SCHOOL OF AERONAUTICS (NEEMRANA)

UNIT-1 NOTES

FACULTY NAME: Er. SAURABH MALPOTRA **CLASS: B.Tech AERONAUTICAL**

SUBJECT CODE: 6AN2 **SEMESTER: VI**

SUBJECT NAME: - MECHANICS OF COMPOSITE MATERIALS

INTRODUCTION TO COMPOSITE MATERIALS :-

- *Classification of composites, particulate composites fibrous composites. Use of fiber reinforced composites Fibers, matrices and manufacture of composites; properties of various type of fibers like glass, Kevlar, Carbon and Graphite,*
- *Methods of manufacture, surface treatment of fibers, various forms of fibers, matrix materials, polymers: Thermosetting and thermoplastic polymers, properties of polymers like epoxies, phenolics, polyester peek etc.*

1.1 WHAT ARE “COMPOSITES?

- Composite: Two or more chemically different constituents *combined macroscopically* to yield a useful material.

- Examples of naturally occurring composites permeated with holes filled with liquids
  - Wood: Cellulose fibers bound by lignin matrix
  - Bone: Stiff mineral “fibers” in a soft organic matrix permeated with holes filled with liquids
  - Granite: Granular composite of quartz, feldspar,and mica.
- A composite material is made by combining two or more materials– often ones that have very different properties.

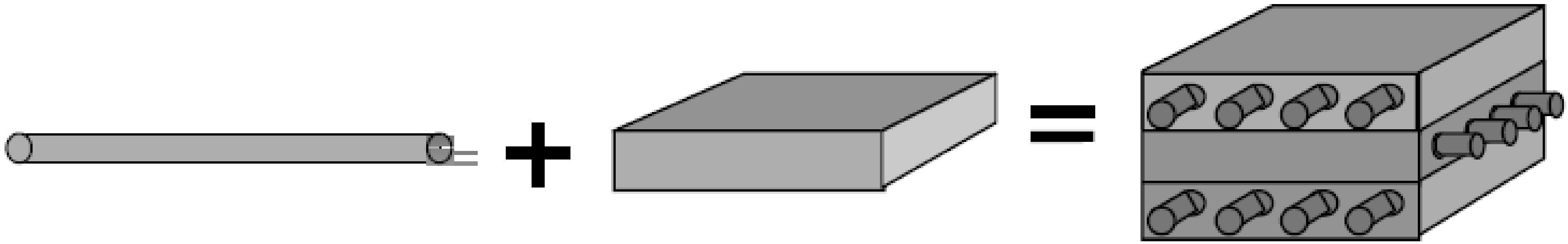
- The two materials work together to give the composite unique properties.
- However, within the composite you can easily tell the different materials apart as they do not dissolve or blend into each other.
- Composite materials are materials made from two or more constituent materials with significantly different properties, that when combined, produce a material with characteristics different from the individual components.

- Composite materials consist of two or more chemically distinct constituent on a macro scale having a dispersed interface separating them and having bulk performance which is considerably different from those of any of its individual constituents.

Examples:- Cement, Concrete, Fiber-reinforced polymer, etc.

- Some examples of man-made composites
  - Concrete: Particulate composite of aggregates (limestone or granite), sand, cement and water
  - Plywood: Several layers of wood veneer glued together
  - Fiberglass: Plastic matrix reinforced by glass fibers
  - Cemets: Ceramic and metal composites
  - Fibrous composites: Variety of fibers (glass, kevlar, graphite, nylon, etc.) bound together by a polymeric matrix

Composition of Composites



Fiber/Filament Reinforcement

- High strength
- High stiffness
- Low density

Matrix

- Good shear properties
- Low density

Composite

- High strength
- High stiffness
- Good shear properties
- Low density

1.2 THESE ARE NOT COMPOSITES :-

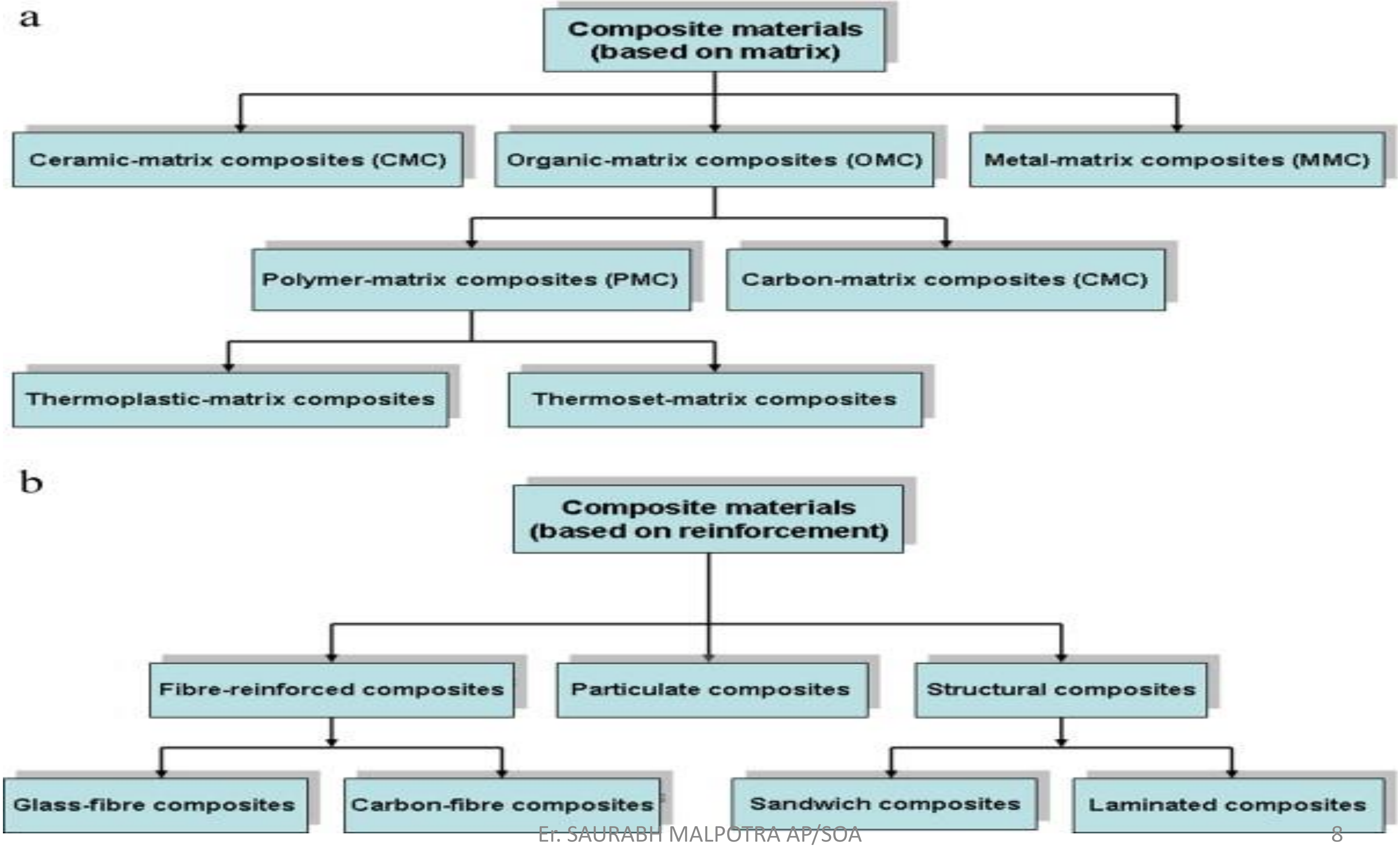
- Plastics: Even though they may have several "fillers", their presence does not alter the physical properties significantly.
- Alloys: Here the alloy is *not macroscopically heterogeneous*, especially in terms of physical properties.
- Metals with impurities: The presence of impurities does not significantly alter physical properties of the metal.

1.3 APPLICATION OF COMPOSITE MATERIALS :-

- Automotive industry: Lighter, stronger, wear resistance, rust-free, aesthetics
  - Car body Brake pads
  - Drive shafts
  - Fuel tanks
  - Hoods
  - Spoilers
- Aerospace: Lighter, stronger, temperature resistance, smart structures, wear resistance
  - Aircraft: Nose, doors, struts, trunnion, fairings, cowlings, ailerons, outboard and inboard flaps, stabilizers, elevators, rudders, fin tips, spoilers, edges
  - Rockets & missiles: Nose, body, pressure tanks, frame, fuel tanks, turbo-motor stators, etc.
  - Satellites: Antennae, frames, structural parts

- Sports: Lighter, stronger, toughness, better aesthetics, higher damping properties
  - Tennis Bicycles
  - Badminton
  - Boats
  - Hockey
  - Golfing Motorcycles
- Transportation & Infrastructure: Lighter, stronger, toughness, damping
  - Railway coaches Bridges
  - Ships and boats
  - Dams
  - Truck bodies and floors
  - RV bodies
  - Biomedical industry
  - Consumer goods
  - Agricultural equipment

1.5 CLASSIFICATION OF COMPOSITES :-



1.5.1 ORGANIC MATRIX COMPOSITES (OMCS) :-

- **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:-**

Thermosetting plastics :-

1. Thermosets have qualities such as a well-bonded three-dimensional molecular structure after curing.
2. This polymer is hard and infusible on heating.
3. These are not soft on heating under pressure and they are not remoluded.
4. These polymers are cross linked or heavily branched molecules
5. These polymers we cannot reused or recycle.

Ex. Some common examples are bakelite, urea-formaldelyde resins, etc

- **Thermoplastic polymers :-**

1.These are the polymers having intermolecular forces between elastomers and fibres.

2.They are those polymers which can be softened on heating and hardened on cooling room temperature.

3. They may be linear or branched chain polymers.

4. These polymer can be recycled many times. Ex , Polythene, polyesterne, PVC.

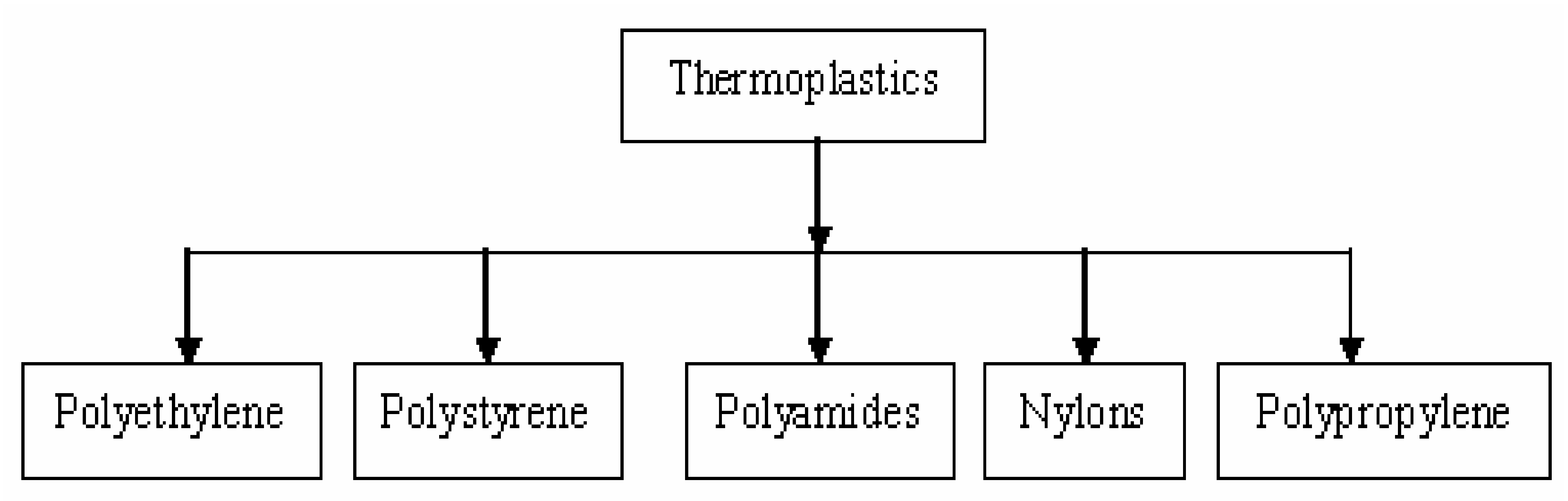


Fig. 1.1 Types of thermoplastic polymers

- 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.
- Thermosets are the most popular of the fiber composite matrices without which, research and development in structural engineering field could get truncated. Aerospace components, automobile parts, defense systems etc., use a great deal of this type of fiber composites.

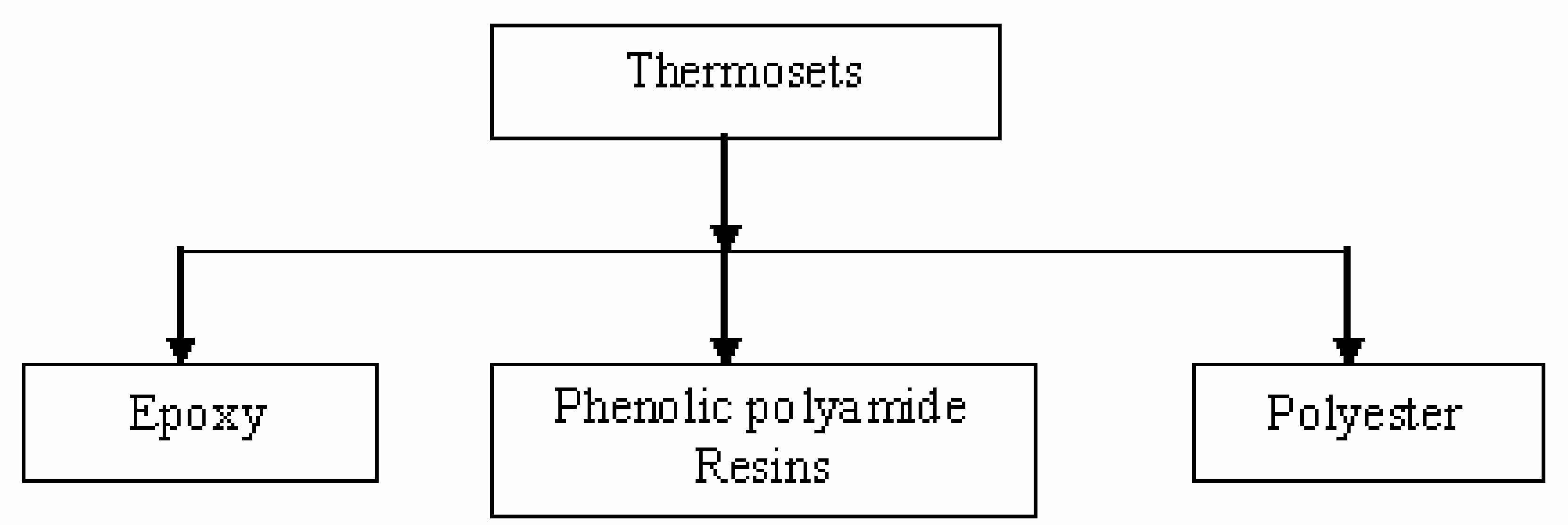


Fig. 1.2 Types of thermoplastic polymers

1.5.2 METAL MATRIX COMPOSITES (MMC) :-

- Metal matrix composites, at present though generating a wide interest in research fraternity, are not as widely in use as their plastic counterparts. High strength, fracture toughness and stiffness are offered by metal matrices than those offered by their polymer counterparts. They can withstand elevated temperature in corrosive environment than polymer composites. Most metals and alloys could be used as matrices and they require reinforcement materials which need to be stable over a range of temperature and non-reactive too.
- However the guiding aspect for the choice depends essentially on the matrix material. Light metals form the matrix for temperature application and the reinforcements in addition to the aforementioned reasons are characterized by high moduli.
- Most metals and alloys make good matrices. However, practically, the choices for low temperature applications are not many. Only light metals are responsive, with their low density proving an advantage.
- Titanium, Aluminium and magnesium are the popular matrix metals currently in vogue, which are particularly useful for aircraft applications.
- The melting point, physical and mechanical properties of the composite at various temperatures determine the service temperature of composites.

1.5.3 CERAMIC MATRIX MATERIALS (CMM) :-

- Ceramics can be described as solid materials which exhibit very strong ionic bonding in general and in few cases covalent bonding. High melting points, good corrosion resistance, stability at elevated temperatures and high compressive strength, render ceramic-based matrix materials a favourite for applications requiring a structural material that doesn't give way at temperatures above 1500ºC. Naturally, ceramic matrices are the obvious choice for high temperature applications.
- High modulus of elasticity and low tensile strain, which most ceramics posses, have combined to cause the failure of attempts to add reinforcements to obtain strength improvement. This is because at the stress levels at which ceramics rupture, there is insufficient elongation of the matrix which keeps composite from transferring an effective quantum of load to the reinforcement and the composite may fail unless the percentage of fiber volume is high enough.
- When ceramics have a higher thermal expansion coefficient than reinforcement materials, the resultant composite is unlikely to have a superior level of strength.

- 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.
- In that case, the composite will develop strength within ceramic at the time of cooling resulting in microcracks extending from fiber to fiber within the matrix. Microcracking can result in a composite with tensile strength lower than that of the matrix.

1.5.4 PARTICLE REINFORCED COMPOSITES :-

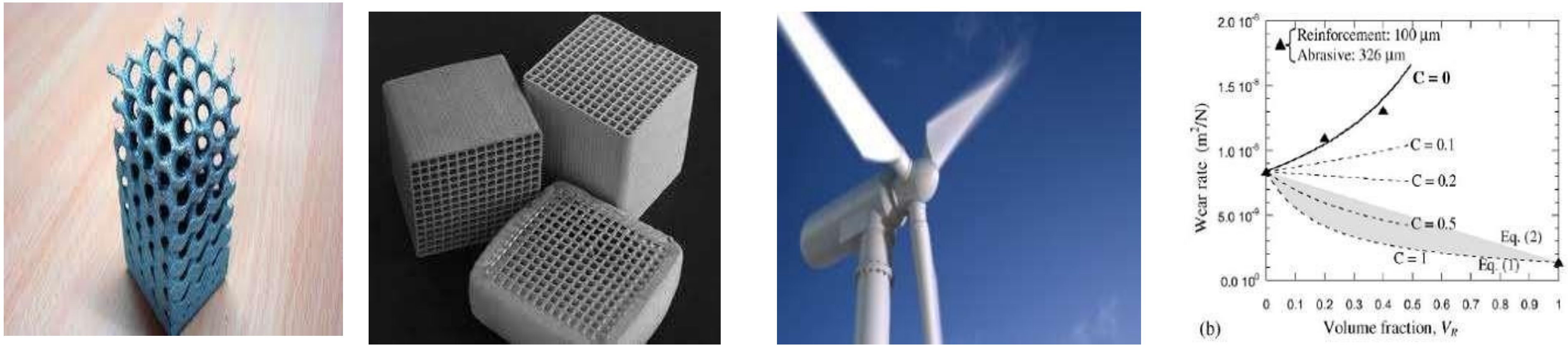


Fig. 1.4 Example of particle reinforced composites

- One form of composites is particulate reinforced composites with concrete being a good example. The aggregate of coarse rock or gravel is embedded in a matrix of cement. The aggregate provides stiffness and strength while the cement acts as the binder to hold the structure together.
- There are many different forms of particulate composites. The particulates can be very small particles (< 0.25 microns), chopped fibres (such as glass), platelets, hollow spheres, or new materials such as Bucky balls or carbon nano-tubes. In each case, the particulates provide desirable material properties and the matrix acts as binding medium necessary for structural applications.

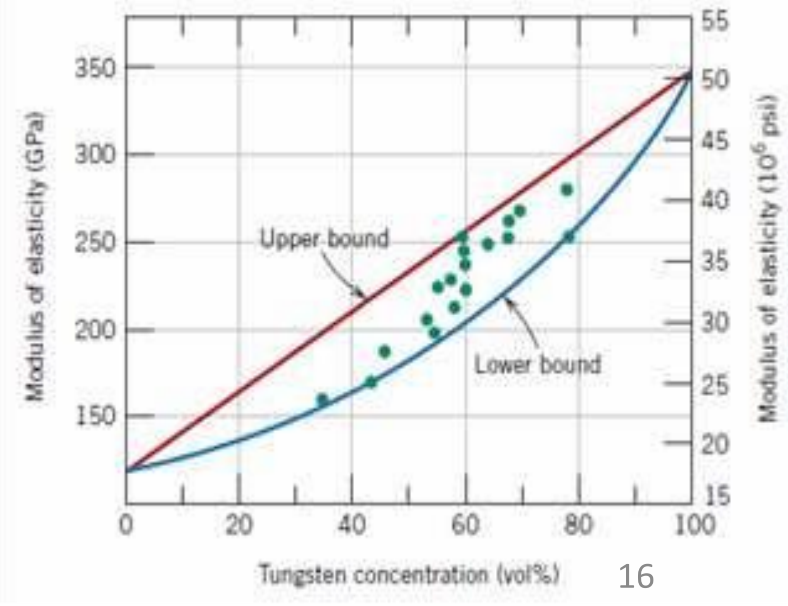
1.5.5 LARGE-PARTICLE COMPOSITE :-

- Some polymeric materials to which fillers have been added are really large- particle composites. The fillers modify or improve the properties of the material. Example of large-particle composite is concrete, which is composed of cement (the matrix), and sand and gravel (the particulates).Particles can have quite a variety of geometries, but they should be of approximately the same dimension in all direction (equated).
- For effective reinforcement, the particles should be small and evenly distributed throughout the matrix. The volume fraction of the two phases influences the behavior; mechanical properties are enhanced with increasing particulate content.
- Rule of mixture: equation predict that the elastic modulus should fall between an upper and lower bound as shown:
- **Example:** Fig. 1.1 plots upper and lower bound Ec – versus Vp curves for a copper – tungsten composite; in which tungsten is the particulate phase.
  - **Where:-**

Ec: elastic modulus of composite Ep: elastic modulus of particle Em: elastic modulus of matrix Vm: volume fraction of matrix Vp: volume fraction of particle

$$E_c(u) = E_m V_m + E_p V_p$$

$$E_c(l) = \frac{E_m E_p}{V_m E_p + V_p E_m}$$



1.5.6 DISPERSION STRENGTHENED COMPOSITE :-

- Dispersion-strengthened means of strengthening materials where in very small particles (usually less than 0.1 µm) of a hard yet inert phase are uniformly dispersed within a load – bearing matrix phase.
- The dispersed phase may be metallic or nonmetallic, oxide materials are often used.

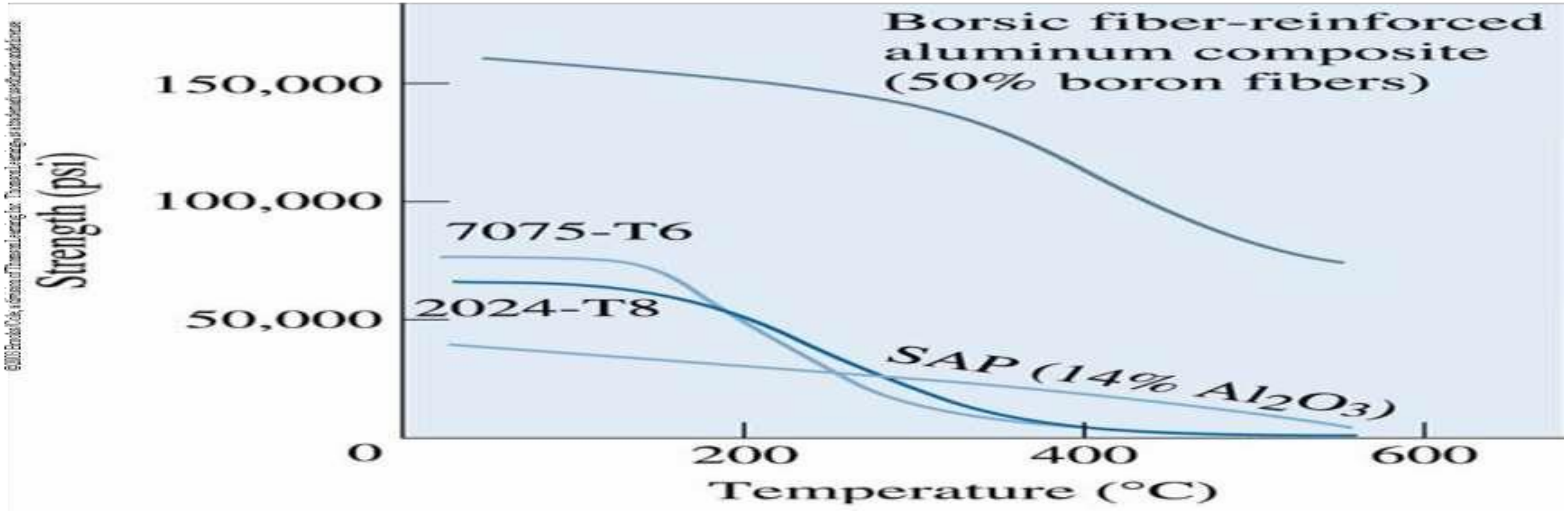


Figure 1.5 Comparison of the yield strength of dispersion-strengthened sintered aluminum powder (SAP) composite with that of two conventional two-phase high-strength aluminum alloys. The composite has benefits above about 300°C. A fiber-reinforced aluminum composite is shown for comparison.

1.5.7(ON THE BASIS OF REINFORCEMENT) FIBER-REINFORCED COMPOSITES

- The Rule of Mixtures in Fiber-Reinforced Composites

$$\rho_c = f_m\rho_m + f_f\rho_f$$

- Strength of Composites - The tensile strength of a fiber-reinforced composite (TS_c) depends on the bonding between the fibers and the matrix.

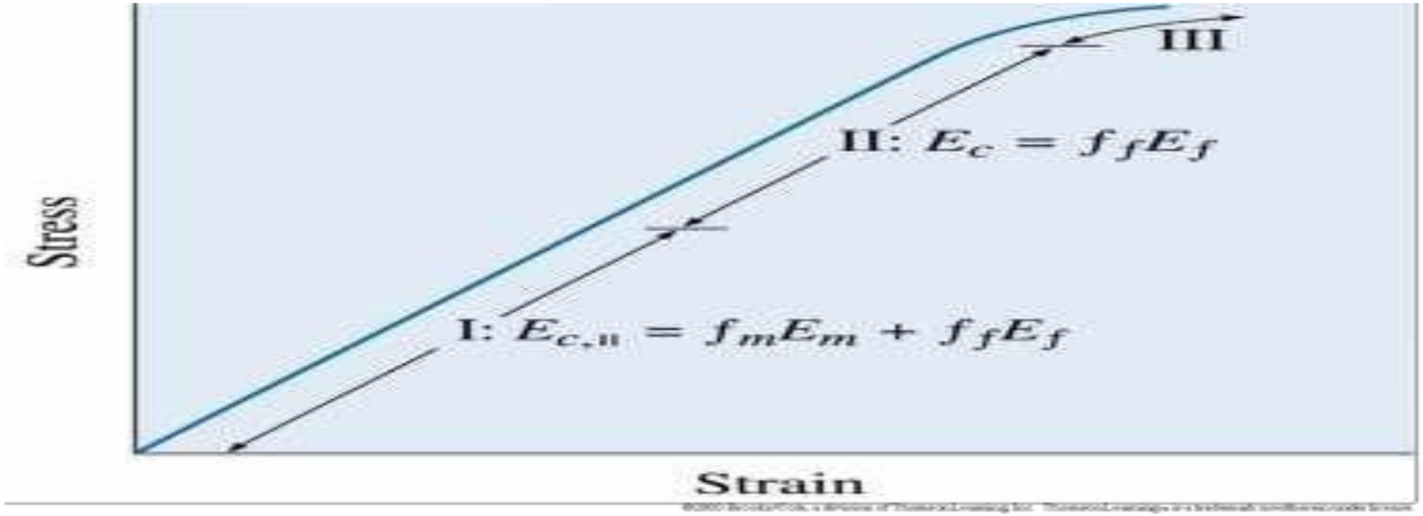


Figure 1.6 The stress-strain curve for a fiber-reinforced composite. At low stresses (region l), the modulus of elasticity is given by the rule of mixtures. At higher stresses (region ll), the matrix deforms and the rule of mixtures is no longer obeyed.

1.5.8 TYPES OF FIBRE REINFORCED COMPOSITE:-

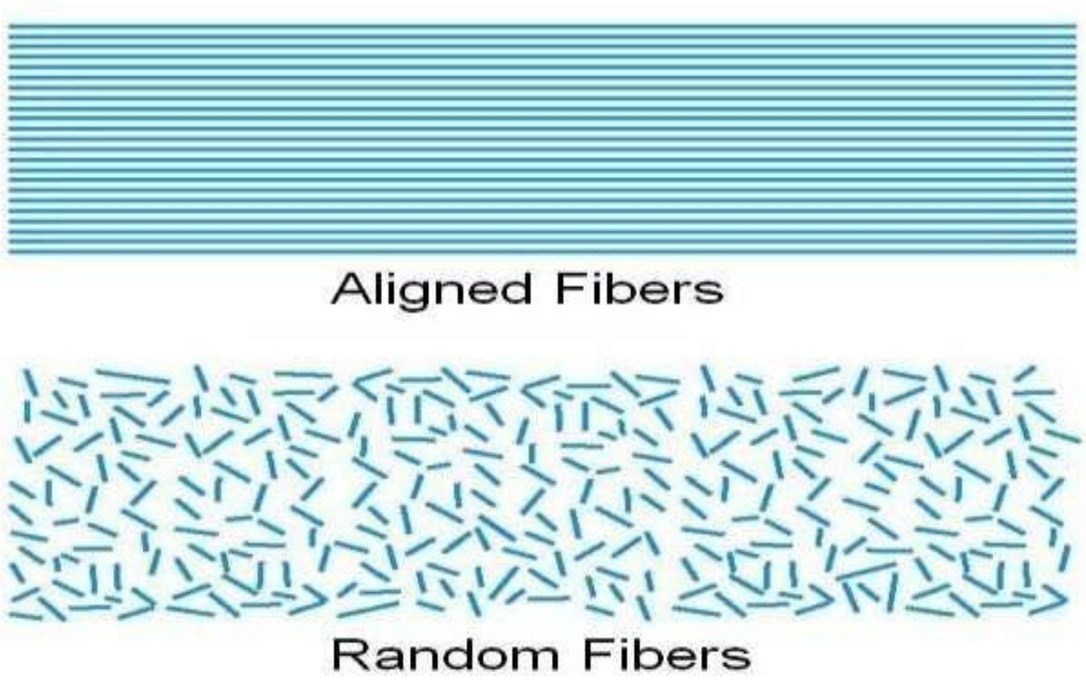


Fig. 1.7 Alingned or Continuous and Random fibres

- **Continuous & Aligned**

  The fibres are longer than a critical length which is the minimum length necessary such that the entire load is transmitted from the matrix to the fibres. If they are shorter than this critical length, only some of the load is transmitted. Fibre lengths greater that 15 times the critical length are considered optimal. Aligned and continuous fibres give the most effective strengthening for fibre composites.

- **Discontinuous & Aligned**

  The fibres are shorter than the critical length. Hence discontinuous fibres are less effective in strengthening the material, however, their composite modulus and tensile strengths can approach 50-90% of their continuous and aligned counterparts. And they are cheaper, faster and easier to fabricate into complicated shapes.

- **Random**

  This is also called discrete, (or chopped) fibres. The strength will not be as high as with aligned fibres, however, the advantage is that the material will be isotropic and cheaper.

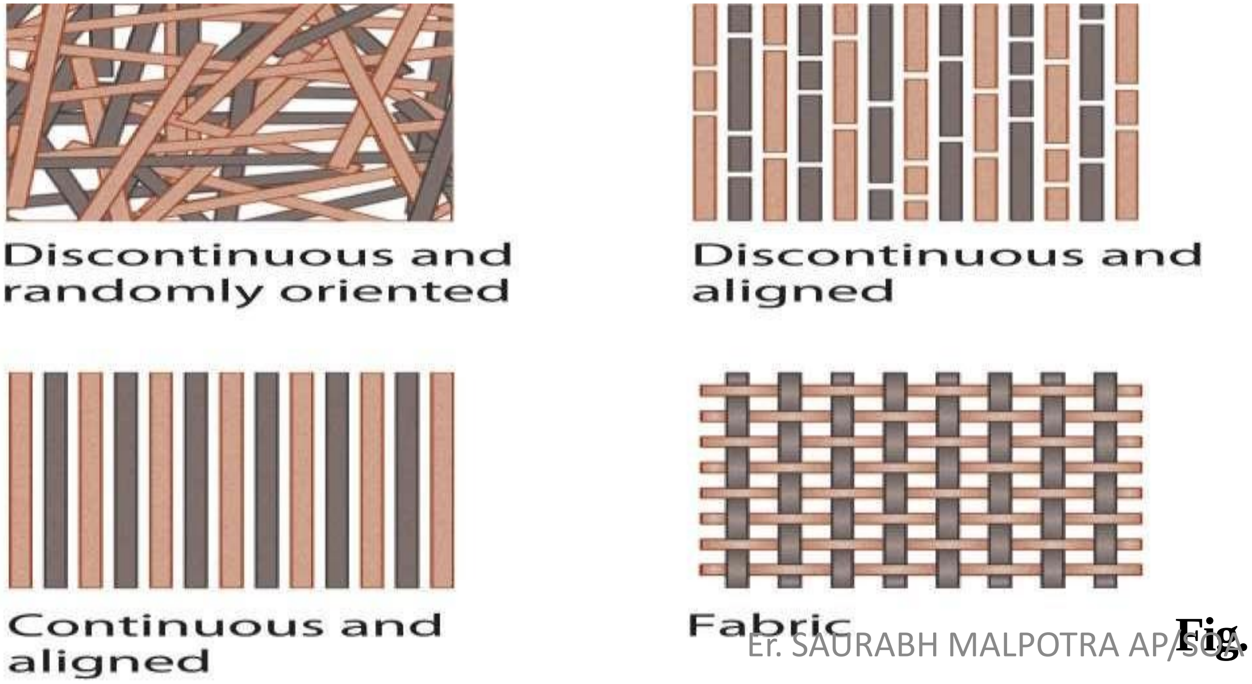


Fig. 1.7 Types of fibre reinforced composite

1.5.9 USES OF FIBER-REINFORCED COMPOSITES :-

- Sports equipment, such as a time-trial racing bicycle frame which consists of carbon fibers in a thermoset polymer matrix. Body parts of race cars and some automobiles are composites made of glass fibers (or fiberglass) in a thermoset matrix.
- Fiber orientation in fiber reinforced composites.

