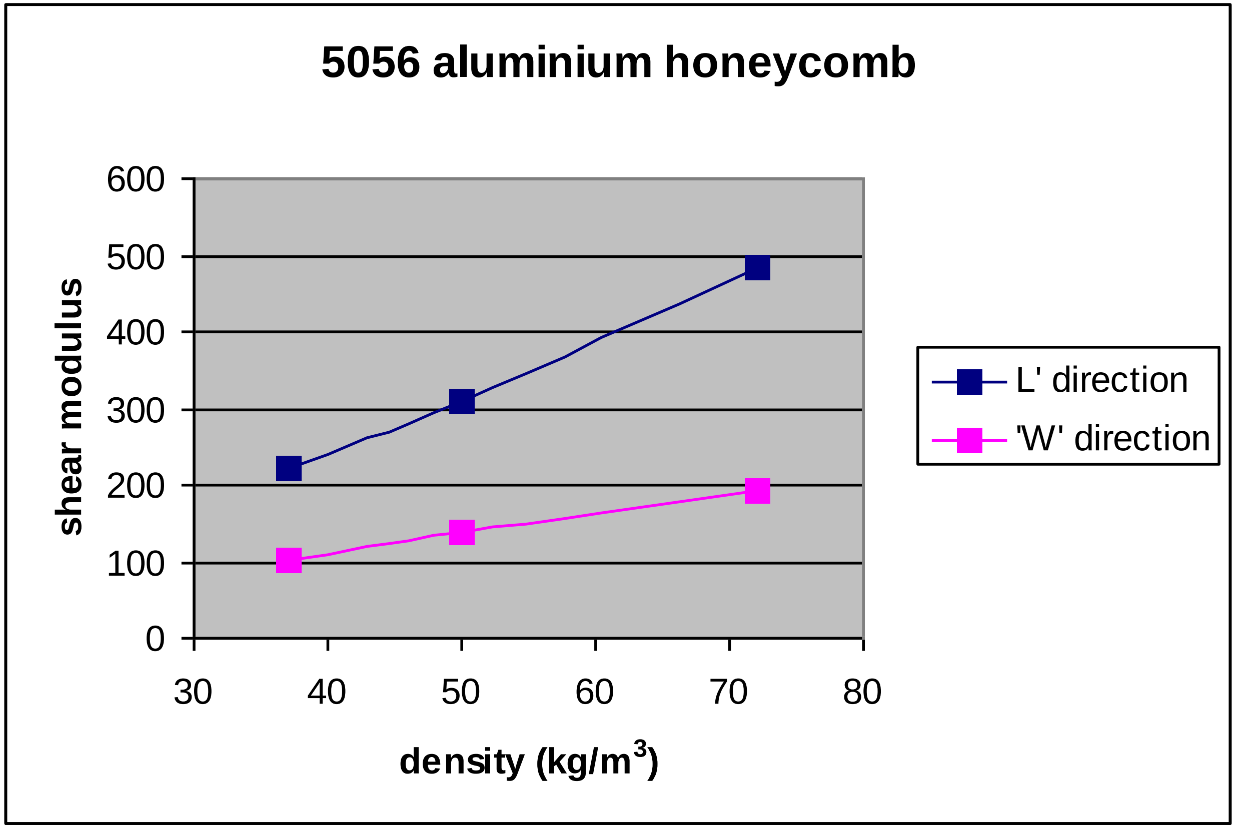
Cells are usually hexagonal:



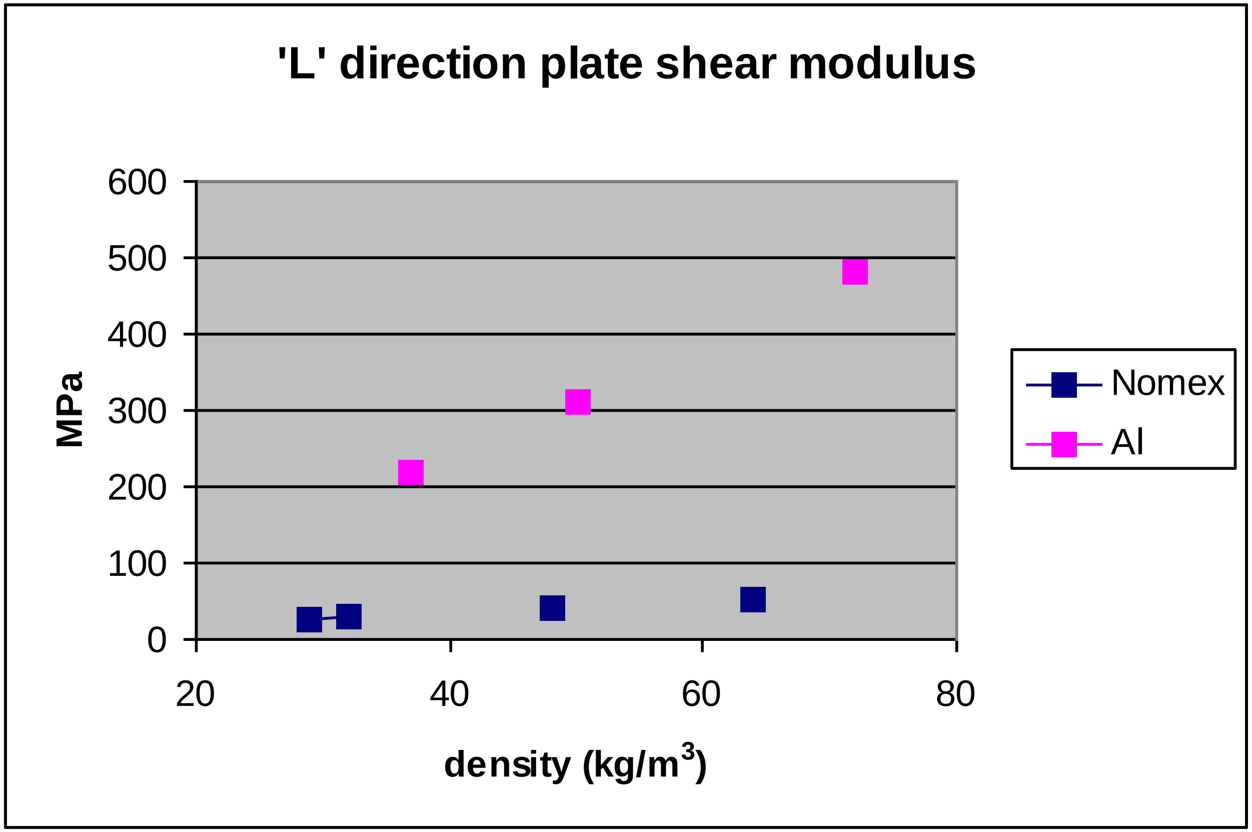
but ‘overexpanded’ core is also used to give extra formability:



Core properties depend on density and cell size. They also depend on direction - the core is much stronger and stiffer in the ‘ribbon’ or ‘L’ direction:

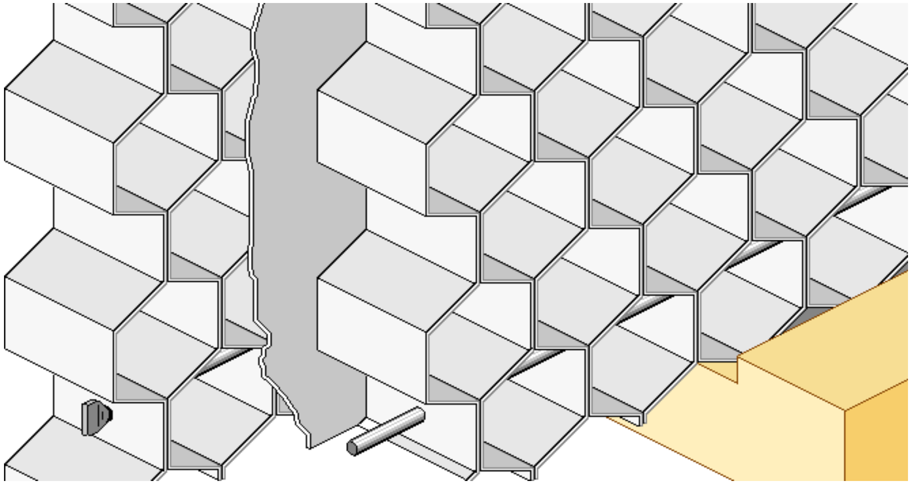


Aluminium generally has superior properties to Nomex honeycomb, e.g:



Aluminum Honeycomb

- relatively low cost
- best for energy absorption
- greatest strength/weight
- thinnest cell walls
- smooth cell walls
- conductive heat transfer
- electrical shielding
- machinability



Aramid Fiber (Nomex) Honeycomb

- flammability/fire retardance
- large selection of cell sizes, densities, and strengths
- formability and parts-making experience
- insulative
- low dielectric properties

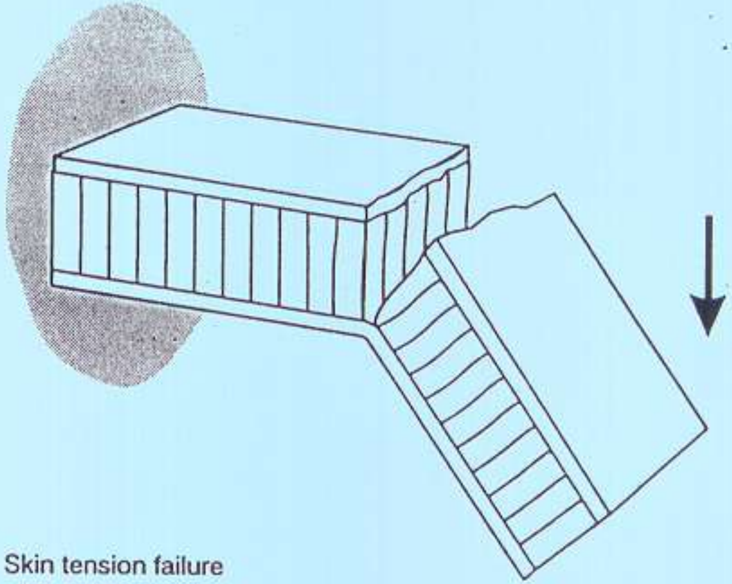
Sandwich Construction

- Many different possible failure modes exist, each of which has an approximate design formula.

1. Strength

The skin and core materials should be able to withstand the tensile, compressive and shear stresses induced by the design load.

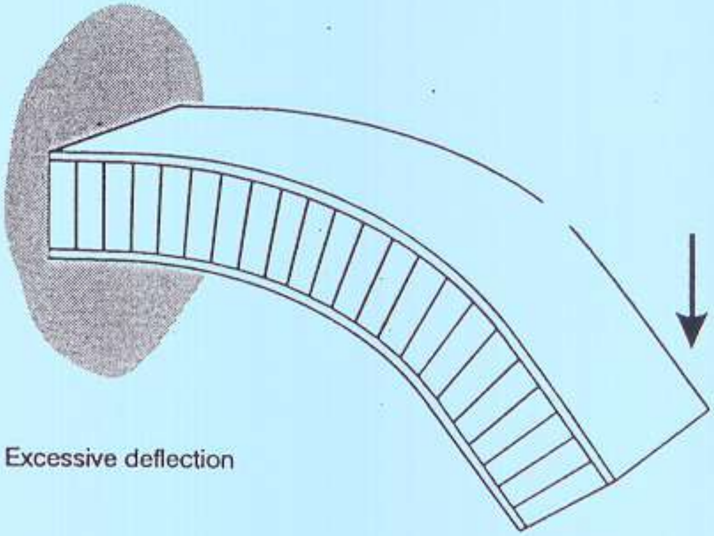
The skin to ccre adhesive must be capable of transferring the shear stresses between skin and core.



Skin tension failure

2. Stiffness

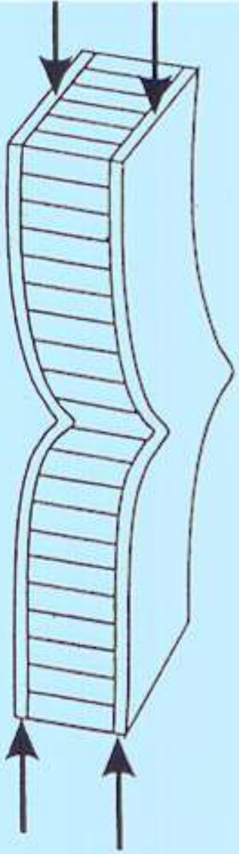
The sandwich panel should have sufficient bending and shear stiffness to prevent excessive deflection.



Excessive deflection

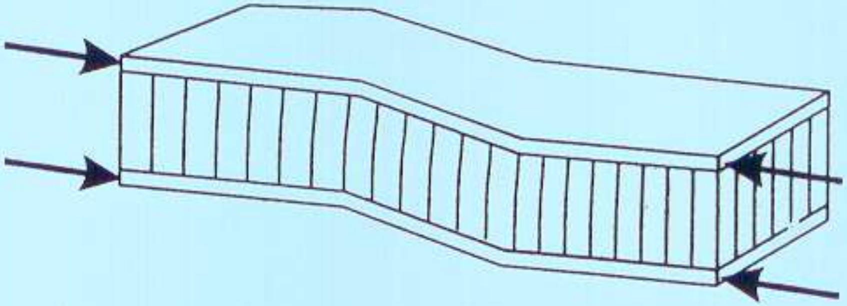
3. Panel buckling

The core thickness and shear modulus must be adequate to prevent the panel from buckling under end compression loads.



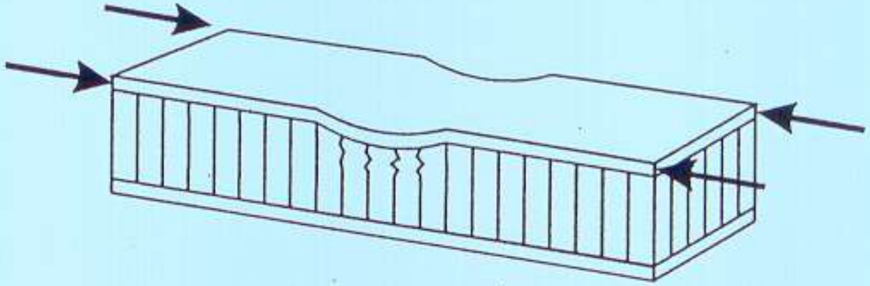
4. Shear crimping

The core thickness and shear modulus must be adequate to prevent the core from prematurely failing in shear under end compression loads.



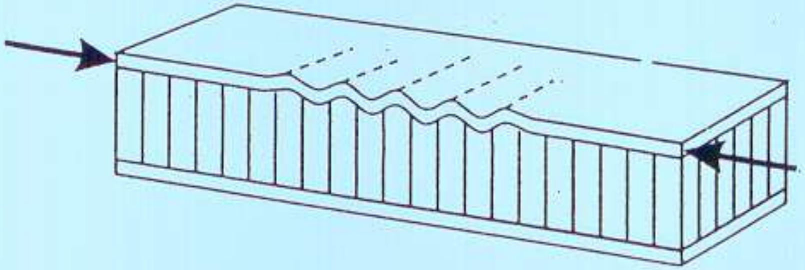
5. Skin wrinkling

The compressive modulus of both the core and the facing skin must be high enough to prevent a skin wrinkling failure.