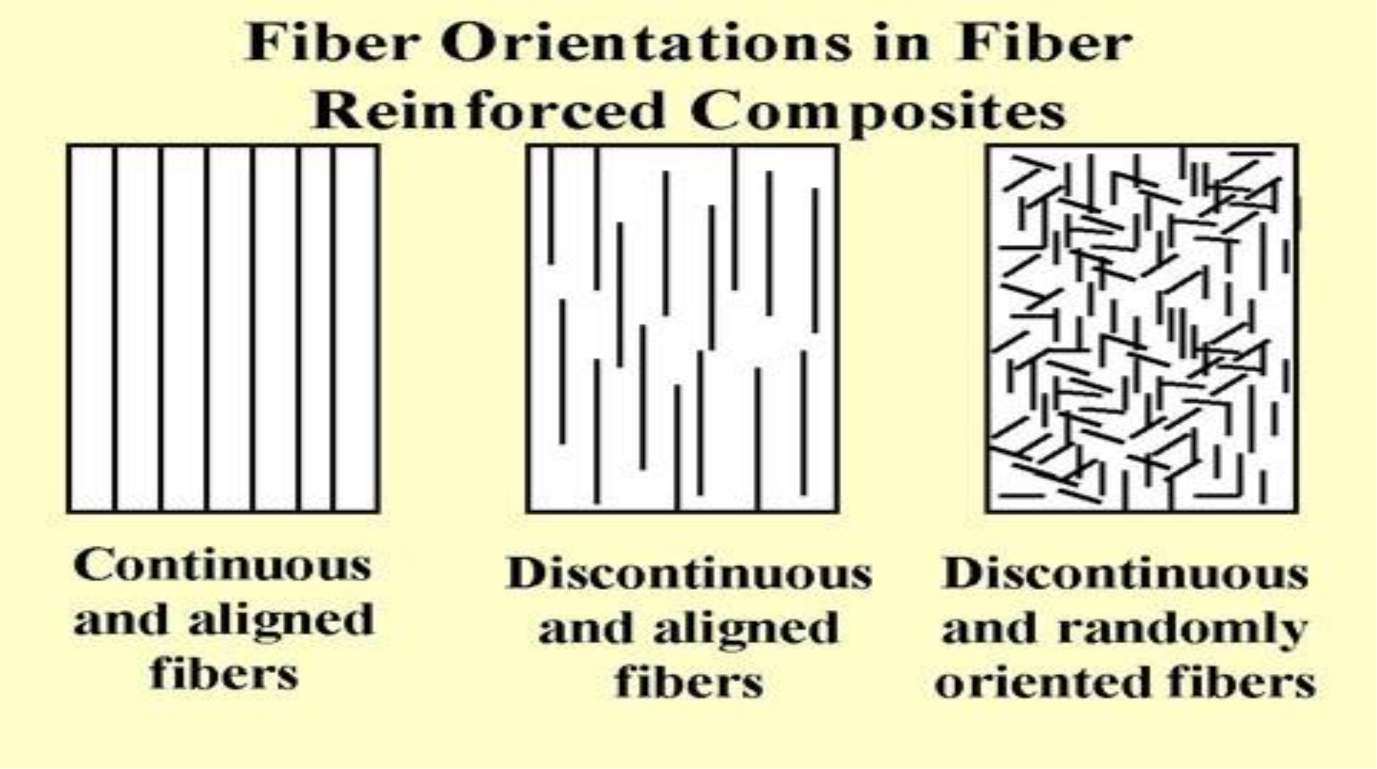
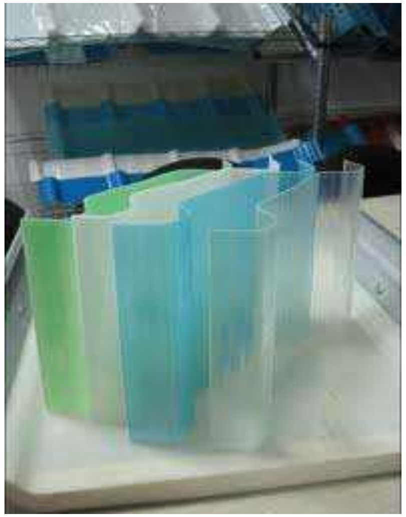


Fig. 1.8 Types of fiber-reinforcement composites



Commonly used fibres

- **<u>GLASS</u> :-** Insulating material to form a very strong and light FRP composite material called glass-reinforced plastic (GRP), popularly known as "fiberglass“ not as strong or as rigid as carbon fiber, it is much cheaper and significantly less brittle.

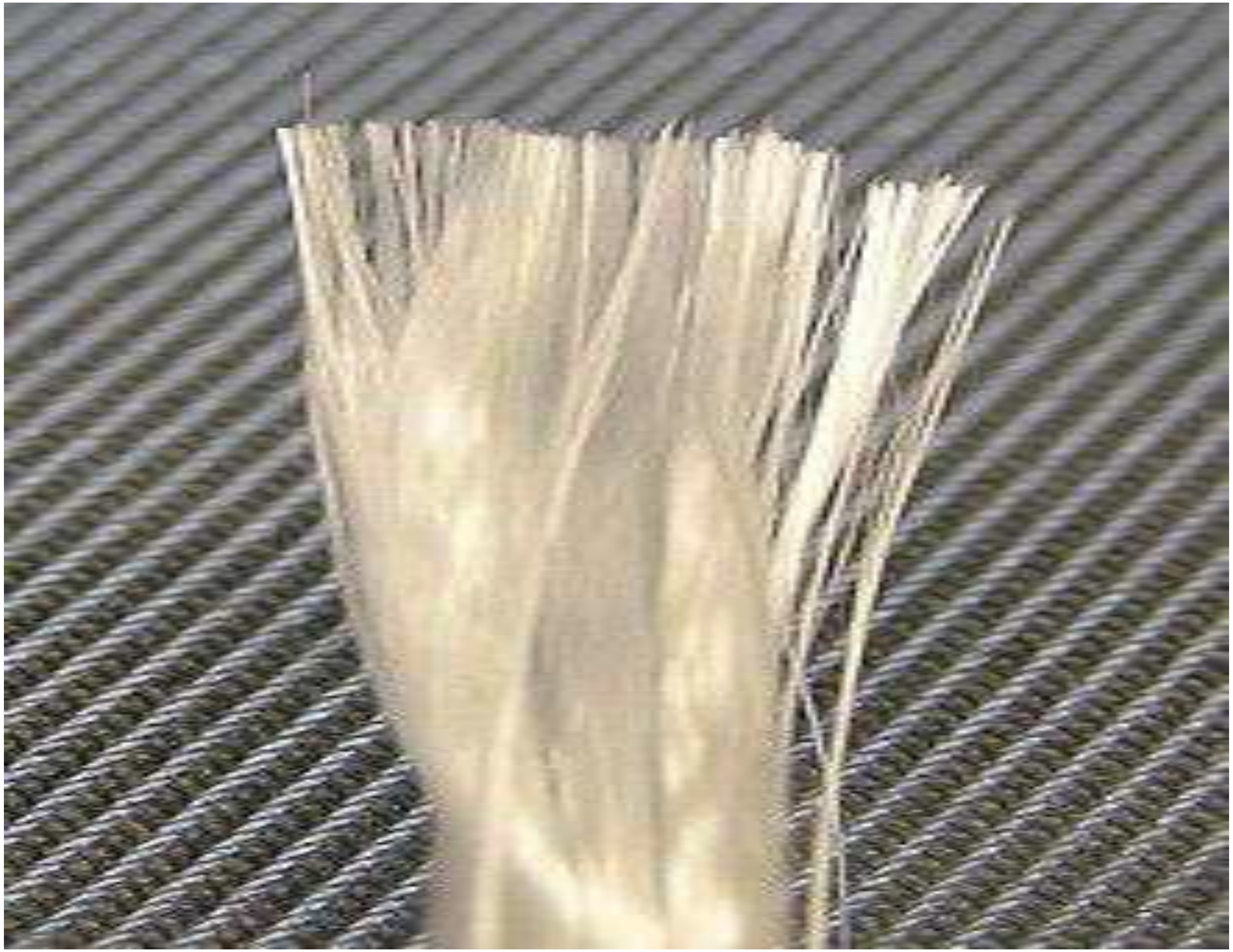


Fig. 1.9 Glass fibre

- **CARBON:-** fibers about 5–10 μm in diameter and composed mostly of carbon atoms carbon atoms are bonded together in crystals that are more or less aligned parallel to the longaxis of the fiber. The crystal alignment gives the fiber high strength-to-volume ratio (makes it strong for its size). high stiffness, high tensile strength, low weight, high chemical resistance, high temperature tolerance and low thermal expansion.

Fig. 1.10 Carbon fibre

- Silicon , aluminium oxide and metal wires are also used as reinforcing material. The polymer is usually Epoxy vinyl ester polyester thermosetting plastic phenol formaldehyde resins

Fig. 1.11 Silicon fibreglass sheating

1.5.10 STRUCTURAL COMPOSITES :-

- A structural composite consists of both homogeneous and composite material. There properties depend on, the characteristic properties of the constituent materials as well as the geometric design.
- Structural composite are of two types:-

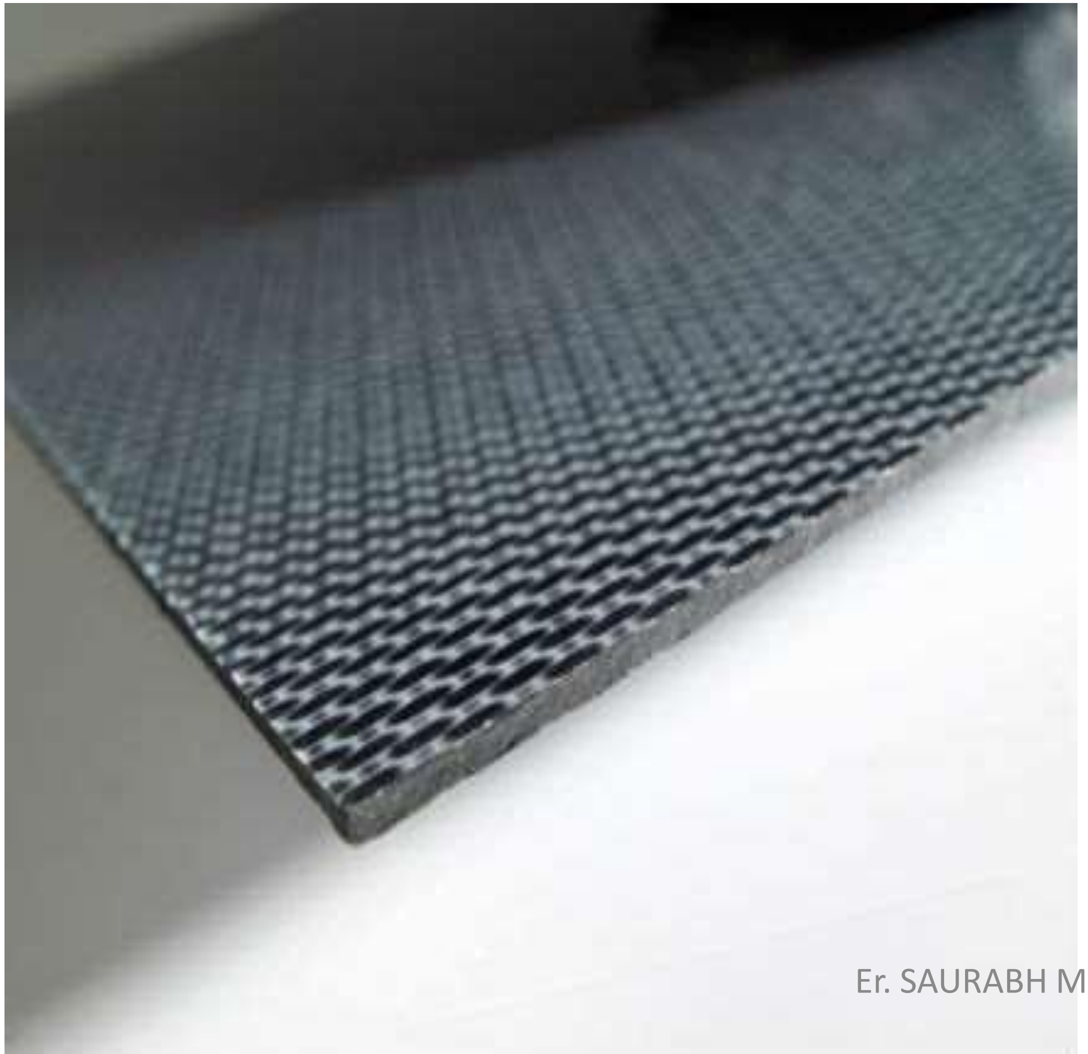
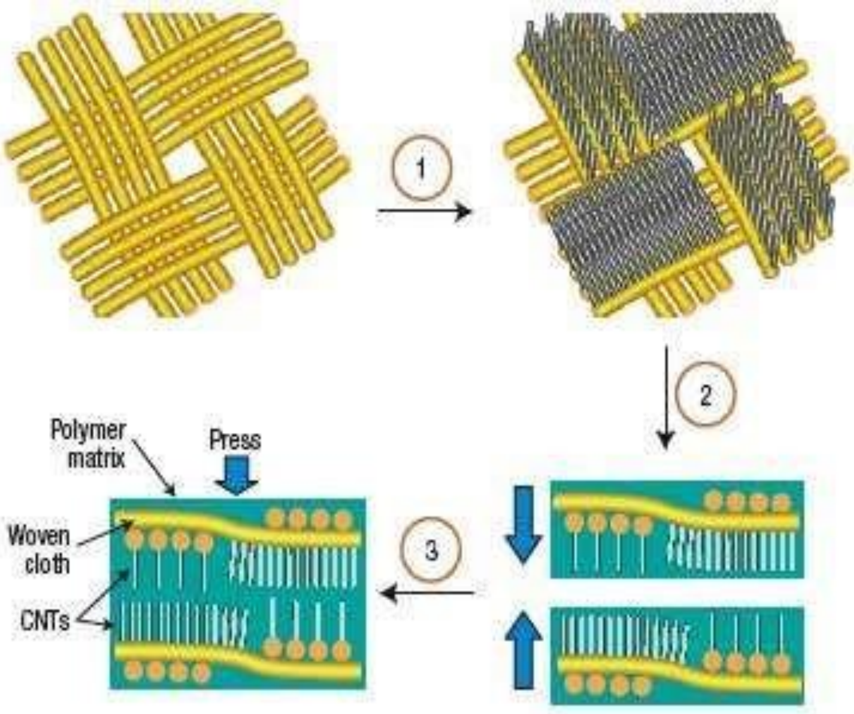


Fig. 1.12 Laminar compost

Fig. 1.13 Sandwich panel

1.5.11 **LAMINAR COMPOSITE** :-

- It consists of panels or sheets which are two dimensional. These panels possess preferred directions to achieve high strength.



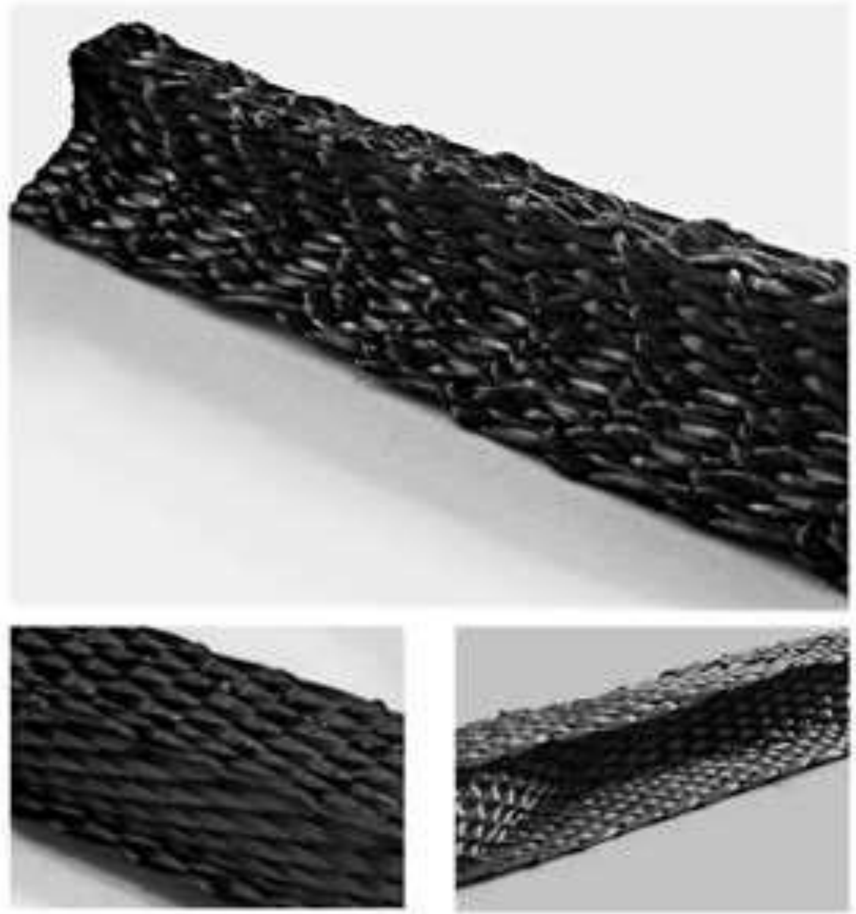
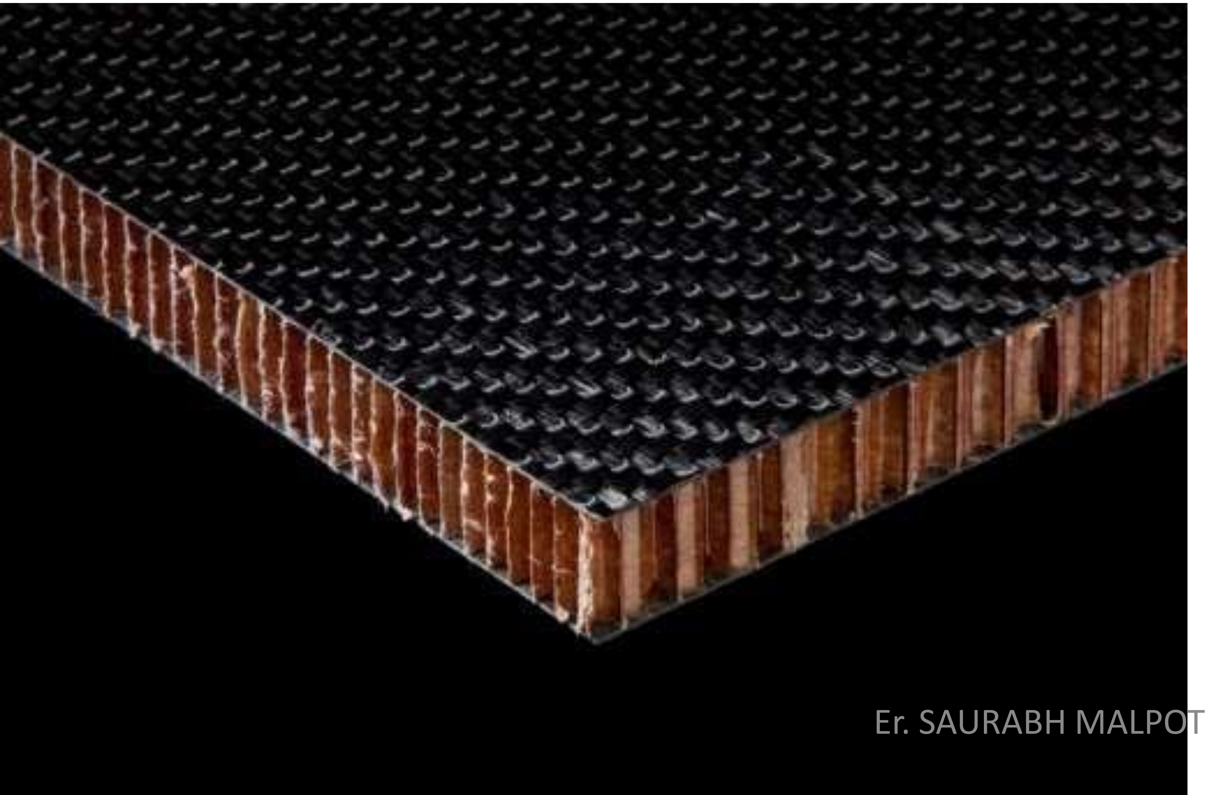


Fig. 1.14 Laminar composite

- Such successively oriented layers are stacked one above with preferred directions and then are cemented. Such an arrangement or orientation ensures varying highest strength with each successive layer involved in material.
- For example :- Plywood

1.5.12 SANDWICH PANEL :-

- Sandwich panel is also a kind of layered composite. It consists of ‘faces’ and ‘core’
- With increase in thickness of core, its stiffness increases as seen in the most common sandwich panel ‘honeycomb’.



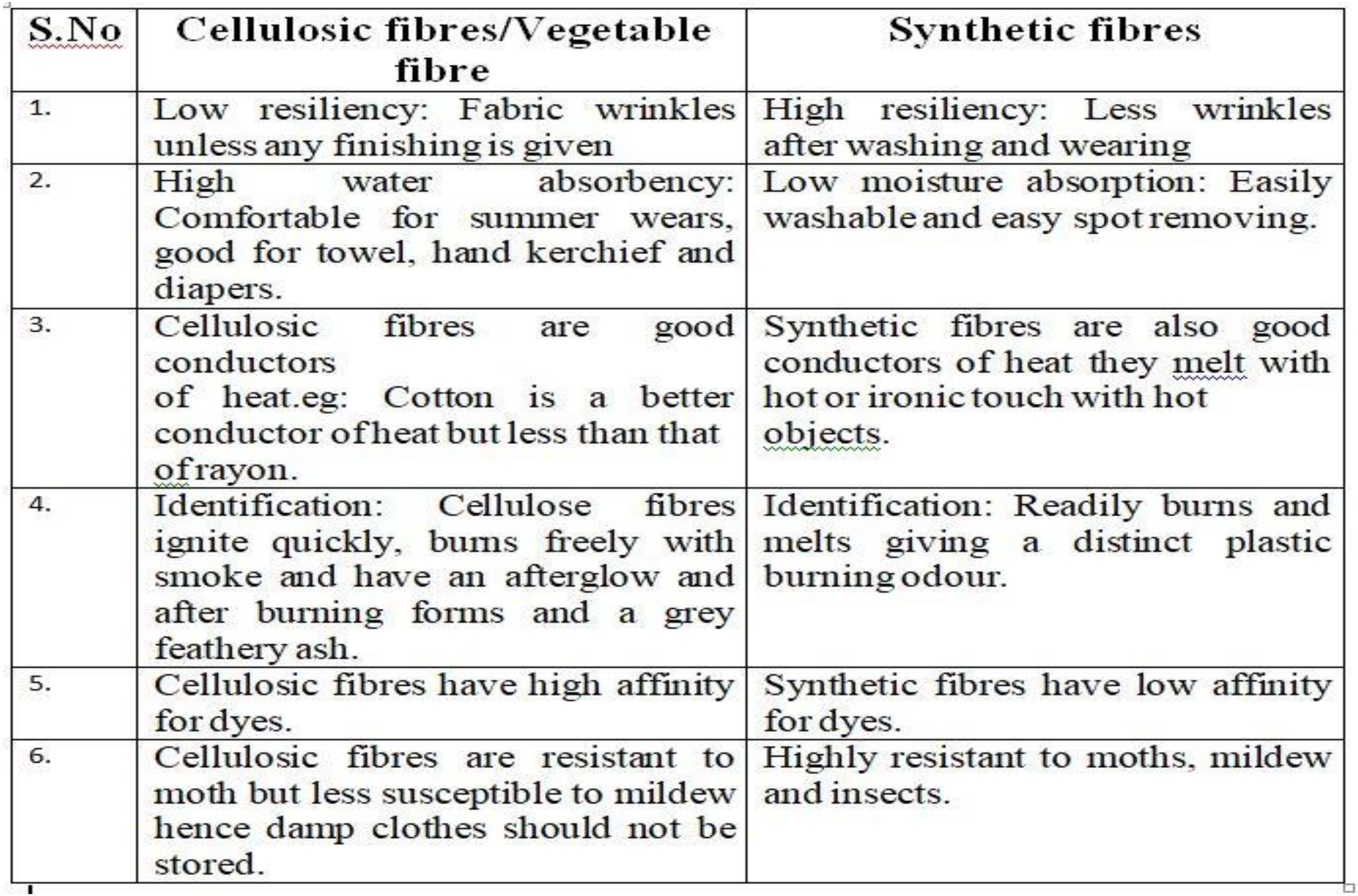
- **Faces**:-They are formed by two strong outer sheets.
- **Core**:-Core is layer of less dense material.
- **Honeycomb**:-Structure which contain thin foils forming interlocked hexagonal cells with their axes oriented at right angles in the direction of face sheet.

Fig. 1.14 Sandwich panel

1.5.13 APPLICATIONS OF COMPOSITE MATERIAL :-

1. In automobile industries (e.g. Steel &Aluminium body)
2. Marine applications like shafts, hulls, spars (for racing boats)
3. Aeronautical application like components of rockets, aircrafts (business and military), missiles etc.
4. Communication antennae, electronic circuit boards (e.g. PCB, breadboard)
5. Safety equipment like ballistic protection and Air bags of cars.

Fig. 1.15 Applications of composite material



S.No	Cellulosic fibres/Vegetable fibre	Synthetic fibres
1.	Low resiliency: Fabric wrinkles unless any finishing is given	High resiliency: Less wrinkles after washing and wearing
2.	High water absorbency: Comfortable for summer wears, good for towel, hand kerchief and diapers.	Low moisture absorption: Easily washable and easy spot removing.
3.	Cellulosic fibres are good conductors of heat.eg: Cotton is a better conductor of heat but less than that of rayon.	Synthetic fibres are also good conductors of heat they melt with hot or ironic touch with hot objects.
4.	Identification: Cellulose fibres ignite quickly, burns freely with smoke and have an afterglow and after burning forms and a grey feathery ash.	Identification: Readily burns and melts giving a distinct plastic burning odour.
5.	Cellulosic fibres have high affinity for dyes.	Synthetic fibres have low affinity for dyes.
6.	Cellulosic fibres are resistant to moth but less susceptible to mildew hence damp clothes should not be stored.	Highly resistant to moths, mildew and insects.

Table 1.1 Differenec vetween cellulosic fibre and synthetic fibre

1.6 FIBERS :-

1. Fabric is made of fibers.
2. Fibers are made of twisted filaments.
3. Types of fibers and fabric:
    - Natural—*animal, vegetable, or inorganic*
    - Artificial—*synthesized or created from altered natural sources.*

- **TYPES OF FIBERS :-**

Synthetic	**Natural**
Rayon	Silk
Nylon	Cotton
Acetate	Wool
Acrylic	Mohair
Spandex	Cashmere
Polyester	

Fig. 1.16 Inner structure of fibre

1.7 CLASSIFICATION OF FIBERS :-

NATURAL FIBERS ARE CLASSIFIED ACCORDING TO THEIR ORIGIN:

1. Vegetable or cellulose
2. Animal or protein
3. Mineral

Fig. 1.17 Cotton Vegetable fibre

1.7.1 CELLULOSE FIBERS :-

1. **Cotton**—vegetable fiber; strong, tough, flexible, moisture-absorbent, not shape-retentive
2. **Rayon**—chemically altered cellulose; soft, lustrous, versatile
3. **Cellulose acetate**—cellulose that is chemically altered to create an entirely new compound not found in nature.

Fig. 1.18 Cotton

Fig. 1.19 Rayon

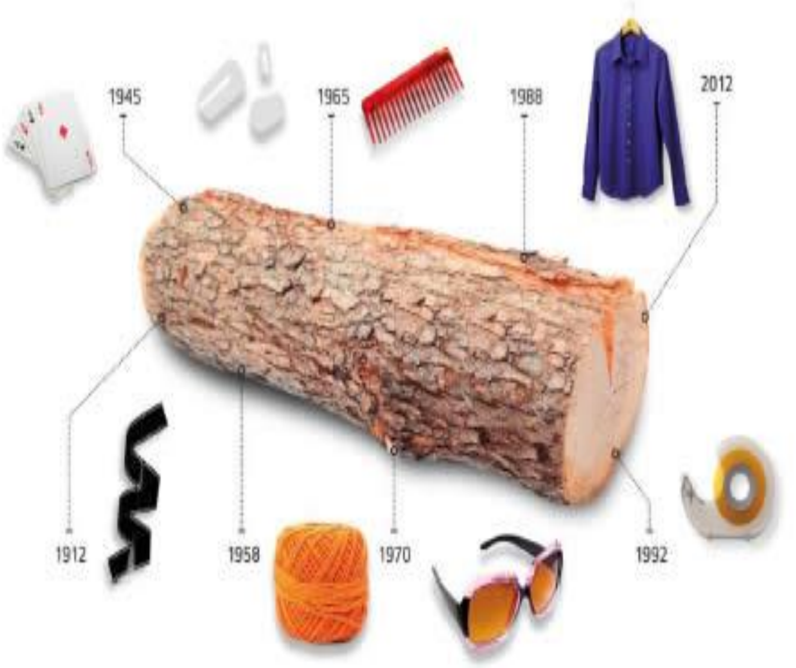


Fig. 1.20Cellulose acetate

1.7.2 PROTEIN FIBERS :-

1. **Wool**—animal fiber coming most often from sheep, but may be goat (mohair), rabbit (angora), camel, alpaca, llama, or vicuña
2. **Silk**—insect fiber that is spun by a silkworm to make its cocoon; the fiber reflects light and has insulating properties.

Fig. 1.21 Protein fibers

1.7.3 MINERAL FIBERS :-

1. **Asbestos**—a natural fiber that has been used in fire-resistant substances

2. **Rock wool**—a manufactured mineral fiber

3. **Fiberglass**—a manufactured inorganic fiber

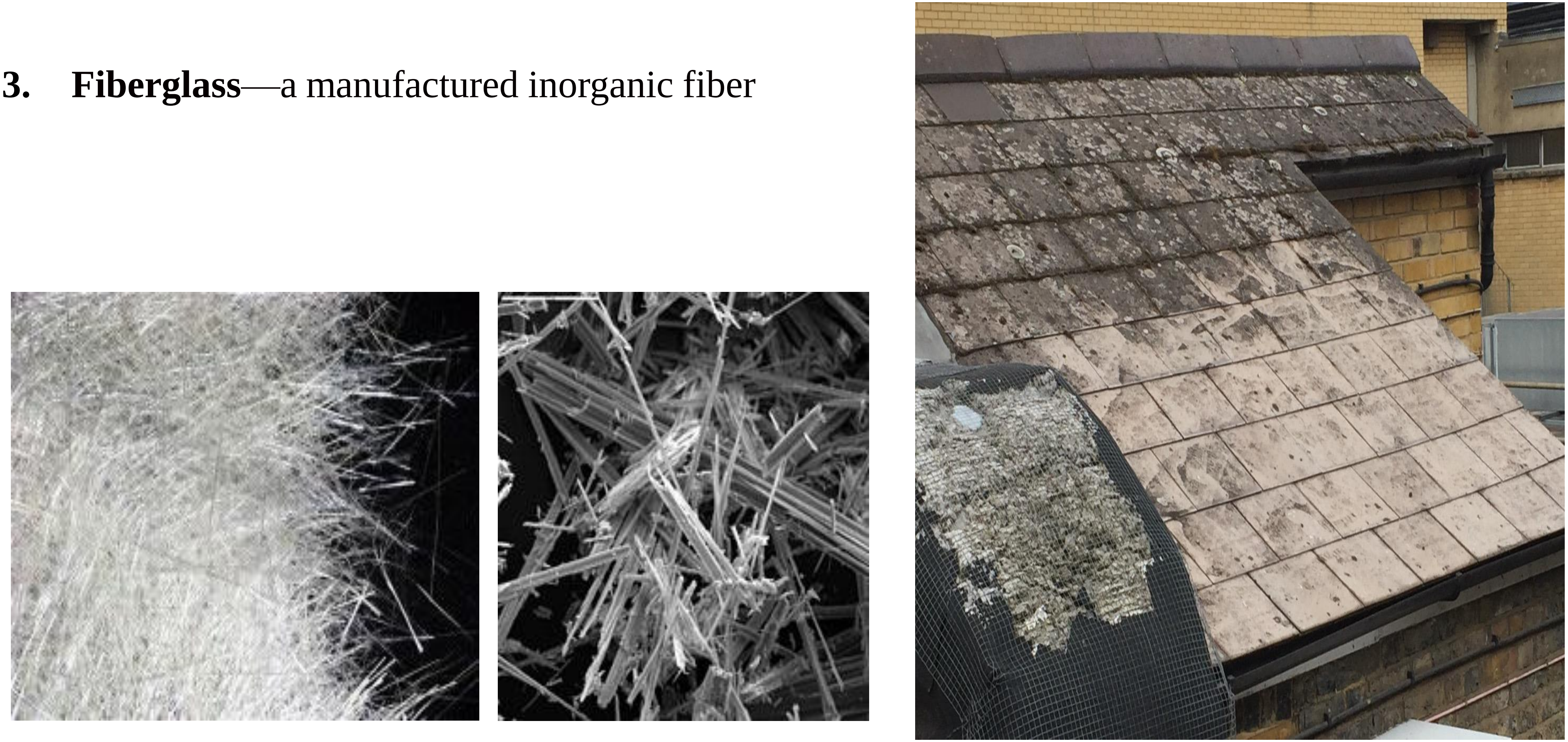


Fig.1.22 Asbestos

1.7.4 SYNTHETIC FIBERS :-

Made from derivatives of petroleum, coal, and natural gas.

1. **Nylon**—most durable of man-made fibers; extremely lightweight
2. **Polyester**—most widely used man-made fiber
3. **Acrylic**—provides warmth from a lightweight, soft, and resilient fiber
4. **Spandex**—extreme elastic properties

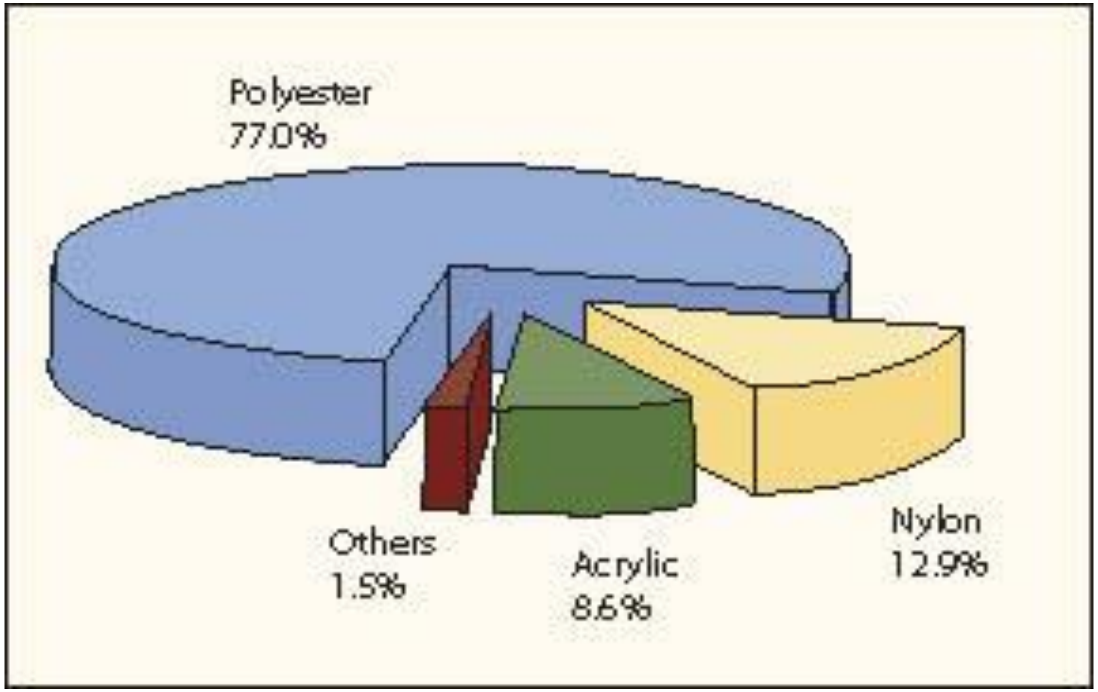


Fig. 1.24 World-wide usage of synthetic fibers

1.7.5 MATRIX MATERIAL :-

- While the principal strength and stiffness of the composite is provided by the fibres, the matrix material also has a large part to play in the overall mechanical properties. The matrix is not designed to bear much of the load. Instead, the matrix binds the fibres together and distributes the load. It also provides ductility and protects the fibres from surface damage. It separates the fibres and prevents propagation of cracks from one fibre to the next. Also, unless the matrix chosen is a particularly flexible one then it will assist in prevention of the fibres buckling under compression.
- The requirements of a good matrix material are that it can infiltrate between the fibres and form a strong interfacial bond. It is also essential that there is no chance of chemical reaction between the matrix material and fibres and that the matrix material does not cause damage to the fibres.
- There are three main types of composites based on the type of matrix they employ –
- 1. polymer matrix composites (PMC)
- 2. ceramic matrix composites (CMC) and
- 3. metal matrix composites (MMC).
- The most common type are polymer matrix composites. They are produced in the largest quantities, due to their good room temperature properties, ease of manufacture and low cost.

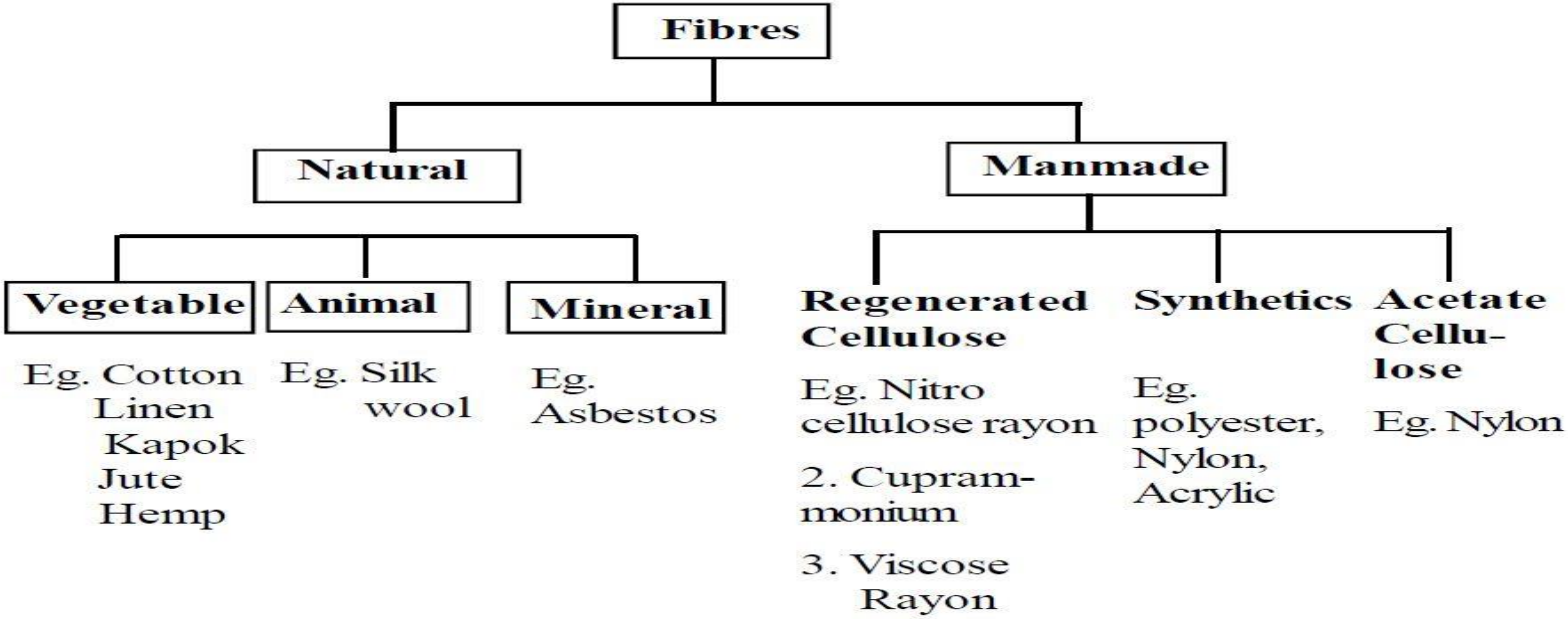
- Fibers and whiskers in composites are held together by a binder known as *matrix*. This is required since fibers by themselves:
  - Given their small cross-sectional area, cannot be directly loaded.
  - Further, they cannot transmit load between themselves.

- This limitation is addressed by embedding fibers in a matrix material.

- Matrix material serves several functions, the important ones being:
  - Binds fibers together.
  - Transfers loads and stresses within the composite structure.
  - Support the overall structure
  - Protects the composite from incursion of external agents such as humidity, chemicals, etc.
  - Protects fibers from damage due to handling.
  - Matrix material also significantly limits a composite’s maximum permissible operating temperature.

- Most of the matrix materials are relatively lighter, more compliant, and weaker vis-à-vis fibers and whiskers.
- However, the combination of fibers/whiskers and matrix can be very stiff, very strong, and yet very light.
- Thus most of modern composites have very high specific strengths, i.e. very high strength/density ratios.
- This makes them very useful in aerospace applications, where weight minimization is a key design consideration.

1.8 PROPERTIES OF DIFFERENT FIBRES :-



- **Fibres**
  - **Natural**
    - **Vegetable**: Eg. Cotton, Linen, Kapok, Jute, Hemp
    - **Animal**: Eg. Silk, wool
    - **Mineral**: Eg. Asbestos
  - **Manmade**
    - **Regenerated Cellulose**: Eg. Nitro cellulose rayon; 2. Cuprammonium; 3. Viscose Rayon
    - **Synthetics**: Eg. polyester, Nylon, Acrylic
    - **Acetate Cellulose**: Eg. Nylon

1. COTTON

- Cellulosic fiber
- From “bolls” (seed pods) growing on bushes
- “Environmentally friendly” cotton can be grown in a range of colors
- Main textile products of China, India, Iran, Pakistan and Egypt.
- Made into a wide range of wearing apparel.

Fig. 1.25 Cotton

Advantages:

- Comfortable
- Absorbent
- Good color retention
- Dyes & prints well
- Washable
- Strong
- Drapes well
- Easy to handle and sew
- Inexpensive

Disadvantages:

- Shrinks in hot water
- Wrinkles easily
- Weakened by perspiration and sun
- Burns easily
- Affected by mildew

Fig.1.26 mildew

2. LINEN (FLAX) :-

- Flax is the fiber name; linen is the fabric name.
- World’s oldest textile fiber, dates back to Stone Age 5,000 years.
- Cellulosic fiber from stem of flax plant.
- Towels, sheets, and tablecloths are called “linens”.

Fig. 1.27 Linen (flax)

Advantages:

- Strong
- Comfortable
- Hand-washable or dry-cleanable
- Absorbent
- Dyes and prints well
- Resists dirt and stains
- Durable
- Withstands high heat
- Lint-free

Disadvantages:

- Wrinkles easily
- Can be expensive
- Shrinks
- Burns easily
- Affected by mildew and perspiration
- Ravels
- Difficult to remove creases
- Shines if ironed

3. JUTE :-

- Jute is a long, shiny vegetable fiber that can be spun into coarse, strong threads.
- The fibers are off-white to brown, and 1–4 meters (3–12 feet) long. Bangladesh is the world’s largest exporter of jute. Jute is grown in the same land-water area as rice and is a very difficult crop to grow and harvest.
- Other important jute export countries include India, China, Burma (Myanmar), Pakistan, Nepal and Thailand.

Advantages :-

- Great antistatic properties
- Low thermal conductivity.
- Moisture Regain properties is good enough (about 13.75%).
- 100% Biodegradable; so it is environment friendly fiber like Cotton.
- Cheap in market.
- Can be widely used in Agriculture Sector, Textile Sector, Woven Sector, Nonwoven Sector.
- Jute Fiber can be blended with Natural and Synthetic fibers.

Disadvantages :-

- The crease resistance of Jute is very low.
- Drape Property is not good enough.
- Create Shade effect and becomes yellowish if sunlight is used.
- If Jute is wetted it lose it's strength.

Fig. 1.28 Jute

4. COIR :-

- Is a natural fiber extracted from the husk of coconut
- Products such as floor mats, doormats, brushes, mattresses, etc.
- Technically, coir is the fibrous material found between the hard, internal shell and the outer coat of a coconut.
- Other uses of brown coir (made from ripe coconut) are in upholstery padding, sacking and horticulture.
- White coir, harvested from unripe coconuts, is used for making finer brushes, string, rope and fishing nets.

Fig. 1.29 Coir

5. HEMP :-

- Hemp fiber was widely used throughout history. Items ranging from rope, to fabrics, to industrial materials were made from hemp fiber.
- Hemp was often used to make sail canvas, and the word *canvas derives from cannabis.*
- Today, a modest hemp fabric industry exists, and hemp fibers can be used in clothing.
- Pure hemp has a texture similar to linen.

Fig. 1.30 Hemp

6. BANANA FIBERS :-

- It is used to make fancy items like bags, table mats, purses, etc and their latest venture is weaving of banana fiber fabric.
- A native plant of Southeast Asia, banana is now grown extensively in all tropical countries for fruit, fiber or foliage.
- These fibers are obtained mainly from stem.
- The fibers obtained from the central core are of lower quality compared to the fibbers obtained mainly from pseudo stem.

Fig. 1.31 Hemp

7. WOOL :-

- Protein fiber from sheep or lambs.
- Worsted wool is higher quality with long staple fibers (over 2 inches)

natural insulator.

- The term wool can only apply to all animal hair fibers, including the hair of cashmere or angora goat.
- As well as the specialty hair fibers of camel, alpaca, llama, or vicuna.

Fig. 1.32 llama

Advantages:

- Warm
- Lightweight
- Wrinkle-resistant
- Absorbent
- Dyes well
- Comfortable
- Durable
- Creases well
- Easy to tailor
- Recyclable

Disadvantages:

- Affected by moths
- Shrinks with heat and moisture
- Needs special care, dry cleaning
- Absorbs orders
- Scratchy on skin
- Weakens when wet
- Harmed by bleach, perspiration

8. SILK :-

- Silkworms spin cocoons in filaments
- Filament is a very long, fine, continuous thread
- It can take as many as 500 cocoons to create 1 blouse .

Fig. 1.33 Silk

Advantages:

- Soft
- Drapes well
- Dyes and prints well
- Very strong
- Lightweight
- Resists soil, mildew, and moths
- Comfortable
- Absorbent

Disadvantages:

- Expensive
- Needs special care, dry cleaning
- Stains with water
- Yellows with age
- Weakened by perspiration, sun, soap
- Attacked by insects, silverfish

9. SISAL FIBERS :-

- Sisal is a perennial hardy plant, which unlike the other fibers is not a seasonal crop.
- It can establish and easily grow in all states of India covering sub humid to arid and semiarid regions, which cover major parts of India.

Fig. 1.34 Sisal fibre

10. PINEAPPLE(PINA) FIBER :-

- Piña is a fiber made from the leaves of a pineapple and is commonly used in the Philippines
- It is sometimes combined with silk or polyester to create a textile fabric.
- The people there used to extract fibers from pineapple leaves and through hand spinning, made a soft, sheer and a little stiff fabric- the piña fabric. It's regal and exotic!

Fig. 1.34 Pineapple(pina) fiber

1.8 MANUFACTURING OF DIFFERENT FIBRES :-

1. Manufacturing of cotton:-

Cotton is obtained plant source and it is classified as a natural material as it is obtained from the seeds of cellulose seed fibre staple fibre measuring 10-65mm in length and white to beige in color in its natural state. It is composed basically of a substance called cellulose. As cotton occupies 50% of the consumption of fibres by weight in the world it is called as the king of all fibres.

Cotton is the fabric for every home and is the most widely produced of textile fabrics today. It has now been proved that India was the first country to manufacture cotton. Among the recent findings at Mohenjo-Daro were a few scrapes of cotton sticking to the side of a slivers vase. Cotton is the white downy covering of the seed grown in the pods. The cotton plant grown in the tropics needs a climate with 6 months of summer weather to blossom and produce pods.

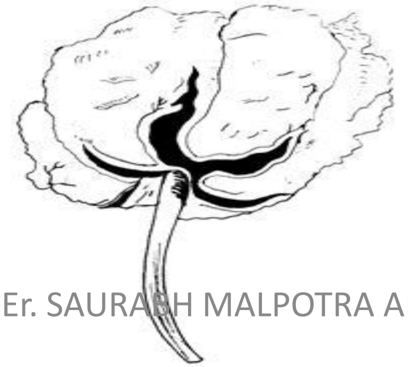


Fig.1.35 Cotton Boll

- The cotton fibre is the shortest of all the textile fibres. Its length varies from 8/10 of an inch to 2 inches. Cotton with short length fibres is technically known as “short staple”. The one with the long fibres is called “long staple” and it more used since it is used for making fine qualities of cloth. Long staple is especially suitable as it is easy to spin and produces a strong smooth yarn.
- **CULTIVATION OF COTTON:-**

The principal cotton producing regions are Egypt, southern United States, India, Brazil the western and southern cost of America and East Indies. It requires 200 days to continue warm weather with adequate moisture and sunlight. Frost (a small ice cubes) is harmful to the plant. March and April months are suitable for plantation. America produces more than 40% of the world’s cotton. India ranks second to the United States as a producer and exporter of cotton.

- **MANUFACTURE OF HAND MADE COTTON IN INDIA:-**

The tools and appliances used by cotton weaves consist of a spinning wheel (charkha) and a spindle (takli). The cotton is the first ‘separated’ and ‘carded’. A bow shaped beater known as ‘dhun’ is used for the purpose. The string of the bow is placed on the cotton and is made to vibrate by means of a wooden hammer.

MANUFACTURE OF MACHINE MADE COTTON :-

Cotton pods
↓
Ginning (Removal of Seeds)
↓
Lap Formation
↓
Carding
↓
Doubling --> Combing
↓
Drawing
↓
Roving
↓
Spinning

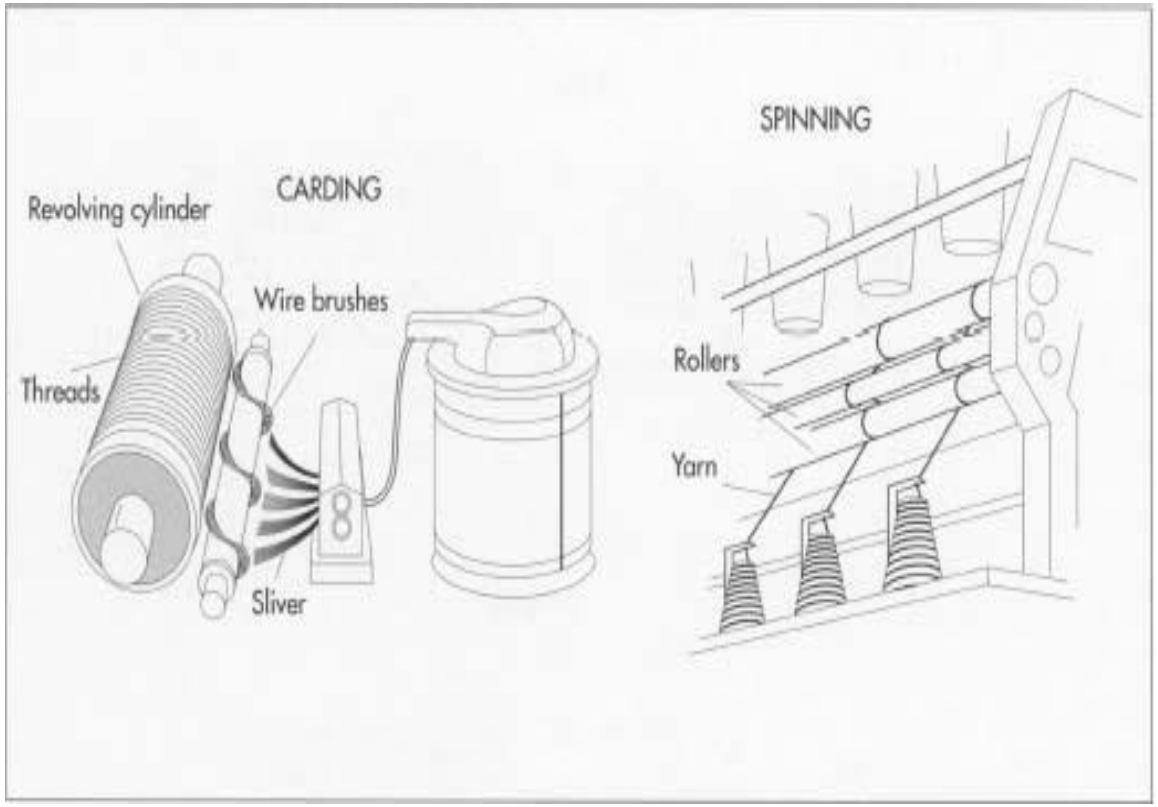


Fig. 1.35 Machine made cotton

- **Forming the laps**: In the step dirt from cotton fibre is removed and fibres are made in to a soft roll or lap. Then several laps are combined into one.
- **Carding:** These fibres are drawn together to form a loose rope called sliver.
- **Doubling:** Slivers are combined here for uniformity.
- **Combing**: This process is continuation and refinement of carding process. All cotton yarns for fabrics are carded but not all are combed. Yarns that are combed are finer even and free from all woody stalk of the plant. They are used for finer quality fabrics such as voile and organdie. Fabrics made from these fabrics are expensive too. The slivers are called carded slivers.
- **Drawing:** The slivers is then combined, smoothened and stretched. The slivers may be drawn reduced further in size and given a slight twist by a process. called roving in which the slivers is passed through rollers and wound on to bobbins set into spindles. It is done in a speed frame.
- **Roving:** The bobbins are placed on the roving frame where further drawing and twisting takes place until the cotton stock is about a pencil lead in diameter.
- **Spinning:** Done on the spinning frame where the stock passes through sets of high speed rollers and gives the yarn of desired thickness.

- **Weaving and dying:** The yarn is then knitted or woven in any one of the variety of weaves and structures. Warp yarns are usually more strongly twisted than filling yarns since they must withstand greater strain in weaving and finishing. Dye stuffs may be applied to raw cotton, yarn or piece goods.
- **Finishing:** It includes starching, calendaring, mercerizing or other finishes as it is necessary for the particulars use for which the cloth is intended. These finishes may be applied to yarns but are usually applied to fabric. The fabrics may be given these special finishes before or after dyeing.

2. MANUFACTURE OF PROTEIN FIBRES :-

- This unit gives us the information regarding the manufacture of physical and:- chemical properties of protein fibres.
- (1) Silk (2) Wool
- Silk is considered as “Queen of all textile fibres” as it has beauty and elegance and good properties of performance. Silk is the natural protein fiber obtained from silk worm cocoons. Japan is known for producing best variety of silk.
- India produces different varieties of silk and is famous for hand woven silk textiles. There is a tremendous silk production increase in recent years. The production of silk is called Sericulture. To obtain quality and quantity of silk rearing conditions are controlled carefully throughout the life cycle of silk moth.
- These are two types of silk mulberry or cultivated silk and wild silk. Cultivated silk is creamy silk white or yellowish white in color. White wild silk color range from brownish to golden yellow in color.

2.1 PRODUCTION OF SILK:-

- Silk worms feed on mulberry tree leaves and therefore for rearing them, the growing of mulberry trees is the first essential step. These are grown by the agriculturists. Silk worms have a short life of only about two months and during which these pass through the following four stages:-

1. Egg 2.worm or larvae 3. Pupa and 4. moths.

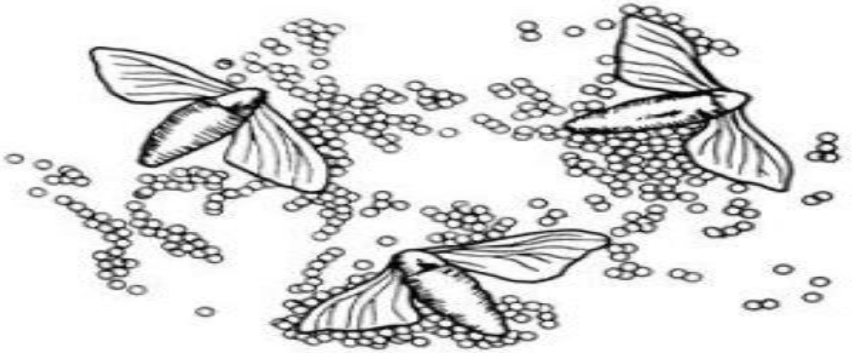


Fig. 3.1Silk moth and eggs

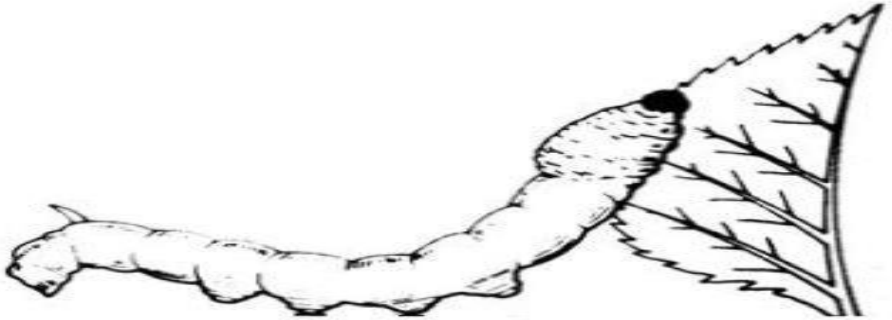


Fig. 3.2 Larva of Italian Bombyx mori silkworm moth

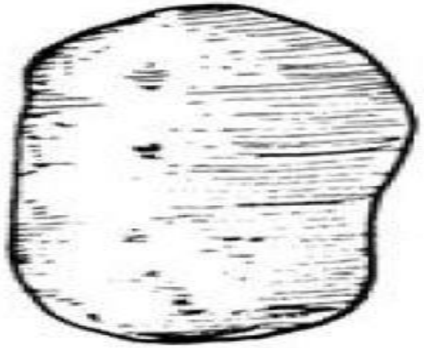


Fig. 3.3 Cocoon of Bombyx mori

Fig. 3.4 Male Bombyx mori or mulberry–feeding silk worm moth

- Silk worms are made to lay eggs on specially prepared paper for this purpose. The eggs can be stored in cold storage for six weeks. Eggs are collected and kept at low temperature until they are hatched. Eggs take ten days to hatch Emerged caterpillars of ant head size are fed on fresh mulberry leaves. At this stage the worm needs special care bamboo trays with straw mats are provided for them. When the caterpillar is about eight weeks old it secretes a viscous fluid from two glands on its head which oozes out from the common opening near its mouth. The fluid is called 'fibrion'. At the same time it also secretes a gummy kind of fluid called 'sericin' which passes through the same opening. The fibroin gets hardened when exposed to air.
- The silk worm spins around itself to form a cocoon. The cocoon contains 2000 to 4000 yards of reelable silk. For separating the silk thread from the cocoons they are immersed in hot water. This immersion also kills the warm inside. Then the cocoons are dries and stored.
- **Reeling:** The process of unwinding the filament from the cocoon is called reeling. The care and skill in the reeling operation prevents defects in the raw silk.
- **Throwing:** As the fibres are combined and pulled on to the reel, twist can be inserted to hold the filaments together.

- **Spinning:** Short ends of silk fibres from the outer and inner edges of the cocoons and from broken cocoons and spun into yarns in a manner similar to that used for cotton. This is called spun silk.
- **Degumming:** Sericin or gum up to 30% of the weight of the silk fibre. It is not usually removed until after the cloth is woven because serves as warp sizing that protects the yarns from mechanical injury during weaving.
- **Bleaching:** Silk thread is treated with hydrogen peroxide.
- **Dyeing:** Silk has great affinity for the dyes. Acid dyes produce brilliant shades on silk.
- **Printing:** Silk may be left plain or may be printed by any method like roller printing, Screen printing or block printing. Silks are usually dried and then printed.
- **Finishing:** Silk fabrics require very few finishes because they have natural lustre, softness and drapability.
- **Weighting of silk:** When silk is boiled to remove the excess of natural gum or sericin it looses weight.

3. **WOOL :-**

- Wool has the one of the first fibres to be converted into fabric. Wool fibre grows from skin of sheep. It is composed of protein known as keratin. It is crimp and has scales on its surface depending upon the breed of sheep.
- The natural protein fibre consist of amino acids. Wool has 19 amino acids, keratin, protein and other organic acids. Man uses wool as clothing in the very early stages of human history. The primitive man is used it in the form of skin of certain animals to protect as well as to decorate his body. Man then discovered the use of hair of sheep after interlocking and twisting them together under pressure and thus hair of sheep were used in making fabrics The interlocking of woolen fabrics is known as felting.
- Wool was probably known to the primitive man as he used sheep skin to cover his body even before the discovery of other fibres.
- Wool is yellowish white fibre and has medium luster. It is considered to be weak fibre than many other fibres however other properties such as resiliency and elasticity compensate for low strength.

3.1 MANUFACTURING OF WOOL:-

- **Shearing:-** Sheep are generally shorn of their fleeces in spring but the time of shearing differs in different parts of the world. Machine clippers remove the fleece faster and closer than hand clippers. Superior wool variety comes from the sides and shoulders where it grows longer, finer and softer is treated as good quality fleece.
- **Preparation :-** An average about 8 pounds of fleece is made from one sheep. Then the fibers are packed in bags or bales. The raw wool or newly sheared fleece is called Grease wool because it contains the natural oil of the sheep. When Greese wool is washed, it loses from 20 to 80% of its original weight.
- **Sorting and grading :-** Skilled workers do wool sorting. Each grade is determined by type, length, fineness, elasticity and strength. Separating of fibre by touch and sight.
- **Scouring :-** Washing of raw wool is an alkaline solution is known as scourcing. The wool is treated with warm water, soap, mild solution of soda ash or other alkali to remove dirt in the fibres. If the raw wool is not sufficiently clear of vegetable, substance after scouring is put through the carbonizing bath. The fibres are then put through a dilute solution of sulphuric or hydrochloric acid which destroys any vegetable.

- **Garnetting**:- Recycled wool fibres are obtained by separately reducing the unused and used fibrous mass by a picking and shredding process called garnetting.
- **Drying**: Wool is not allowed to become absolutely dry usually about 12 to 16% of moisture is left in wool to condition it for subsequent handling.
- **Oiling:** As wool is un manageable after scouring the fibre is usually treated with various oils including animals, vegetable, mineral or a blend of these to keep it from being becoming brittle or lubricate it for the spinning operation.
- **Dyeing:** If the wool is to be dyed in raw stock it is dyed at this stage. Some wool fabrics piece dyed, some are yarn or skin dyed and some are top dyed.
- **Blending**: Wool of different grades or pure wool fibres and other textile fibers may be blended mixed together at this point.
- **Carding**: The carding process introduces the classification of woolen yarns and worsted yarns. It makes the fibre parallel and some amount of dirt is removed due to straightening of fibres. Fibres are used for the worsted yarn are more straightened than the wool yarns.

- **Gelling and combing**: The carded wool which is to be made into worsted yarn is put through gilling and combing operations. The geilling process removes the shorter staple and straightens the fibre. This process removes short fibres from 1 to 4 inch length places the long fibre as parallel as possible and further cleans the fibre by removing any remaining loose impurities.
- **Drawing**: Drawing is an advanced operation for worsted yarns which doubles and redoubles slivers of wool fibres. The process draws, drafts, twists and winds the stock making slivers more compact and thinning them into slubbers.
- **Roving**: This is the final stage before spinning roving is actually a light twisting operation to hold thin slubbers intact.
- **Spinning**: In the spinning operation the wool roving is drawn out and twisted into yarn. Woolen yarns are chiefly spun on the mule-Spinning machine are worsted yarns are spun on any kind of spinning machine mule, ring, cap or flyer.

4. MANUFACTURING OF SYNTHETIC FIBRES :-

- This unit gives us the information regarding the manufacture and properties of man-made fibers.

(1) Rayon

(2) Polyester.

- ***1. RAYON:-*** A rayon fiber was the first man-made composed of pure cellulose the substance of which is the man constituent of cell walls of trees and cotton. Rayon fibers are made from cellulose that has been reformed or regenerated. Consequently, these fibers are identified as "regenerated cellulose fibers". Because of its lustre and soft hand feel, it resembled silk and came to be known as "artificial silk". However it is more like cotton in its chemical composition
- Robert Hooke, the English naturalist, had prophesied the production of a fiber such as rayon, the first of the man made fibers long ago in 1664. He believed that it was possible to make an "artificial glutinous composition" much resembling, if not fully like silk worm secretion George Audemars, a Swiss chemist, discovered how to make cellulose nitrate. In 1884, "count Hilaire de" produced the first man made textile fibers from nitro cellulose. He is known as "father of Rayon".

4.1 MANUFACTUTING OF RAYON:-

- All types of rayon are made from cellulose. There are main four main procedures by which cellulose is transformed into rayon. They are

(1) The nitrocellulose process.

(2) The cuprammonium process.

(3) The viscose process.

(4) The cellulose acetate process.

- The general principles of rayon yarn production involve the following steps.

(a)To treat cellulose chemically for rendering from it a liquid.

(b)To force the liquid through fine holes.

(c)To change from liquid stream into solid cellulose filaments.

4.1.1 The Viscose Process :-

This is discovered in 1892 in England. In this process Spruce, a type of tree chip sare used. Spruce logs are reduced to wood pulp and purified for cellulose base. Wood pulp is treated with caustic soda (sodium hydroxide, NaOH) to form alkali cellulose. It is treated with carbon disulphide to form cellulose xanthate. This is dissolved in dilute caustic soda solution. A reddish or orange liquid is formed. This liquid is filtered and then kept for ageing until a thick fluid is formed which is called ‘Viscose’. This fluid is forced through fine jets into a dilute solution of sulphuric acid. In this way cellulose is regenerated into continuous fibers.’

- The largest production of rayon today is manufactured by this process. The cost is low.

4.2 MANUFACTURING OF POLYESTER:-

- Polyester is a synthetic fiber invented in 1941. The first polyester fiber is known as ‘Dacron’ in America and ‘Terylene’ in Britain. Later various types of polyesters are produced. Terylene fiber is made by synthesizing terephthalic acid and ethylene glycol.
- The ground work for development of polyester fiber is done by W.H. Carothers. Polyester fiber is the long chain polymer produced from elements derived from coal, air, water and petroleum. Polyester is a thermoplastic fiber and has good strength. It melts in flame and forms a grey hard non-crushable bead. It is an easy care fabric and can be easily washed.
- Polyester fiber looks like a smooth, glass rod similar to Nylon.
- **Method of Manufacture :-**
- Generally each company produces its own variety of polyester through there are likely modifications under specific trademarks. Eg : PET (Principle raw material is ethylene diamine and terepthalic acid) obtained from petroleum and PCDT polyester.

. **Spinning of Fiber**

- The molten polymer is rigourously maintained at airtight condition, as oxygen will affect its stability. The viscous melt is extruded through spinneret, and the filaments are subsequently drawn into desired polyester fiber. Variations in production process depends on desired end results.