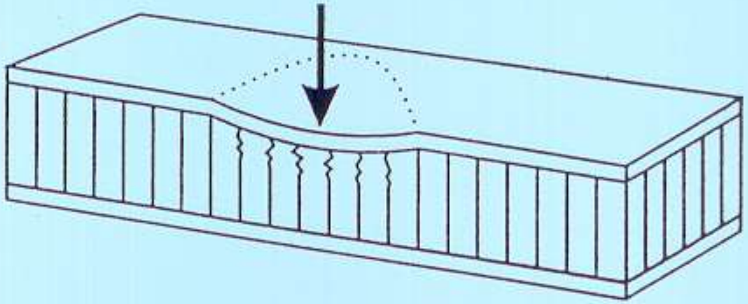
6. Intra cell buckling

For a given skin material, the core cell size must be small enough to prevent intra cell buckling.



7. Local compression

The core compressive strength must be adequate to resist local loads on the panel surface.



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UNIT - V FABRICATION PROCESS

Various Open and closed mould processes. Manufacture of fibers – Types of resins and properties and applications – Netting analysis.

TEXT BOOKS

T [1] –	Jones R.M. (1999), “Mechanics of Composite Materials”, McGraw-Hill, Kogakusha Ltd., Tokyo.
T [2] –	N.G.R.lyengar.(2016), “Composite Materials and Structural Analysis”, viva Books Pvt.Ltd.; First edition., New Delhi.

REFERENCES

R [2] -	Lubin, G (1989). “Handbook on Advanced Plastics and Fibre Glass”, Von Nostrand Reinhold Co., New York
R [3] -	Autar K.Kaw (2005), “Mechanics of Composite Materials”, Second Edition, CRC press, University of South Florida, Tampa,USA

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FABRICATION PROCESS

Manufacturing Techniques

There are plenty of methods to cast a composite structure whether it is simple or complex, single or multiple. Each method has its own merits and limitations. Selection of particular manufacturing process is based on the type of matrix and fibers, temperature to form and cure the matrix, the geometry of the end product and cost effectiveness.

The two important parameters that control the manufacturing techniques are temperature and pressure. High temperature is required for the chemical reaction of resin to prevail whereas pressure is required for the highly viscous resin to flow into the fibers and to bind the fibers which are initially unbonded. The chemical reaction of resin forming cross linking is called curing. The time required to complete the curing is called the cure cycle.

Degree of cure

The degree of cure at any time, t is defined by

$$\alpha_C = H/H_R \qquad (2.1)$$

where, H - the amount of heat released in time t

H_R - heat of reaction

The degree of cure is determined experimentally using Differential Scanning Calorimeter (DSC). This detail will be useful in processing composites.

Gel time:

On curing, the viscosity of the matrix increases with increasing cure time and temperature. The rate of viscosity increase is low at the early stage of curing. After a threshold degree of cure is achieved, the resin viscosity increases at a very rapid rate. The time at which this occurs is called the gel time.

Gel time test:

This test is conducted to determine the curing characteristics of a resin-catalyst combination. The procedure of the test is as below:

1. Take resin and catalyst and mix them thoroughly.
2. Pour the mix into a standard test tube which is suspended in a 82°C water bath.
3. Insert a thermocouple in the test tube to monitor the temperature rise.
4. Record the time and the corresponding temperature rise.
5. Plot the graph Time vs Temperature.
6. From the graph, note down the point at which there is a sudden rise in temperature. The time corresponding to that point gives the gel time.

The typical gel time graph is shown in Fig.2.1.

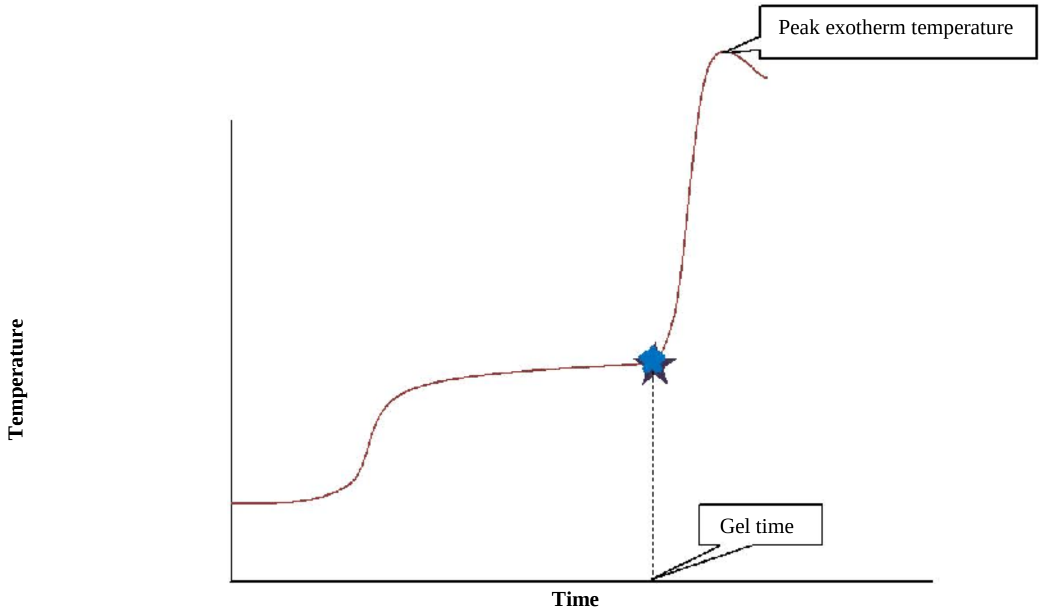


Figure 2.1 Temperature-time curve in Gel time test

Types of Composite Manufacturing:

Composites are manufactured through different techniques. The techniques are chosen based on type of fiber, resin and the size of the product. Some of the commonly used manufacturing techniques are given below.

- Lay-up
    - Hand lay-up
    - Spray lay-up
    - Prepreg Lay-Up
    - Automatic tape lay-up
- Prepregs Compression
- molding
    - Resin injection molding
    - Incremental molding
    - Stamp molding
    - High-pressure compression molding
    - Injection molding
- Bag molding
    - Pressure bag molding
    - Vacuum bag molding
- Autoclave molding
- Filament winding
    - Helical winding
    - Hoop winding
- Resin transfer molding (RTM)
    - Flexible RTM (FRTM)
    - Continuous RTM (CRTM)
    - Vacuum assisted RTM (VARTM)
    - High-speed RTM (HSRTM)
- Pultrusion
- Molding compounds
    - SMC (sheet molding compound)
    - BMC (bulk molding compound)
- Centrifugal Casting
- Extrusion method

(i) Prepregs:

Pre-impregnated fiber materials are called as prepregs. No thickening agent is used in making prepregs. Prepregs have a higher fiber content of 65%. They are available in both cloth or tape form. Usually, woven cloths are pre-impregnated, but woven rovings and chopped strand mats are also pre-impregnated.

Characteristics of good prepreg

1. The fiber to resin ratio should be high and should not vary from place to place.
2. Volatile contents and solvents should be minimum.
3. The prepreg should be flexible and tack free.
4. The material should have long storage life.
5. During moulding, the resin should be soften and flow filling the mold cavity should be without voids and defects.

Materials

Glass fiber is the most commonly used as reinforcing material, but other fibers like carbon fiber, boron have also been used. Epoxy and polyester resins are used as the impregnating agents.

Preparation of prepregs

a. Method:

Prepregs can be made by basically two methods:

1. Wetting the glass fiber cloth with the resin and heating it to a B-stage of curing (partial curing) so that the material becomes tack free. After sometime, if the heat is withdrawn and the material is stored at -18°C the cross linking operation can be stopped. At the correct B-stage the cloth will be tack free and very flexible. The prepregs are slightly

heated before processing to get soften and bond with the successive layers. After shaping (winding, press moulding), the material is heated to take it to the full cure.

2. If the matrix is in powder form it cannot go through the B-staging. In such cases, the resin is dissolved in a suitable solvent and brought to required viscosity.

b. Equipment:

The Machine used for manufacture of prepreg is called Tower. Fibers tensioned by tensioning device are passed through resin bath. It is then passed through a set of scrap bars to squeeze out the excess resin. The wetted fibers are then passed through drying oven, where temperature gradually increases. Volatiles are removed and resin reaches a tack free stage called B-stage. The prepreg fibers are covered by polythene sheet and completely rolled in aluminium foil.

c. Storage Condition:

The prepregs are stored in refrigerated chambers. The temperature of the storage area is important in improving the shelf life of the material. Moisture should be completely avoided. Shelf life is 6-8 months when stored at -18°C.

Evaluation of Prepregs:

Parameters to be evaluated in cured state are:

1. Weight per unit area
2. Tackiness and durability
3. Resin content
4. Fiber content
5. Volatile content
6. Resin flow

(ii) Hand layup method:

It is the oldest molding method for making composite products. It requires no technical skill and no machinery. It is a low volume, labor intensive method suited especially for large components, such as boat hulls. A male and female half of the mould is commonly used in the hand lay-up process. A typical structure of hand lay-up product being made is shown in Fig.2.2.

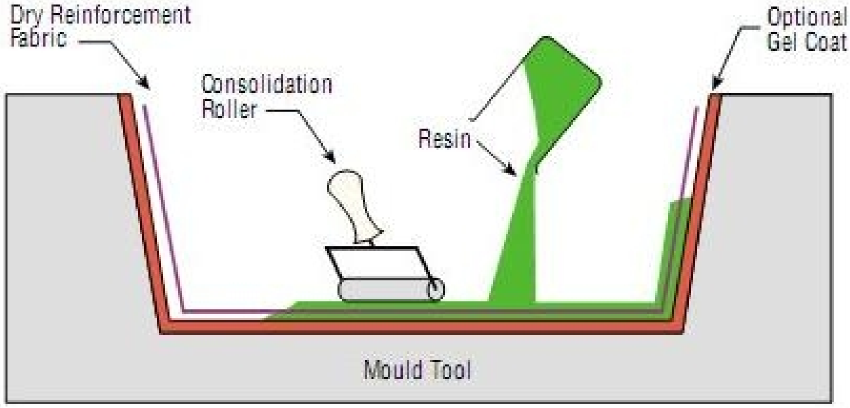


Figure 2.2 Hand layup method

Mould:

The mould will have the shape of the product. In order to have a glossy or texture finish on the surface of the product, the mould surface also should have the respective finish. If the outer surface of the product to be smooth, the product is made inside a female mould. Likewise, if the inner side has to be smooth, the moulding is done over a male mould. The mould should be free from defects, since the imprint of any defect will be formed on the product.

Release Film or Layer:

Since, the resins used are highly adhesive, the product may get stuck to the mould. So, a proper releasing mechanism should be incorporated. The release of the product can be affected.

- By the use of a release layer of wax or polyvinyl alcohol (PVA).
- By using a thin film like polyester film (Mylar).

Since, the Mylar sheet has to be fit into the mould profile, this method is not used for complex shapes.

Gel coat:

The gel coat gives the required finish of the product. It is usually a thin layer of resin about mm thickness applied on the outer surface of the product. The colour is obtained by adding appropriate pigments to the resin. The gel coat forms a protective layer that protects the glass fiber getting in contact with water and chemicals.

If the gel coat is too thin, the fiber pattern will become visible. If it is too thick, crazing and star crack can appear on the gel coat.

Surface Mat Layer:

A surface mat layer will be placed beneath the gel coat layer. The fibers of the mat will not give high strength like reinforcement fibers, but the mat provides crack resistance and impact strength to the resin rich layer. It is an optional layer used only in specific cases.

Laminates of Glass Fiber:

The glass fiber layer wetted with resin is laid up one after another to the required thickness and this finished material is called the laminate. The laminate gives the strength and rigidity to the product. Glass fiber in the chopped strand mat (CSM) is commonly used to get composite products. Woven roving, unidirectional and bi-directional mats are also used to get high strength composite products.

Finishing surface mat layer / resin coat:

The glass fiber laminate provides a rough surface finish. In order to get a smoother surface, a surface mat layer or resin coat may be applied over the laminate layer and smoothened by placing a thin Mylar film layer.

ADVANTAGES

It is a low volume, labor intensive method suited for many products such as boat manufacturing, automotive components, ducts, tanks, furniture, corrosion resistant equipment etc.

No costly machinery is required. Nearly all shapes and sizes can be made.

Colour and texture finish can be obtained by this hand lay-up method.

LIMITATIONS

The quality of the product depends on the skill of the operator.

It is not suitable for mass production of small products at high speeds.

It is difficult to get a void free composite product

SELECTION OF HAND LAY-UP AS A FABRICATION PROCESS

The following conditions favor hand lay-up as the method of fabrication.

- Only one side need to have good smooth finish.
- The product is large in size and very complex in shape.
- Only a few numbers of mouldings are required.

MOULDS

Open mould process of FRP fabrication makes use of either male or female mould. Open mould hand lay-up can be done in moulds made out of plaster of paris, wood, FRP, or metals. Plaster of Paris mould is good for one or at most two pieces since the mould may break during the release of product. Wooden mould requires finishing work on every cycle of moulding. FRP moulds are ideal for complex shapes. When heating and pressing is required, metallic moulds are preferable.

Material Selection:

Plaster of Paris, teak or rose wood, FRP, aluminium and die steel are good materials for making moulds.

Mould Thickness:

Since, GRP is a costly material, the right thickness shall be chosen for GRP moulds. For a small complex shape product the mould thickness should be double the thickness of the product. For large size products in order to make economical, ribs or stiffeners are to be used rather than increasing the mould thickness. To avoid the warping of the mould, suitable flanges or stiffeners must be provided all round the edges.

Mould Trim Line Size:

In hand lay-up the products are made with additional dimensions so that the product will have the required dimension after trimming. In case of cold pressing, extra space must be given to the mould for holding the excess resin squeezed out during pressing. This can be achieved by placing about 1/2" wide extra fiber mat all round which will act as a bleeder layer to absorb the resin.. The mould dimension is to be slightly larger than the product to hold the trim lines and bleeder layers. A bleeder layer is a synthetic material , available in variety of thicknesses and weights. It provides continuous air path for the pulling of vaccum from the composite products.

Mould Taper:

For deep drawn products a taper has to be provided for ease release. It is a common practice that a 1 in 1000 taper for epoxy and a 1 in 100 taper for polyester are found to be adequate for easy release.

Split Mould Design:

For large size and complex shaped products split moulds have to be provided. Flanges are provided at the two halves and it is connected by the bolted joints. The flange area should be 50% thicker than the mould shell thickness. A minimum flange width of 30mm with staggered bolting array may be provided.

Pattern and Pattern Making:

For a small size product the mould is made by carving the wood. If the mould is made by GRP means it requires a pattern. For a large size and complex shape product like automobile body plaster of Paris is recommended.

Plaster of Paris Pattern and Moulds:

The procedure for making mould and pattern making by plaster of Paris are the same. If the thickness is more than 15 to 25 mm, the plaster will take more time to set. So the construction should be such that there should not be any cracking. To prevent cracking chopped fibers will be added to the plaster.

Plaster moulds or patterns can be done by different methods which include, Rotational sweeping, linear sweeping, by using template and by sculpturing.

Rotational sweeping:

If the product has an axi-symmetric shape, the pattern can be shaped by rotating the template having the profile of the product to reproduce the shape.

Linear sweeping:

It is used for product having same profile along its length.

By using templates:

If the product is of irregular shape, templates can be prepared to represent the product profile and to locate at their respective positions. The space between the templates is filled with plaster of Paris.

By sculpturing:

It is used to carve a profile from the cast plaster of Paris.

Since, the plaster of Paris has a porous surface it is smoothened with non-oil based putty like nitro cellulose putty or Duco putty. Finally, the Duco putty thinner is sprayed on the surface and polished with 400 grade emery sheet to have a smooth finish.

MOULD PREPARATION AND APPLICATION OF RELEASE AGENTS

The mould should be thoroughly cleaned and free from dirt’s before the releasing agent is applied. Then, the mould surface is coated with silicone free wax (e.g. mansion polish). After some time the wax has to be removed to have a glassy finish on the mould surface. In certain cases release of the product is difficult with wax alone. So, a layer of poly vinyl alcohol (PVA) is applied. Since, PVA is water soluble material, 15% solution in water is applied with sponge. The brush application will leave the prints of brush lines so, sponge is preferable. After the water evaporates, a thin layer of PVA forms on the mould surface. The PVA layer must be completely dry before the gel coat is applied perhaps it will create wrinkles called 'elephant skin'. MEK or cellulose acetate, casein, carboxyl-methyl cellulose and methyl cellulose are the other film formers used as releasing agents.

GEL COAT APPLICATION

The gel coat resin is generally of the same as the matrix material used for making the composite product. The gel coat resin is prepared by adding 2 to 3 % of aerosol powder to the resin and stirring it well. The aerosol powder provides the required thixotropy. It is a property by which a liquid which remains as a thick viscous fluid with very little flow, but when some external force is applied (like stirring it well), it flows easily like a relatively low viscous fluid.

The viscosity of the resin can also be increased by adding fine calcium carbonate or other fillers. The filler percentage must be as low as possible otherwise, the cured resin will become brittle.

Pigments can be added with the resin to get the required colour. Titanium dioxide and carbon black will give white and black colour respectively. For products exposed to sunlight, UV stabilizers must be added to the gel coat resin. The required quantity of gel coat mix for a batch of same colours can be mixed at a time by adding pigments and accelerator to avoid colour variation.

Gel coat resin when applied must be free from air bubbles and dirt. About 600 gms. of resin will be required to give 0.5 mm thick gel coat on one sq. m. area. This will be applied as two coats. The second coat will be applied after the first coat is cured.

SURFACE MAT LAYER

The surface mat layer must be applied only after the gel coat is cured. Otherwise the surface finish will be affected. The surface layer can be any one of the following.

- Glass fiber surface tissue mat.
- Polyester woven cloth of fine thickness
- Nylon woven cloth of fine thickness

A thin layer of resin is applied over the surface and the mat is wetted with brush. It may also be lightly rolled with roller to remove the air bubbles.

LAY-UP OF LAMINATES

The lay-up should start as soon as the gel coat layer is cured. The lamination should satisfy the following requirements:

a) The fiber layers should be uniformly placed and they should fit correctly into the contour of the product.
b) The fiber should not be damaged during lay-up
c) The fiber to resin ratio should be correctly maintained.

Preparation of the Resin Mix:

The resin mix can be prepared at least one day ahead so that the entrapment of air bubbles escape before the lay-up begins. The mix consists of the resin, accelerator, fillers, and additives if any. The addition of accelerator to resin will not cause any cross linking until catalyst is added.
The mixing can be done by either manually using a paddle or by using an air operated mixer.

Vigorous stirring can cause entrapment of air bubbles therefore; mixing should be done at a very low rpm. The container in which resin mix is stored may be closed air tight to minimize the vaporization and loss of styrene.

Preparation of the color fiber Mat:

The required number layers to obtain the thickness can be determined by taking into account the mat density and the glass-to-resin ratio by weight. The following points must be taken into account while preparing the mat:

Wherever joints are there, there should be a minimum overlap of 25 mm, in case of chopped strand and a 50 mm overlap is required in the case of woven roving mat.

Whenever, there is change in thickness the thickness must not abruptly change and instead it must gradually change.

Tools for Lay-up:

1. Weighing balance - to weigh the chemicals.
2. Brushes - to apply resin for both gel coat application and for lamination.
3. Rollers - to remove the air bubbles and also for applying resin.

Long rollers are used to consolidate large areas but short rollers are used for corners and curved surfaces.

Mugs and small bowls - for taking the resin mix for lay-up.

Solvents:

Solvents are required for cleaning the rollers and brushes during or after the lay-up sequence is over. Acetone or nitrocellulose thinner can be used as solvents.

Lamination procedure:

In the process of lamination a thin layer of resin is applied on the gel coat layer. Then, a chopped strand mat is placed over it. The resin is again applied over the mat by using brush to wet the mat. By using the roller the air bubbles are removed.

After the first layer is laid up, subsequent layers are laid in a similar manner. More than, 4 layers of resin and glass mat should not be applied without allowing the resin to cure at a time. When WRM is laid up, CSM is used in between in order to increase the inter-laminar shear strength. The lay-up procedure for WRM and CSM are identical except that the resin used for WRM is half the quantity of that is needed for CSM.

Curing of Resin:

The curing of resin process undergoes through four stages:

Gelation Stage:

It is the stage at which the resin becomes tack free and unworkable. It depends on the percentage of catalyst and accelerator added. Normally, it takes 15 to 30 minutes to gel.

Green Stage:

This is the stage at which the resin resembles to hard cheese which when pressed with the thumb it breaks up. The resin is considered to be set but not cured.

Cured Stage:

It is the stage at which more than 90% of the cure is completed. The product can be released from the mould after this stage.

Fully Cured Stage:

It is the stage at which the physical properties of the moulding are developed. Normally, it takes 5 to 10 days. At a fully-cured state, GRP will produce a metallic sound if it tapped with a coin.

Release of the Moulding from the Mould:

This process should be done very carefully. Any of the following methods can be used for releasing the product.

Construct a 'grapple' point in the part so that when a hoist is engaged to lift upwards, the weight of the mould will cause to drop it off.

Wedges are inserted into the flange and by tapping it all around the mould; the two halves will be dropped.

(iii) Pultrusion:

Pultruded composites consist of fibers predominantly in axial directions impregnated by resins in order form a most efficient composite product. Surface mats are used for surface appearance and also to improve chemical and weather resistance. Polyester resins are widely used in the pultruded products.

Pultrusion process:

The pultrusion process (Fig.2.3.) generally consists of pulling of roving/ mats through performing fixture to take its shape of the product and then heated where the section is cured continuously.

Description of Pultrusion Machine:

The following are the facts of Pultrusion machine and the details of these facts are given below.

a. Creel.
b. Resin wet out tank
c. Forming dies
d. Heated matched metal die
e. Puller or driving mechanism.
f. Cut-off saw.
g. Mandrel (for Hollow shapes)

a. Creel:

Creel generally consists of bookcase type shelves where rovings from individual packages are pulled out for a resin bath. Metal book shelves are best since they can be grounded to avoid static charges produced. Vinyl tubes are installed to avoid the roving crossing over each other, as it generates "fuzz ball" to build up in the resin mix tank raising its viscosity.

b. Resin wet out tank:

The resin bath or wet out tank generally consists of sheet metal of aluminum through series of rolls. A grid or comb is attached at the entry and exits of resin wet out tank in order to maintain horizontal alignment and also to avoid the excessive resin.

c. Preforming Fixtures:

These fixtures consolidate the reinforcements and move them closer to the final shape provided by the die. Generally, fluorocarbon or ultra high molecular weight polyurethanes are used as fixtures since these are easy to manufacture and also it is easy to clean it for later purpose.

d. Heated Dies:

The chrome plated matched metal die maybe heated by electrical cartridges or by strip heaters. Thin sections are generally used by conduction of heat. In case of thick section the curing can be speeded up by using both radio frequency (RF) radiation and conductive heat.

e. Pulling Section:

A pair of continuous caterpillar belts containing pads are used for pultrusions. A double set of cylinders with pad pullers can be synchronized for an intermittent pull.

f. Cut-Off saw:

A conventional saw with an abrasive or a continuous rim diamond wheel with coolant is generally used for cutting the desired product.

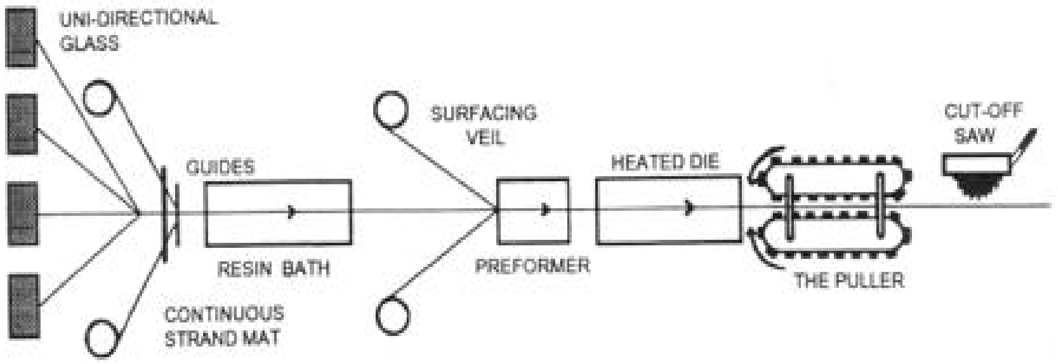


Figure 2.3 Pultrusion method

The pultruded sheet consists of both CS rovings as well as mat layers. Mat layers are added to increase the transverse strength. Generally, the matrix materials used in pultrusion are polyester and vinyl ester from thermoset polymers (epoxy has long cure time) and PEEK and polysulfone from thermoplastic polymers.

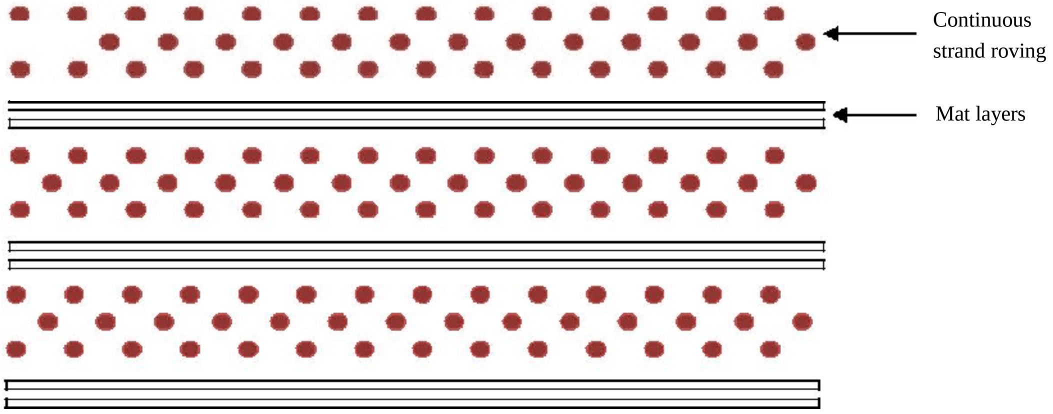


Figure 2.4 Pultruder sheet

The pultruded sheets (Fig.2.4.) are pulled through a liquid resin bath to thoroughly wet every fiber. The reinforcements are then guided and formed, or shaped, into the profile to be produced before entering a die. As the material progresses through the heated die, which is shaped to match the design profile, the resin changes from a liquid to a gel, and finally, into a cured, rigid plastic.

A pulling device grips the cured material and literally pulls the material through the die. It is the power source for the process. After the product passes through the puller, it is sawed into desired lengths. Although pultrusion is ideally suited for custom shapes, some standard products include solid rods, hollow tubes, flat sheets, hat sections bars, angles, channels, and I-beams.

Applications of Pultrusion:

- Electrical application including transformers.
- Supports in bridges and structures.
- Automobiles.
- Pipes and rods.

Pultrusion part design:

1. **FRP property design criteria:**

   The design factor and load factor are to be considered before producing the product based on the application. It is necessary to depict its ultimate strength for safe operations. Apart from it various other properties like thermal and electrical properties are to be determined.

Table 1.25 Designs

Type of Loading	Minimum Design Factor
Static Short-term loads	2.0
Static Long-term loads	4.0
Variable or changing loads	4.0
Repeated loads, load reversal, fatigue loads	6.0
Impact loads	10.0

Pultrusion part design principles:

In this section the principles of product manufacturing and the handling factors of the product are discussed.

Table 1.26 Details of Pultrusion process

Size	Shaping die and equipment pulling capacity influence size limitations
Shape	Straight, constant cross sections, some curved sections possible
Reinforcements	Fiberglass Carbon fiber Aramid fiber
Resin Systems	Polyester Vinyl ester Epoxy Silicones
Fiberglass Contents	Roving, 40-80% by weight Mat, 30-50% by weight Woven roving, 40-60% by weight
Mechanical Strengths	Medium to high, primarily unidirectional, approaching isotropic
Labor intensity	Low to medium
Mold cost	Low to medium
Production rate	Shape and thickness related

2. Structural shapes:

Early pultruded structural shapes were made to conform to standard steel practice. It was found out that since FRP shapes were heterogeneous materials and their shrinkage due to cure was subject to the type and quantity of resin used, warpage was a problem. These structural shapes should contain continuous strand mats as well as continuous rovings. An uneven number of plies of continuous strand mat are used with rovings placed between each two layers of mat.

Pultrusion die design:

Pultrusion dies are considerably simpler in construction than most matched mould dies.

a. **Die Steel:**

Any good tool steel can be used to make a Pultrusion die. Coated dies are in trend in order to withstand heat and also to avoid corrosion. Ceramic coated steel dies have been successfully used.

b. **Bell Mouth entrance:**

In order to assist the wet reinforcements to enter the mould a bell mouth is machined around the shape periphery. As the part size increases in width and area this bell mouth should be used for very large structural shapes.

c. **Mounting Provisions:**

The die must be fastened to the heating platens with clamps or bolts. A less expensive and reliable method is to fasten the dies to the platens with bolts and angle clamps.

d. **Die surface finish:**

All internal mould surfaces that see the FRP materials should have a good mould finish. Final polishing should be in longitudinal direction.

e. **Chrome plating:**

The internal areas of the Pultrusion die through which the materials are pulled must receive a hard chrome plate to provide a long working life for the die.

f. **Heating:**

Pultrusion dies are to be heated with strip heaters, electrical cartridge heaters, or cored for hot oil. After it became useful to have several zones with different controlled temperatures and a different temperature at start up than during operation. The use of electrical cartridge heaters with thermocouple has now almost become a standard practice.

g. **Cold Junction:**

A cold junction is used on the portion of the die that extends outside the heated platen area. Cooling water should enter the bottom cold junction port first and then the top plate as to insure that air pockets do not collect in the system.

(iv) Compression molding:

It is considered as the primary method of manufacturing for many structural automotive components, including road wheels, bumpers, and leaf springs. It is done by transforming sheet-molding compounds (SMC) into finished products in matched molds. It has the ability to produce parts of complex geometry in short periods of time. It allows the possibility of eliminating a number of secondary finishing operations, such as drilling, forming, and welding. Moreover the entire molding process can be automated.