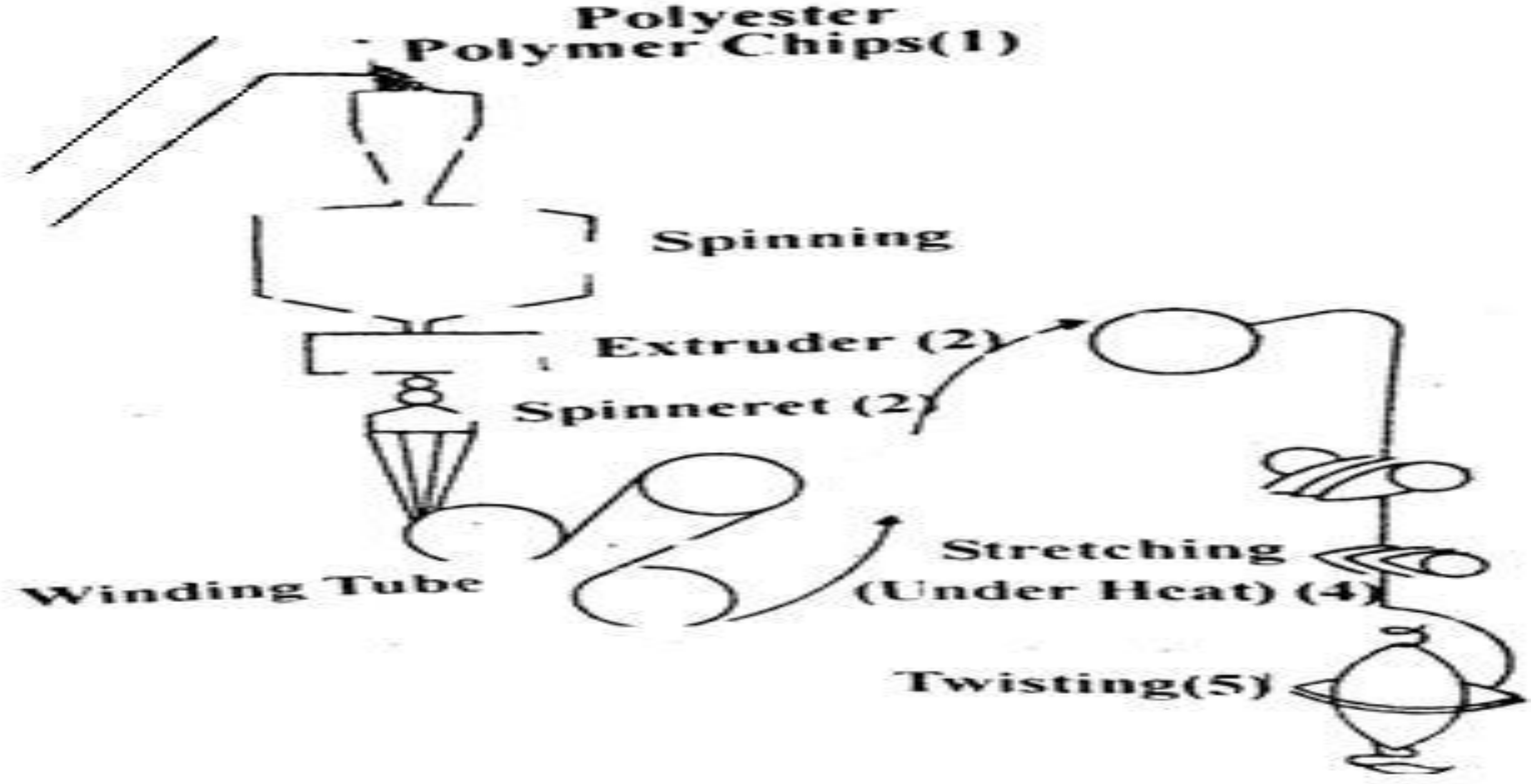


Fig. 1.36 Flow chart of manufacturing process of polyester

The holes of spinneret may be round or modified to be trilobal, pentagonal, hexagonal or octagonal shapes so, as achieve specific effects such a greater cushioning and insulative properties. Other properties may be obtained with the aid of specific additives given to the spinning solution.

1.9 SURFACE TREATMENT OF FIBERS :-

- This review is based on the surface treatment of natural fibres which can be used in technical applications. Natural fibres on their own have some draw backs regarding moisture uptake, quality variations, low thermal stability, and poor wettability. Insufficient adhesion between polymer matrix and fibre leads in time to debonding. Overcoming the weaknesses of these natural fibres gave the motivation for this study where physical and chemical methods of modification were considered.
- Physical methods such as electric discharge and mercerization were reported as well as the chemical methods such as graft copolymerization and treatment with isocyanates, and the results due to these modifications were discussed. This study reveals that natural fibres are good candidates for reinforcement but they have to be suitably treated to improve their properties if they are to be used in technical applications. The various fibre surface treatments actually improve the interfacial adhesion between the fibre surface and the matrix, thereby giving good mechanical properties to the resulted polymer composites.

- To achieve a strong fibre-matrix interfacial adhesion there is an absolute need for the fibres to be treated either by using physical or chemical methods. The uses of physical and chemical methods optimize the interface between the fibre and the matrix. These modification methods are of different efficiencies for the adhesion between matrix and fibre.
- Textile fibers either natural or man-made (biodegradable and/or non biodegradable) are being increasingly used in non-traditional sectors such as technical textiles (automotive applications), medical textiles (e.g., implants, hygiene materials), geotextile (reinforcement of embankments), agrotextiles (textiles for crop protection), and protective clothin (e.g., heat and radiation protection for fire fighter, bulletproof vests, and spacesuits).Textile structures (roving, knitted, woven or non woven) are also being increasingly used in textile reinforced composites.
- Surface treatments of textile fibers, yarns or fabrics play an important role in their processing and end-use. The AFM-Atomic Force Microscopy seems a very valuable tool for investigating the effect of different fiber surface treatments and their impact on the final textile material properties. The AFM probe has been used to understand the frictional behaviour of sized glass fibers, and to study the impact of an air-atmospheric plasma treatment on polyethylene terephthalate fabrics

Physical Methods

Physical methods such as stretching, calendaring, thermo treatment and the production of hybrid yarns do not change the chemical composition of the fibres but however they change the structural and surface properties of the fibre and thereby influence the mechanical bonding to polymers.

- Other ways of treating fibre surface using physical method could be electric discharge such as (corona, cold plasma). Corona treatment is one of the most interesting techniques for surface oxidation activation. It is a process that changes the surface energy of the cellulose fibres and in case of wood surface activation increases the amount of aldehyde groups. Depending on the type and nature of the gases used, a variety of surface modification could be achieved by using cold plasma treatment which will in turn introduce surface crosslinking while surface energy could be increase or decrease and reactive free radicals and groups could be produced.
- Electric discharge methods are known to be very effective for “non-active” polymer substrates as polystyrene, polyethylene, polypropylene, etc. They are successfully used for cellulose-fibre modification, to decrease the melt viscosity of cellulose-polyethylene composites and improve mechanical properties of cellulose-polypropylene composites.
- There is also a physical method called mercerization, this is actually an old method used in modifying cellulose fibre, it has been widely used on cotton materials. Mercerization is an alkali treatment of cellulose fibres which

1.10 PROPERTIES OF DIFFERENT POLYMER :-

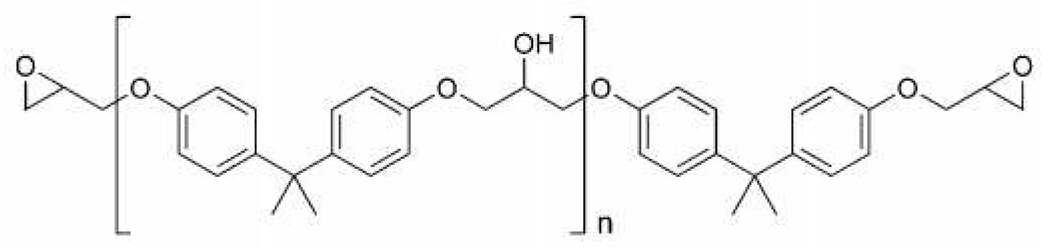
1.10.1 EPOXY POLYMER:-

Found by C. Castan in 1930s on his search for dental use and successfully introduced by Ciba (Central Institute of Brackishwater Aquaculture) by end 1940s in the electro industry as insulating material, as coating and laminating material, as well as adhesive.

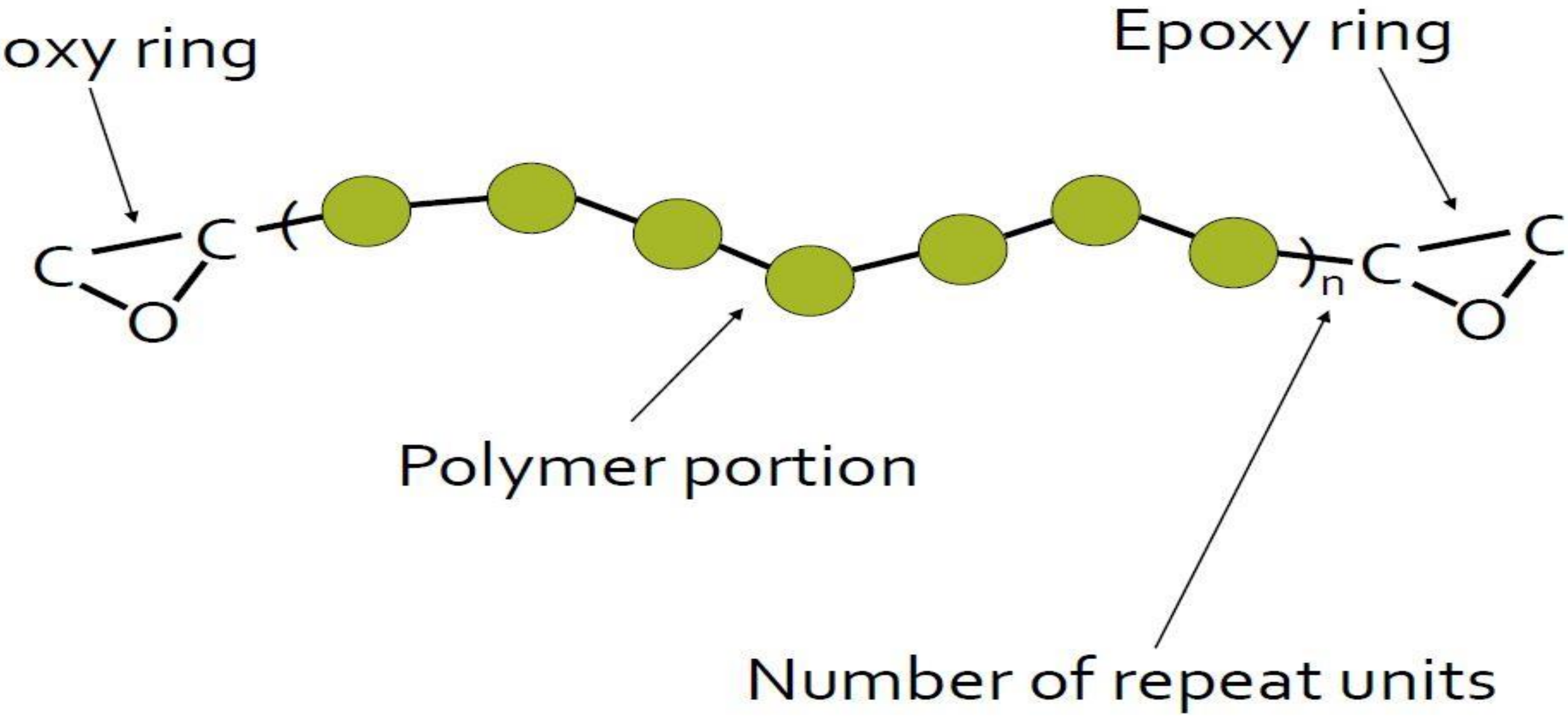
- Also called "epoxy" or "polyepoxide".
- Second most widely used family of thermosets copolymer(after polyesters)
- Large portion of uses are non-reinforced (adhesives, paints, etc.)
- Circuit boards are the largest reinforced application (low conductivity, low volatiles)

GENERAL PROPERTIES:-

- High Mechanical Properties: large cohesive force
- Good Adhesive Performance: great number of polar group
- Excellent stability: without impurities(base and salt)
- Flexibility and diversity in Designing



Epoxy Structure



Epoxy ring

Epoxy ring

Polymer portion

Number of repeat units

Fig. 1. 37 Epoxy polymer

- **PROPERTIES OF EPOXY RASINS**:-

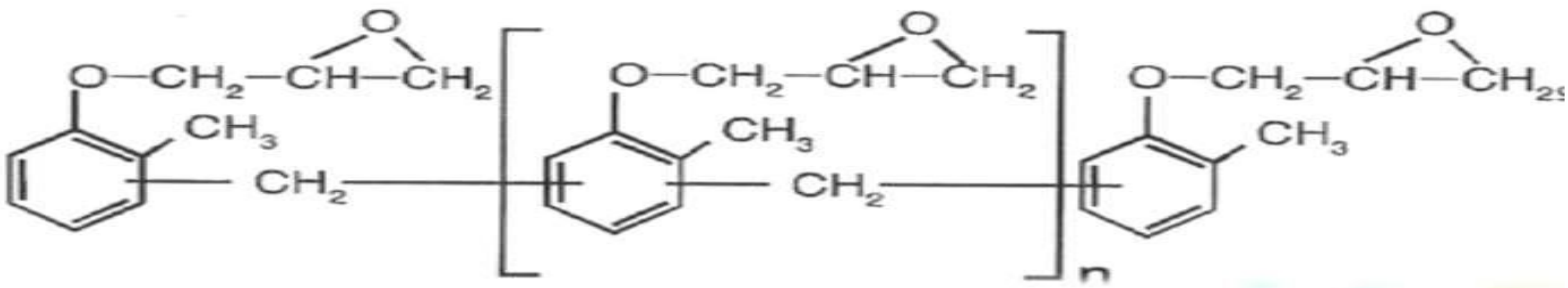
  1. Chemical stability – due to ether linkage.
  2. High reactivity – epoxy/ hyroxyl group.
  3. Excellent adhesion to surface.
  4. Outstanding electrical properties – industrial application.
  5. Ability to form co-polymer with various polymer.

IMPROVED EPOXY RESINS :-

1.10.1 Epoxy Cresol Novolac (ECN)

In the mid sixties, new multi functional epoxy resins of phenol novolac were introduced in the market.

The chemistry of these resins is very similar to that of Bisphenol-A type resins. The main purpose of using these resins was to improve the cross linking density of the formulation



1.10.2 NOVOLAC EPOXY RESIN :-

- Reaction of phenols with formaldehyde and subsequent glycidylation with epichlorohydrin produces epoxidised novolacs, such as epoxy phenol novolacs (EPN) and epoxy cresol novolacs (ECN).
- These are highly viscous to solid resins with typical mean epoxide functionality of around 2 to 6.
- The high epoxide functionality of these resins forms a highly crosslinked polymer network displaying high temperature and chemical resistance, but low flexibility.
- 100% solids hybrid novolac epoxy resin systems have been developed that contain no solvents and no volatile or organic compounds. These hybrid novolac epoxies have been documented to withstand up to 98% sulfuric acid.

1.10.3 BISPHENOL A EPOXY RESIN :-

- The most common and important class of epoxy resins is formed from reacting epichlorohydrin with bisphenol A to form diglycidyl ethers of bisphenol A.
- Reacting two moles of epichlorohydrin with one mole of bisphenol A to form the bisphenol A diglycidyl ether (commonly abbreviated to DGEBA or BADGE).
- DGEBA resins are transparent colourless-to-pale-yellow liquids at room temperature, with viscosity typically in the range of 5-15 Pa.s at 25 °C.
- Since pure DGEBA shows a strong tendency to form a crystalline solid upon storage at ambient temperature. which are semi-solid to hard crystalline materials at room temperature depending on the molecular weight achieved.
- As the molecular weight of the resin increases, the epoxide content reduces and the material behaves more and more like a thermoplastic. Very high molecular weight polycondensates (ca. 30 000 – 70 000 g/mol) form a class known as phenoxy resins.

1.10,4 ALIPHATIC EPOXY RESIN :-

- There are two types of aliphatic epoxy resins: glycidyl epoxy resins and cycloaliphatic epoxides.
- Glycidyl epoxy resins are typically formed by the reaction of epichlorohydrin with aliphatic alcohols or polyols to give glycidyl ethers or aliphatic carboxylic acids to give glycidyl esters.
- This reaction is normally done in the presence of an alkali, such as sodium hydroxide, to facilitate the dehydrochlorination of the intermediate chlorohydrin. The resulting resins may be monofunctional (e.g. dodecanol glycidyl ether), difunctional (diglycidyl ester of hexahydrophthalic acid), or higher functionality (e.g. trimethylolpropane triglycidyl ether).

- These resins typically display low viscosity at room temperature (10-200 mPa.s) and are often used as reactive diluents. As such, they are employed to modify (reduce) the viscosity of other epoxy resins.
- This has led to the term ‘modified epoxy resin’ to denote those containing viscosity-lowering reactive diluents. However, they are also used without other epoxide ingredients along with anhydride curing agents such as hexahydrophthalic anhydride to make molded objects such as high voltage insulators. This is in fact the main use of the diglycidyl esters.

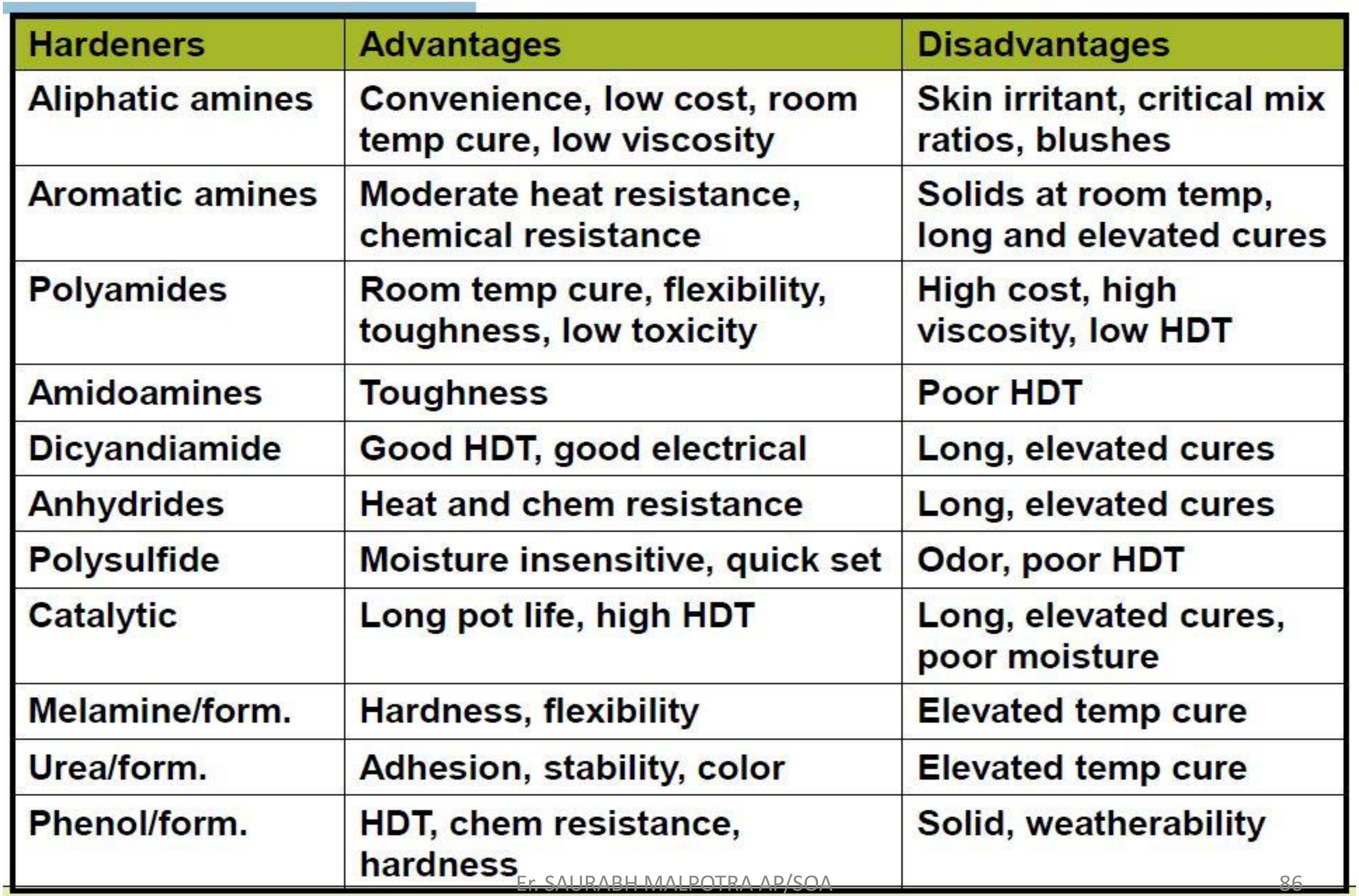
1.10.5 THE CYCLOALIPHATIC EPOXIDES :-

- Contain one or more cycloaliphatic rings in the molecule to which the oxirane ring is fused (e.g. 3, epoxycyclohexylmethyl-3,4- epoxycyclohexane carboxylate). They are formed by the reaction of cyclo-olefins with a peracid, such as peracetic acid.
- This class also displays low viscosity at room temperature, but offers significantly higher temperature resistance and correspondingly better electrical properties at high temperatures to cured resins than the glycidyl aliphatic epoxy resins.

1.10.6 GLYCIDYLAMINE EPOXY RESIN :-

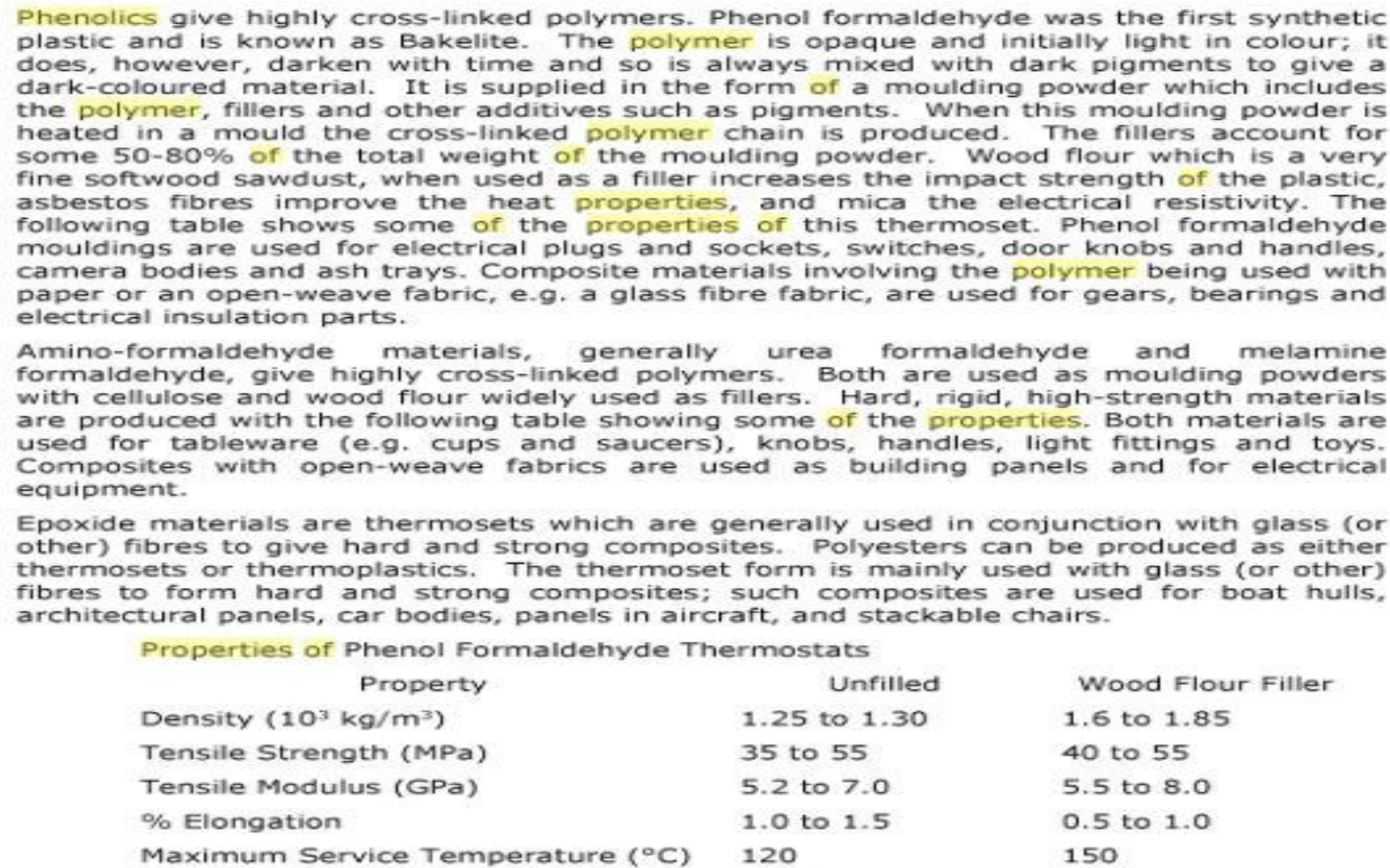
- Glycidylamine epoxy resins are higher functionality epoxies which are formed when aromatic amines are reacted with epichlorohydrin.
- Important industrial grades are triglycidyl-p-aminopheno (functionality 3) and N,N,N,N-tetraglycidyl-4,4-methylenebis benzylamine (functionality 4).
- The resins are low to medium viscosity at room temperature, which makes them easier to process than EPN or ECN resins.
- This coupled with high reactivity, plus high temperature resistance and mechanical properties of the resulting cured network make them important materials for aerospace composite applications.

1.10.7 EFFECTS OF VARIOUS HARDENERS :-



Hardeners	Advantages	Disadvantages
Aliphatic amines	Convenience, low cost, room temp cure, low viscosity	Skin irritant, critical mix ratios, blushes
Aromatic amines	Moderate heat resistance, chemical resistance	Solids at room temp, long and elevated cures
Polyamides	Room temp cure, flexibility, toughness, low toxicity	High cost, high viscosity, low HDT
Amidoamines	Toughness	Poor HDT
Dicyandiamide	Good HDT, good electrical	Long, elevated cures
Anhydrides	Heat and chem resistance	Long, elevated cures
Polysulfide	Moisture insensitive, quick set	Odor, poor HDT
Catalytic	Long pot life, high HDT	Long, elevated cures, poor moisture
Melamine/form.	Hardness, flexibility	Elevated temp cure
Urea/form.	Adhesion, stability, color	Elevated temp cure
Phenol/form.	HDT, chem resistance, hardness	Solid, weatherability

1.11 PROPERTIES OF PHENOLICS :-



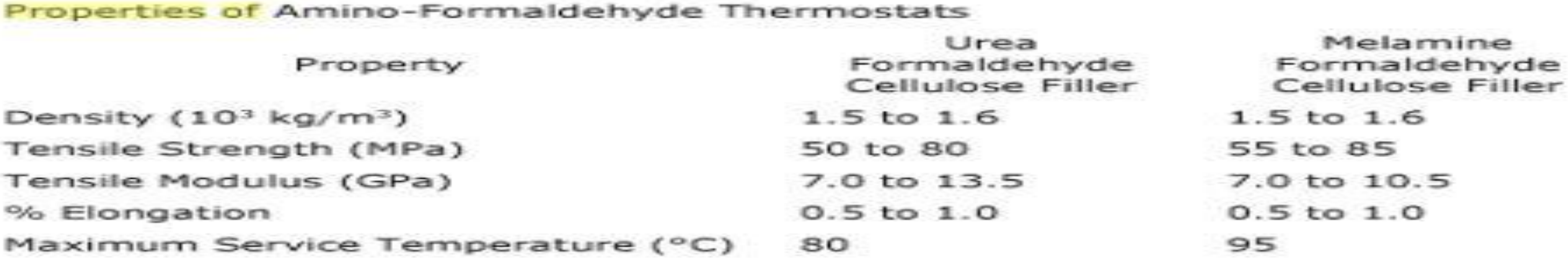
Phenolics give highly cross-linked polymers. Phenol formaldehyde was the first synthetic plastic and is known as Bakelite. The polymer is opaque and initially light in colour; it does, however, darken with time and so is always mixed with dark pigments to give a dark-coloured material. It is supplied in the form of a moulding powder which includes the polymer, fillers and other additives such as pigments. When this moulding powder is heated in a mould the cross-linked polymer chain is produced. The fillers account for some 50-80% of the total weight of the moulding powder. Wood flour which is a very fine softwood sawdust, when used as a filler increases the impact strength of the plastic, asbestos fibres improve the heat properties, and mica the electrical resistivity. The following table shows some of the properties of this thermoset. Phenol formaldehyde mouldings are used for electrical plugs and sockets, switches, door knobs and handles, camera bodies and ash trays. Composite materials involving the polymer being used with paper or an open-weave fabric, e.g. a glass fibre fabric, are used for gears, bearings and electrical insulation parts.

Amino-formaldehyde materials, generally urea formaldehyde and melamine formaldehyde, give highly cross-linked polymers. Both are used as moulding powders with cellulose and wood flour widely used as fillers. Hard, rigid, high-strength materials are produced with the following table showing some of the properties. Both materials are used for tableware (e.g. cups and saucers), knobs, handles, light fittings and toys. Composites with open-weave fabrics are used as building panels and for electrical equipment.

Epoxide materials are thermosets which are generally used in conjunction with glass (or other) fibres to give hard and strong composites. Polyesters can be produced as either thermosets or thermoplastics. The thermoset form is mainly used with glass (or other) fibres to form hard and strong composites; such composites are used for boat hulls, architectural panels, car bodies, panels in aircraft, and stackable chairs.

Properties of Phenol Formaldehyde Thermostats

Property	Unfilled	Wood Flour Filler
Density (10^3 kg/m^3)	1.25 to 1.30	1.6 to 1.85
Tensile Strength (MPa)	35 to 55	40 to 55
Tensile Modulus (GPa)	5.2 to 7.0	5.5 to 8.0
% Elongation	1.0 to 1.5	0.5 to 1.0
Maximum Service Temperature (°C)	120	150



Properties of Amino-Formaldehyde Thermostats

Property	Urea Formaldehyde Cellulose Filler	Melamine Formaldehyde Cellulose Filler
Density (10^3 kg/m^3)	1.5 to 1.6	1.5 to 1.6
Tensile Strength (MPa)	50 to 80	55 to 85
Tensile Modulus (GPa)	7.0 to 13.5	7.0 to 10.5
% Elongation	0.5 to 1.0	0.5 to 1.0
Maximum Service Temperature (°C)	80	95

Table 1.3 Properties of Amino-formaldehyde thermostats

The phenolic resins are one of the most popular and versatile high-volume resin systems. They are fine machinable, lightweight and have excellent corrosion, and temperature resistance up to 300-350 °C. Furthermore, they have outstanding dimensional stability, high resistance to creep at elevated temperatures, low humidity absorption, high dielectric strength, and an excellent price/performance characteristic.

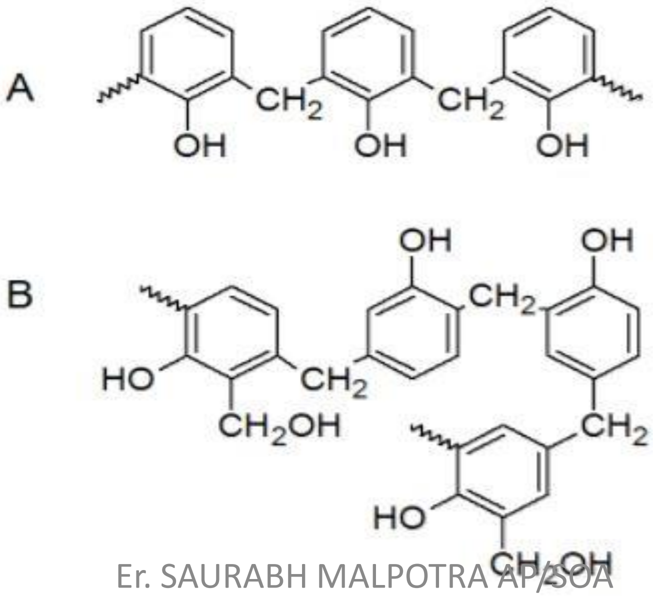


Fig. 1.38 Chemical formula for Phenol

1.11.1 TYPES OF PHENOLICS :-

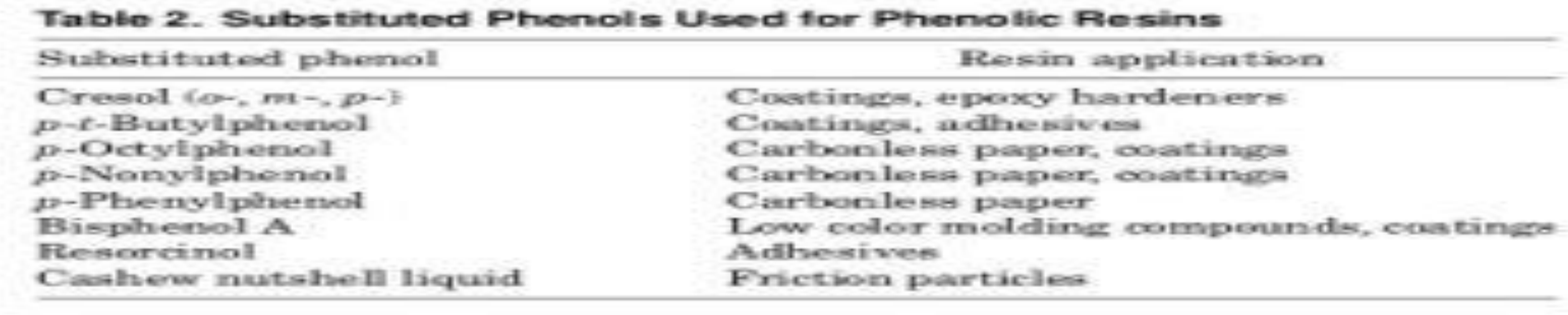


Table 2. Substituted Phenols Used for Phenolic Resins

Substituted phenol	Resin application
Cresol (*o*-, *m*-, *p*-)	Coatings, epoxy hardeners
p-*t*-Butylphenol	Coatings, adhesives
p-Octylphenol	Carbonless paper, coatings
p-Nonylphenol	Carbonless paper, coatings
p-Phenylphenol	Carbonless paper
Bisphenol A	Low color molding compounds, coatings
Resorcinol	Adhesives
Cashew nutshell liquid	Friction particles

Substituted Phenols. Phenol itself is used in the largest volume, but substituted phenols are used for specialty resins (Table 2). Substituted phenols are typically alkylated phenols made from phenol and a corresponding α-olefin with acid catalysts (14). Acidic catalysis is frequently in the form of an ion-exchange resin (IER) and the reaction proceeds preferentially in the para position. For example, in the production of *t*-butylphenol using isobutylene, the product is >95% para-substituted. The incorporation of alkyl phenols such as cresol into the resin reduces reactivity, hardness, cross-link density, and color formation, but increases solubility in nonpolar solvents, flexibility, and compatibility with natural oils.

Formaldehyde. In one form or another, formaldehyde is used almost exclusively in the production of phenolic resins, regardless of the type of phenol (Table 3). It is frequently produced near the site of the resin plant by either of two common processes using methanol (qv) as the raw material. In the silver catalyst process, the reaction takes place at 600–650°C and produces water and hydrogen as by-products. The more common metal oxide process operates at 300–400°C. The gaseous formaldehyde is absorbed in water, and the final product is a formalin solution containing 36–50% formaldehyde. Of the various chemical forms of formaldehyde, the aqueous form is preferred for making phenolic resins, even though at least half of this form is water. The water serves to moderate the reaction and is readily removed in processing equipment (15).