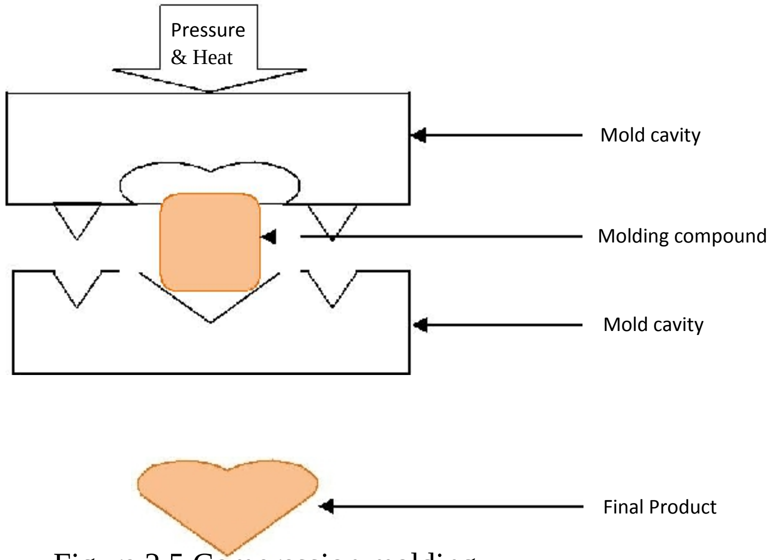


Figure 2.5 Compression molding

The molding compound is first placed in an open, heated mold cavity. The mold is then closed and pressure is applied to force the material to fill up the cavity. A hydraulic ram is often utilized to produce sufficient force during the molding process. Excess material is channeled away by the overflow grooves. The heat and pressure are maintained until the material is cured. The final part after the mold is removed. The molding pressure may vary from 1.4 to 34.5 MPa and the mold temperature is usually in the range of 130^{o}C to 160^{o}C. To decrease the peak exotherm temperature which may cause burning and chemical degradation in the resin, filler may be added. The time to reach peak exotherm is also reduced with increasing filler content, thereby reducing the cure cycle. The cure time may also be reduced by preheat process.

There are two different types of compounds most frequently used in compression molding: Bulk Molding Compound (BMC) and Sheet Molding Compound (SMC). SMC costs higher but can be pre-cut to conform to the surface area of the mold.

Types of Compression Moulding

i. Hot pressing in which the moulding charge is heated while shaping.

ii. Cold pressing which uses a wet lay-up process and the product is pressed to the required shape, but cured without the application of heat.

Advantages

i. Good finish on both sides.

ii. Faster production.

iii. Uniform product quality.

iv. Less labor content.

v. Very little finishing operations required.

Disadvantages

i. This process is not suited for low volume of production because of high cost of moulds and press.

ii. The process is also not suitable for very large sized products.

Equipment:

The Press:

The function of the press in the compressing moulding is to supply the pressure required for moulding the products. There are various types of presses available eg. mechanical, pneumatic and hydraulic. Since, pressure required for GRP are high. Hydraulic presses are mostly used.

Moulds:

Moulds give shapes to the moulding charge. Dimensional accuracy and surface finish of the moulded product depends mainly on the dimensional accuracy of the moulds and it has to be very high. Mould surface should have high class surface finish and resistance to abrasion, since several thousand products have to be obtained from one mould.

Mould Materials

Requirements of mould materials are

i. High strength
ii. High toughness
iii. High Hardness Value
iv. Good Abrasion Resistance
v. Good Machinability
vi. Good weldability
vii. Good Polishability

Three general types of steel are used for mould construction

i. Pre-toughened steel
ii. Case hardening steel

iii. Air hardening steel

Alloy steel AISI-4140 or its equivalent IS-40 C 1 Mo 28 or EN19C pre-hardened to Rockwell C30-32 is used for high class moulds.

Types of Moulds

There are five standard designs for compression mould cavities and forces, these are

1. Flash type mould:

   This design is not recommended, since parts produced may be of poor quality. However, it may be used for large parts made form BMC or SMC.

2. Fully positive mould:

   It is used for large deep draw where maximum density is

required. 3. Landed positive mould:

   These are multi-cavity moulds. Multi-cavity mould may be this type of mould. Vents are incorporated on the force to permit maximum density.

4. Semi-positive vertical flash mould:

   These are more suited for automatic moulding

5. Semi-positive vertical flash mould:

   This is used when no visual flash line mark is permitted on the moulded parts. Mold costs are more because of two areas of proper fit between force and cavity.

(v) Resin Transfer Molding (RTM):

It is also called as liquid molding. It is a low pressure closed molding process for moderate volume production quantities. Dry continuous strand mats and woven reinforcements are laid up in the bottom half mold. Preformed glass reinforcements are often used for complex mold shapes. The mold is closed and clamped, and a low viscosity, catalyzed resin is pumped in, displacing the air through strategically located vents.The injection pressure of resin is in the range of 70-700 kPa.

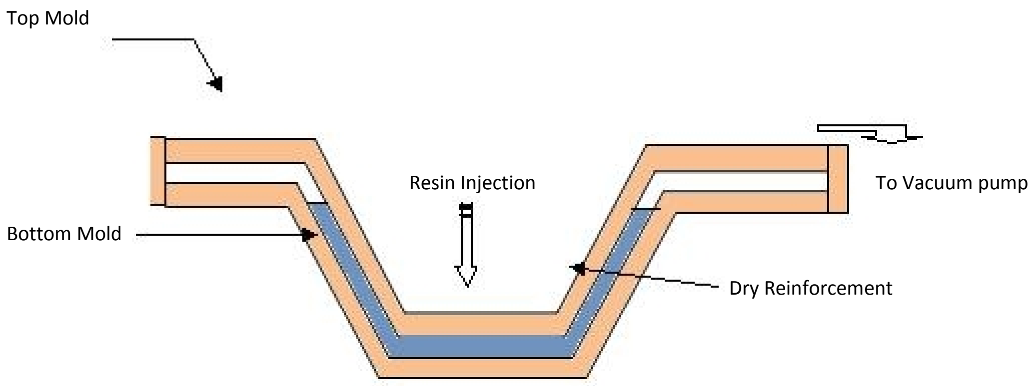


Figure 2.6 Resin Transfer Molding

Advantages and limitations

Unlike in hand layup, RTM process gives better control on product thickness and good finish on both sides. It is not essential to have metallic moulds because the product curing is generally done under ambient temperature. By applying gel coats on both sides, the product will have a smoother finish on both sides.

When the injection pressure is increased, as in very closely packed fibers, there is a tendency for fiber wash. This tendency can be countered by using continuous strand mats or special woven performs. Inserting of wood, foam or metal will reduce the secondary bonding. Other advantages can be listed as follows.

1. Controlled usage of fiber and resin reduces the material wastage and unit cost
2. A variety of mould shapes and sizes can be moulded sequentially because of the mobile pumping unit.
3. Styrene emission is practically eliminated during resin transfer into the mould.

There are few limitations which require special attention. Some of the limitations are given below:

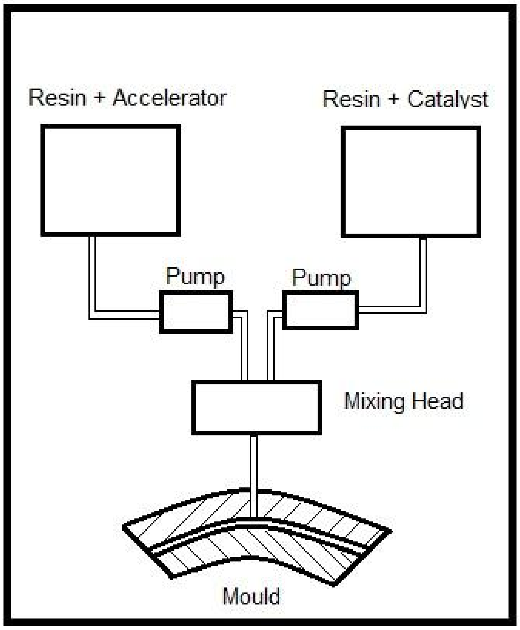
1. Since, this process can develop pressures up to 5 to 10 bars, tool rigidity and clamping techniques have to be designed for such pressures.
2. Handling of large and heavy moulds requires adequate lifting equipments.
3. Unlike in compression moulding, post trimming is required for this process.

PROCESS EQUIPMENT AND TOOLS

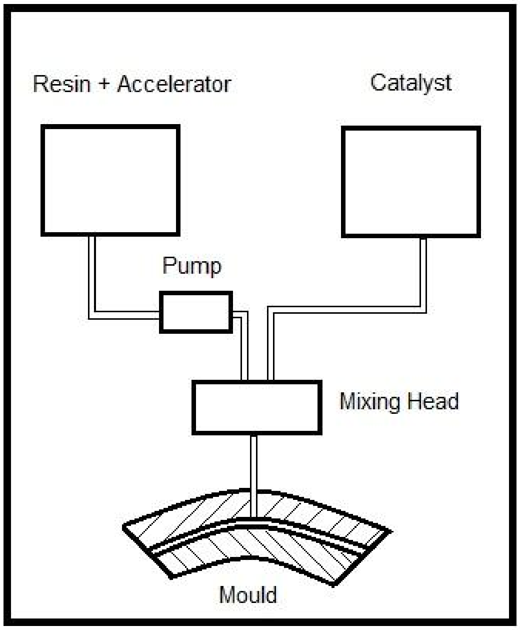
Types of RTM machines

The machines used for RTM include a mixing head attached to a nozzle, a pumping unit, and a solvent flushing unit. The pumping unit generates the pressure to inject the resin through the layers of reinforcement. The solvent flushing unit pumps solvent such as acetone to clean the mixing and injection chamber free of resin.

There are three types of RTM injection equipments based on position of mixing of catalyst with resin.



A two pot RTM machine



A catalyst dispersing type RTM machine

Figure 2.6a Two pot RTM machine Figure 2.6b catalyst dispersed RTM machine

a. Two pot system

This system has two equal volume containers or pots. In one of these pots the resin is mixed with accelerator. In the other pot the resin is mixed with the catalyst. Two pumps are used to pump these mixtures (as shown in fig.2.6a) to the injection points where they are mixed well in the mixing head.

b. Catalyst injection system

In this system the catalyst is not mixed with the resin until it reaches the entry pot attached to the mould (Fig.2.6b). The resin mixed with accelerator is pumped into the injection chamber. The catalyst is taken separately into the chamber by means of controlling valve. The advantage of this system is that the gel and cure time can be controlled by varying the amount of catalyst added.

c. Pre-mixing system

This is a simple process by mixing the resin, accelerator, and catalyst in a vessel directly and injecting the mixture into the mould. A thick walled airtight metallic cylinder provided with inlet and outlet holes is taken. The injection is carried out through the outlet by means of compressed air. The cylinder has to be washed periodically with acetone to prevent clogging by cured resin.

MOULDS AND MOULD DESIGN

MOULD STRUCTURE

The mould essentially consists of male and female halves, clamped by a clamping arrangement. Other parts include the injection ports, the air vents, the guide pins, and the gasket along the partition line.

Injection ports:

Injection port is the nozzle through which the resin is injected into the mould. The correct location of injection port is very much essential to ensure proper filling of the mould. As far as possible, the injection port must be located at the middle so that the resin flows radially to the periphery.

Air vents:

Air vents are provided at suitable locations in the mould for allowing the volatiles and trapped air from the part.

Guide pins:

Guide pins are provided in the mould for guiding the two halves of the mould to a perfect closure without lateral displacement.

Gaskets:

Sealing gasket is provided along the parting line while crossing the mould for preventing the flow of resin through the parting line. Neoprene and silicone can be used as the gaskets.

MOULDING PROCESS

Mould preparation

The two halves of the mould are cleaned and the dust must be removed from the surface. Wax polish is then applied which helps in easy release of the mould after curing. Over the layer of wax, a film of PVA is applied to aid the release. The disposable inlet and outlet port and air vents are then fitted in position.

Gel coating

A layer of gel coat with appropriate pigment is applied on the surface of both halves of the mould. The gel coat thickness should not exceed 0.5mm.

Fiber packing and mould closure

The calculated quantity of fiber is placed inside the mould. Wherever, the overlap comes, a 25 to 35 mm overlap must be given. The plies near the inlet port can be stitched together otherwise the fiber wash can occur due to injection pressure. The inserts should be placed correctly before the mould is closed. The clamping of mould has to be tight enough to withstand the injection pressure.

Resin injection and curing

The resin is then injected to the mould using an RTM machine at a calculated pressure. Care must be taken to see that the right quantity of catalyst is dosed into the resin stream and no gelling occurs during pumping. The mixture head has to be pumped with acetone at 15 minutes interval so that the resin does not set within the mixture head.

Demoulding and cleaning

The mould is left undisturbed until the resin is fully cured. For products with large thickness, the high exotherm may lead to degradation of resin hence mould cooling is necessary to reduce the heat. Demoulding is done by removing the clamps and by releasing the mould without any damage to the mould. The product and the mould are then cleaned thoroughly. The product can be polished by using emery paper.

MOULD TIME CYCLE

Total moulding time is given by the relation:

$T_T = T_{mf} = T_{gel} = T_c = T_u = T_{cl} + T_p + T_{fp}$

T_{mf} = mould fill up time

T_{gel} = gel time

T_c = cure time

T_u = un mould time

T_{cl} = cleaning time

T_p = preparation time

T_{fp} = fiber packing time

(vi) Filament winding:

Filament winding consists of winding resin impregnated fibers or rovings of glass, aramid, or carbon on a rotating mandrel in predetermined patterns.

The method makes void free product possible and gives high fiber volume ratio up to 80%. In the wet method, the fiber picks up the low viscosity resin either by passing through a trough or from a metered application system. In the dry method, the reinforcement is in the pre impregnated form.

After the layers are wound, the component is cured and removed from the mandrel. This method is used to produce pressure vessels, rocket motor cases, tanks, ducting, golf club shafts, and fishing rods and to manufacture prepregs. Thermoset resins used in filament wound parts include polyesters, vinyl esters, epoxies, and phenolics.

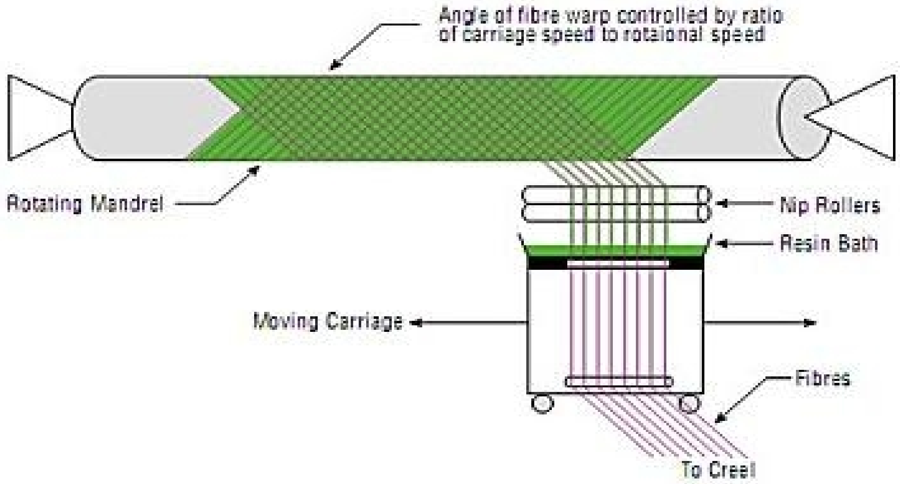


Figure 2.7 Filament winding

This method can be automated and provides high production rates. Highest-strength products are obtained because of fiber placement control. Control of strength in different direction is also possible.