Aqueous Formaldehyde. Water solutions of formaldehyde consist mainly of telomers of methylene glycol having <100 ppm of the formaldehyde as CH_2O (5). Alcohols form hemiformals with aqueous formaldehyde according to the following, where n = 1, 2, 3, etc.

$$ROH + HOCH_2OH \rightleftharpoons ROCH_2OH + H_2O$$

$$RO(CH_2O)_nH + HOCH_2OH \rightleftharpoons RO(CH_2O)_{n+1}H + H_2O$$

1.12 PROPERTIES OF POLYESTER :-

- **Polyether ether ketone (PEEK)** is colourless organic thermoplastic polymer in the polyaryletherketone (PAEK) family, used in engineering applications. It was originally introduced by Victrex PLC, then Imperial Chemical Industries (ICI) in the early 1980s.
- PEEK polymers are obtained by step-growth polymerization by the dialkylation of bisphenolate salts. Typical is the reaction of 4,4'-difluorobenzophenone with the disodium salt of hydroquinone, which is generated in situ by deprotonation with sodium carbonate. The reaction is conducted around 300 °C in polar aprotic solvents - such as diphenyl sulphone.

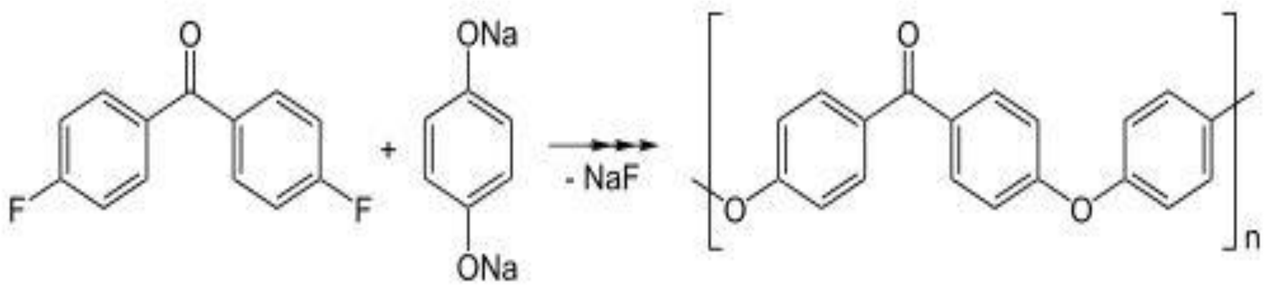


Fig. 1.39 Polyether ether ketone

- PEEK is a semi-crystalline thermoplastic with excellent mechanical and chemical resistance properties that are retained to high temperatures.
- The processing conditions used to mold PEEK can influence the crystallinity and hence the mechanical properties.
- The Young's modulus is 3.6 GPa and its tensile strength 90 to 100 MPa.
- PEEK has a glass transition temperature of around 143 °C (289 °F) and melts around 343 °C (662 °F). Some grades have a useful operating temperature of up to 250 °C (482 °F).
- The thermal conductivity increases nearly linearly with temperature between room temperature and solidus temperature. It is highly resistant to thermal degradation, as well as to attack by both organic and aqueous environments. It is attacked by halogens and strong Bronsted and Lewis acids, as well as some halogenated compounds and aliphatic hydrocarbons at high temperatures.
- It is soluble in concentrated sulfuric acid at room temperature, although dissolution can take a very long time unless the polymer is in a form with a high surface-area-to-volume ratio, such as a fine powder or thin film. It has high resistance to biodegradation.

How to make Polyester :-

- PEEK melts at a relatively high temperature (343 °C / 649.4 °F) compared to most other thermoplastics. In the range of its melting temperature it can be processed using injection moulding or extrusion methods.
- It is technically feasible to process granular PEEK into filament form and 3D printing parts from the filament material using fused deposition modeling – FDM (or fused filament fabrication – FFF) technology. PEEK filaments have been demonstrated for producing medical devices up to class Iia.With this new filament, it is possible to use the FFF method for different medical applications like dentures.

1.12 PROPERTIES OF DIFFERENT FIBRE :-

GENERAL PROPERTIES OF TEXTILE FIBRES:-

1. Staple Fibres :-

- Natural or man made or short length fibres which measures in inches or fraction of inch example 3/4 inch to 18 inches except silk all other natural fibres are staple fibres. Staple fibres are of limited length.

2. Filament :-

- Long continuous fibres strands of indefinite length measured in yards or meters fibres of continuous length long enough to be used in fabric as such Natural silk filament is 360-1200 meters. Synthetic filaments can be made many kilometers long. The only natural fibre available is silk.

3. Texture (Apparence)

- It is the tactile sensation experienced when hand is passed over a surface. Staple fibres and fabrics made from staple are lightly rough while filaments and fabrics made from filaments fibres are smooth..

4. Resilience

- It means that when fibre is compressed and later when the pressure is released. It will tend to return to its original shape. Resistance to compression varies from fibre to fibre. This quality causes the fabric to be wrinkle resistant with the resistance varying according to the degree of elasticity inherent in the fibre. Wool has outstanding resiliency while it is poor in cotton.

5. Luster

- It is seen when light reflected from a surface. It is more subdued than shine. Silk and synthetics have luster than cellulosic fibres. Infact synthetics have high luster which is purposefully removed during spinning.

6. Static Electricity

- It is generated by the friction of a fabric when it is rubbed against itself or other objects. If the electrical charge that is not conducted away, It tends to build up on the surface and when fabric comes in contact with a good conductor a shock or transfer occurs. This transfer may sometimes produce sparks. This is more feel during hot and humid conditions.

7. <u>Crimp</u>

- Wool fibre is more or less wavy and has twists. This waviness is termed as crimp. Finer the wool more will be the crimps in it. Marino wool will have 30 crimps per inch while coarse wool has only one or two. This property of having crimps gives elasticity to the fibre.

8. <u>Elasticity</u>

- It is the ability of stretched material to return immediately to its original.

1.13 PROPERTIES OF CELLULOSE FIBRE :-

Physical properties

- **a. Structure:** The cotton fibre is short (1/2 inch -2 long inch) and cylindrical or tubular as it grows. The cotton fibre is essentially cellulose consisting of carbon, hydrogen and oxygen. Bleached cotton is almost pure cellulose raw cotton contains about 5% of impurities.
- b**. Strength:** Cotton fibre is relatively strong which is due to the intricate structure and 70% crystalline.
- **c. Elasticity:** Cotton is relatively inelastic because of its crystalline polymer system and for this reason cotton textile wrinkle and crease readily.
- **d. Hygroscopic moisture:** Cotton does not hold moisture so well as wool or silk but absorbs it and so feels damp much more quickly. It also rapidly spreads throughout the material.
- **e. Electrical property:** The hygroscopic nature ordinarily prevent cotton textile materials from developing static electricity.
- **f. Absorbency:** As cotton has cellulose it is a good absorbent of fibre**.**

- **THERMAL PROPERTIES:-**
- Cotton fibres have the ability to conduct heat energy, minimizing any destructive heat accumulation thus they can withstand hot ironing temperature.
- **Drap ability:** Cotton does not have good body to drape well in shape. The type of construction of the fabric may improve this property.
- **Resilience:** Cotton wrinkles easily some wrinkle resistant finishes may reduce this property.
- **Cleanliness and wash ability:** Though cotton absorbs dust due to its rough nature. It can be washed easily in the hot water and strong soaps without damaging the fibre.
- **Lustre:** The natural cotton has no pronounced lustre. This can be improved by the mercerization finish of the cotton(that is sodium hydroxide treatment).
- **Shrinkage:** The fibre itself does not shrink but cotton fibre which has been stretched in the finishing process tends to relax back creating shrinkage.

1.14 PROPERTIES OF SILK :-

- **MICROSCOPIC PROPERTIES:-**

  STRENGTH: Silk is the strongest natural fibre. It has a tenacity of 2.4 to 5.1 grams per denier. More over smoothness of the silk filament yarn reduces the problem of wear from abrasion. The strength of the spun silk yarns depends on the length of silk staple.

- **SHAPE AND APPEARANCE:** Silk filaments are very fine and long. They frequently measure about 1000 to 1300 yards in length. The width of the silk is from 9 to 11 microns.

- **ELASTICITY**: It is an elastic fibre and its elasticity varies as it is natural fibre. Silk fibre may be stretched from 1/7 to 1/5 its original length before breaking. Cultivated degummed silk view longitudinally under a microscopic, resembles a smooth transparent rod under microscope. Silk in the gum has rough irregular surface. Wild silk tend to be quite uneven and is some what dark. It may have longitudinal striations.

- **RESILIENCE:** Silk retains the shape and resists wrinkling rather well. This is more in fabrics made from pure silk rather than spun silk or weighted silk.

- **DRAPABILTY:** Silk has a pliability and suppleness' that aided by its elasticity and resilience gives it excellent drapability.
- **HEAT CONDUCTIVITY:** Since silk is a protein fibre. It is a non conductor of heat like wool. Hence it is used for winter apparel.
- **ABSORBENCY:** The good absorbtive property of silk also contributes to its effect in warmer atmosphere. Silk generally absorbs about 11% of its weight in moisture which makes silk for easy dying and printing.
- **CLEANLINESS AND WASH ABILITY:** Silk is hygienic material because it smooth surface does not attract dirt. It can also be easily cleaned by mil soaps and dry cleaning.
- **SHRINKAGE:** Due to the filament in length, smooth surface silk have normal shrinkage which can be easily restored by ironing at moderate heat and damp conditions.
- **EFFECT OF LIGHT:** Continous exposure to light weakens silk faster than either cotton or wool.

1.15 PHYSICAL PROPERTIES OF WOOL :-

- **Strength:** It is stronger than silk. When wet wool looses about 25% of its strength. Longer the fibre the greeter will be the strength of yarn.
- **Resiliency:** Wool is highly resilient and comes to its original shape when hanged after wrinkled or created.
- **Stretchability:** Wool is highly elastic. It is about 10 to 30% stretched when dry and 40 to 50% when wet upon receiving pressure upon drying it readily regains its original dimensions.
- **Shrink ability:** Wool is resistant shrinkage. However long exposure to moisture may cause shrinkage.
- **Effect of friction:** Friction will soften the wool fibre especially when wet and thus is advantageous in maintaining smooth, soft texture of fabrics.
- **Crimps:** Wool fibre is more or less wavy and has twists. This waviness is termed as ‘crimp’. Finer the wool the more will be the crimps in it. Merino wool has 30 crimps per inch while coarse wool has one or two.
- **Effect of moisture:** Wool is the most hygroscopic in nature. It can absorb up to 50% of its weight and carry upto 20% weight, without giving the feeling of being wet. Upon drying it losses moisture slowly preventing rapid evaporation thus avoiding chilling feel to the user. It absorbs perspiration after violent exercise and guards the body against sudden change in temperature.

- **HEAT CONDUCTIVITY:** Wool fibre is a part is a poor conductor of heat and therefore the fabrics made from the fibre are considered most suitable as winter wear.
- **FELTING:** Wool fibres interlock and contract when exposed to heat, moisture, and pressure. The scale like exterior of the fibres contributes to felting. The fibres get softened in weak alkaline solutions due to expansion of scales at their free edges, with friction and pressure they again interlock to form a felt. This property is used in making felts for hats, shoes, floor-coverings and sound proofing purposes.
- **EFFECT OF HEAT:** Low heat has no effect but strong heat weakens the fibre and destroys the colour of the fibre.

1.16 PROPERTIES OF RAYON :-

- **PHYSICAL PROPERTIES:-**
- **Strength :** The tensile strength of viscose rayon is greater than that of wool but is only half as great as silk. Viscose rayon is also weaker than cotton and its strength is reduced to 40 to 70 percent when wet. Yet it produces fairly durable, economical and serviceable fabric whose smoothness of surface favorably withstands with friction of wear
- **Elasticity :** Viscose rayon has greater elasticity than cotton but less than wool and silk. While viscose rayon fabrics have some inherent extensibility, undue strain might cause them to sag or even burst.
- **Resilience :** Viscose rayon lacks the resilience. It should be remembered that the resistance of a fabric to creasing depends on the kind of yarn, weave and finishing process.
- **Drapability :** Viscose rayon possesses a marked quality of drapability because it is relatively heavy weight fabric.
- **Heat Conductivity :** Viscose rayon is a good conductor of heat and is therefore appropriate for summer clothing like cotton.

- **Absorbency :** Viscose rayon is one of the most absorbent of all textiles. It is more absorbent than cotton or linen, but less than wool and silk.
- **CHEMICAL PROPERTIES :-**
- **Resistance to Mildew :** Like cotton, Viscose rayon have tendency to mildew. Such fabrics should not be allowed to remain in damp conditions.
- **Reaction to Alkaline :** Concentrated solutions of alkalies disintegrate Viscose rayon. A mild soap with lukewarm water is recommended in washing rayons.
- **Reaction to Acids :** Being pure cellulose, the fabric is disintegrated by hot dilute and cold concentrated acids similar to that of cotton.
- **Affinity of Dyes :** Viscose rayon fabrics absorb dye evenly and can be dyed with a variety of dyes, like acid, chrome, and disperse.
- **Resistance to Perspiration :** It is fairly resistant to deterioration from perspiration.

1.17 PROPERTIES OF POLYESTER FABRICS :-

- **Properties of Polyester**
- · It resists wrinkling.
- · It is easy to launder (wash or iron)
- · It dries quickly
- · It's resistant to stretching.
- ***PHYSICAL PROPERTIES*** **:-**
- **Shape and Appearance :** These fibers are generally round and uniform. The fiber is partially transparent and white to slightly off -white in colour.
- **Strength :** The PET polyesters are in general, stronger. Polyester is found in industrial uses and the highly durable fabrics.
- **Elasticity :** Polyester fibers do not have high degree of elasticity. In general polyester fiber is characterized as having a high degree of stretch resistance, which means that polyester fabrics are not likely to stretch out of shape too easily.
- **Resilience :** Polyester fibers have high degree of resilience. Not only does a polyester fabric resist wrinkling when dry, it also resists wrinkling when wet.

- **Heat Conductivity :** Fabrics of polyester filament are good conductors of heat. Polyester staple does not provide greater insulation in the yarns and fabrics. One of the reason for apparel greater warmth of polyester is its low absorbency.
- **Absorbency :** Polyester is one of the least absorbent fibers. This low absorbency has important advantages- they will dry very fast, suited for water repellent purposes, such as rain wear and they do not stain easily.

1.18 PROPERTIES OF FIBERS :-

KEVLAR:-

- Kevlar is a registered trademark for a synthetic fiber produced by DuPont, a chemical company. Kevlar was developed in 1965 and being used commercially since 1970. DuPont can also be credited for the development of other polymers such as Neoprene, Nylon, Teflon, Nomex etc..
- Chemical name for kevlar is poly-para-phenylene terephthalamide.
- Kevlar is a polymer
- Kevlar is a high strength material
- It is very light when compared to its strength
- It is 5 times stronger than steel of same weight
- It has very high tensile strength
- Thus it can be said as a *Super strong plastic*

1.18.1 STRUCTURE OF KELVAR:-

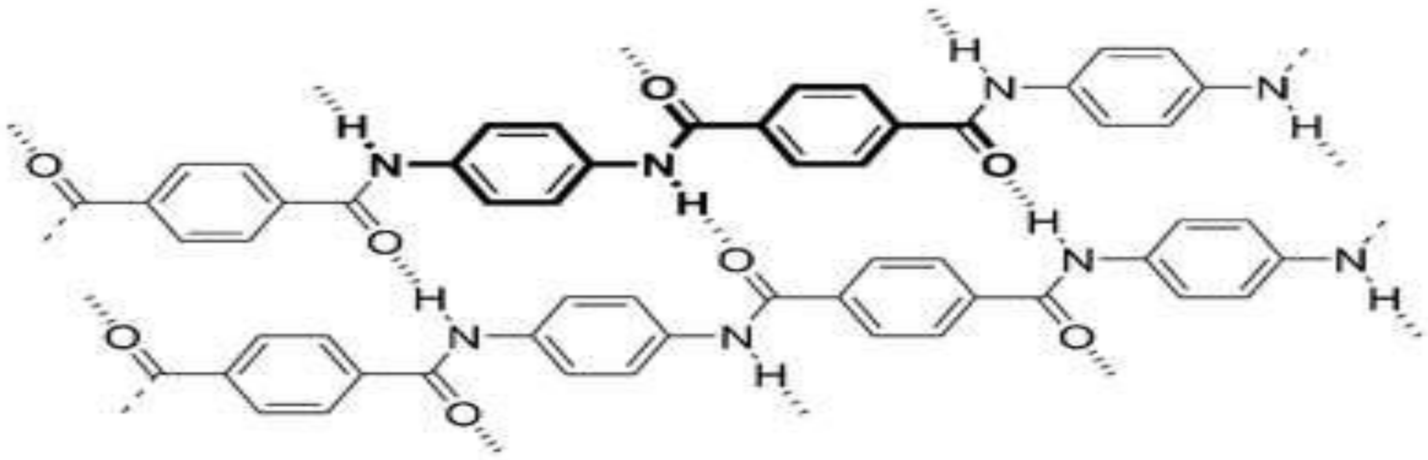


Fig. 1.40 Structure of kelvar

Kevlar is a polymer chain with cross linkages which owe to its high strength. The hydrogen bonds also strengthen the bonds.

Types of Kevlar

Although Kevlar is main product, there are various other grades of Kevlars produced

1. Kevlar
2. Kevlar K29
3. Kevlar K49

4. Kevlar K100

5. Kevlar K119

6. Kevlar K129

7. Kevlar AP

8. Kevlar XP

9. Kevlar KM2

PROPERTIES :-

1. Strength to weight ratio is more

2. Withstands temperatures upto 450ºC and as low as -196º C

3. Self extinguishable

4. Resistant to almost all types of chemicals

5. Negative co-efficient of thermal expansion

6. Abrasion resistance

ADVANTAGES :-

1. Higher strength to weight ratio
2. Impact resistance
3. Abrasion resistance
4. Doesn’t expand on heating

DISADVANTAGES :-

1. Absorb moisture
2. Poor compressive strength
3. Difficult to cut and drill

1.19 CARBON FIBRE :-

- Carbon Fiber's reputation as a material has taken on mystical proportions! Not only does it have a reputation for being the best and the strongest, but it's also become cool to have something made of carbon fiber.
- Carbon Fibre, not surprisingly, is made of carbon crystals aligned in a long axis**.** These honeycomb shaped crystals organize themselves in long flattened ribbons. This crystal alignment makes the ribbon strong in the long axis. In turn these ribbons align themselves within fibers. The fiber shape is the original shape of the material (its precursor) used to produce the Carbon Fiber. I don't know of any process where fibers are shaped after carbonizing. These fibers (containing flat ribbons of carbon crystals) in turn are bundled by the manufacturer in thicker fibres and are woven into carbon cloth, made into felt, twisted or bundled without twisting. This is referred to as Roving. Carbon fiber is also offered as chopped strands and powder.

1.19.1PROPERTIES OF CARBON FIBRE :-

1. High Strength to weight ratio
2. Rigidity
3. Corrosion resistance
4. Electrical Conductivity
5. Fatigue Resistance
6. Good tensile strength but Brittle
7. Fire Resistance/Not flammable
8. High Thermal Conductivity in some forms
9. Low coefficient of thermal expansion
10. Non poisonous
11. Biologically inert
12. X-Ray Permeable
13. Relatively Expensive
14. Requires specialized experience and equipment to use

1. **Carbon Fiber has High Strength to Weight Ratio (also known as specific strength):-**

- Strength of a material is the force per unit area at failure, divided by its density. Any material that is strong and light has a favourable Strength/Weight ratio. Materials such as Aluminium, titanium, magnesium, Carbon and glass fiber, high strength steel alloys all have good strength to weight ratios. It is not surprising that Balsa wood comes in with a high strength to weight ratio.

2. **Carbon Fiber is very Rigid :-**

- Rigidity or stiffness of a material is measured by its Young Modulus and measures how much a material deflects under stress. Carbon fiber reinforced plastic is over 4 times stiffer than Glass reinforced plastic, almost 20 times more than pine, 2.5 times greater than aluminium.

3. **Carbon fiber is Corrosion Resistant and Chemically Stable:-**

- Although carbon fibers themselves do not deteriorate measurably, Epoxy is sensitive to sunlight and needs to be protected. Other matrices (whatever the carbon fiber is embedded in) might also be reactive. Carbon fibres can be affected by strong oxydizing agents

4. **Carbon fiber is Electrically Conductive:-**

- This feature can either be useful or be a nuisance. In Boat building conductivity has to be taken into account just as Aluminium conductivity comes into play. Carbon fiber conductivity can facilitate Galvanic Corrosion in fittings. Careful installation can reduce this problem.

6. Carbon Fiber has good Tensile Strength:-

- Tensile strength or ultimate strength, is the maximum stress that a material can withstand while being stretched or pulled before necking, or failing. Necking is when the sample cross-section starts to significantly contract. If you take a strip of plastic bag, it will stretch and at one point will start getting narrow. This is necking. Tensile Strength is measured in Force per Unit area. Brittle materials such as carbon fiber does not always fail at the same stress level because of internal flaws.

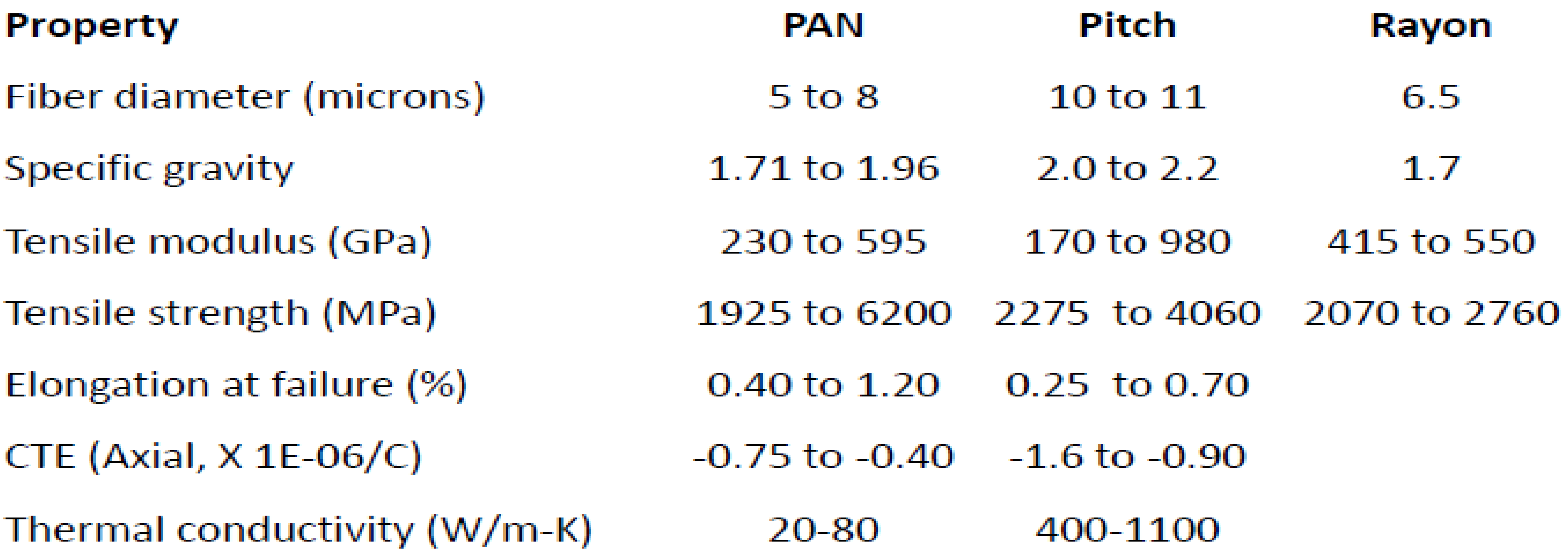
7-. Fire Resistance/Non Flammable:-

- Carbon fibre is classified as non conbustible and has no listed flash point. If it is exposed to high heat in the presence of fuel burning, it can eventually oxidize but as soon as the flame and fuel is removed the flame does not continue. Because carbon fibre is almost always used in a matrix such as epoxy, plastic or concrete, the tolerance of the matrix to high temperature is the more significant factor.

1.20 GRAPHITE FIBRE :-

- Graphite and carbon fibers are extensively used in high-strength, high modulus applications.
- Graphite fibers have carbon content in excess of 99%.
- Carbon fibers have carbon content in the range 80-95%
- Fiber’s carbon content depends on processing method for these fibers.
- Significantly more expensive than glass fibers.
- Key application areas include aerospace, sporting, railway, infrastructure, automotive, oil drilling, as well as consumer sector industries.
- Graphite structure consists of hexagonally packed carbon atoms in layers, and several such layers are interconnected through weak van der Waals forces. Thus, such a structure generates:
- High inplane modulus
- Significantly less modulus in out-plane direction

1.20.1 PROPERTIES OF GRAPHITE FIBRE :-



Property	PAN	Pitch	Rayon
Fiber diameter (microns)	5 to 8	10 to 11	6.5
Specific gravity	1.71 to 1.96	2.0 to 2.2	1.7
Tensile modulus (GPa)	230 to 595	170 to 980	415 to 550
Tensile strength (MPa)	1925 to 6200	2275 to 4060	2070 to 2760
Elongation at failure (%)	0.40 to 1.20	0.25 to 0.70	
CTE (Axial, X 1E-06/C)	-0.75 to -0.40	-1.6 to -0.90	
Thermal conductivity (W/m-K)	20-80	400-1100	

Fig. 1. 41 Properties of graphite fibre

UNIT- II

Manufacture of Composites: Hand layup technique, pressure bag and vacuum bag moulding techniques, puftrusion, resin-transfer moulding, injection moulding, Bulk moulding compound, sheet moulding compound. Application of composites in Aircraft Industry.

Module II - Manufacturing Techniques

Manufacturing of Composites

There are a lot of techniques to cast a composite structure whether it is straightforward or mind boggling, single or numerous. Every method has its own particular benefits and confinements. The combination of fibers and matrix material is depending upon the final use and required applications in the various field. Other important parameter include temperature, pressure, curing of matrix and end use of product to form cost effectiveness method.

The control of these various parameter is challenge to form adequate manufacturing techniques for composites. For adequate chemical reaction high temperature and pressure is required for highly viscose resins to get adhere and flow inside the fibers so, that good bonding between fiber and matrix material to be formed. 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

$$\alpha c = H/HR \qquad (1.1)$$

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

HR – reaction heat

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.

The typical gel time graph is shown in Fig.1.1.

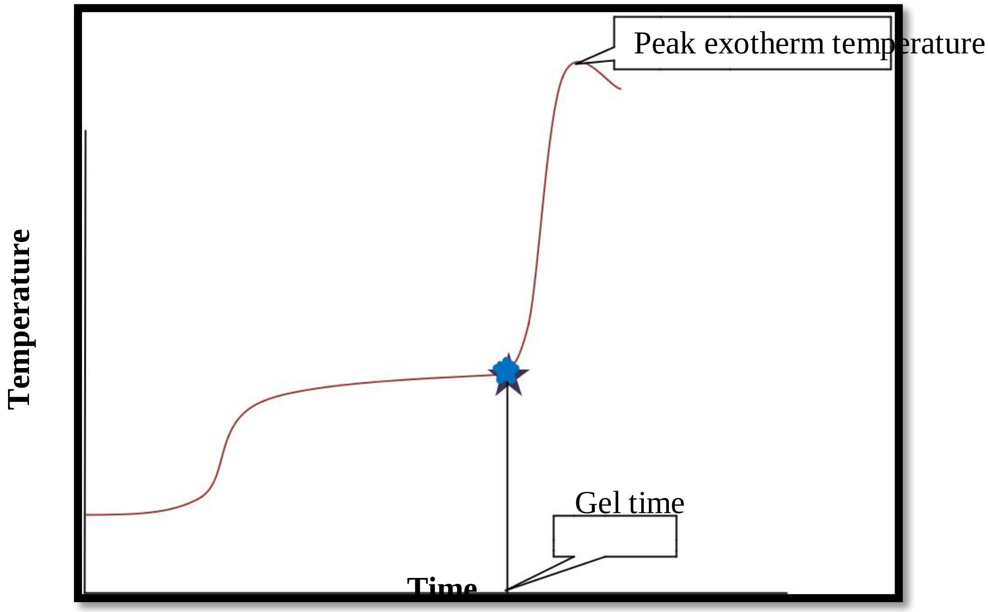


Figure 1.1 Temperature-time curve in Gel time test

Composite Manufacturing:

Composite: Two or more chemically different constituents combined macroscopically to yield a useful material.

Examples of naturally occurring composites permeated with holes filled with liquids

1. Wood: Cellulose fibers bound by lignin matrix
2. Bone: Stiff mineral "fibers" in a soft organic matrix permeated with holes filled with liquids
3. Granite: Granular composite of quartz, feldspar and mica.

A composite material is made by combining two or more materials– often ones that have very different properties.

The two materials work together to give the composite unique properties. However, within the composite you can easily tell the different materials apart as they do not dissolve or blend into each other.

Composite materials are materials made from two or more constituent materials with significantly different properties, that when combined, produce a material with characteristics different from the individual components.

Composite materials consist of two or more chemically distinct constituent on a macro scale having a dispersed interface separating them and having bulk performance which is considerably different from those of any of its individual constituents.

Composites are the mixture of two or more 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.

Examples: -   Cement, Concrete, Fiber-reinforced polymer, etc.

Some examples of man-made composites

Concrete: Particulate composite of aggregates (limestone or granite), sand, cement and water

Plywood: Several layers of wood veneer glued together

Fiberglass: Plastic matrix reinforced by glass fibers

Cemets: Ceramic and metal composites

Fibrous composites: Variety of fibers (Glass, Kevlar, Graphite, Nylon, etc.) bound together by a polymeric matrix.

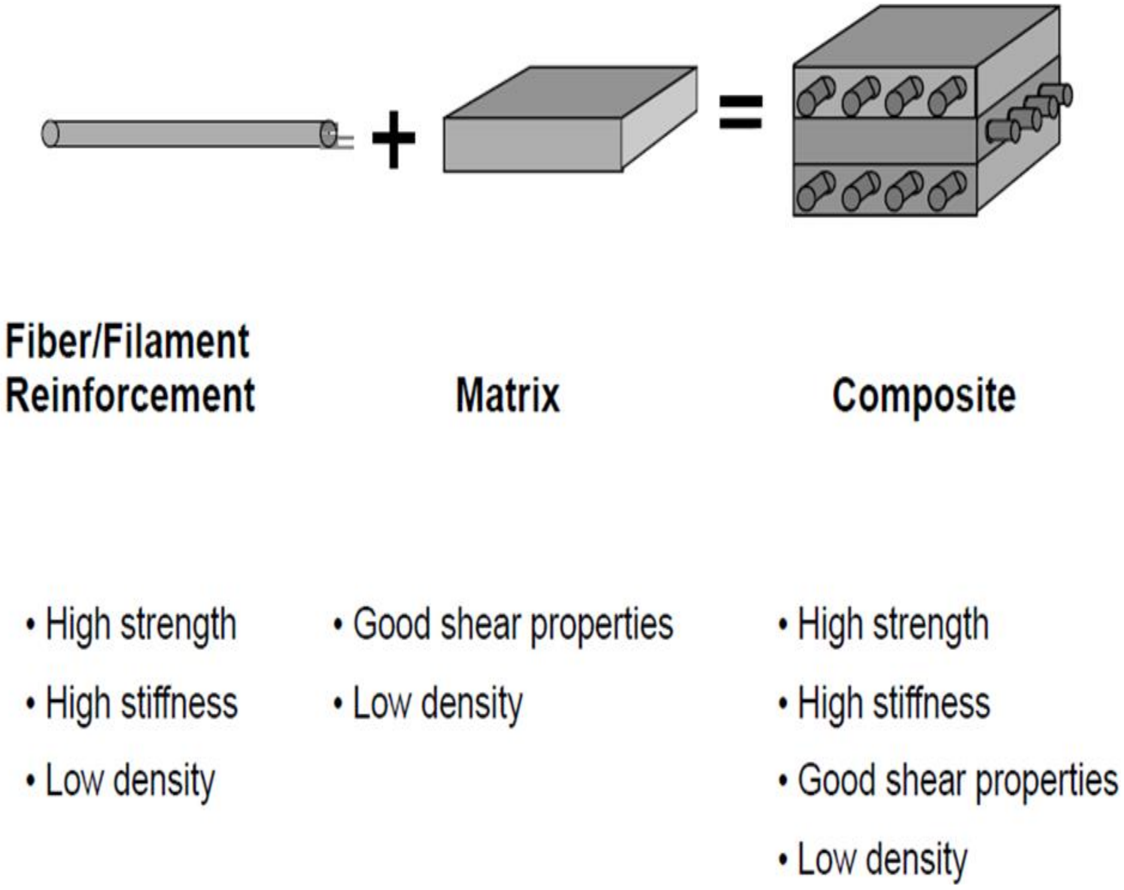


Fig. 1.2 Formation of composites

The different stages of existence of composite constituents up to the final product: -

Stage A: At this stage, the materials appear in raw basic form. For fibers, these consist of fiber either in the form of filaments or fiber bundles. Fibers may also be woven into fabrics or braided into braided perform. For matrix, the material usually appears in liquid form for thermoset resin or in granular form in the case of thermoplastics.

Stage B: At this stage, the fibers and matrix may be combined into a single layer. For the case of thermoset matrix composite, the matrix may appear in a semi-liquid, semi-solid form so that the sheet can hold its shape. For the case of thermoplastic composite, the matrix is solidified. This form for thermoset matrix composites is called prepreg. For thermoplastic composites, it is called towpreg.

Stage C**:** At this stage, the layers in stage b are stacked on top of each other to make flat plate laminates. This intermediate step is important for the analysis where material properties are tested or calculated. However, this step is usually bypassed in the manufacturing process of practical composite parts.

Stage D**:** This is the final stage where the final product configuration is formed.

Types of Composite manufacturing techniques: -

- Lay-up
    - Hand lay-up
    - Spray lay-up
    - Prepreg Lay-Up
    - Automatic tape layup
- Prepregs
- Compression molding
    - Resin injection molding
    - Injection molding
- Bag molding
    - Pressure bag molding
    - Vacuum bag molding
- Resin transfer molding (RTM)
    - Flexible RTM (FRTM)

- Continuous RTM (CRTM)
- Vacuum assisted RTM (VARTM)
- High-speed RTM (HSRTM)

Mouldng components

- SMC (sheet molding compound)
- BMC (bulk molding compound)

(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 prepreg should be flexible and tack free.
2. The fiber to resin ratio should be high and should not vary from place to place.
3. During moulding, the resin should be softening and flow filling the mold cavity should be without voids and defects.
4. Volatile contents and solvents should be minimum.