Matrix Application Methods:

The important purpose of the matrix is to bind the filament together and convert into a solid material. The matrix should be free from voids and dirt particles. The matrix application can be divided into seven methods as given below:

a. Wet Winding:

In the wet winding process the matrix in liquid form is placed in a resin bath and the fibers are dipped in that bath and wound. The matrix will be in the liquid form or is brought to liquid form by making a solution. Solids like thermoplastics can be brought to liquid form by melting also.

b. Dry Winding and Liquid Infiltration:

In this process the fibers are initially wound without the matrix and after winding the matrix is allowed to infiltrate into the fibers by pressure injection or vacuum impregnation. The viscosity has to be very low for such impregnations.

c. Dry Winding and Vapour Infiltration:

The fibers are wound first and the matrix is deposited by Chemical Vapour Deposition (CVD) or Physical Vapour Deposition (PVD).

d. Powder Injection:

In this method the matrix material is in the form of powder and is injected into the fibers during winding and then it is converted into solid by sintering or melting.

e. Prepreg Winding:

Prepregs are the fibers, tapes or clothes previously impregnated with the resin. The prepreg will have the fiber to resin ratio correctly maintained. Since the prepregs are in semi solids, winding is more convenient and after winding it is converted into solids by heating or sintering.

f. Winding of Woven or Comingled Fabrics:

In this method the woven fabrics are made by weaving the fiber and the resin which is in the form of fiber. Bundles of reinforcement and matrix filaments are taken as warp and weft fibers and are woven. In the comingled type each bundle of filament will have the matrix and the reinforcement fibers. After winding, the materials are heated to melt the matrix filaments.

g. Plasma Spraying:

The fibers are wound and simultaneously the matrices can be sprayed into it by plasma spraying.

Conversion of Matrix into Solids

This conversion process can be broadly divided into two processes as below.

a. Reactive Process:

In the reactive process the matrix is formed by a chemical reaction which may be a polymerization process as in Reaction Injection Moulding (RIM) or cross-linking process. In the case of carbon-carbon composites, the infiltrated phenolic is converted into graphite by the polymer pyrolysis.

I. Reaction Injection Winding:

In this process the monomers of the polymeric is infiltrated into the filaments. The reaction continues in-situ converting the monomer into a polymer.

II. Polymer Cross-Linking:

Thermoset resins like epoxies, polyesters, phenolics can be made into liquid linear polymer form. Winding is then done with the resins adding the cross-linking additives. The cross-linked operation continued during winding and after winding the liquid linear polymer is converted into cross-linked solid material.

b. Non-Reactive process:

Some of these conversions can be described as follows:

Melt Processing:

Prepregs are first made by coating the fibers with thermoplastics. The prepregs are then used for winding and after winding the thermoplastics are melted and fused into solids. The prepregs can be made by solution impregnation, melt impregnation, film or powder coating etc.

Sintering:

In this process the matrix is in powder form. The fibers are pre-coated with the powder before winding and during winding process the powder is incorporated into fiber by infiltration or powder injection. The powder is subsequently sintered into solid by heating. This method is suitable for materials like polytetra fluoro ethylene (PTFE) which requires very high temperature to melt.

Vapour Deposition:

Vapours of metals, ceramics, carbon etc. can be infiltrated into the fiber which is then cooled to form the matrix.

Advantages of Filament Winding

1. Filament winding is semi-automated which can be done more neatly with less workers.
2. Filament winding can give a fiber content as high as 70% by weight in the case of glass fiber.
3. This process is used for making large products like storage tanks up to 15 or 16 m diameter by using special winding machines.
4. It is possible to vary the strength of the wound product in different directions by varying the angle of winding.

Limitations

1. Products with complicated profiles and reverse curvature cannot be wound.
2. The inter-laminar shear strength of the product is low.

3. The ultimate bearing strength is low. They are rigid but less ductile.
4. The laminate quality of the filament wound product is generally lower than that of the product made by autoclave processing.

MATERIALS

Reinforcement Fibers

Glass fiber is the common reinforcement fiber for commercial applications like chemical tanks, petroleum tanks, pipe lines etc. Aramid fibers including Kevlar 49, 29, and 149 are used for making products such as aerospace structures, rocket motor casing etc. Kevlar fibers have poor compressive and shear strength and are not usable for high temperature since they melt at 140°C. Carbon is the next versatile fiber because of their high modulus, strength and temperature resistance. Natural fibers provide good strength for applications like boats and silos by winding process but further research is needed to improve their durability.

Thermoset Resins

Polyester, vinylester, and epoxies are commonly used as thermosets. Polyester including isophthalic and bisphenol resins are used for chemical plants, petroleum tank and pipeline applications. Epoxies, because of their superior shear strength and mechanical and electrical properties used for high performance applications like aerospace and electrical insulation products. Vinylester finds applications in chemical resistant product. Polymide, silicones, phenolics and furan resins finds applications in very special requirements like high temperature resistances.

Thermosets are used in wet winding, prepregs and wet rerolled rovings. Wet rerolled rovings are rovings impregnated with resin and rolled in to spool form and stored under low temperature and then unwound and used for winding.

Thermoplastic Resins

These resins are used to make prepregs by coating the thermoplastics on the fiber by melt dip coating, fiber transfer or by powder coating. The fiber reinforced thermoplastic prepreg tapes are then wound using a tape winding machine. After winding the product can be heated to a level at which the resin melts and fuses into a solid.

WINDING FACILITY

Mandrels

The mandrel constitutes the important part of the winding setup. It is the tool around which the matrix impregnated rovings are wound. The profile of the mandrel gives the profile of the filament wound product. The mandrel must be smooth and easily removable after the product is fully cured.

Mandrels are broadly classified into (i) open ended non-collapsible mandrels and (ii) collapsible mandrels.

Open ended non-collapsible mandrels:

They are generally made of steel with smooth surface finishes and an axial taper of 1:200 for easy release of the product from mould. Screw and hydraulic extractors are used for the release of the product.

Collapsible mandrels:

a. Segmented metallic collapsible mandrels

The mandrel is made of several segments. The segments are dismantled to release the product.

b. Water soluble mandrels

Water soluble mandrels are made by casting over a centered axis and polar fittings, sand and water soluble polyvinyl alcohol.

c. Spider plastic mandrels

Plaster of Paris layer is made over removable or collapsible tooling. Plaster can be finished with either duco putty or with release films. After winding central mandrel is removed and the plaster is chopped off.

d. Inflatable mandrel

Mandrel is made by inflating a bag. They also present the problem of larger transmission.

e. Low melting alloy mandrels

Low melting alloys and metals like lead can be used for making the mandrel. Later, the mandrel material cannot be recovered.

f. Non-removable liners

Liners can be made from metals or plastics or FRP for liquid resistant surfaces.

WINDING MACHINES

The winding machine has facilities for wetting the fiber, tensioning the filament, laying the fiber or tapes in the required angle in a uniformly spreaded pattern. Winding machines can be broadly divided into three groups.

a. Helical winding machines

b. Polar winding machines

c. Special purpose and advance winding machines

a. Helical winding machine

The helical winding machine is designed to lay the fiber on a rotating mandrel at winding angles varying from 0°(axial) to 90°(hoop) with axis of rotation. The basic movement of the helical winder is the mandrel rotation and the feed traverse. By varying the speed of two movements, it is possible to vary the winding angle. The feed eye moves to and fro from one end to other end creating an angle ply or netting structure on the mandrel surface.

The fiber is fed to the feed eye through a resin bath in the wet winding process. The resin bath also moves along with the feed eye. In case of prepreg winding the fibers or tapes are fed from a spool or creed stand. The creed stand is stationary or it is fixed with the resin carriage so that the stand also moves along with the feed eye. Fig.2.8 shows the layout of a typical helical winding machine.

Helical winding machines can be made with constant helix angles in which fibers can be wound only at constant angle with the axis or variable angle machines where the angle of winding can be varied from 0° to 90° with the axis. The variation is achieved by varying the mandrel surface speed and the feed point speed. Accurate speed variations can be possible by using numerically controlled step motors with or without servo hydraulic pulse motors. These machines have the advantage that winding angle can be changed along the length by pre-programmed using punched tapes or by using computers.

b. Polar winding machine

Polar winding is done generally for spherical, ellipsoidal or other closed axis symmetric shells. The two ends of the mandrel is called poles. The winding is done from one pole to the other. Fig.4.9 shows a typical polar winding machine.

The polar winding machine can be made in two different ways

1. The feeding eye is rotating while the mandrel is on a fixed axis with only rotating motion. This system needs the resin bath and fiber spool to travel with the feed eye.
2. The feeding eye is fixed while the mandrel has two motions with rotation about its axis and a rotation about one of the mounting supports. The advantage in this is the resin bath need not travel around the mandrel, but the rotation of heavy mandrel has to be done using a cantilever arrangement and the support system must be rigid enough to carry the load without causing any deflections.

Depending upon the way mandrel is supported, the winding machines can be classified into cantilever type or with both ends supported. In the cantilever type, the mandrel is supported at one end and the other end is free which helps to take round the mandrel without any obstruction.

c. Combined polar and helical winding machine:

Products like pressure vessels, road tankers, petroleum tanks etc. require a cylindrical shell with end domes having spherical, ellipsoidal shapes. One way is to make them separately and joined them together, which gives a weak joint at the junction. The better way is winding the shell and domed ends using combined helical and polar winding machines.

d. Special purpose machines:

Several other variations of filament winding machines have been developed for specific end uses and a few machines are described below.

1. Fixed mandrel machines:

For winding very large cylindrical tanks, rotating the mandrel for winding becomes very costly. In such cases the mandrel is kept stationary on a vertical axis. The resin bath together with fiber creels move around the mandrel and up and down to create the helical path around the mandrel

2. Race track machines:

In these machines the resin bath and fiber creel travels on a race track and the mandrel rotates about its axis. The winding angle is achieved by tilting the mandrel to the required positions.

3. Continuous pipe making machines:

These machines have stationary mandrels. The fiber spools are mounted on a circular ring which rotates around the mandrel. Two such rings rotating in the opposite direction create the helical or angle ply pattern on the mandrel. By controlling the linear and rotary motions of the ring the required winding angle can be obtained.

4. **Braiding machine:**

It is similar to the continuous filament winding except that the fibers get knitted during the winding process. Braiding without resin is used for fiber insulation of electrically conductive wires. Braiding with resin is used for making filament wound high pressure hoses.

Resin Curing System

In normal machines, the mandrel with wet wound shell is transferred to an oven where it is cured as per the cure schedule. In order to present the resin dripping, the mandrel is rotated slowly in the chamber until the resin gels. The rotation must be slow to prevent the resin coming to surface due to the centrifugal force. After curing the product is removed and then post cured if necessary.

Another way to cure is to use infrared rays which will be focused on to the wet wound shell. As the mandrel rotates slowly, the radiated heat helps to cure the resin.

For cold curing system, the cure can be achieved by keeping the mandrel rotated slowly until the resin gels. After curing the product will be released and it is post cured if necessary.

For large products, curing the product in oven is expensive. Hence, such products can be post cured using hot air circulation, local heating etc.

Mandrel extraction facility:

The extraction of the mandrel from the product is a difficult task in many cases particularly when the product is very large in size and also when the resin has a high cure shrinkage. The mandrel extraction can be done by different ways.

1. A hydraulic extractor can be used to pull out the mandrel.
2. The mandrel can be dismantled into pieces and pulled out through the side opening.
3. Dissolving of mandrel.

(vii) Spray-up molding:

Spray-up molding is an open mold method (Fig.2.8) that can produce complex parts more economically than hand lay-up. Chopped fiberglass reinforcement and catalyzed resin, and in some cases, filler materials, are deposited on the mold surface from a combination chopper/spray gun.

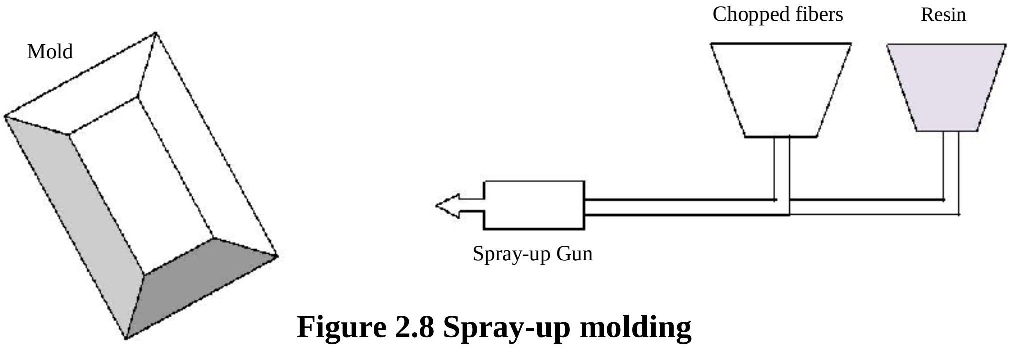


Figure 2.8 Spray-up molding

Rollers or squeegees are used to manually remove entrapped air and work the resin into the reinforcements. Woven fabric or woven roving is often added in specific areas for greater strength. As in hand lay-up, gel coats are used to produce a high quality colored part surface.

(viii) Vacuum Bag Molding:

Vacuum impregnation is a process in which the resin to fiber wetting is assisted by a vacuum. The main purpose of vacuum process is it removes the air which is trapped inside the laminate thus reducing the defect and improving the strength of the laminate.

Advantages of vacuum impregnation method:

- Improves the strength of the laminates by reducing the defects.
- Low cost when compared with compression mould laminates.
- Density of laminate is considerably lower than that of compression mould laminates.

Materials:

Reinforcements:

All types of fiber reinforcements can be impregnated with resin using vacuum method.

Effects of vacuum method on reinforcements:

- Good formability.
- High strength.
- Good surface quality
- Wear resistance.
- High complex forms.

Resins:

The curing procedure of the resin, initial viscosity, the gelation time, and wettability, are the important properties to be considered for processing. For vacuum impregnation purpose the volatile content should be as low as possible. Both polyester and epoxy resins are used.

Factors to be considered for resins in vacuum method:

- Long pot life
- Less viscosity (11 Pa.s or 100 CP or less)
- Short gel time (less than 1 hour)

Mold ReleasingAgents:

Releasing agents used include backed on Teflon (PTFE) or PVA coatings on the mould parts. For vacuum bag systems PTFE films which are porous are used along with conventional materials.

Adaptation of vacuum impregnation method:

Vacuum impregnation process is used in many related FRP fabrication processes such as:

- Vacuum impregnation
- Vacuum injection moulding
- Vacuum bag moulding

Vacuum impregnation:

Vacuum impregnation is used for the manufacture of products which need precisely controlled mechanical properties, thermal and electrical stability and good dimensional control.