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.

(ii) Hand layup method:

It is the oldest molding method for making composite products. Manual lay-up involves cutting the reinforcement material to size using a variety of hand and power-operated devices.

These cut pieces are then impregnated with wet matrix material, and laid over a mold surface that has been coated with a release agent and then typically a resin gel-coat.

The impregnated reinforcement material is then hand-rolled to ensure uniform distribution and to remove trapped air. More reinforcement material is added until the required part thickness has been built-up. Manual lay-up can also be performed using pre impregnated reinforcement material, called 'prepreg'.

The use of prepreg material eliminates separate handling of the reinforcement and resin, and can improve part quality by providing more consistent control of reinforcement and resin contents.

Prepreg must be kept refrigerated prior to use, however, to prevent premature curing. The productivity of the manual lay-up can be automated using CNC machines. These machines are used for both prepreg tape-laying and prepreg fiber-placement primarily in the aerospace industry.

There is virtually no limit to the size of the work that can be tape-rolled, but the shape has to be relatively flat to butt each successive row without gaps, overlaps or wrinkles.

Automatic, multi axis fiber placement machines overcome this limitation by dispensing numerous, narrow individual tapes of material which are collimated as they are laid on the mold surface.

Resins are impregnated by hand into fibers in the form of weaves and fabrics. Rollers or brushes are typically used. The composite is left to cure under standard atmospheric conditions.

The major disadvantage is the lack of consistency;

1. Resins need to be low in viscosity to be workable by hand.
2. This generally compromises the mechanical and thermal properties of the composite and creates a health risk for the laminator.

The quality of the product is highly dependent on the skill of the laminator.

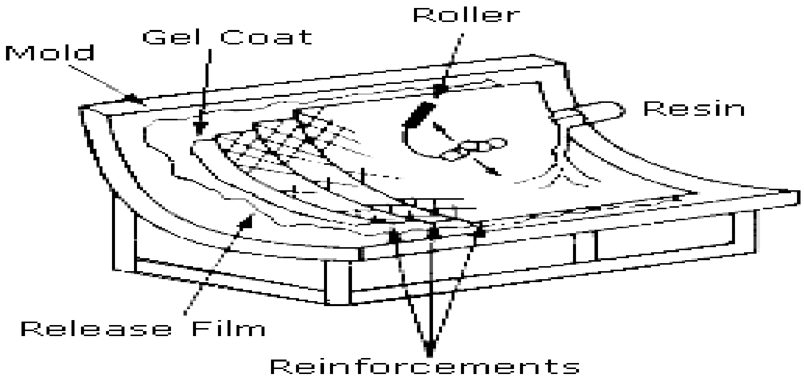


Figure 1.3 Hand layup method

The hand-layup method 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.1.3.

Mould:

The mould will have the replica shape of the product. The surface of mould sould be having fine surface finishing to get glossyor texture finishing at the end of the process. 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 material and surface is two important parameters while selection of mould for hand-layup technique.

Release Film or Layer:

The function of releasing film is to non-sticking of mould to the final product so, that final part is easy to dismantle from the mould surface. Lubricants are use as a Releasing film also, like Grease, Vaseline, hair spray etc.

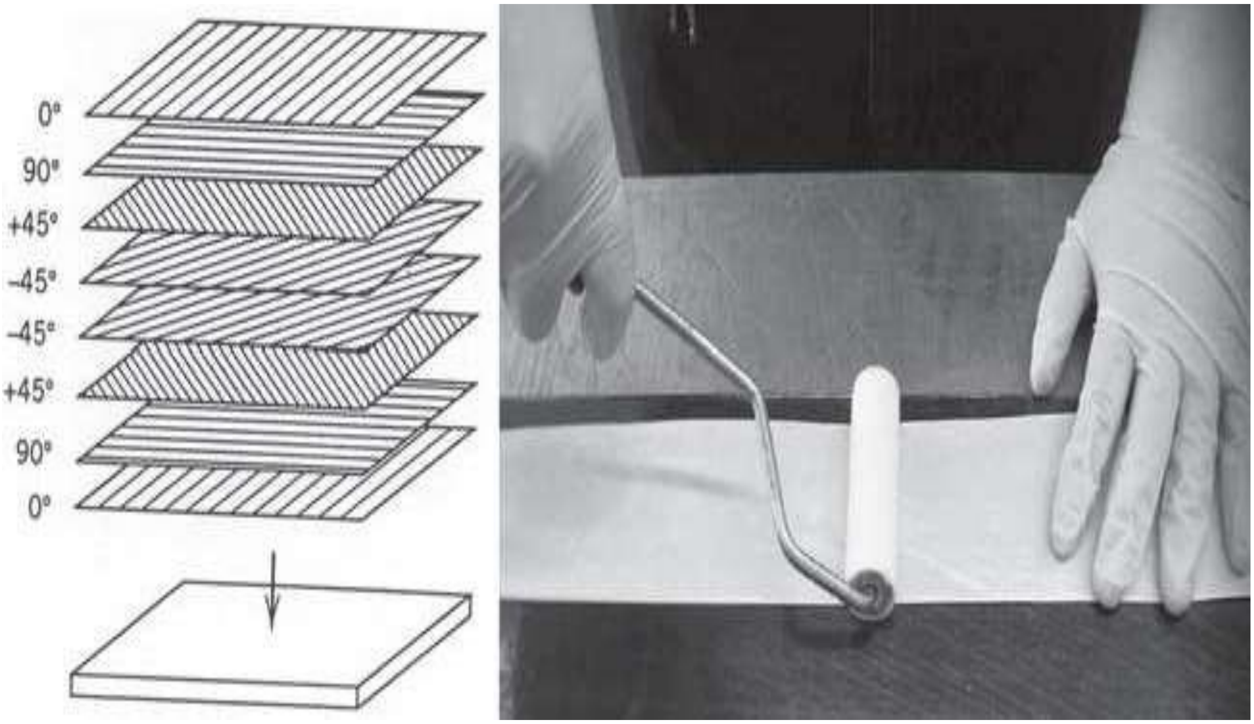


Fig 1.4 Hand-lay-up fabrication method and a representative lay-up sequence. Individual layers can be cut by hand or by a computerized machine cutter. The layers can be stacked one on top of the other by hand or by a robot. (source)

Gel coat:

The gel coat gives the required finish of the product. It is usually a thin layer of resin about 015" to .020" mm thickness applied on the outer surface of the product. The gel coat forms a protective layer that protects the glass fiber getting in contact with water and chemicals.

If gelcoat is to be sprayed on with a gelcoat gun, spray up to a thickness of .015" to .020". When gelcoat has cured long enough that your fingernail cannot easily scrape it free (test at edge of mold where damage will not show on part) then proceed with next step.

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:

Other required thickness of glass fibre layer wetted with resin is laid on the surface mat layer and this finished material is called the laminate. The laminate gives the hardness, rigidity and strength to the product. Glass fiber in the chopped strand mat (CSM) is commonly used to get 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: -

1. 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.
2. No costly
3. Versatile: wide range of products

LIMITATIONS: -

1. Time consuming

2. Easy to form air bubbles
3. Disorientation of fibers
4. Inconsistency

APPLICATION: -

1. Making of custom parts in low to medium volume quantities.
2. Bathtubs,
3. Swimming pools,
4. Boat hulls,
5. Storage tanks,

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, Fiber reinforcement plastics, aluminium and die steel are good materials for making moulds.

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.

MOULD PREPARATION AND APPLICATION OF RELEASE AGENTS

Before applying the releasing agent, the mould should be thoroughly cleaned and free from any dirt's. Then, the mould surface is coated with silicone free wax. 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.

LAYING FIBERGLASS REINFORCEMENT

For boat application, a 12 ft. boat, two layers of 1½ oz. or 2 oz. mat and one layer of roving may be adequate, depending upon design. For a 14 ft. boat, an additional layer of mat and roving will add additional strength. Apply each layer as in step 3, but it will not be necessary to wait for curing between these layers. Be sure to shake all acetone out of brushes and rollers before applying resin. Acetone drips can result in uncured spots in the lay-up.

TRIM

On a small lay-up, the fiberglass laminate which hangs over the edge of the mold can be trimmed off easily with a razor knife if you catch the "trim stage," of the period after the lay-up has gelled but before it has hardened. On a larger lay-up, it can be trimmed with a saw or diamond blade.

CURE

The cure may take from two hours to overnight, depending upon turnover desired, temperature, catalyzation, and nature of the part. If laid up in a female mold, longer cure will affect shrinkage and easier parting. In the case of the male mold, the part comes off more easily before it shrinks appreciably. If the part is subject to warping, a longer cure may be necessary. In any case, when the part is removed, it should be supported in its desired shape until fully cured.

REMOVE PART FROM MOLD

First, examine the trim edge all the way around the mold and make sure there is no resin bridging the line between the mold and the part. Sand this edge where necessary. Then wooden or plastic wedges can be pushed into the edges to start the separation. Continue separation by pulling and flexing. In some cases, it is necessary to drill a small hole in the mold and apply air or water pressure.

FINISH

Trim edges and back of part may need to be sanded and coated with surfacing resin or interior gelcoat.

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.

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.

(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:

Pultrusion is a continuous process used primarily to produce long, straight shapes of constant cross-section. Pultrusion is similar to extrusion except that the composite material is pulled, rather than pushed, through a die.

The pultrusion process (Fig. 1.5) 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.

Fibers are pulled from a creel through a resin bath and then on through a heated die. As the fiber passes through the die, the resin cures. This process is limited to components with constant, or near constant, cross-sections. Additionally, the cost of the heated die can be high.

Pultrusion yields smooth finished parts that typically do not require post processing. A wide range of continuous, consistent, solid and hollow profiles are pultruded, and the process can be custom-tailored to fit specific applications such as the constant cross-section spar in some windmill.

Pultrusions are produced using continuous reinforcing fibers called 'roving' that provide longitudinal reinforcement, and transverse reinforcement in the form of mat or cloth materials. These reinforcements are resin impregnated by drawing through a resin wet-out station; and generally shaped within a guiding, or preforming, system. They are then subsequently shaped and cured through a preheated die or set of dies. Once cured, the pultrusion is saw-cut to length. Pultrusions can be hollow or solid, and applications include bar and rod, pipe, tubing, ladder rails and rungs, and supports of many kinds.

Components 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.

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 necessary characteristics for a resin to be used to make pultruded products are that it has low viscosity and that gel time and cure time are short to allow for the high rate of production. If, for example, a rate of production of 20 cm/minute is desired, for the length of a die of 100 cm long, the duration of the resin inside the mold is 5minutes. The resin should flow through the interstices of the tows, wet the fibers, gel and cure during this time. When the resin gels, it also shrinks, which helps to release the composite from the die wall.

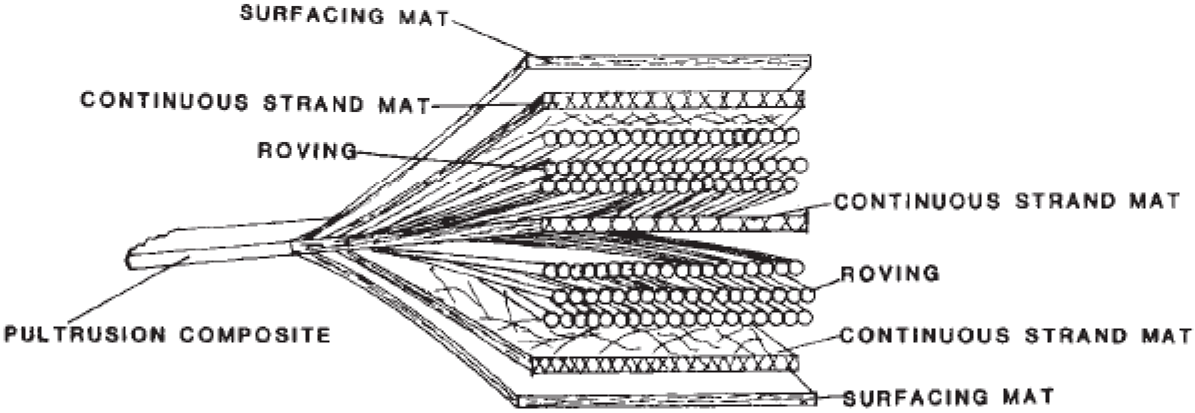


Fig. 1.5 Exploded view of materials in pultrusion (reproduced from *Handbook of Pultrusion Technology*, by R. W. Meyer, with permission from Springer)

d. Heated Dies:

The chrome plated matched metal die maybe heated by electrical cartridges or by strip heaters. Desired amount of temperature depending upon the fiber and resin material can be control by the controllers inside this heating die arrangement. 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. Puller:

A pair of continuous caterpillar belts containing pads are used for pultrusion. 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.

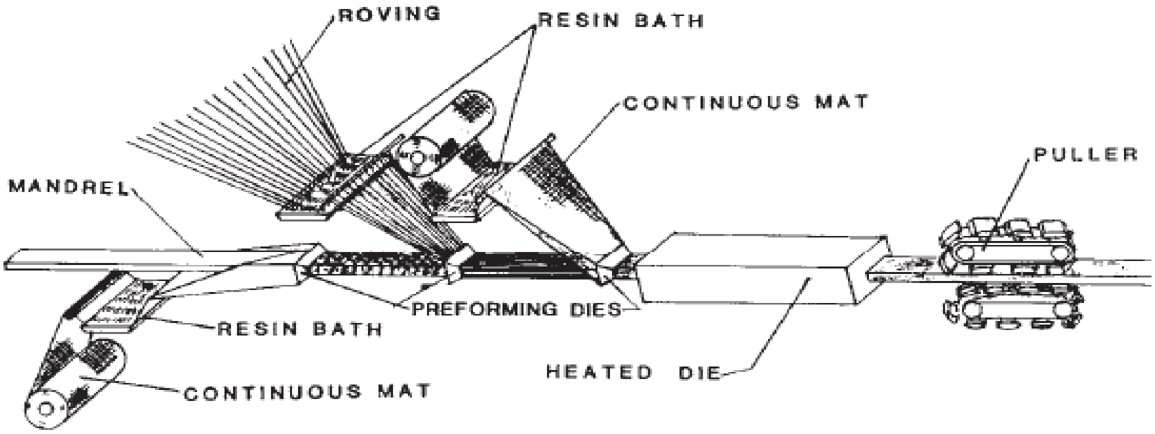


Figure 1.4 Pultrusion method

The pultruded sheets (Fig.1.6) 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.

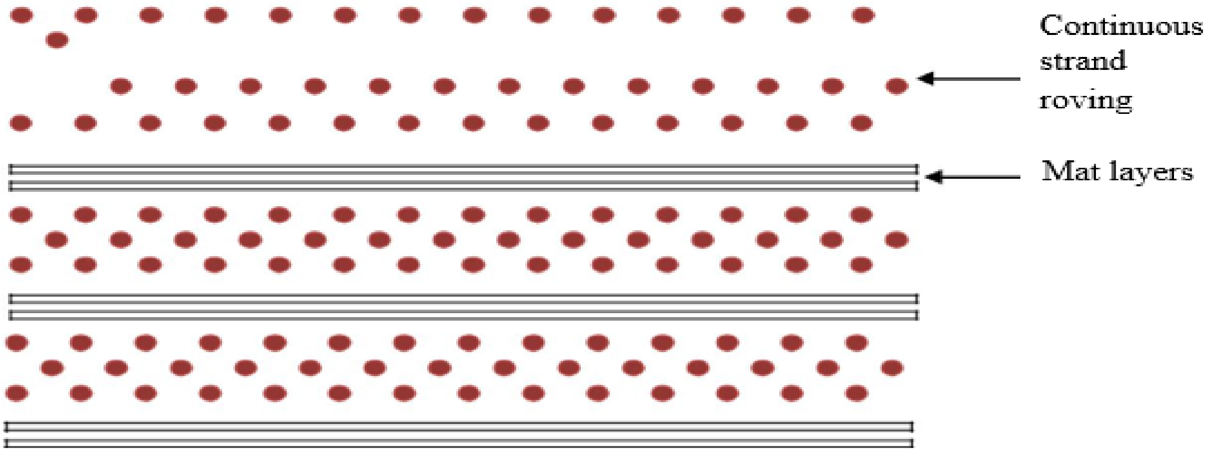


Fig 1.6 Pultruder sheet

Process of pultrusion: -

1. Continuous roll of reinforced fibers/woven fiber mat
2. Tension roller
3. Resin Impregnator
4. Resin soaked fiber
5. Die and heat source
6. Pull mechanism
7. Finished hardened fiber reinforced polymer

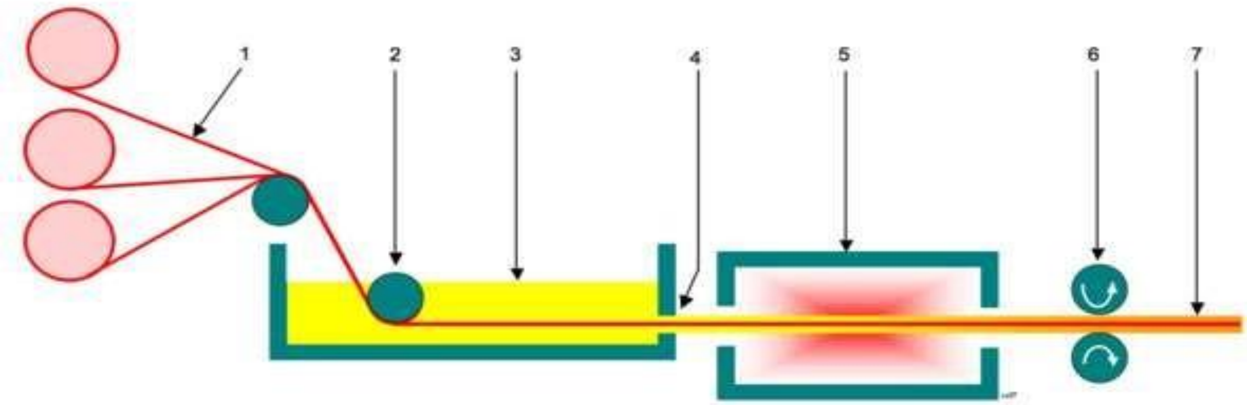


Fig. 1.7 Pultrusion process lay-out

Pultrusion in a continuous manufacturing process utilized to make pultruded profiles with constant cross-sections whereby reinforcements, in the form of roving and mats, are saturated with resin and guided into a heated die. Once in the die, the resin undergoes a curing process known as polymerization. The once resin saturated reinforcements exit the die in a solid state and in the form of the cross section of the die. The pultrusion process requires little labor and is ideal for mass production of constant cross section profiles.

ADVANTAGES OF PULTRUSION PROCESS: -

Pultrusion is an automated process with the following advantages:
1. It is a continuous process and can be completely automated to get the finished part. It is suitable for making high-volume composite parts. Typical production speeds are 2 to 10 ft/min.
2. It utilizes low-cost fiber and resin systems and thus provides production of low-cost commercial products.

DISADVANTAGES OF PULTRUSION PROCESS: -

Pultruded components are used on a large scale in infrastructure, building, and consumer products because of lower product cost. However, pultrusion has the following limitations.
1. It is suitable for parts that have constant cross-sections along their length. Tapered and complex shapes cannot be produced.
2. Very high-tolerance parts on the inside and outside dimensions cannot be produced using the pultrusion process.
3. Thin wall parts cannot be produced.

APPLICATIONS OF PULTRUSION PROCESS: -

1. Electrical application including transformers.
2. Supports in bridges and structures.
3. Automobiles.
4. Pipes and rods.

The pultrusion process is a very efficient way to manufacture fiber reinforced composite products. It allows pultrusion manufacturers to produce continuous lengths of fiber-reinforced polymer (FRP) profiled shapes.

This “pulling” process permits the strategic placement of continuous strand glass fiber, fiberglass mats and C/W Barrier, allowing for optimization of structural properties. FRP Pultruded structural shapes have a superior long-term resistance to chemical corrosion and other weathering. Pultruded shapes will not rust, rot, scale or mildew.

The term “pultrusion” is actually a combination of the words “pull” and “extrusion”. This makes sense when we realize that the pultrusion process involves a machine pulling the fiberglass through a liquid resin and then pulling that combination of glass and resin through a heated die. Extrusion is the process of creating objects of a fixed cross-sectional profile through a pushing process.

Fiber Reinforced Polymers or Plastic is a versatile material that can be tailored to customers’ specifications through the pultrusion process. Because FRP composites are a mixture of resin, fiber reinforcement and additives, the amount and “ingredient” can be adjusted to make an optimal product for your specific project.

The process provides maximum flexibility in the design of pultruded fiber reinforced polymer profiles. Since the process is continuous, length variations are limited to shipping capabilities. Specific strength characteristics can be designed into the composite, optimizing laminate performance for a particular application by strategic placement of high performance reinforcements. Color is uniform throughout the cross section of the profile, eliminating the need for many painting requirements. Processing capabilities include the production of both simple and complex profiles, eliminating the need for much post-production assembly of components.

In the standard pultrusion process the reinforcement materials like fibers or woven or braided strands are impregnated with resin, possibly followed by a separate preforming system, and pulled through a heated stationary die where the resin undergoes polymerization. The impregnation is either done by pulling the reinforcement through a bath or by injecting the resin into an injection chamber which typically is connected to the die. Many resin types may be used in pultrusion including polyester, polyurethane, vinylester and epoxy Resin provides the resistance to the environment, (i.e., the corrosion resistance, the UV resistance, the impact resistance, etc.) and the glass provides strength, in addition to safety from fire.

A surface veil can also be added to protect against erosion or “fiber bloom” and provide corrosion resistance and ultraviolet resistance.

The technology is not limited to thermosetting polymers. More recently, pultrusion has been successfully used with thermoplastic matrices such as polybutylene terephthalate (PBT), polyethylene terephthalate (PET) either by powder impregnation of the glass.

Pultrusion part design principles:

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

There are different types of materials to be used for making any product from pultrusion process, different resins materials, fiber materials and temperature etc.

Table 1.1 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

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.

(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.

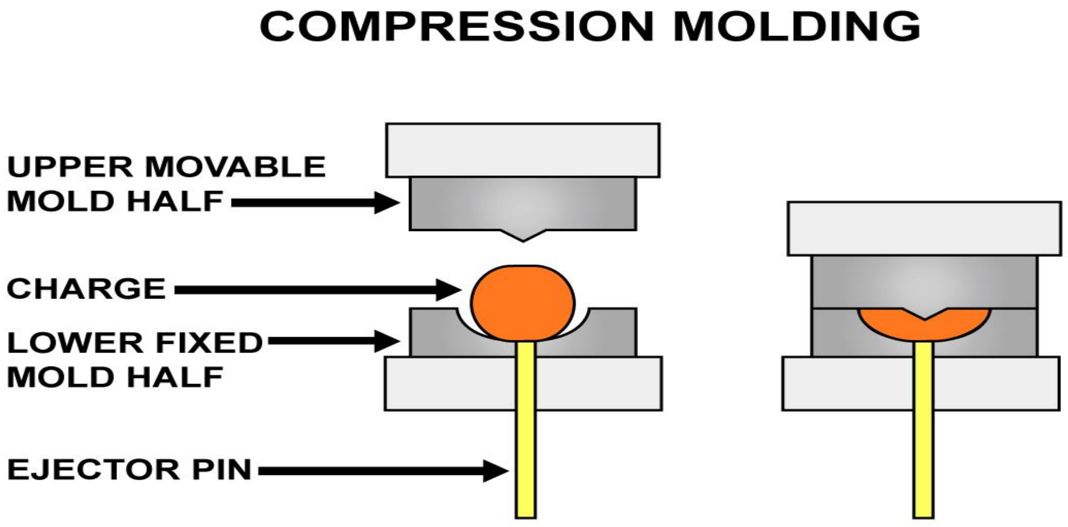


Fig. 1.8 Compression moulding setup

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.

Advantages

- i. Good finish on both sides.
- ii. Faster production.
- iii. Uniform product quality.
- iv. Less labor contents.
- 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.

(v) Resin Transfer Molding (RTM):

Resin transfer moulding (RTM) is an increasingly common form of moulding, using liquid composites. It is primarily used to mold components with large surface areas, complex shapes and smooth finishes.

RTM is unlike reaction injection moulding and structural reaction injection moulding processes (SRIM), in which the chemical reaction is induced by the mixture of reactants.

It is also called as liquid molding. The chemical reaction for resins used in RTM are thermally activated from the fiber mat or preform and mold wall. The reaction speed of RTM is much slower than that in SRIM, allowing for a longer fill time at lower injection pressure. Final RTM products will be light in weight and high in strength.

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.

PROCESS: -

1. Material held in a closed mold
2. Resin injected

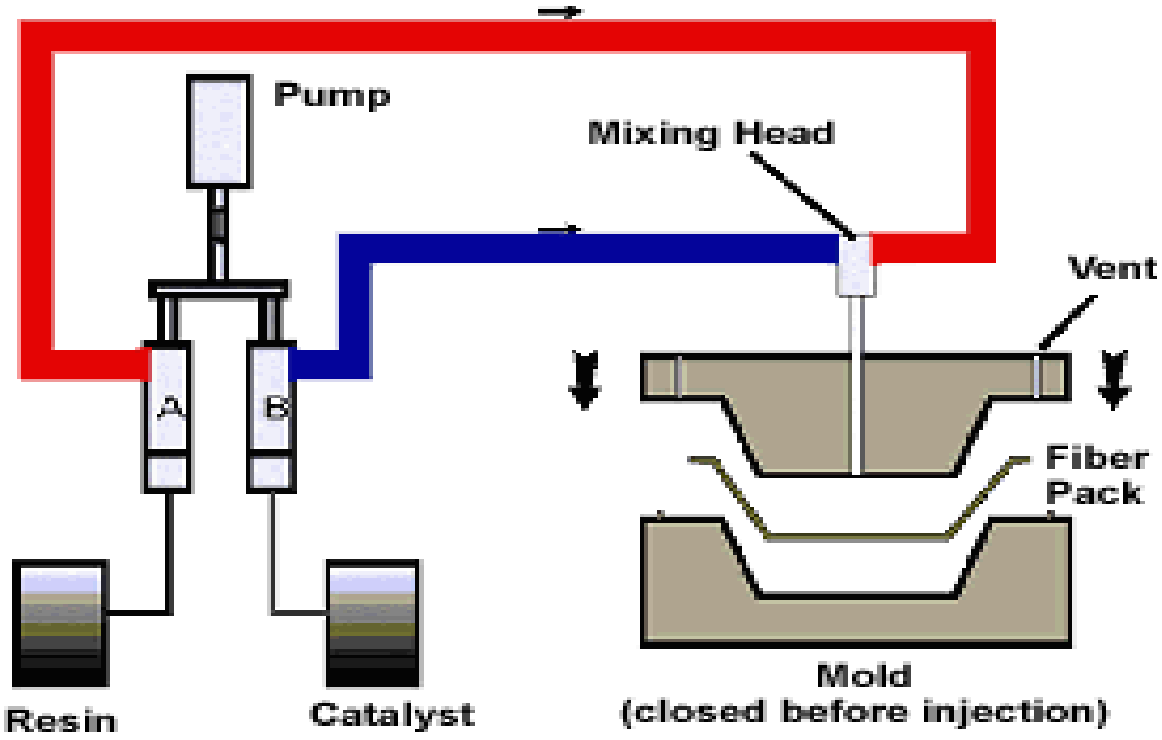


Fig. 1.8 Resin transfer moulding machine

RTM is a closed-mold, vacuum-assisted process that employs a flexible solid counter tool used for the B-side surface compression. This process yields excellent strength-to-weight characteristics, high glass-to-resin ratio and increased laminate compression. In this process, fiber preform or dry fiber reinforcement is packed into a mold cavity that has the shape of the desired part. The mold is then closed and clamped. Catalyzed, low viscosity resin is then pumped into the mold under pressure, displacing the air at the edges, until the mold is filled.

After the fill cycle, the cure cycle starts during which the mold is heated, and the resin polymerizes to become rigid plastic.

Gel coats may be used to provide a high-quality, durable finished product. This process is well-suited for mass production of 100 to 10,000 units/year of high-quality composite fiber glass or fiber-reinforced plastic parts.

It is recommended for products that require high strength-to-weight requirements. Tooling used in this process can be made from various materials including aluminum, nickel shell, mild steel and polyester.

The light RTM (LRTM) process, on the other hand, is similar to that of RTM, but differs in the method of closing the mould. The closure of the mould is done mechanically or by applying vacuum between two seals in the mould peripheral flange.

ADVANTAGES OF RESINS-TRANSFER METHOD

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.

1. Components will have good surface finish on both sides
2. Selective reinforcement and accurate fiber management is achievable
3. Ability to build-in fiber volume fraction loadings up to 65%
4. Uniformity of thickness and fiber loading, uniform shrinkage
5. Inserts may be incorporated into moldings
6. Tooling costs comparatively low
7. Uses only low-pressure injection

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.

DISADVANTAGES OF RESINS-TRANSFER METHOD

1. Waste some material
2. Curing time long

3. Hard for intricate parts
4. High tooling cost
5. Handling of large and heavy moulds requires adequate lifting equipments.
6. Since, this process can develop pressures up to 5 to 10 bars, tool rigidity and clamping techniques have to be designed for such pressures.

In 1976, Osborne Industries, Inc., originated and initiated the closed-mold molding process that was later known in the plastics industry as resin transfer molding, or RTM. The resin transfer molding process has been in use ever since. RTM is one of the best methods for mass production of composite parts. It is primarily used to mold components with large surface areas, complex shapes and smooth finishes. RTM is a vacuum-assisted, resin transfer process with a flexible solid counter tool for the B-side surface compression. This process yields increased laminate compression, a high glass-to-resin ratio, and outstanding strength-to-weight characteristics. RTM parts have two finished surfaces.

Resins: Generally, epoxy, polyester, vinylester and phenolic, although high temperature resins such as bismaleimides can be used at elevated process temperatures.

Fibres: Any. Stitched materials work well in this process since the gaps allow rapid resin transport. Some specially developed fabrics can assist with resin flow.

Cores: Not honeycombs, since cells would fill with resin, and pressures involved can crush some foams.

Reinforcement mat or woven roving is placed in the mold, which is then closed and clamped. Catalyzed, low-viscosity resin is pumped in under pressure, displacing the air and venting it at the edges, until the mold is filled. Molds for this low-pressure system are usually made from composite or nickel shell-faced composite construction.

Suitable for medium volume production of larger components, resin transfer molding is usually considered an intermediate process between the relatively slow spray-up with lower tooling costs and the faster compression molding methods with higher tooling costs.

Recommended for products with high strength-to-weight requirements

Best suited for mid-volume production rates, in the range of 200 to 10,000 parts per year*

APPLICATION OF RESIN-TRANSFER METHOD: -

RTM is of major interest for various moulding applications as it promises performance improvements and cost savings over traditional methods. Some of the major applications of the RTM process include: -

1. Truck panels
2. Boat hulls
3. Wind turbine blades
4. Aerospace and automobile parts
5. Medical composites

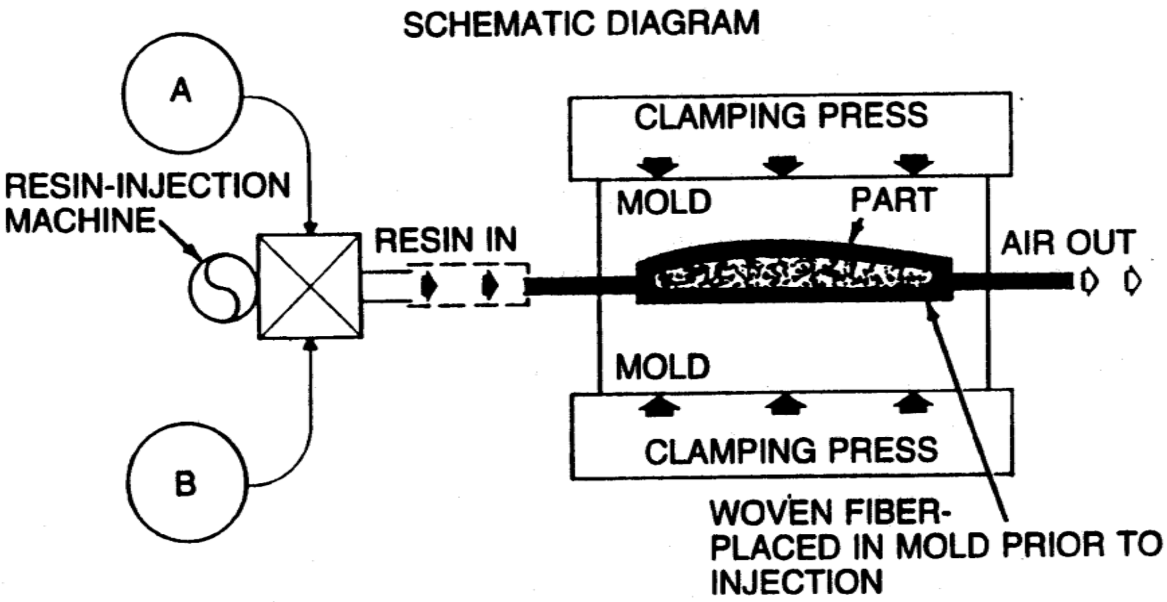


Fig. 1.9 Schematic diagram of Resin-transfer

PROCESS EQUIPMENT AND TOOLS

Types of RTM machines

The machine used for Resin transfer moulding consisting of two mixing head unit one is the mixture of resin + accelerator and second one is Resin-catalyst, they both are connected with two different pumps and then finally, these two pump pipes are connected with single mixing head unit to nozzle.

Similarly, second case there is two different unit one is resin + accelerator and second one is catalyst unit, the resin + accelerator is connected with pump and finally both pipes are connected with mixing head and to nozzle. 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.