(Fig 2.9a) Mould surface is treated with releasing agent. Reinforcements are then placed inside the mould. While closing the mould, care has to be taken to see whether it is completely sealed. Otherwise, when vacuum is applied to the mould, full vacuum may not be generated in the mould cavities.

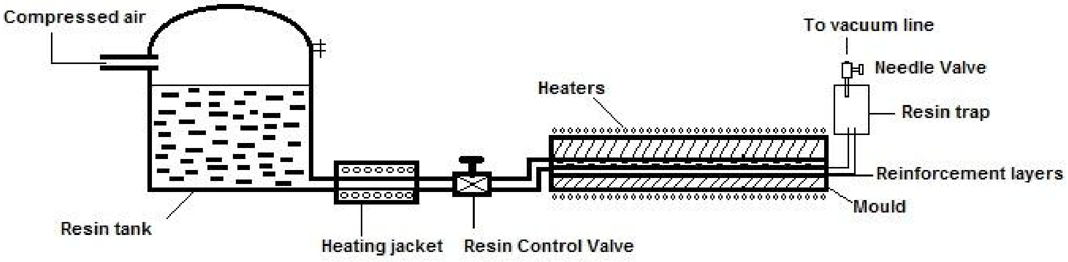


Figure 2.9a Vacuum impregnation

Vacuum is applied so that the resin gradually fills up the mould cavity and wets the reinforcements. Once the resin is completely filled in, the heating can be applied to accelerate the gelation and curing of the resin. After cure, the mould is declamped and the product is taken out.

Vacuum injection moulding:

It is a process where combination of vacuum impregnation and resin injection system are adapted. It is also known as Hoechst process. Moulds for this process can be made of GRP, lower half is of a rigid construction while the upper half is more flexible. A vacuum channel is built into the mould around the periphery for mould closure.

As usual the mould surfaces are waxed, polished and coated with PVA release agent. The reinforcements are cut to shape and fitted in the lower half of the mould. Once the upper half in position, vacuum is applied on the gasket channel sealing the mould and renders it air tight.

Catalyzed resin is injected under pressure. The air remaining in the mould is sucked out, while the flexible top half forces the resin to flow through the reinforcements until the mat is thoroughly impregnated and compacted.

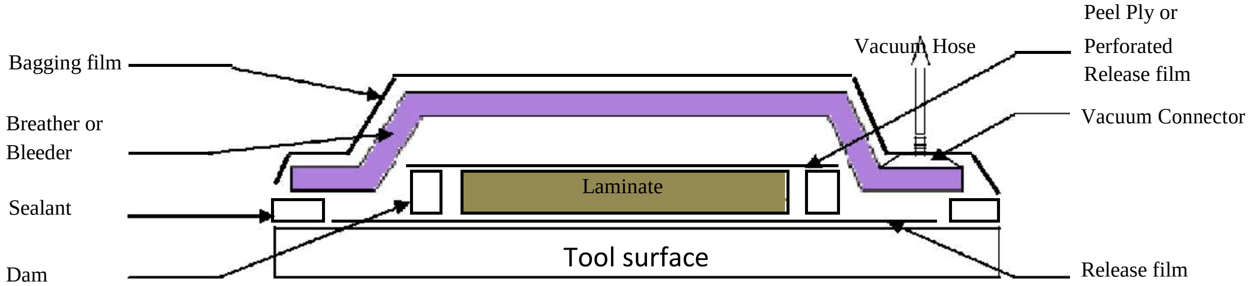


Figure 2.9b Vacuum Bag method

The lay-up is placed in the mould with separator on top of it usually made of Teflon coated glass. The bleeder is placed to absorb the excess resin from the lay-up, thus controlling the amount content during the curing process. Pressure plates are introduced to supply additional compression to the lay-up. Barrier film is used to control the resin flow in the bleeder.

Fig.2.9b Breather film is given beneath the vacuum bag to allow the uniform application of vacuum all over the area of the laminate and removal of excess air or volatiles developed during the cure.

Vacuum bag is used to contain the vacuum generated by the pump and applied to the lay-up. The application of vacuum bag is very critical. Bag porosity or punctures can result in a porous product. Complex tools may require the bag to be folded in places and thus require excess bag material. If the folds are not properly made or placed, wrinkles may be developed in the parts. The vacuum may be maintained till the resin gels.

(ix) Pressure Bag Molding

Pressure bag molding is similar to the vacuum bag molding method except that air pressure, usually 200 to 350 kPa, is applied to a rubber bag, or sheet that covers the laid up composite to force out entrapped air and excess resin (from Fig.2.10). Pressurized steam may be used instead, to accelerate the cure. Cores and inserts can be used with the process, and undercuts are practical, but only female and split molds can be used to make items such as tanks, containers, and wind turbine blades.

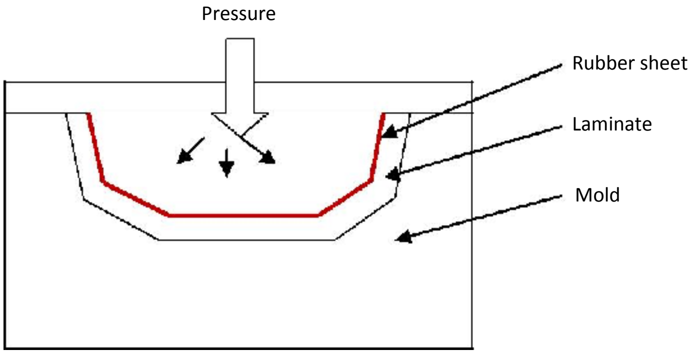


Figure 2.10 Pressure bag molding

(x) Autoclave Molding

Autoclave molding is a modification of pressure-bag and vacuum-bag molding. This advanced composite process produces denser, void free moldings because higher heat and pressure are used for curing. and resin, a nonadhering film of polyvinyl alcohol or nylon is placed over the lay-up and sealed at the mold flange. Autoclaves are essentially heated pressure vessels usually equipped with vacuum systems into which the bagged lay-up on the mold is taken for the cure cycle.

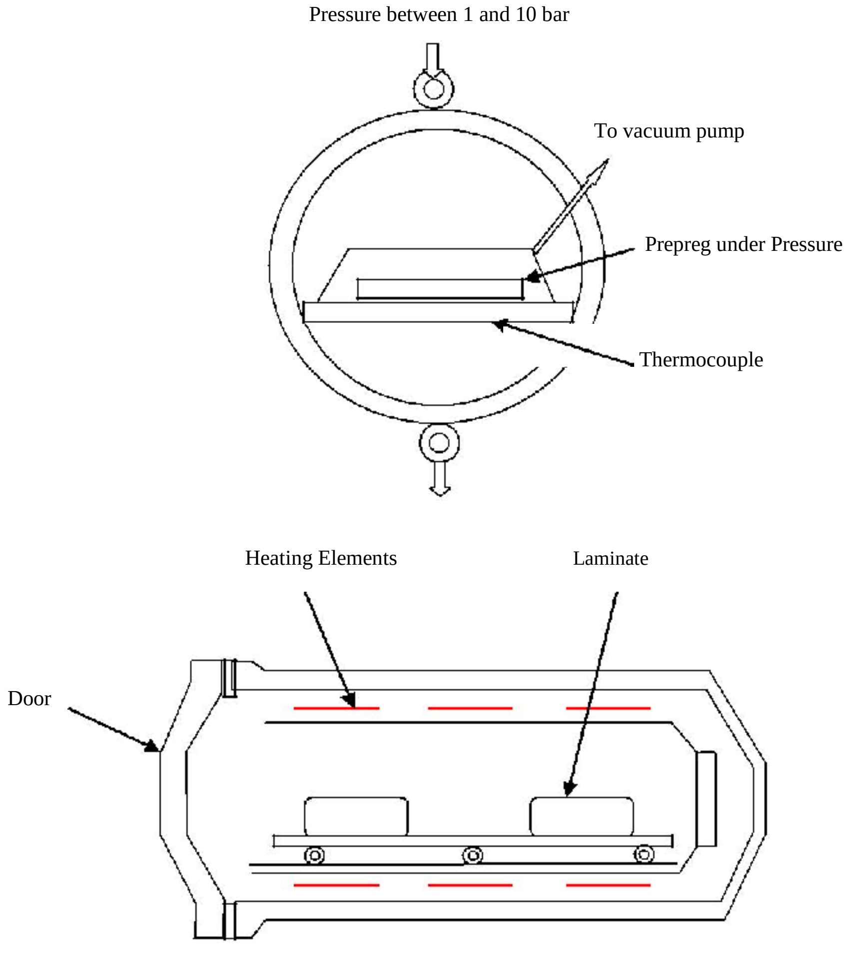


Figure 2.11 Autoclave molding

Curing pressures are generally in the range of 350 to 700 kPa and cure cycles normally involve many hours. The method accommodates higher temperature matrix resins such as epoxies, having higher properties than conventional resins.

Autoclave size limits part size. It is widely used in the aerospace industry to fabricate high strength/weight ratio parts from preimpregnated high strength fibers for aircraft, spacecraft and missiles. Many large primary structural components for aircraft, such as fins, wing spars and skins, fuselages and flying control surfaces, are manufactured by this method.

The starting material for autoclave moulding process is prepreg (Fig.2.11). A prepreg contains 42% weight of resin. If this prepreg is allowed to cure without any resin loss the cures laminate would contains 50% volume of fibers. Since, nearly 10% weight of resin flows out during the moulding process, the actual volume of fiber in the cured laminate is 60%.

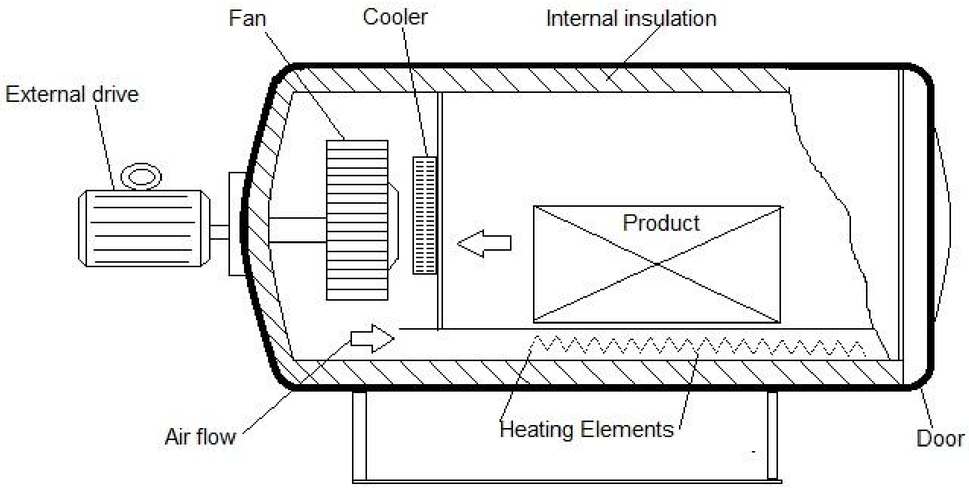


Figure 2.11a Autoclave Setup

After layup, a porous release cloth and a few layers of bleeder papers are placed on top of the prepreg stack. The bleeder paper is used to absorb the excess resin in the moulding process. The complete layup is covered with another Teflon sheet and then a thin heat resistant vacuum bag. The entire assembly is kept inside a preheated autoclave where a combination of pressure and temperature is applied and the plies are converted into a solid laminate.

As the prepreg is heated in the autoclave, the resin viscosity in the B-stage prepreg decreases up to its minimum and then increases rapidly as the curing reaction begins.

Cure cycle of an epoxy prepreg consists of two stages:

The first stage consists of increasing the temperature up to 130°C and dwelling at this temperature for 60 min. When the minimum viscosity reaches external pressure is applied to flow out the excess resin into the bleeder papers. This will remove the air entrapment and volatile from the prepreg.

At the end of temperature dwell, the autoclave temperature resets to the actual curing temperature of the resin. The cure temperature and the pressure is maintained for 2 hours or complete cure takes place. At the end of the cure cycle, the temperature is slowly reduced while the laminate is still under pressure. Finally, the laminate is removed from the bag and post cured if needed.

Equipment

The following data have to be specified for autoclave:

1. Maximum operating temperature
2. Rate of temperature rise
3. Rate of temperature decrease
4. Temperature control stability
5. Stabilized temperature uniformity
6. Maximum pressure
7. Pressurizing medium
8. Pressurization
9. Depressurization
10. Number of vacuum stations

11. Maximum exterior surface temperature
12. Workspace size
13. Heating
14. Cooling

Bagging materials, release sheets, peel plies and breather cloths

Bagging: Applying an impermeable layer of thin film over an uncured part and sealing edges so that a vacuum can be drawn.

Bagging film sealant tape: This is a soft mastic type of tape which is slightly tacky and is used to seal bagging film.

Breather cloth: A loosely woven material such as a glass fabric that will serve as a continuous vacuum path but not direct contact with the part. Its purpose is to allow removal of air, thereby applying atmospheric pressure to the part.

Bleeder cloth: A non-structural layer of material, used to allow the escape of gas and excess resin during the cure. The bleeder cloth is removed after the curing.

Peel ply: A layer of open-weave material, applied directly to the surface of a prepreg layup. Peel ply is removed from the cured laminate.

Release film: A material of thin film, used to keep the resin from bonding to the mould. Release films are made from non stick materials such as polyvinyl fluoride (PVF), fluorinated ethylene propylene (FEP), polyester and nylon.

Other techniques

There are few techniques which are recently developed for making composite products, This includes :

- Tube rolling
- Elastic reservoir molding
- Resin film infusion
- Reaction Injection Molding (RIM)
- Structural reaction injection molding

16BTAR_E19 COMPOSITE MATERIALS AND STRUCTURES 3 0 0 3 100

Multiple Choice Based Questions & Answers

(for all the FIVE units)

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UNIT - I STRESS STRAIN RELATION

S.No.	Questions	opt1	opt2	opt3	opt4	Answer
1	Combination of two or more materials is called	Composite material	polimer matrix	metal matrix	ceramic matrix	**composite material**
2	Concrete is an example for	polimer matrix	Composite material	ceramic matrix	metal matrix	**composite material**
3	Advanced composite material are used mainly in	automotive industry	aviation industry	aerospace industry	mechanical industry	**aerospace industry**
4	Composite materials are divided into __ number of phases	four	one	three	two	**two**
5	The primary phase of a composite material is	matrix	ceramic	polimer	metal	**matrix**
6	The secondary phase of a composite material is	two factors	dispersed phase	matrix phase	reinforcement phase	**dispersed phase**
7	The dispersed phase is also called as	two factors	dispersed phase	Reinforcement phase	matrix phase	**Reinforcement phase**
8	Polymers are best example for	resin	reinforcement phase	dispersed phase	matrix phase	**matrix phase**
9	Fibres are best example for	dispersed phase	resin	Reinforcement phase	matrix phase	**dispersed phase**
10	Classification of composite material is based on	one factors	two factors	three factors	four factors	**two factors**
11	_______ provieds necessary strength and bonding require to form a composite stracture.	matrices	reinforcement	resin	metal	**reinforcement**
12	An isotropic material has uniform properties in _________	one direction	two direction	All direction	Three direction	**All direction**
13	If material has three mutualy perpendicular planes of material cementry. It is called as _________	Isotrophic material	Anisotrophic material	orthotrophic material	composite material	**Orthotrophic material**
14	The independent constant is redused to __________. It is defind as orthotrophic material.	7	6	8	9	**9**
15	The independent variables is reduced to __________. This type of material is known as isotrophic material.	7	9	2	3	**2**
16	The independent variables is _________. This type of material is known as isotrophic material.	20	21	36	7	**21**
17	composite material classified into _________ type.	2	3	4	5	**3**
18	Thermal heat resistance should be high in _______ matrix composite.	metal matrix	ceramic matrix	polimer matrix	hybride matrix	**ceramic matrix**
19	corrosion resistance high in __________	metal matrix	polimer matrix	ceramic matrix	hybride matrix	**polimer matrix**

20	Rubber is the ________ type of matrix composite.	MMC	CMC	PMC	HMC	**HMC**
21	MMC subdivided into ________ type.	2	3	4	5	**3**
22	The material of the fiber directly influences the mechanical performance of a composite	True.	False.			**True.**
23	Annual growth of composites is at a steady rate of	5 percent.	10 percent.	15 percent.	-15 percent.	**10 percent.**
24	Current service temperature limits for polymers reach	750 degrees Fahrenheit.	1750 degrees Fahrenheit.	450 degrees Fahrenheit.	350 degrees Fahrenheit	**750 degrees Fahrenheit.**
25	Thermoset plastic polymers have the following type of bonding	Covalent bond.	Vanderwaals bond.	Atomic bond.	none of the above	**Covalent bond.**
26	The units of fracture toughness are	MPa-m.	MPa^0.5-m.	MPa-m^0.5.		**MPa-m^0.5.**
27	Mechanical fasteners are made of what type of composite	Boron-Epoxy.	Graphite-Epoxy.	Carbon-Carbon.	All of the above.	**Carbon-Carbon.**
28	Graphite fibers have one of the following carbon content	99%.	less than 99%.	more than 99%.	98%.	**more than 99%.**
29	A typical range of carbon content in carbon fiber is	93-95%.	92-95%.	93-94%.	90-95%	**93-95%.**
30	Reducing one pound of mass in a commercial aircraft can save up to how many gallons per year?	50	350	3500	30000	**350**
31	The most common fiber shape is	Rectangular.	Triangular	Circular.	composite material	**Rectangular.**
32	Anisotropic materials are materials with	different properties in all directions.	same properties in all directions.	different properties at different locations	same properties at different locations.	**different properties in all directions.**
33	Size range of dispersoids used in dispersion strengthened composites	001-01 µm	0.01-0.1 nm	0.01-0.1 mm	0.02-0.05 mm	**0.01-0.1 µm**
34	Rule-of-mixture provides _________ bounds for mechanical properties of particulate composites	Lower	Upper	Both	None	**Both**
35	Al-alloys for engine/automobile part s are reinforced to increase their	Strength	Wear resistance	Elastic modulus	Density	**Wear resistance**
36	Mechanical properties of fibe r-reinforced composites depend on	Properties of constituents	Interface strength	orientation, and volume fraction	Volume fraction	**Fiber length, orientation, and volume fraction**
37	Longitudinal strength of fiber reinforced composite is mainly influenced by	Fiber strength	Fiber orientation	Fiber volume fraction	Fiber length	**Fiber strength**
38	The following material can be used for filling in sandwich structures	Polymers	Cement	Wood	Wood ,Cement &Polymers	**Wood ,Cement &Polymers**
39	Not an example for laminar composite	Wood	Bimetallic	Coatings/Paints	Claddings	**Wood**
40	% C in medium carbon steels ranges from _____________.	0.3 – 0.4	0.3 – 0.5	0.3 – 0.6	None	**0.3 – 0.6**
41	Stainless steel is so called because of its ________________.	High strength	High corrosion resistance	High ductility	Brittleness	**High corrosion resistance**
42	In white cast irons, carbon present as ________________.	Graphite flakes	Graphite nodule	Cementite	Carbon does not exsist	**Cementite**

43	Which one of them are Refractory metal?	Ag	W	Pt	Ni	**W**
44	Metal matrix composite are commonly used in	aircraft sturctures	engineering structures	automotive sturctures	stuctural analysis	**engineering structures**
45	The type of matrix which provides high strength is	ceramic matrix	polimer matrix	metal matrix composite	resin	**metal matrix composite**
46	Both the fibre and the matrix are	Graphite flakes	High corrosion resistance	Cementite	homogenuous	**homogenuous**
47	The matrix are free from	voids	Graphite nodule	Cementite	Brittleness	**voids**
48	E in a stress strain relationship stands for	Boron-Epoxy.	young's modulus	Both	bulk modulus	**young's modulus**
49	G in a stress strain relationship stands for	bulk modulus	boron epoxy	Shear modulus	young's modulus	**Shear modulus**
50	Composite materials are classified based on:	Type of matrix	Size-and-shapeof reinforcement	Both	None	**Both**

UNIT - II METHODS OF ANALYSIS

S.No.	Questions	opt1	opt2	opt3	opt4	Answer
1	Classical lamina theory is applicable to	Orthotropic fibres	Fiber	Both	Can not be defined	**Orthotropic fibres**
2	Assumption of laminate in a lamination theory is	matirx	thin and wide	Both are of equal strength	Can not be defined	**thin and wide**
3	Cross ply is not	ductility	toughness	uni axial	both	**uni axial**
4	n' for a laminate stands for	Galvanic	Pitting	Crevice	number of laminas	**number of laminas**
5	__ is an extent to which a liquid will spread over a solid surface	Wettability	Fiber	Both	Can't define	**Wettability**
6	A combination of a mat in a composite is	Galvanic	Pre pregs	both	fiber	**Pre pregs**
7	__ is an example for natural fibres	Pre pregs	both	cotton	cloths	**cotton**
8	Wool is an example for	Physical reactions	Chemical reactions	Both	Natural fibres	**Natural fibres**
9	SMC stands for	Sheet Moulding compound	Galvanic	Pitting	Crevice	**Sheet Moulding compound**
10	Corner joint is a form of	Galvanic	Adhesive bonded joint	Pitting	Weather ,Temparature & radiation	**Adhesive bonded joint**
11	The advantage of bonded structure is	Orthotropic fibres	Fiber	Weight saving	thin and wide	**Weight saving**
12	__ contain either more than one fibre or one matrix system in laminate	Matrix	Reinforcement	Orthotropic fibres	hybrid composite	**hybrid composite**
13	__ is a progressive and localised structural damage that occurs when a material is subjected to cyclic loading	Fatigue	toughness	elasticity	hardness	**Fatigue**
14	A substance capable of holding two materials together is	Temperature	Adhesive	elasticity	hardness	**Adhesive**
15	Composite materials are classified based on	Type of matrix	Size-and-shapeof reinforcement	Both	None	**Both**
16	Major load carrier in dispersion-strengthened composites	Matrix	Fiber	Both	Can't define	**Matrix**
17	Usually softer constituent of a composite is	Matrix	Reinforcement	Both are of equal strength	Can't define	**Matrix**
18	Usually stronger constituent of a composite is	Matrix	Reinforcement	Both are of equal strength	Can't define	**Reinforcement**
19	Last constituent to fail in fiber reinforced composites	Matrix	Fiber	Both fails at same time	Can't define	**Matrix**
20	Which one of them are not a noble metal?	Cu	Ag	Au	Pt	**Cu**
21	Which one of them are Noble metal ?	Al	Ag	Mo	W	**Ag**
22	Impact strength refers to a metal's:	ductility	toughness	elasticity	hardness	**toughness**
23	Corrosion of metals involves	Physical reactions	Chemical reactions	Both	None	**Chemical reactions**
24	The following factors play vital role in corrosion process	Temperature	Solute concentration	Both	None	**Both**
25	Following equation is related to corrosion rate	Nernst equation	Faraday's equation	Either	Neither	**Faraday's equation**

26	Passivity is due to	Higher EMF	Lower EMF	Oxide film	Oxide film&Lower EMF	**Oxide film**
27	Passivity is not reason for inertness of the following	Au	Al	Ti	Ni	**Pitting**
28	Difficult to monitor and very dangerous form of corrosion	Galvanic	Pitting	Crevice	Stress	**Crevice**
29	This form of corrosion occurs due to concentration difference in a component	Uniform	Galvanic	Inter-granular	Stress	**Inter-granular**
30	Main form of ceramic degradation	Corrosion	Weathering	Dissolution	Swelling	**Dissolution**
31	The following influences deterioration of polymers	Weather	Radiation	Temparature	Weather ,Temparature & radiation	**Weather ,Temparature & radiation**
32	Following is not the main form of polymer deterioration	Corrosion	Swelling and Dissolution	Weathering	Scission	**Corrosion**
33	When Pt and Co are electrically connected, which one gets corroded	Pt	Co	None	Can't decide	**Co**
34	To calculate stress-strain relationship for a lamina each lamina is ______&________.	Orthotrophic & Homogeneous	Isotrophic & Helerogeneous	Anisotrophic & Polymer material	Symmentric & Ceramic material.	**Orthotrophic & Homogeneous**
35	Thermo dynamically stable disporsoids are essential for _________	High pressure application	High temperature application	High stress-strain application	High viscous application	**High temperature application**
36	The disadvantage of mechanical joint is	High pressure application	prone to corrosion	Anisotrophic & Polymer material	Symmentric & Ceramic material.	**prone to corrosion**
37	The failure criteria in bolted joints is	Weather	Radiation	baring failure	Scission	**baring failure**
38	The advantage of compression moulding	Homogeneous material	polumer material	ceramic material	low capital cost	**low capital cost**
39	__ is defined as the gel coated fibre reinforced particulate structure	blisters	Galvanic	Inter-granular	Stress	**blisters**
40	___ number of laminates are available	High pressure application	low capital cost	High stress-strain application	high capital cost	**low capital cost**
41	Helicopter blades are one of the applications of	Orthotrophic & Homogeneous	Isotrophic & Helerogeneous	Filament windings	Stress	**Filament windings**
42	The variables influencing the cycle of failure is	low frequency	High temperature application	high frequency	Frequency	**Frequency**
43	Fatigue is a ___ link process which depends on a local stress in a small area	weakest link	Bolted joints	baring failure	Scission	**weakest link**
44	Bearing failure is a failure mode in	computational limitation	Defect	Intraction between constituents	Bolted joints	**Bolted joints**
45	A laminate is the _________ constraction.	gride	layer	truss		**layer**
46	_________ constitues distribute the major part in the composite structure.	matrix	reinforement material	resin	metal	**matrix**
47	Micro mechanics is the study of ___________	Composite material	Metal matrix composite	Alloy	Polymer matrix composite.	**composite material**
48	Macromechanics is the study of composite material assumed to be __________	Hetrogeneous material	Homogeneous material	polumer material	ceramic material	**Homogeneous material**
49	Macromachanic study properties of composite material is used to account for _________	Failure of material	computational limitation	Defect	Intraction between constituents	**Defect**
50	Lamina theory is used to develop a relationship such as _________	shear and axial force	Bending	Twisting moments	All the above	**All the above**

UNIT - III LAMINATED PLATES

S.No.	Questions	opt1	opt2	opt3	opt4	Answer
1	The type of matrix which provides high temperature resistant is	metal matrix composite	Ceramic matrix composite	polymer matrix composite	resin matrix	**metal matrix composite**
2	PEEK stands for ___________	Solder ability.	polyether ether ketone	Super conductivity	Malleability	**polyether ether ketone**
3	A metal matrix composite are __	Super conductivity	Malleability	Easily fabricated	Ceramic matrix	**Easily fabricated**
4	The matrix which provide strong ionic bonding	polyether ether ketone	Super conductivity	Malleability	Ceramic matrix	**Ceramic matrix**
5	__ type of matrix have higher thermal expansion coefficient	Ceramic matrix composite	metal matrix composite	polymer matrix composite	resin matrix	**Ceramic matrix composite**
6	The most common matrix material used in differnet applications	metal matrix composite	polymer matrix composite	Ceramic matrix composite	resin matrix	**polymer matrix composite**
7	The polymer matrix composites can be classified into	one	four	three	five	**three**
8	Thermosets is a classification of __ type of composites	metal matrix composite	Ceramic matrix composite	resin matrix	polymer matrix composite	**polymer matrix composite**
9	Thermo plastics are __ type of composites	polymer matrix composite	metal matrix composite	Ceramic matrix composite	resin matrix	**polymer matrix composite**
10	Example for particulate re-inforced composites	layer	mica flakes	silica content	wood	**mica flakes**
11	The composite used in electrical applications is	polymer matrix composite	metal matrix composite	particulate composites	resin matrix	**particulate composites**
12	____________is a general form of composite material available	layer	Lamina	Laminate	wood	**wood**
13	The type of matrix which provides high impact resistant	metal matrix composite	Ceramic matrix composite	polymer matrix composite	resin matrix	**metal matrix composite**
14	Polypropylene is classified into ___________	2	3	4	1	**3**
15	S glass stands for	High melting point	Easy to fabricate	Silica content	Rudder	**Silica content**
16	Analysis carried out in a laminated composites in macroscopic level is called as	micro mechanics	Lamina	Laminate	macro mechanics	**macro mechanics**
17	A lamina is also called as	layer	thin and wide	Malleability	easily fabricated	**layer**
18	The other name for ply in a laminate	layer	Lamina	Laminate	Rudder	**Lamina**
19	A __ is a stack of plies of composites	lamina	layer by layer	Laminate	Normalizing	**Laminate**
20	Air craft strcutural component made of composite material	thin and wide	Malleability	easily fabricated	Rudder	**Rudder**
21	The properties of matrices	High melting point	mica flakes	silica content	wood	**High melting point**
22	Long fibres are	thin and wide	Easy to fabricate	Laminate	macro mechanics	**Easy to fabricate**
23	Short fibres possess __ compared to long fibres	low strength	both	High strength	lamina	**High strength**
24	FRP stands for	thin and wide	Malleability	easily fabricated	Fibre reinforced composite	**Fibre reinforced composite**