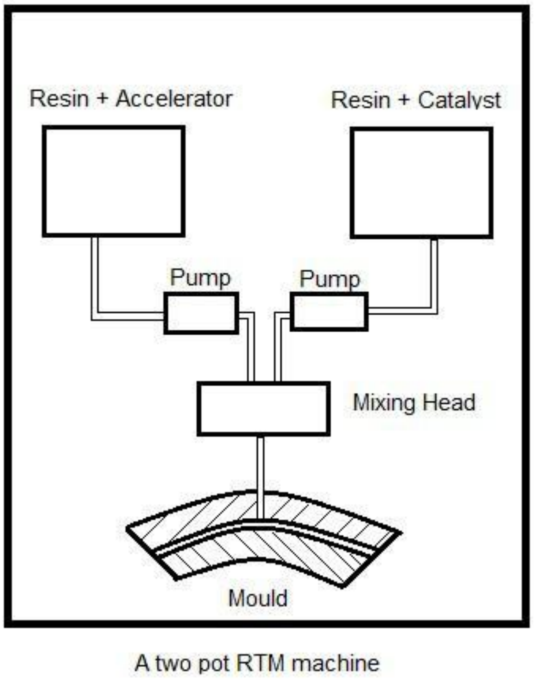


Figure 1.10 a Two pot RTM machine

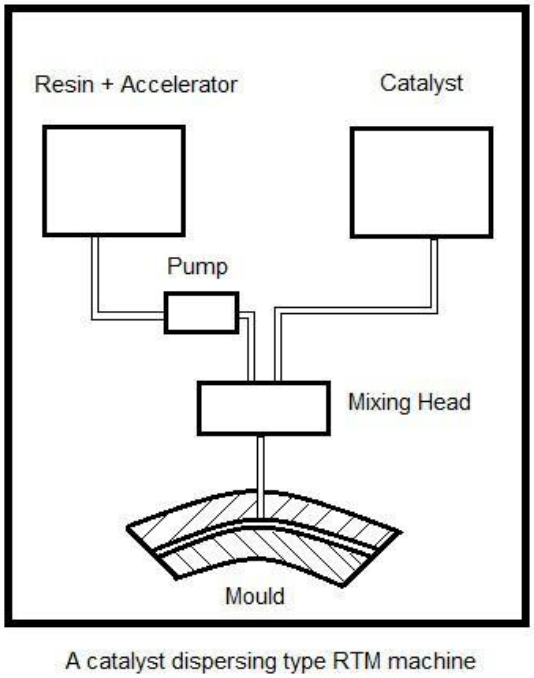


Figure 1.10b catalyst dispersed RTM machine

a. **Two pot system**

This system has two equal volume containers or pots. In one of these pots the accelerator and resin is mixed. Similarly, in the another pot the resin is mixed with the catalyst. Two pumps are used to pump these mixtures (as shown in fig.1.10a) 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.1.10b). 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.

MOULDING PROCESS

Mould preparation

The two halves (male and female die) of the mould are cleaned and the dust must be removed from the surface using some brushes and small grain sand papers. 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 male and female of the mould. The gel coat thickness should be >0.5mm.

Resin injector and curing

The resin is then injected to the mould using an resin-transfer moulding machine at desired pressure. There should be a right quantity of catalyst is dosed into the resin stream and no gelling occurs during pumping.

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:

TT = Tmf = Tgel = Tc= Tu = Tcl + Tp + Tfp

Tmf = mould fill up time

Tgel = gel time

Tc = cure time

Tu = un mould time

Tcl = cleaning time

Tp = preparation time

Tfp = fiber packing time

(vi) Pressure Bag Molding

This technique is widely used for high performance mouldings such as for aerospace applications. This vacuum consolidation method produces high- quality mouldings, with complete exclusion of air bubbles and improvement to the inner surface of the moulding, which is not in contact with the mould. The controlled curing conditions also improve quality and consistency and allow superior resin systems to be used, while opening the way to a more rapid cure with faster turn round of moulds.

Pressure bag molding is similar to the vacuum bag molding method except that air Pressure 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.

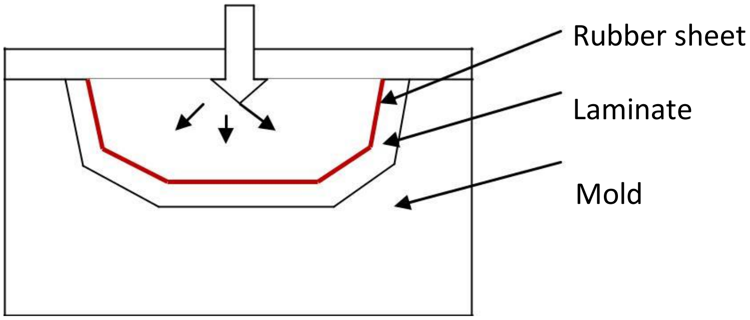


Figure 1.11 Pressure bag molding

Vacuum bag moulding is a modification of hand lay-up, in which the lay-up (necessarily smaller) is completed and placed inside a bag made of flexible film and all edges are sealed. The bag is then evacuated, so that the pressure eliminates voids in the laminate, forcing excess air and resin from the mould. By increasing external

pressure, a higher glass concentration can be obtained, as well as better adhesion between the layers/plies of laminate.

The bag used in this method had two-fold objectives.

1. It provides a means for removing volatile products during cure
2. It provides a means for the application of pressure of one atom which is adequate for some materials.

Definition "*A vacuum bag is a clamping method that use atmospheric pressure to hold the adhesive or resin-coated components of a laminated in place until the adhesive cure*".

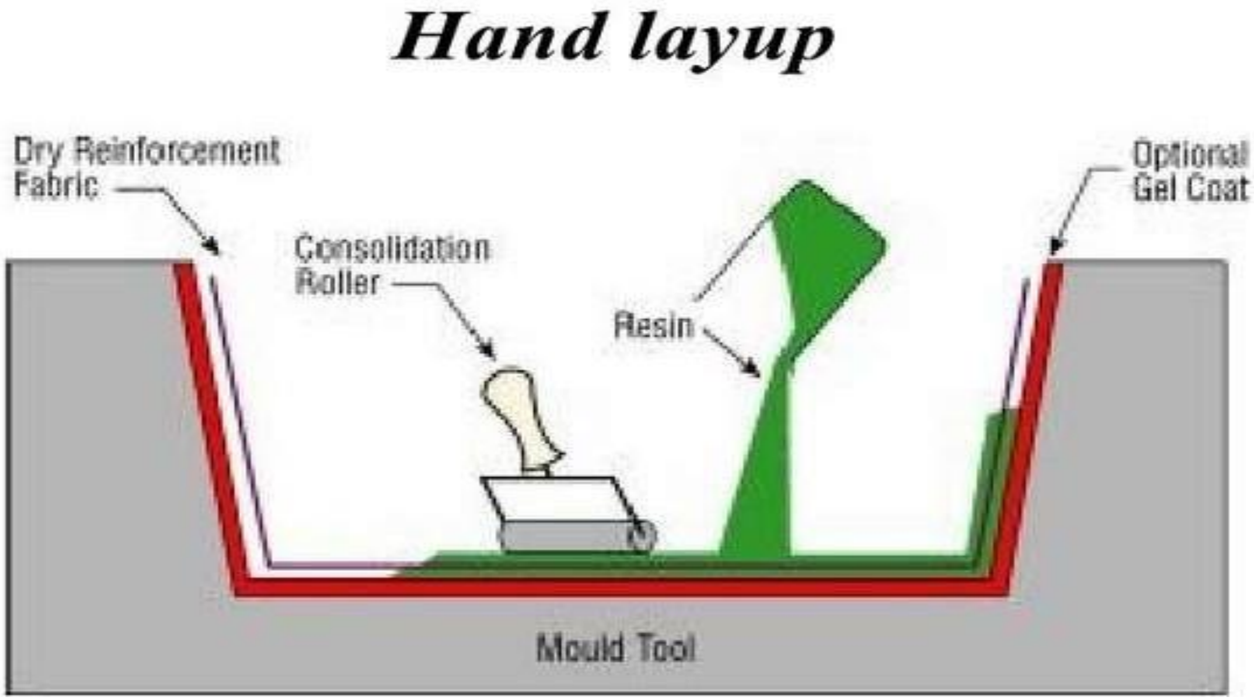


Fig. 1.12 Conventional hand lay-up method

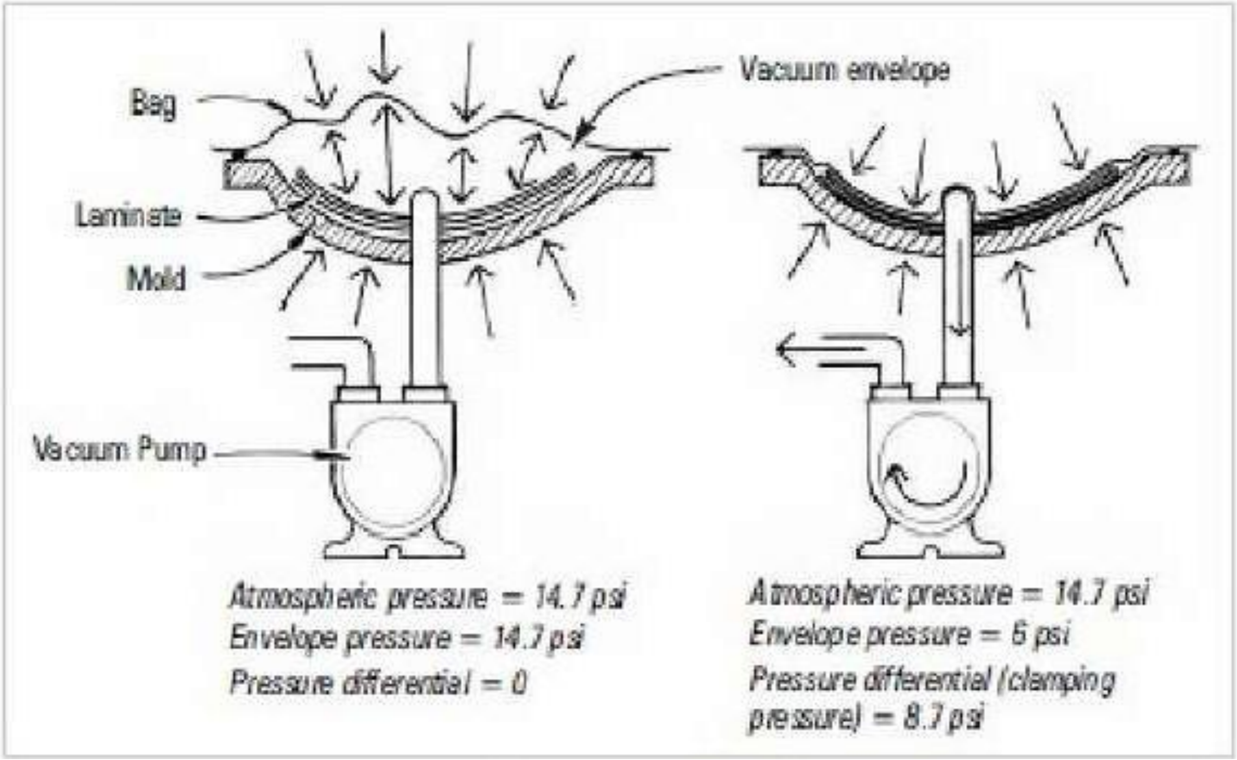


Fig. 1.13 Effect of atmospheric pressure on vacuum moulding

ADVANTAGES OF VACUUM BAGGING MOULDING: -

1. Even clamping pressure
2. Control of resin content
3. Custom shapes
4. Efficient laminating
5. higher fibre volume fractions/lower void contents.
6. better fibre wet-out due to pressure/resin flow.
7. heavier fabrics can be wet-out.
8. volatile organic compounds are largely contained during the curing stage.
9. the additional consolidation pressure can help the reinforcement to conform to tight curvatures.
10. improved mechanical properties consequent upon the higher fibre volume fraction.

DIADVANTANTAGES OF VACUUM MOULDING PROCESS: -

1. higher labour skills for the bagging stage.
2. low production rates due to bagging stage joining bagging film for large items.
3. mould tool must be vacuum tight.
4. costs for consumables and equipment.
5. the vacuum pump may strip volatiles from resin
6. consumable material compatibility with resin

VACUUM BAGGING MATERIALS: -

1. Release fabric
2. Perforated film
3. Breather material
4. Vacuum bag
5. Mastic sealant
6. Plumbing system
7. Mold release

1. Release fabric: -

Smooth woven fabric – not bond to epoxy.

Use to separate breather and laminate.

2. **Perforated film: -**

Used in conjunction with release fabric

This film helps to hold the resin in laminate, when high vacuum pressure is used with slow curing resin system.

3. **Breather material or breather cloth: -**

Allow air from all parts of the envelope- to be drawn to a port manifold by provide slight air space between the bag and laminate.

4. **Vacuum bag: -**

If vacuum pressure is less than 5psi (10kg) at room temperature – 6mil polyethylene plastic is used.

Clear plastic material is preferred as compared to opaque.

5. **Mastic sealant: -**

Provide a continuous air tight sealant between bag and mold.

Also use to seal the pint where the manifold enters to the bag and to repair leaks in the bag.

6. **Mold release: -**

Necessary to prevent epoxy to sticking.

There are various three types of mold release material: -

a. **Carnauba based paste wax: -**

Usually 5 layers of new mold and at least one layer before each new part of mold.

Also use PVA in wax

b. **Semi-permanent formulation: -**

Liquid release system

Fine detail and gloss level are obtained as well as texture.

c. **General contaminated variety: -**

Grease, Vaseline, toilet bowl wax, hair spray, hair gel.

vi. <u>INJECTION MOULDING MACHINE</u>: -

- It is a manufacturing technique for making parts from thermoplastic and thermosetting material.

- The plastics used in the injection molding process are liquefied at temperatures between 220° C and 270° C.
- Molten plastic is injected at high pressure (ranges 70MPa to 200MPa) into a mold, which is the inverse of the desired shape.
- The mold is made from metal, usually either steel or aluminium
- Widely used for manufacturing a variety of parts, from the smallest component to entire body panels of cars.

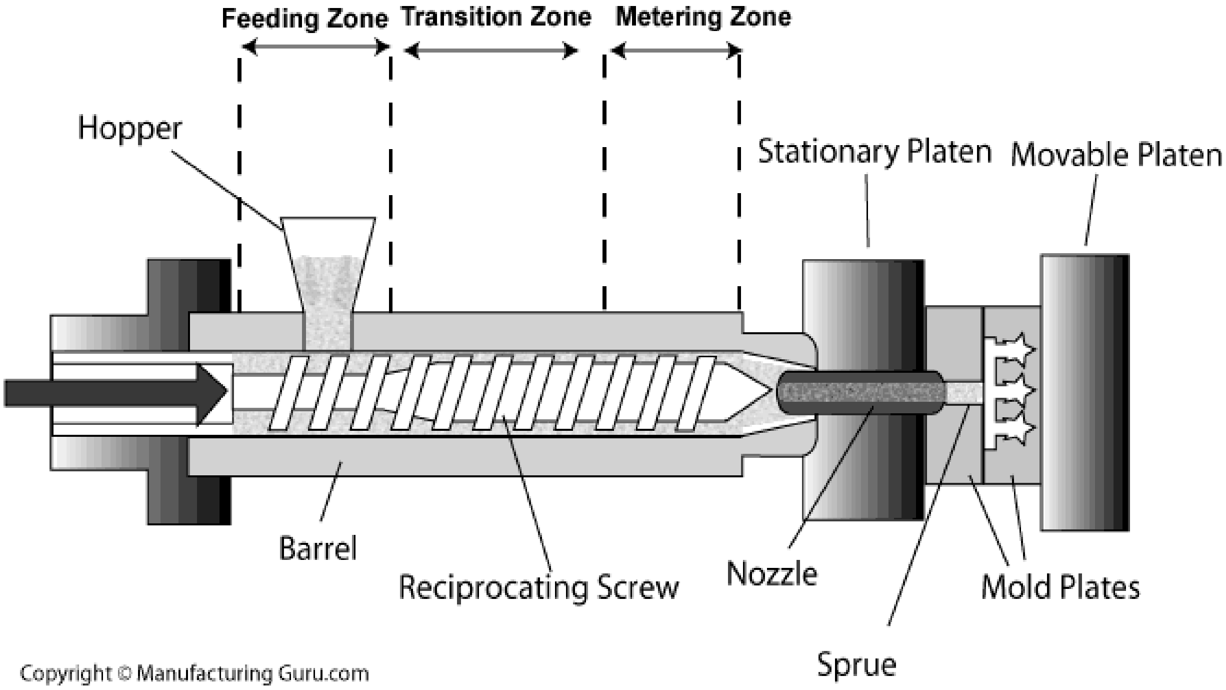


Fig. 1.11 Injection moulding machine

Fig. 1.12 Actual model of Injection moulding machine

It is a manufacturing technique for making parts from thermoplastic and thermoset materials. In contrast to the extrusion (which makes continuous parts of constant cross section), injection molding makes discrete parts (with complex and variable cross section) Molten plastic is injected at high pressure into a mold, which is the inverse of the desired shape. The mold is made from metal, usually either steel or aluminium. Widely used for manufacturing a variety of parts, from the smallest component to entire body panels of cars

Injection unit: -

From hopper – hole (feed throat)

Barrel made of heavy steel cylinder to withstand the pressure and temperature involved in melting the resin

2 types of system used in injection molding;

Reciprocating screw- similar to extruder screw but with unique reciprocating action

Ram injector

Design of screw- similar to an extrusion screw 3 sections:

1.Feed section- to advance the resin

2. Compression section- to melt the resin

3. Metering section- to homogenize the resin and pump it forward

The screw of injection molding machine is shorter than extruder, L/D ratios are 12:1 and 20:1. Low L/D ratios suggest the mixing is less efficient in the injection molding machine. The compression ratio (diameter of root at feed zone to the diameter of root at metering zone) often in the range of 2:1 and 5:1. Low compression ratio means less mechanical action is added during melting process

Hopper: -

The thermoplastic material used in the plastic injection molding process is supplied in the form of small pellets. These pellets are loaded into the hopper, then gravity- fed into the barrel and the screw assembly.

Barrel: -

This is a chamber in which the reciprocating screw is located. The barrel is heated by electric heater bands.

Nozzle: -

The nozzle forms a sealed connection between the barrel and the sprue bushing of the mold. The temperature of the nozzle is usually set near the plastic’s melt temperature.

The mold’s sprue bushing has a concave radius. The nozzle fits into this radius with the aid of a locating ring.

Reciprocating Screw: -

The reciprocating screw compresses and melts the plastic material. It also moves the material toward the die.
The reciprocating screw is divided into three zones: the feeding zone, the transition zone, and the metering zone.

The most commonly used thermoplastic materials are: -

1. polystyrene (low-cost, lacking the strength and longevity of other materials)
2. ABS or acrylonitrile butadiene styrene (a co-polymer or mixture of compounds used for everything from Lego parts to electronics housings)

3. nylon (chemically resistant, heat-resistant, tough and flexible - used for combs)
4. polypropylene (tough and flexible - used for containers
5. PVC (more common in extrusions as used for pipes, window frames, or as the insulation on wiring where it is rendered flexible by the inclusion of a high proportion of plasticizer).
6. Lubricant and coolent: - Obviously, the mold must be cooled in order for the production to take place. Because of the heat capacity, inexpensiveness, and availability of water, water is used as the primary cooling agent. To cool the mold, water can be channeled through the mold to account for quick cooling times. Usually a colder mold is more efficient because this allows for faster cycle times. However, this is not always true because crystalline materials require the opposite: a warmer mold and lengthier cycle time.

Process Method: -

1. Clamping: - Initially both parts of the mold clamped (locked) and this clamping force is given in tonnage. Powder or granules from a hopper into a steel barrel with a rotating screw. The barrel is surrounded by heaters The screw is forced back as plastic collects at the end of the barrel.

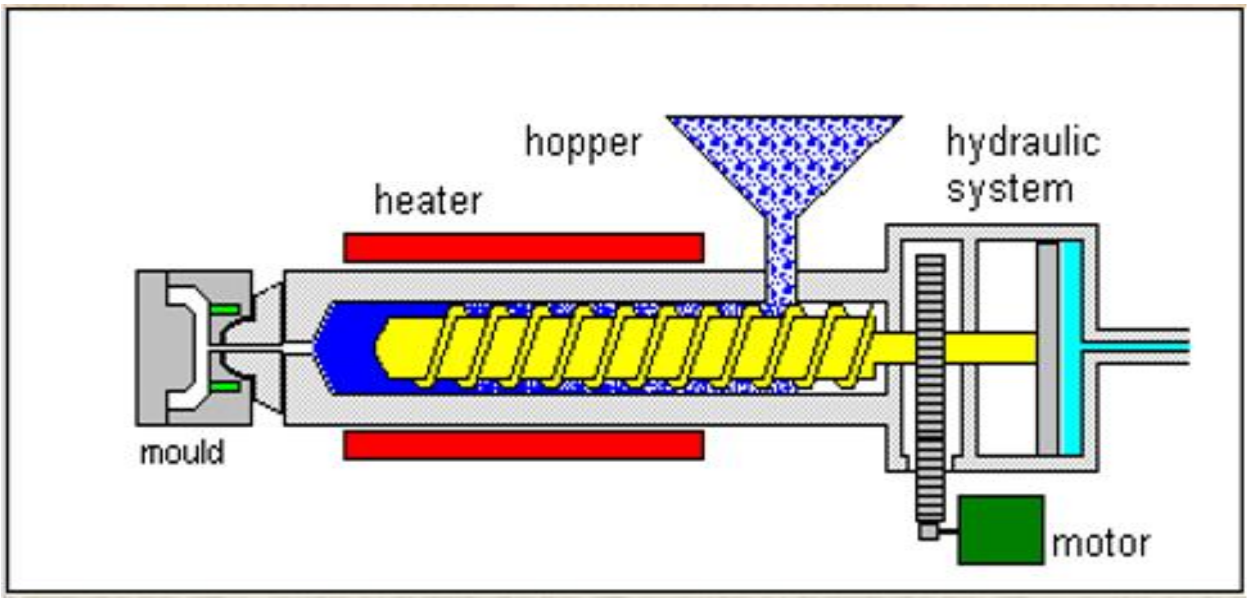


Fig. 1.13 Injection moulding machine

2. Injection: -Once a sufficient charge of melted plastic has accumulated a hydraulic ram forces the screw forward injecting the thermoplastic through a sprue into the mould-cavity. Normally the screw will stay in the forward position, until resin began to harden in the mold.

PROCESS CAPABILITIES: -

1. High production rate
2. Good dimensional control
3. Cycle time range 5 to 60 sec's
4. Mold materials- tool steels, beryllium - Cu, Al
5. Mold life- 2 million cycles (steel molds) 10000 cycles (Al molds)

ADVANTAGES OF INJECTION MOLDING

1. High Production rates
2. Design flexibility
3. Repeatability within tolerances
4. Can process a wide range of materials
5. Relatively low labor
6. Little to no finishing of parts
7. Minimum scrap losses

DISADVANTAGES OF INJECTION MOLDING

1. High initial equipment investment
2. High startup and running costs possible
3. Part must be designed for effective molding
4. Accurate cost prediction for molding job is difficult

APPLICATION OF INJECTION MOLDING MACHINE

1. Aerospace components
2. Automotive components
3. Avionics components
4. Cable assemblies
5. Computer electronics
6. Electronics components
7. Encapsulations
8. New product design &development
9. R&D labs Test specimens
10. Engineering prototypes
11. Geophysics
12. Instrumentation
13. Marketing samples
14. Material quality testing
15. Medical & dental products
16. Medical laboratories

BULK MOLDING COMPOUND

Bulk molding compound (BMC) or bulk molding composite is a ready to mold, glass-fiber reinforced thermoset polyester material primarily used in injection moulding and compression moulding. The material is provided in bulk or logs. BMC is manufactured by mixing strands (>1”) of chopped glass fibers in a mixer with a thermoset resin (commonly polyester resin, vinyl ester or epoxy resin). The glass fibers in BMC result in better strength properties than standard thermoplastic products. Typical applications include demanding electrical applications, corrosion resistant needs, appliance, automotive, and transit. It is a polyester mounding material¦ that resembles dough and which has been supported with appropriate glass fiber. It can be adjusted by changing the additive materials according to the required feature. It is in the thermoset plastics group because of its main characteristics and it can be produced with hot press (straight, transfer, injection) mounding method.

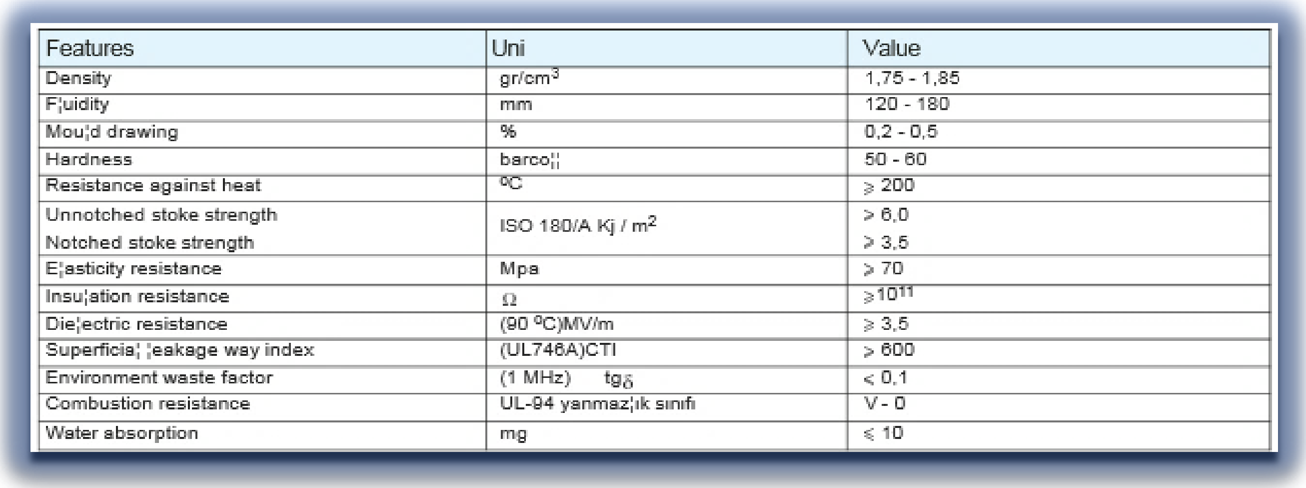
BMC Characteristic Features: -

- Having high mechanical¦ forces not only under static loads but also under dynamic loads
- Having well adjustment in measurements with its low tensile properties
- High thermo stability
- Having ¦ow rated dehumidification feature
- High electrical¦ features (insulation)
- Feature of flame delaying formulate preparation
- Low cost
- The temperature in BMC coating is averagely between 140 - 180 ^{o}C.
- The pressure is between 100 - 140 kg/cm2 bar.

An idea¦ coating material¦ must have the following features:

- Low melting temperature
- High fluidity
- Remaining in fluid form for a long time
- Hardening in high speed.

Federal has been realizing the thermoset material¦ production, in composite plastic area, by BMC (Bulk Mounding Compound) as mounding dough for 15 years in its structure. Al the needed machinery and the equipment's for the productions are found in its facilities. By using special formulations, BMC productions having required colors and properties can be made.



Features	Uni	Value
Density	gr/cm^3	1,75 - 1,85
F¦uidity	mm	120 - 180
Mou¦d drawing	%	0,2 - 0,5
Hardness	barco¦¦	50 - 60
Resistance against heat	^{o}C	⩾ 200
Unnotched stoke strength Notched stoke strength	ISO 180/A Kj / m^2	> 6,0 ⩾ 3,5
E¦asticity resistance	Mpa	⩾ 70
Insu¦ation resistance	Ω	⩾10^{11}
Die¦ectric resistance	(90 ^{o}C)MV/m	⩾ 3,5
Superficia¦ ¦eakage way index	(UL746A)CTI	⩾ 600
Environment waste factor	(1 MHz) tg$_{\delta}$	⩽ 0,1
Combustion resistance	UL-94 yanmaz¦ık sınıfı	V - 0
Water absorption	mg	⩽ 10

Table.2 Properties of BMC composite material

The glass fiber that is found in the structure of the BMC material provides it high and superior insulation feature, high stroke resistance and many similar important features by combining its superior mechanical¦ feature with polyester resin and other components.

In the moulds that have been designed and produced from raw material¦ production, the parts are shaped under heat and pressure in press shops, and the produced semi products turn into final products.

The glass fiber that is found in the structure of the BMC material provides it high and superior insulation feature, high stroke resistance and many similar important features by combining its superior mechanical¦ feature with polyester resin and other components.

In the moulds that have been designed and produced from raw material¦ production, the parts are shaped under heat and pressure in press shops, and the produced semi products turn into final products.

The bulk moulding compound is composed of polyester resin, glass fibers and filler. Strength is lesser than that obtained by other moulding processes. Moulding compounds can be prepared as continuous sheets. Due to the longer fibers and high glass content, their strength is better than those made in bulk moulding method. BMC (Bulk Moulding Compound) can be moulded both in injection or compression process for large-scale production of medium-size or small complex parts.

BMC is, like SMC, a polymeric composite material, which consists primarily of a thermosetting resin, mineral fillers and glass fiber reinforcement. The resin used is generally unsaturated polyester (UP) or vinyl-ester (VE). Additional ingredients such as thermoplastic components, catalysts, inhibitors, mould release agents, thickeners and colour pigments are used to enhance the performance and moulding process of the final product. The transformation or mounding process is carried out by compression in a hot mould at temperatures between 130 – 170ºC and under pressure (typically 20 – 100 bar), or in injection machines (mould temperature between 145 – 175ºC, pressure 80 – 160 bar) specially designed for this process applications are wide-ranging in the Automotive & Transportation, Electrical & Energy, Building & Construction, Industrial, Service, Sanitary, Domestic and Medical markets.

BMC is a thermoset plastic made up of a polymer resin, various inert fillers, fiber reinforcement, catalysts, stabilizers, and pigments that form a viscous, 'playdough like' compound for molding. BMC is highly filled and reinforced with short fibers. Glass reinforcement represents between 5% to 30%, with glass length typically between 1/8" and 1/2".

Depending on the end-use application, compounds are formulated to achieve tight dimensional control, flame resistance, high dielectric strength, corrosion and stain resistance and color stability. Its excellent flow characteristics make BMC well suited to a wide variety of applications requiring precision in detail and dimensions. The material is available in a wide variety of colors.

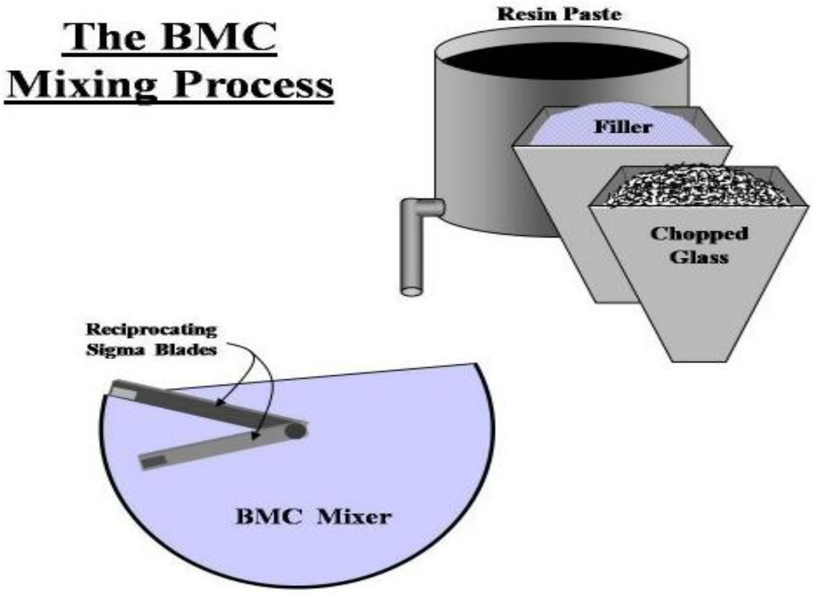


Fig. 1.14 Mixing unit of BMC machine

Many different fabrication processes are available to make advanced composite structures. However, the available options begin to narrow if highly intricate components with superior performance need to be produced at higher volume production rates. Compression molding with long chopped fiber thermoplastics is one of the methods that can fulfill these requirements.

Fig. 1.15 BMC materials

Figure 1.16 Bulk molding compound.

Thermoplastic Bulk Molding Compounds: -

Since the 1990s, long, discontinuous fiber, thermoplastic composites have been used to make compression molding components. Materials such as polypropylene and fiberglass were used in some automotive applications. Thermoset based sheet molding compounds (SMC) had been in use before this period and are still used.

For the past several years, SMCs have been used by the aerospace industry to make secondary structures such as covers. SMCs are different from BMCs, which are composed of chips, chopped flakes, or lengths of prepreg fibers instead of a continuous sheet of material consisting of continuous or discontinuous fibers.

The high strength and stiffness characteristics of carbon fiber make it suitable for the aerospace industry. Aircraft structures, as shown in Figure 2, have been fabricated using carbon fiber thermoset BMCs.

Fig. 1.17 Thermoplastic bulk moulding components

Processing of thermoplastic BMCs needs to be carried out at temperatures higher than that of many thermosets. During cool down, a higher degree of temperature control is required in order to maintain the crystallinity of the polymer and to achieve an even cooling profile throughout the component.

A range of BMCs has been developed by TenCate/CCS, containing the four-major aerospace grade thermoplastic polymers such as PEKK, PEI, PPS, and PEEK with many different types of fibers. The XPress process allows molding of these compounds under consistent and rapid heating and cooling with monitoring of the tool surface, thus minimizing part warpage, internal and surface defects.

SHEET METAL MOULDING: -

Sheet moulding compound (SMC) or sheet moulding composite is a ready to mould glass-fibre reinforced polyester material primarily used in compression moulding. The sheet is provided in rolls weighing up to 1000 kg. Alternatively, the resin and related materials may be mixed on site when a producer wants greater control over the chemistry and filler.

SMC is both a process and reinforced composite material. This is manufactured by dispersing long strands (usually >1”) of chopped fiber (commonly glass fibers or carbon fibers on a bath of thermoset resin (commonly polyester resin, vinyl ester or epoxy resin)). The longer fibers in SMC result in better strength properties than standard bulk moulding compound (BMC) products. Typical applications include demanding electrical applications, corrosion resistant needs, structural components at low cost, automotive, and transit.

PROCESS: -

Paste reservoir dispenses a measured amount of specified resin paste onto a plastic carrier film. This carrier film passes underneath a chopper which cuts the fibers onto the surface. Once these have drifted through the depth of resin paste, another sheet is added on top which sandwiches the glass. The sheets are compacted and then enter onto a take-up roll, which is used to store the product whilst it matures. The carrier film is then later removed and the material is cut into charges. Depending on what shape is required determines the shape of the charge and steel die which it is then added to. Heat and pressure act on the charge and once fully cured, this is then removed from the mould as the finished product. Fillers both reduce weight and change the physical properties, typically adding strength. Production challenges include wetting the filler, which could consist of glass microspheres or aligned fibers rather than random chopped fibers;

adjusting die temperature and pressure to provide the proper geometry; and adjusting chemistry to end use.