25	Epoxy is an example for	Resin matrix	metal matrix composite	Ceramic matrix composite	polymer matrix composite	**Resin matrix**
26	Ceramics are example for	Resin matrix	Non metal matrix	metal matrix composite	Ceramic matrix composite	**Non metal matrix**
27	The stresses are transerred between the phases through __	metal matrix composite	Ceramic matrix composite	Resin matrix	polymer matrix composite	**Resin matrix**
28	Cotton is an example for	Lamina	Laminate	Rudder	Natural fibres	**Natural fibres**
29	Glass is an example for	Manmade fibre	Malleability	easily fabricated	Fibre reinforced composite	**Manmade fibre**
30	Aramid is also called as __	Manmade fibre	Kevlar	Rudder	Natural fibres	**Kevlar**
31	Clay is a form of __ in composite	Rudder	Natural fibres	fillers	lamina	**fillers**
32	Pigments is a form of __ in composite	Malleability	easily fabricated	Fibre reinforced composite	Additives	**Additives**
33	The fibres are classifed into __	3	4	6	2	**3**
34	C glass stands for	uni axial	Corrosion	fillers	Additives	**Corrosion**
35	Classical lamina theory is applicable to	metal matrix composite	Ceramic matrix composite	Orthotropic fibres	Natural fibres	**Orthotropic fibres**
36	Assumption of laminate in a lamination theory is	Ceramic matrix composite	Orthotropic fibres	Natural fibres	thin and wide	**thin and wide**
37	Cross ply is not	uni axial	Manmade fibre	Kevlar	Rudder	**uni axial**
38	n' for a laminate stands for	magnetic materials.	number of laminas	Laminate	thin and wide	**number of laminas**
39	Which of the following can be used for cathodic protection:	Al	Cd	Cu	Zn	**Al**
40	Materials which can store electrical energy are called	magnetic materials.	semi conductors.	dielectric materials.	super conductors.	**magnetic materials.**
41	ACSR (Aluminium Conductor Steel Reinforced) are u sed as	over head transmission lines.	super conductors	fuse	underground cables.	**over head transmission lines.**
42	Brass is an alloy of	copper and zinc.	copper and iron.	copper and Aluminium.	copper and tin.	**copper and zinc.**
43	Property of material which allows it to be drawn out into wires is	Ductility.	Solder ability.	Super conductivity	Malleability	**Ductility.**
44	Aluminium is	Silvery white in colour.	Yellow in colour	Reddish in colour.	Pale yellow in colour.	**Silvery white in colour.**
45	zinc by immersing the metal in a bath of molten zinc at a temperature of around 860 °F (460 °C).	Quenching	hot dipping	Annealing	Normalizing	**hot dipping**
46	strength, corrosion resistance, war resistance and cutting ability are increased.	Quenching	Annealing	Hardness	hot dipping	**Hardness**
47	Wrought iron is	high in strength	least resistant to corrosion	highly resistant to corrosion	heat treated to change its properties	**highly resistant to corrosion**
48	Steel contains	80% or more iron	50% or more iron	chromium, tungsten nickel and copper	high quantities of sulfur.	**50% or more iron**
49	Cast iron is characterised by minimum of following %age of carbon	0.20%	0.80%	1.30%	2%	**1.30%**
	A laminate is made up of ___________ construction.	gride by gride	layer by layer	truss by truss	Both a and b	**layer by layer**

UNIT - IV SANDWICH CONSTRUCTIONS

S.No.	Questions	opt1	opt2	opt3	opt4	Answer
1	Kevlar fibres are best suited for	space applications	wood	composite mate	alloys	**space applications**
2	Applications are fibre reinforced composite in automotive industry can be classified into	two or more materials	three groups	four groups	both	**three groups**
3	S-N curve stands for	Soften on heating.	Harden on heating.	stress VS numb	composite	**stress VS number of cycles**
4	Vapour infiltration process is used to produce	laminated composite	metal matrix composi	fiber reinforcem	ceramic matrix c	**ceramic matrix composite**
5	Whiskers are a form of	fibre materials	a single material	more than three	only two material	**fibre materials**
6	Sandwich panels are produced for	Strength / density.	Light weight	Young's modulu	Square root of str	**Light weight**
7	Sintering is a process for producing	Structural Metal Composite.	Strong Metal Compos	composite	Sheet Molding C	**composite**
8	Pultrasion is a method for production of composite using	thermoplastic	thermosets	polymer	continuous fibres	**continuous fibres**
9	Poly in a polymer stands for	Many	Graphite.	Boron.	Glass.	**Many**
10	Bakelite is a form of earliest	slice glass.	synthetic fibre	Polyester.	Polymide.	**synthetic fibre**
11	Composite material defined as combination of ________	two or more materials	a single material	more than three	only two material	**two or more material**
12	Flight control surface made up of________	metals	wood	composite mate	alloys	**composite mateirals**
13	Specific modulus is given by	Square root of Young's modulus / density.	Strength / density.	Young's modulu	Square root of str	**Young's modulus / density.**
14	Bullet proof vests use ___________ fibers.	Kelvar.	Graphite.	Boron.	Glass.	**Kelvar.**
15	Amongst the choices given below, high performance applications in the aerospace industr	Kelvar 49.	Kelvar 29.	Kelvar 19.	Kelvar 9.	**Kelvar 49.**
16	The performance indicator for buckling of a rod under a compressive load is	Young's modulus / density.	(Young's modulus ^ 0	(Young's modul	(Young's modulu	**(Young's modulus ^ 0.5) / density.**
17	Which of these polymer is least desirable for smoke emission?	Phenolic.	Epoxy.	Silicone	Polymide.	**Epoxy.**
18	hermoset polymers show which of the following traits.	Decompose on heating.	Soften on heating.	Harden on heati	none of the above	**Decompose on heating.**
19	Out of the following, which polymer has the highest service temperature?	Phenolic	composite	Polyester.	Polymide.	**Polymide**
20	Nanocomposites consist of particles or fibers that are of at most this dimension or less?	0.0000001 m	0.000001 m	0.00001 m	0.0001 m	**0.0000001 m**
21	Out of these polymers, which one has the maximum strength?	Phenolic.	Epoxy.	Polyester.	Polymide.	**Epoxy.**
22	Glass fibers are made from	slice glass.	vapor deposition met	graphite	Foam Method	**slice glass.**
23	A Structural sandwich is a special form of a ________________________	Advanced composite	laminated composite	metal matrix co	fiber reinforceme	**laminated composite**

24	The use of sandwich construction in Boeing 737 aircraft is __________________--	8	18	26	28	**26**
25	Which one of the following is the most common polymer type in fiber-reinforced polyme	elastomers	thermoplastic	thermosets	polymer	**polymer**
26	One of the major drawbacks of advanced composite materials is	their high cost of fabricatio	their low specific elas	that they are ext	their low specific	**their high cost of fabrication.**
27	The acronym SMC stands for	Structural Metal Composite.	Strong Metal Compos	Sheet Molding	All the given opti	**Structural Metal Composite.**
28	Composite materials are classified based on:	Type of matrix	Size-and-shape of rei	Method of Orie	All the given opti	**Type of matrix**
29	Major load carrier in dispersion-strengthened composites	Matrix	Fiber	Both a and b	Can not be defin	**Fiber**
30	Usually softer constituent of a composite is	Matrix	Reinforcement	Both are of equa	Can not be defin	**Reinforcement**
31	The washers used in aircraft are made of	styrene butadiene rubber	silicon rubber	butyl rubber	polysulphide	**styrene butadiene rubber**
32	Thermosetting and thermoplastics resins comes under the classification of	rubber	wax	plastics	mild steel	**plastics**
33	The factors affecting the fatigue life	grain size	fumance oil	electricity	hard coke	**grain size**
34	The classification of composite structures are	two	three	four	one	**three**
35	___ is a process of finding an optimum configuration with structural dimensions	machining allowance	draft allowance	composite sturu	solidification allowance	**composite stuructural design**
36	__ is a factor for material selection in composite structure design	Light weight	Young's modulus / de	Square root of s	Strength	**Strength**
37	Joints in a composite structure are classifed into	three	two	four	one	**three**
38	A glass stands for	straight	Appearance	tapered	prismatic	**Appearance**
39	Green sand is a mixture of:	30% sand and 70% clay	70% sand and 30% clay	50% sand and 50% clay	90% sand and 10% clay	**70% sand and 30% clay**
40	AR glass stands for	alkali resistance	draft allowance	Shrinkage allowance	solidification allowance	**Shrinkage allowance**
41	Which of the following is a non-metallic material	ash	elm	sealants	beech	**sealants**
42	Advantage of mechanical joint is	positive connection	fumance oil	electricity	hard coke	**positive connection**
43	Fuel used in a cupola consists of	steam coal	fumance oil	electricity	hard coke	**hard coke**
44	Which allowance is not provided on the "pattern" made for a casting?	machining allowance	draft allowance	Shrinkage allowance	solidification allowance	**machining allowance**
45	In a well designed gating system, the mould should be filled with in time.	smallest possible time	maximum	2 seconds	prescribed	**maximum**
46	The following will act as a reservoir for molten metal from which metal flows smoothly into the spine	sprue	pouring basin	runner	gate	**sprue**
47	To prevent the entry of slag into down sprue, the pouring basin may contain the following	skim core	core	chill	strainer core	**core**
48	To avoid air aspiration, the sprue should be	straight	tapered	prismatic	rectangular	**straight**

49	The adhesiveness is the property of moulding sand due to which:	the sand grains stick together	it evolves a great amount of steam and other gases	it clings to sides of a moulding box	both A and B	**it clings to sides of a moulding box**
50	ECR glass stands for	skim core	Electical corrosion res	Size-and-shape	Method of Orient	**Electical corrosion resistant**

UNIT - V FABRICATION PROCESS

S.No.	Questions	opt1	opt2	opt3	opt4	Answer
1	Face sheet is a component in a	Sandwich construction	combined form	nodular form	partly in combined state	**Sandwich construction**
2	The core in a sandwich construction provides	High density	Strength	Low toughness	Low hardness	**Strength**
3	_____ in sandwich construction is used to transfer the load	compressive strength	ductility	Adhesive	surface finish.	**Adhesive**
4	Expansion process is used to construct ___	Diamond	Titanium	Iron	Honey comb core	**Honey comb core**
5	bearing failure is a failure mode in	mechanical joint	perfect drag	perfect contour	none of the given	**mechanical joint**
6	Forming is a fabrication process for	combined form	sandwich construction	nodular form	partly in combined state	**sandwich construction**
7	ASTM stands for	ductility	hardness	American Society for testing materials	surface finish.	**American Society for testing materials**
8	ASME stands for	steel alloy	Alluminium alloys	wood	Society for Mechanical	**American Society for Mechanical Engineers**
9	The structural sandwich is a special form of	Laminated composite	Polymers	Ceramics	Metals	**Laminated composite**
10	The outer most layer of sandwich construction is	ribs	skin	spars	formers	**skin**
11	The inner layer in a sandwich construction is	Steel	Nylon	core	Plastics	**core**
12	Boeing dreamliner is made of __ % of composite	above 60%	above90%	above 20%	above 80%	**above 80%**
13	The first type aircraft which used composite material for structural construction is	Boeing 707	airbus 320	boeing 747	both	**Boeing 707**
14	Face sheet provides	fluro rubber	Wear resistant	silicon rubber	butyl rubber	**Wear resistant**
15	FSTD in sandwich construction stands for	Low toughness	High strength	First order shear deformation	chrome molybednum	**First order shear deformation**
16	___ type of composite is used for making sporting goods	Low toughness	High strength	Low hardness	polymeric composite	**Fibre reinforced polymeric composite**
17	A missile structure is made up of	polymeric composite	Low toughness	High strength	Low hardness	**Fibre reinforced polymeric composite**
18	R glass stands for	compressive strength	rigid	ductility	hardness	**rigid**
19	D glass stands for	Ceramics	Metals	Di-electric	Semiconductors	**Di-electric**

20	An important property of malleable cast iron in comparison to grey cast iron is the high	compressive strength	ductility	hardness	surface finish.	**ductility**
21	In mottled cast iron, carbon is available in	free form	combined form	nodular form	partly in combined state	**partly in free and partly in combined state**
22	The performance indicator for buckling of a rod under a compressive load is	Young's modulus / density.	(Young's modulus ^ 0.5) / density.	(Young's modulus ^ 0.3333) / density.	none of the given	**(Young's modulus ^ 0.5) / density.**
23	Pick the composite from the list	Wood	Steel	Nylon	Mica	**Wood**
24	Strong and ductile materials	Polymers	Ceramics	Metals	Semiconductors	**Metals**
25	Presently most used metal in the world	Aluminium	Gold	Steel	Silver	**Steel**
26	Detrimental property of a materi al for shock load applications	High density	Low toughness	High strength	Low hardness	**Low toughness**
27	Democratic material	Diamond	Titanium	Iron	Gold	**Iron**
28	The leading edge is covered with plywood or sheet metal to maintain	perfect weight ratio	perfect drag	perfect contour	none of the given	**perfect contour**
29	Wing flaps especially split type are constructed with aluminium alloy sheet backened by	ribs	spars	formers	stiffeners	**stiffeners**
30	Wind shield and cabin encloseres are frequently constructed by one of transparent plastics such as	plexiglas	2024-T6	2025-T5	chrome molybednum	**plexiglas**
31	Control stick,torsion tubes,push pull tubes,bell cranks are manufactured from aluminium alloys or	Cobalt	Nickel	Ferrous	Steel	**Steel**
32	Which of the following is relatively cheap materials.	steel alloy	Alluminium alloys	wood	Plastics	**wood**
33	Which of the following is not a wood.	ash	bass	elm	none of the given	**none of the above**
34	Which of the following material is used for aircraft brake materials	glass	elm	rubber	ceramic composites	**ceramic composites**
35	Self lubricating bearing uses materials such as	PEI	PES	flurocarbons	glass	**flurocarbons**
36	For the tyres and tubes of aircraft we use	fluro rubber	silicon rubber	butyl rubber	natural rubber	**natural rubber**
37	For hoses, pipes etc ., we use	neoprene rubber	silicon rubber	butyl rubber	natural rubber	**neoprene rubber**
38	The fuel tank,wing structures etc are manufactured by the material	fluro rubber	silicon rubber	butyl rubber	polysulphide	**polysulphide**

39	The most common fibers used in advanced polymer composites are	glass, steel, and aluminum.	glass, graphite, and kelvar.	glass, steel, and kelvar	glass and kelvar	**glass, graphite, and kelvar.**
40	What fiber factors contribute to the mechanical performance of a composite?					
41	A typical example of thermoplastics include	polyethylene.	polyesters.	phenolics.		**polyethylene.**
42	polymer matrix composites are manufactured by the process called _____________.	filament winding.	autoclave forming.	resin transfer molding.	none of the above.	**resin transfer molding.**
43	Bullet resistant vests mainly use the following fiber.	Boron	Glass	Graphite	Kevlar	**Kevlar**
44	Aramid fibers are made up of the following elements	Carbon, Hydrogen, and Oxygen.	Oxygen and Nitrogen.	Carbon, Hydrogen, and Nitrogen	Oxygen and Nitrogen.	**Carbon, Hydrogen, Oxygen and Nitrogen.**
45	Composite materials are	isotropic but not homogeneous.	homogeneous but not isotropic.	both homogeneous and isotropic.	homogeneous or isotropic.	**neither homogeneous or isotropic.**
46	Inter-ply hybrid composites consist of	different composite systems.	different fibers used in the same	both a and b.	none of the above.	**two or more different composite systems.**
47	Which of the following composites are replacing metals in golf club shafts?	Carbon-Carbon.	Graphite/Epoxy.	Boron/Epoxy.		**Graphite/Epoxy.**
48	Which of these polymer is least desirable for smoke emission?	Phenolic.	Epoxy.	Silicone	Polymide.	**Epoxy.**
49	Nanocomposites consist of particles or fibers that are of at most this dimension or less?	0.0000001 m	0.000001 m	0.00001 m	0.0001 m	**0.0000001 m**
50	Amongst the choices given below, high performance applications in the aerospace industry use	Kelvar 49.	Kelvar 29			**Kelvar 49.**