ADVANTAGES: -

Compared to similar methods, SMC benefits from a very high-volume production ability, excellent part reproducibility, it is cost effective as low labor requirements per production level is very good and industry scrap is reduced substantially. Weight reduction, due to lower dimensional requirements and because of the ability to consolidate many parts into one, is also advantageous. The level of flexibility also exceeds many counterpart processes.

PHYSICAL PROPERTIES (PROPERTIES VARY DEPENDING UPON FIBER AND RESIN TYPES): -

Impact Strength: 8–13 ft·lbf/in
Flex Strength: 18-34 KPSI (120-230 MPa)
Flex Mod: 1500-2100 KPSI (10-15 GPa)
Tensile Strength: 8-18 KPSI (55-125 MPa)
Compressive Strength: 24-32 KPSI (165-220 MPa)
CURING Temperature: 80°C-150°C

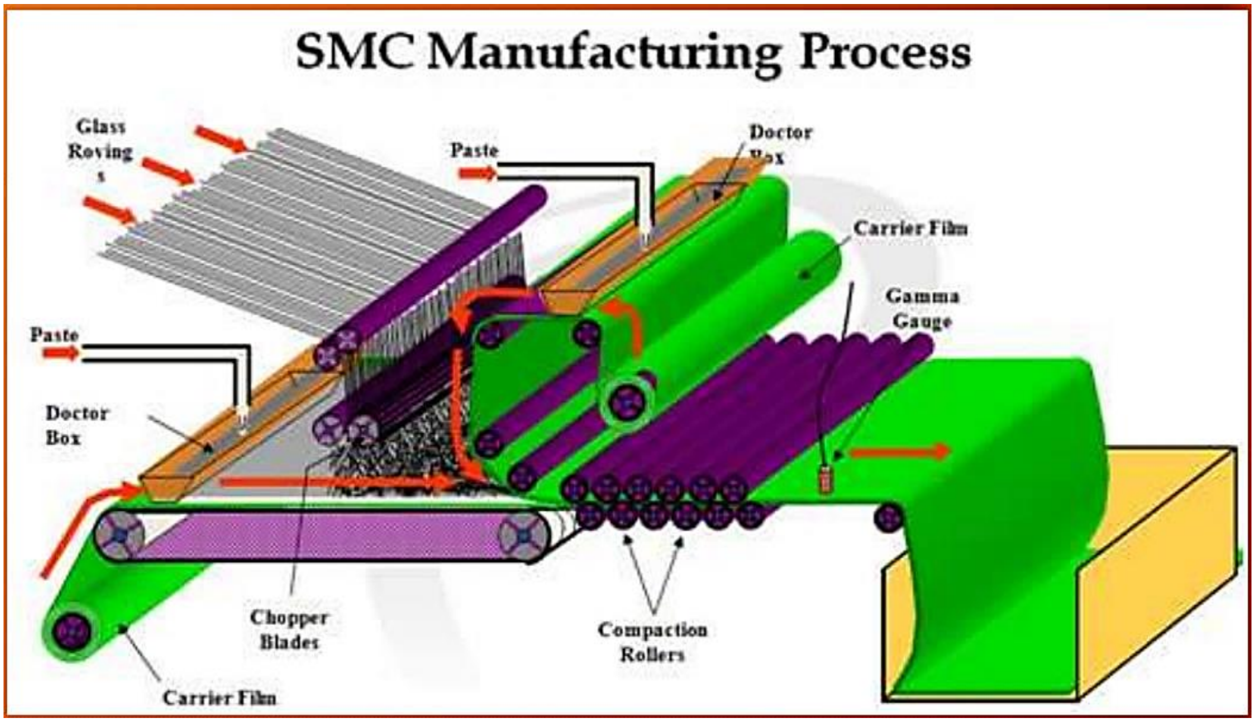


Fig. 1.18 SMC manufacturing process

Brief Introduction

1. **Main Part:** frequency conversion motor drive controlled by pneumatic form the PE sheet and fiberglass roving compact together by belt chains (SS304).
2. **Rolling Part:** Drive by torque motor and speed can be adjusted at any time.
3. **Cutting Part:** Drive by variable speed motor; helical cutting roller (increase service life of rubber roller and blade); If higher fiberglass content is required, such as above 30%, double roller can be designed on the machine.
4. **Electrical Control Part:** Central control system to meet production requirements, all components are well known brand.

Technical Specification: -

1. **Convey device:** conveying the PE sheet by chain belt whose drive and controlled by variable frequency motor with adjusting technology and running stable. Precisely speed adjustment, the precision of varying frequency can be 0.1 Hz.
2. **Resin paste scrapping device:** using high precision scraper and plate with the gap accuracy up to 0.05mm to ensure the resin paste coat evenly on the PE sheet.
3. **PE sheet feed:** feeding the upper and lower PE sheet by Pneumatic controller. The membrane tension is controlled by the stretcher which with the function of flattening and wrinkle-smoothing to ensure that the PE sheet can be conveyed to the belt area with constant tension and without wrinkles. The Pneumatic knife lifting device can make the scraper go up and down quickly and prevent the PE sheet damaged by the grain in the resin paste.

Fig. 1.18 Sheet moulding component machine

4. **Glass fiber cutting device:** Get the pressure from pneumatic control knife roller and Pad pressure roller. There are screws installed blades make it run stable, enhance the service life of the blades and improve the quality of fiber glass yarn. Variable frequency adjusting controlled knife roller can ensure the accuracy. With chain belt speed adjusting device ensure the high precision and stability of the fiberglass content.
5. **Retting and compaction:** consisting of a series of roller, pressing by the pneumatic roller, which can ensure the quality of the sheet.
6. **Roll-up and box-up:** sheet can be packed in roll or in box with tension adjustment equipment for the two-packing way to ensure the quality.

Advantage: -

It adopts advanced mechanical structures & technology. It has achieved domestic advanced level with advanced technology and reasonable craft, high degree automation and high outputs.

- It is PLC digital control; including resin feeding. It can achieve vacuum charging resin to cutting blade, completely mixture, easy cleaning and more automation.
- Easy operation, low noise, obvious electricity conservation, small size, compact
- structure, low energy consumption, high durability, good looking, etc.
- Combined with powder collector to absorb the harmful substances to keep the health of the worker and prolong the service life of the machine.
- Increase the operation rate of the material and lower the cost

Application: -

- A new kind of thermosetting plastic sheet molding compound raw material machine Used for manufacturing of Fiberglass SMC Materials widely used in automotive industry, rail vehicles, construction, electrical, communication engineering, catering appliances, sports equipment etc.

Fig. 1.19 Sheet moulding component machine

APPLICATION OF COMPOSITE MATERIAL IN AEROSPACE INDUSTRIES: -

The main aim of the aerospace/aircraft industries is to reduce weight keeping the same or more strength than the regular metals have. This criterion leads to use composite. Aeronautical engineering comprises of various distinct areas that produces vehicles capable of performing distinct flight programmes. Initially importance was given to weight, speed and power, but other parameters that influence market acceptance of the aircraft should also be considered during design. These conditions call for selection of materials that give less than optimum efficiency in terms of structure and systems. Hence, it is important to consider performance needs as well as service properties. Airframe design starts with evaluation of flight conditions which the aircraft will encounter. In recent designs, wind tunnel tests and analysis are being done to determine the lift and drag forces. Once determined, they are used to develop various related factors of structural engineering. The selection of material, it follows, enters naturally into the picture at the early stage of design itself. The high strength of composites allows designing of higher **aspect ratio** wings in aero foil sections.

Nowadays, composites are used in peripheral structures of **aerodromes**. Conventional constructions of composites ought to cost much less in future and will not be a constraint. Automation along with high standard for filament and matrix materials will also decrease fabrication costs, as the rejection on grounds of quality will be less. Performance, reliability and efficiency of operators alone can assure the success of any programme and the space program in particular.

The potential and application of high-performance composites has revolutionized space structural technology. Glass filaments have been used in space vehicles for several years now as laminations in secondary structures.

As far as its importance as an engineering material is concerned, glass is attractive because of high specific strength, low cost, good forming characteristics, high impact resistance and thermal stability. Thanks to its insulating property, glass has been used to a great extent in thermal isolation components and structures. However, a drawback with glass is its low elastic modulus. Although glass is easily handled, it results in excessive tool wear while machining operations are conducted.

Graphite is a widely available economical reinforcement material with high stiffness, high modulus, high strength and high theoretical efficiency.

Application Use of Composite in Aerospace Structure: -

- The use of composites has been motivated largely by such considerations.

The composites offer several of these features as given below:

1. Light-weight due to high specific strength and stiffness.
2. Fatigue-resistance and corrosion resistance.
3. Capability of high degree of optimization: tailoring the directional strength and stiffness.
4. Capability to mould large complex shapes in small cycle time reducing part count and assembly times: Good for thin-walled or generously curved construction.
5. Capability to maintain dimensional and alignment stability in space environment.
6. Possibility of low dielectric loss in radar transparency.
7. Possibility of achieving low radar cross-section.

These composites also have some inherent weaknesses:

Laminated structure with weak interfaces: poor resistance to out-of-plane tensile loads. Susceptibility to impact-damage and strong possibility of internal damage going unnoticed. Moisture absorption and consequent degradation of high temperature performance. Multiplicity of possible manufacturing defects and variability in material properties.

Advantage of composite material over metals: -

1. Light weight
2. High heat resistance
3. High strength to weight ratio
4. Low density
5. Corrosion resistance
6. High stiffness
7. Fatigue resistance

Graphical representation of use of composite material over the years:-

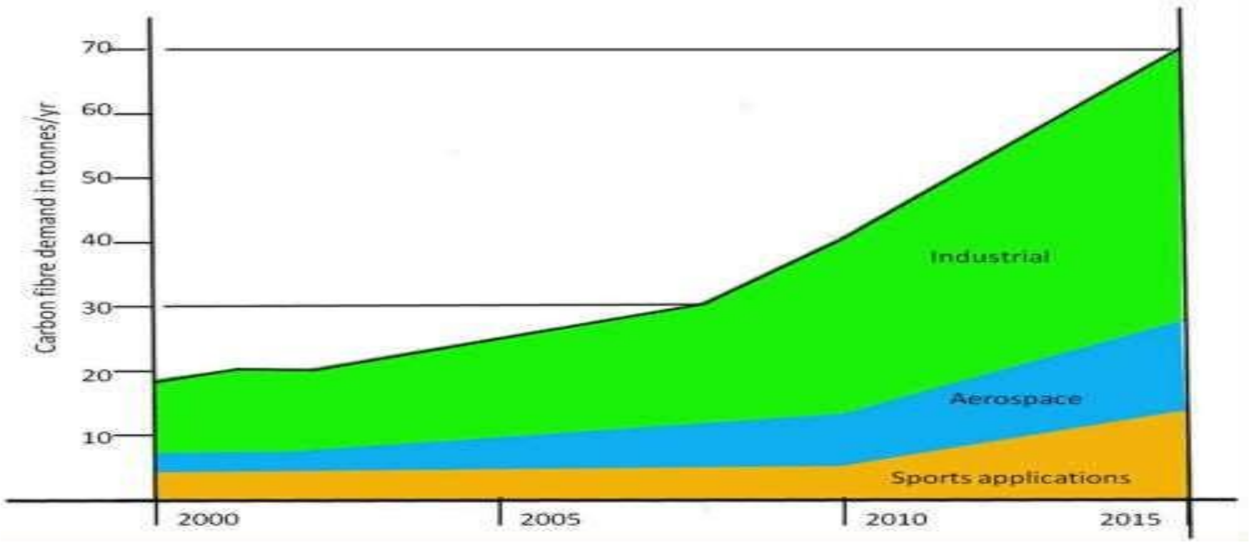


Figure 1.20 Use of composite material over the years

Types of composite used: -

1. Fiber glass
2. CFRP
3. QFRP
4. GFRP
5. GLARE

Application of composite material in Aerospace: -

1. Fuselage (Bulkhead)
2. Wing flaps
3. Rudder
4. Elevators
5. Radome
6. Spoilers
7. Floor beams and panels
8. Helicopter main and tail rotor blades
9. Space vehicles: Satellites, Missiles, Rockets etc.

Aerospace composites: -

The use of composites in the aerospace industry has increased dramatically since the 1970s. Traditional materials for aircraft construction include aluminum, steel and titanium. The primary benefits that composite components can offer are reduced weight and assembly simplification. The performance advantages associated with reducing the weight of aircraft structural elements has been the major impetus for military aviation composites development. New aircraft utilize carbon, boron and aramid fibers (aeromatic polyamide fibre, synthetic fibre) combined with epoxy resins. Such materials have replaced fiberglass reinforcements.

It is important to note that the three most common types of composites that exist are composite materials that are reinforced with fiberglass, carbon fiber and aramid fiber. It is also interesting that each of these types has subtypes which provides for a wide variety of composites that exist in the world.

Throughout the last four decades the exploitation of fibre-reinforced plastics (FRP) in engineering structures has been steadily diversifying from sports equipment and high-performance racing cars, to helicopters and most recently commercial aeroplanes. Composite materials are essentially a combination of two or more dissimilar materials that are used together in order to combine best properties, or impart a new set of characteristics that neither of the constituent materials could achieve on their own. Engineering composites are typically built-up from individual plies that take the form of continuous, straight fibres (eg. carbon, glass, aramid etc.) embedded in a host polymer matrix (eg. phenolic, polyester, epoxy etc.), which are laminated layer-by-layer in order to built up the final material/structure.

Fibre		**Density (g/cc)**	**Modulus (GPa)**	**Strength (GPa)**	**Application areas**
Glass (Electrical)E-Glass		2.55	65-75	2.2-2.6	Small passenger aircraft parts,
(stiffness)S-Glass		2.47	85-95	4.4-4.8	radomes, rocket motor casings Highly loaded parts in small passenger a/c.
Aramid low modulus		1.44	80-85	2.7-2.8	Fairings, non-load bearing parts
Intermediate modulus High modulus		1.44 1.48	120-128 160-170	2.7-2.8 2.3-2.4	Radomes, some structural parts, motor casings. Highly loaded parts
Carbon Standard modulus		1.77-1.80	220-240	3-3.5	Widely used for almost all type of
Intermediate modulus High modulus		1.77-1.81 1.77-1.80	270-300 390-450	5.4-5.7 4.0-4.52	parts in satellites antenna missiles etc.. Space structures, control surface in
					a/c.

Table 3. Use and application of different composite material in aviation industries

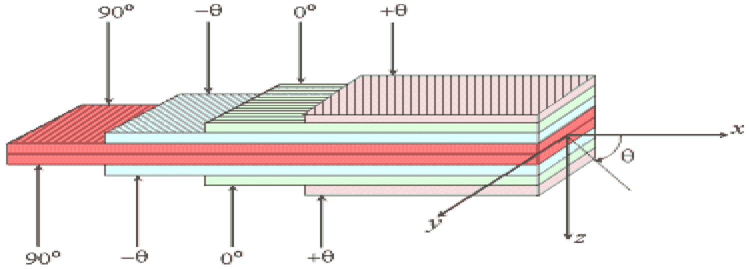
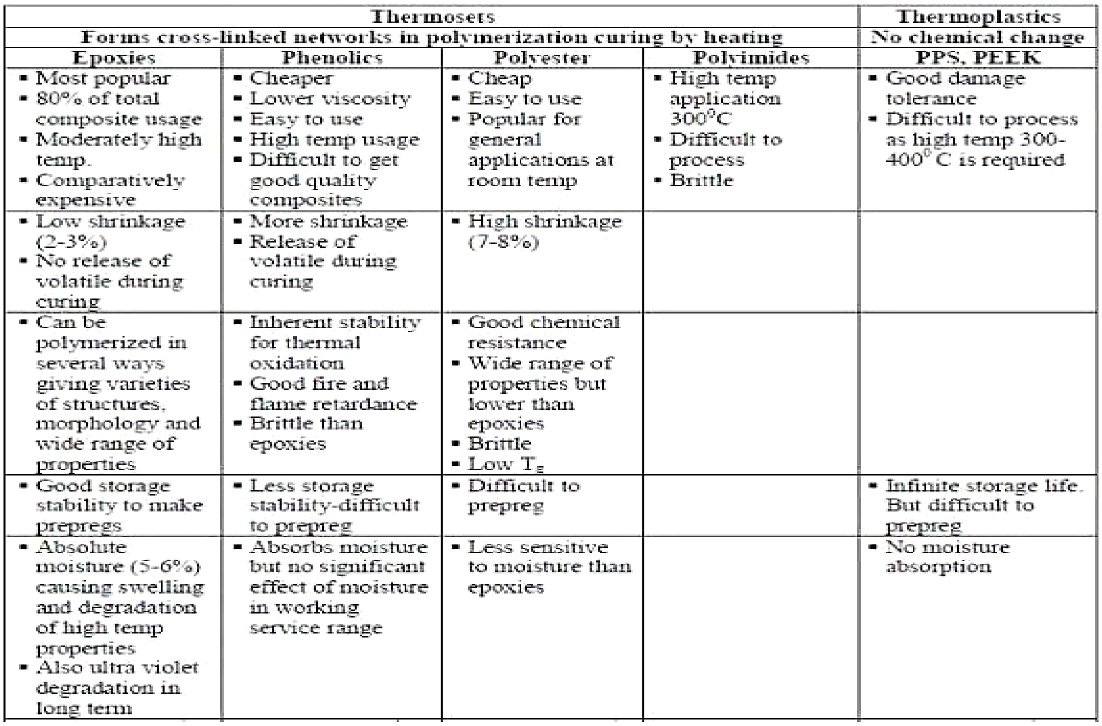


Fig. 1.21 Different orientation of fibres



Thermosets				Thermoplastics
Forms cross-linked networks in polymerization curing by heating				No chemical change
Epoxies	Phenolics	Polyester	Polyimides	PPS, PEEK
▪ Most popular ▪ 80% of total composite usage ▪ Moderately high temp. ▪ Comparatively expensive	▪ Cheaper ▪ Lower viscosity ▪ Easy to use ▪ High temp usage ▪ Difficult to get good quality composites	▪ Cheap ▪ Easy to use ▪ Popular for general applications at room temp	▪ High temp application 300°C ▪ Difficult to process ▪ Brittle	▪ Good damage tolerance ▪ Difficult to process as high temp 300-400°C is required
▪ Low shrinkage (2-3%) ▪ No release of volatile during curing	▪ More shrinkage ▪ Release of volatile during curing	▪ High shrinkage (7-8%)		
▪ Can be polymerized in several ways giving varieties of structures, morphology and wide range of properties	▪ Inherent stability for thermal oxidation ▪ Good fire and flame retardance ▪ Brittle than epoxies	▪ Good chemical resistance ▪ Wide range of properties but lower than epoxies ▪ Brittle ▪ Low T_g		
▪ Good storage stability to make prepregs	▪ Less storage stability-difficult to prepreg	▪ Difficult to prepreg		▪ Infinite storage life. But difficult to prepreg
▪ Absolute moisture (5-6%) causing swelling and degradation of high temp properties ▪ Also ultra violet degradation in long term	▪ Absorbs moisture but no significant effect of moisture in working service range	▪ Less sensitive to moisture than epoxies		▪ No moisture absorption

Table 4. Properties of different fibres

Fabrication process: -

Autoclave Moulding

This method employs an autoclave to provide heat and pressure to the composite product during curing. In this method, prepregs are stacked in a mold in a definite sequence and then spot welded to avoid any relative movement in between the prepreg sheets. After stacking the prepregs, the whole assembly is vacuum bagged to remove any air entrapped in between the layers. The schematic of autoclave molding process is shown in figure. After a definite period of time when it is ensured that all air is removed, the entire assembly is transferred to autoclave.

Here, heat and pressure are applied for a definite interval of time. In this process, matrix is uniformly distributed and intimate contact is achieved through proper bonding between fibers and matrix. After the processing, the assembly is cooled to a definite rate and then vacuum bag is removed. The composite part is taken out from the mold. Initially, a release gel is applied onto the mold surface to avoid sticking of polymer to the mold surface. The raw materials used in these techniques are given in the table.

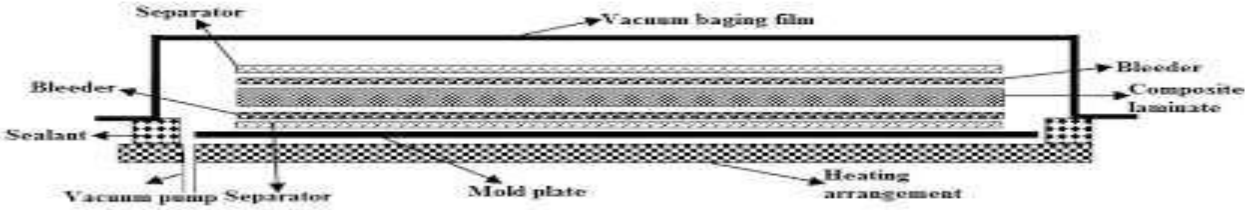


Fig. 1.21 Autoclave moulding

matrix	**Epoxy, polyester, polyvinyl ester, phenolic resin, thermoplastic resin**
Reinforcement	Glass fiber, carbon fiber, aramid fiber.

Filament moulding :-

To begin with, a large number of fibre rovings is pulled from series of creels into bath containing liquid resin, catalyst and other ingredients such as pigments and UV retardants. Fibre tension is controlled by the guides or scissor bars located between each creel and resin bath. Just before entering the resin bath, the rovings are usually gathered into a band by passing them through a textile thread board or stainless-steel comb.

At the end of the resin tank, the resin-impregnated rovings are pulled through a wiping device that removes the excess resin from the rovings and controls the resin coating thickness around each roving.

The most commonly used wiping device is a set of squeeze rollers in which the position of the top roller is adjusted to control the resin content as well as the tension in fibre rovings. Another technique for wiping the resin-impregnated rovings is to pull each roving separately through an orifice.

The latter method results in better control of resin content. Once the rovings have been thoroughly impregnated and wiped, they are gathered together in a flat band and positioned on the mandrel.

Band formation can be achieved by passing through a stainless-steel comb and later through the collecting eye. The transverse speed of the carriage and the winding speed of the mandrel are controlled to create the desired winding angle patterns.

After winding, the filament wound mandrel is subjected to curing and post curing operations during which the mandrel is continuously rotated to maintain uniformity of resin content around the circumference. After curing, product is removed from the mandrel, either by hydraulic or mechanical extractor.

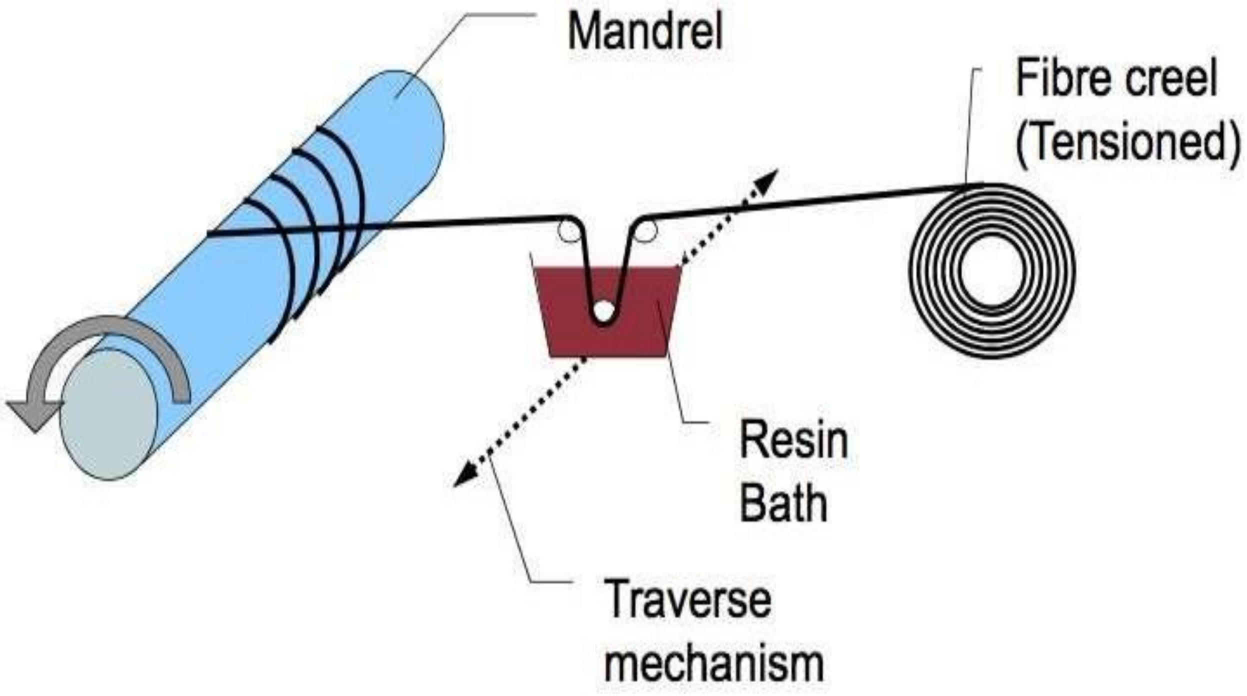


Fig. 1.22 Filament moulding

Example of use of composite in aircraft: commercial and military: -

Commercial: -

1. Boeing 777
2. Boeing 787 “Dreamliner”
3. Airbus A380

Military:

1. B-2 Bomber
2. LCA Tejas (HAL)

BOEING 777: -

Components that uses composite structure are:

1. Horizontal Stabilizer
2. Vertical Fin
3. Radom
4. Wing fairings
5. Passenger floor beams
6. Wing Box
7. Engine Cowlings
8. Engine fairings
9. Reduction in weight is over 5800 pounds.

The Boeing 757 and 767 employs about 3000 pounds each of composites for doors and control surfaces. The 767 rudders at 36 feet is the largest commercial component in service. The 737-300 uses approximately 1500 pounds of composites, which represents about 3% of the overall structural weight. Composites are widely used in aircraft interiors to create luggage compartments, sidewalls, floors, ceilings, galleys, cargo liners and bulkheads. Fiberglass with epoxy or phenolic resin utilizing honeycomb sandwich construction gives the designer freedom to create aesthetically pleasing structures while meeting flammability and impact resistance requirements.

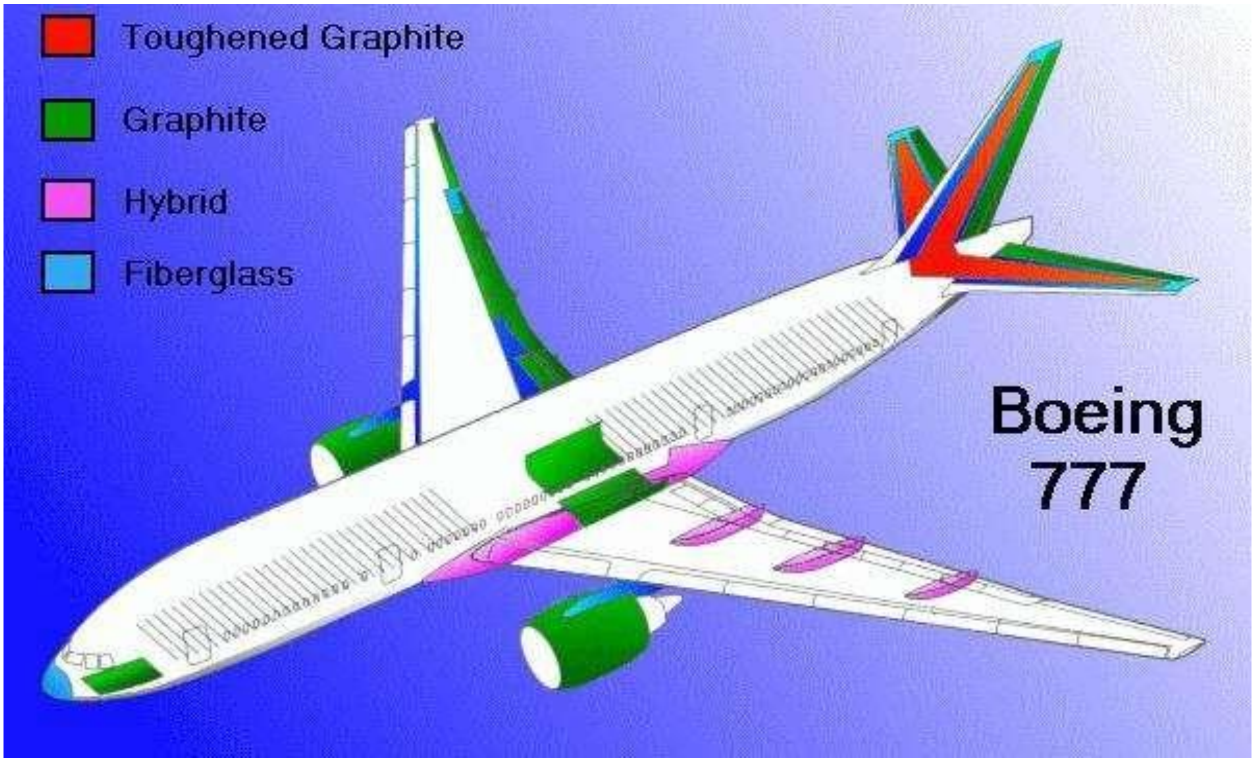


Fig. 1.22 Use of composite material Boeing 777

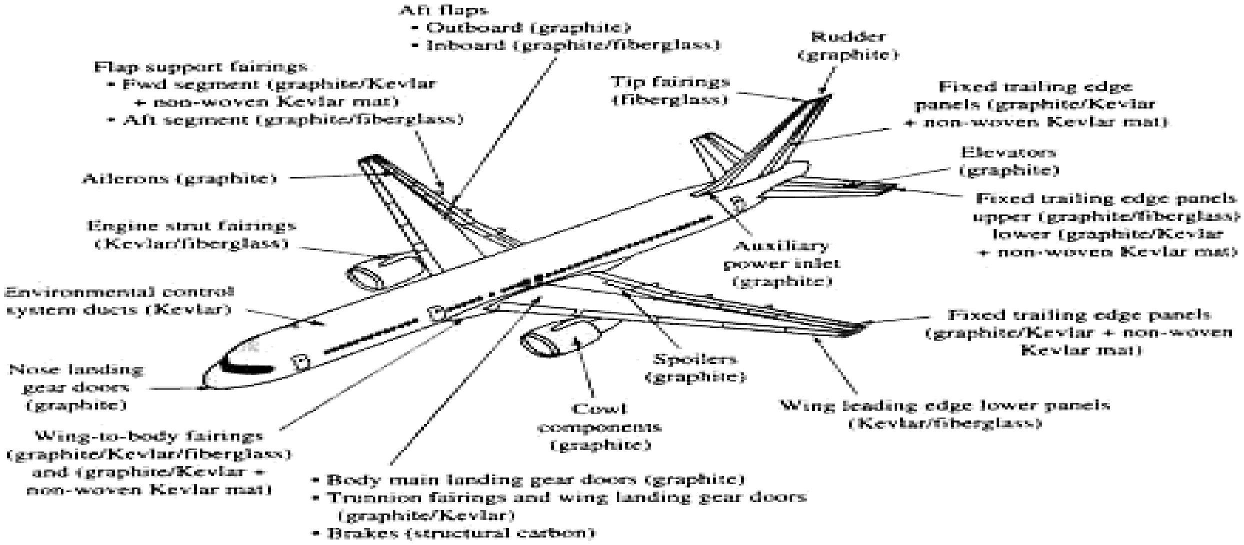


Fig. 1.23 Various parts of boing 777 with composite material

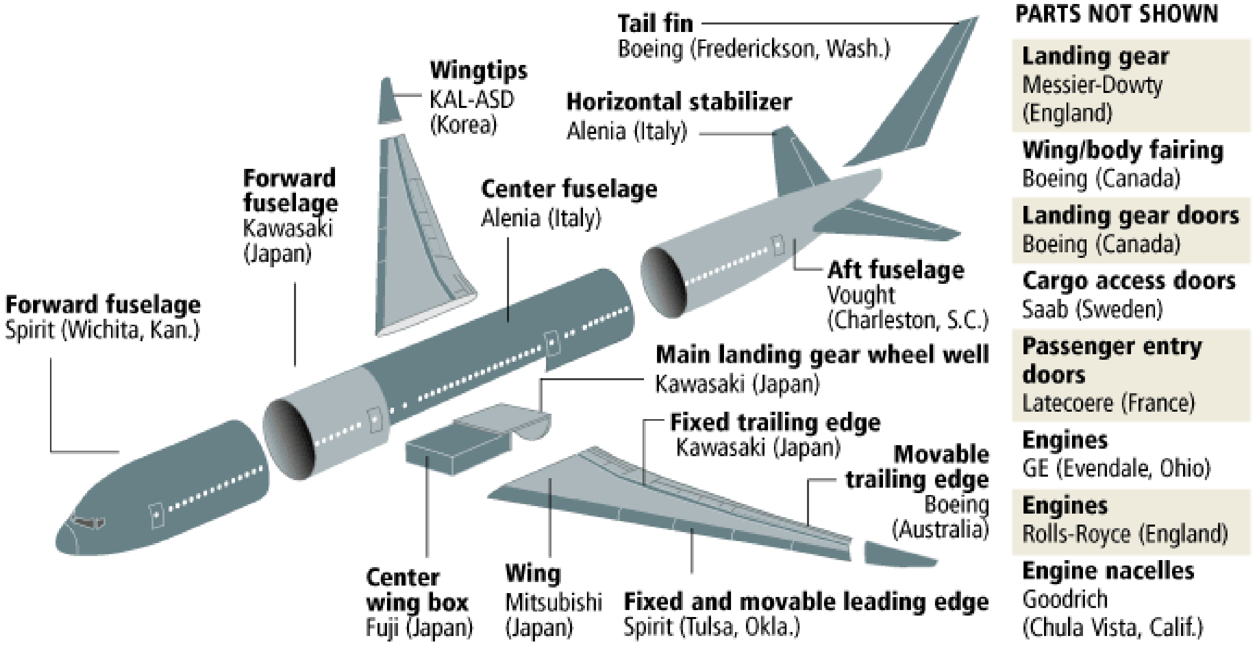


Fig. 1.24 Various parts of boing777 with country manufacturing

Boeing 787 “Dreamliner”

Components that uses composite structure are:

- Almost full fuselage
- Upper and lower wing skin
- Radom
- Wing flaps, elevators, ailerons
- Vertical Fin and Horizontal Stabilizer

Use of composite is 80% by volume and 50% by weight.

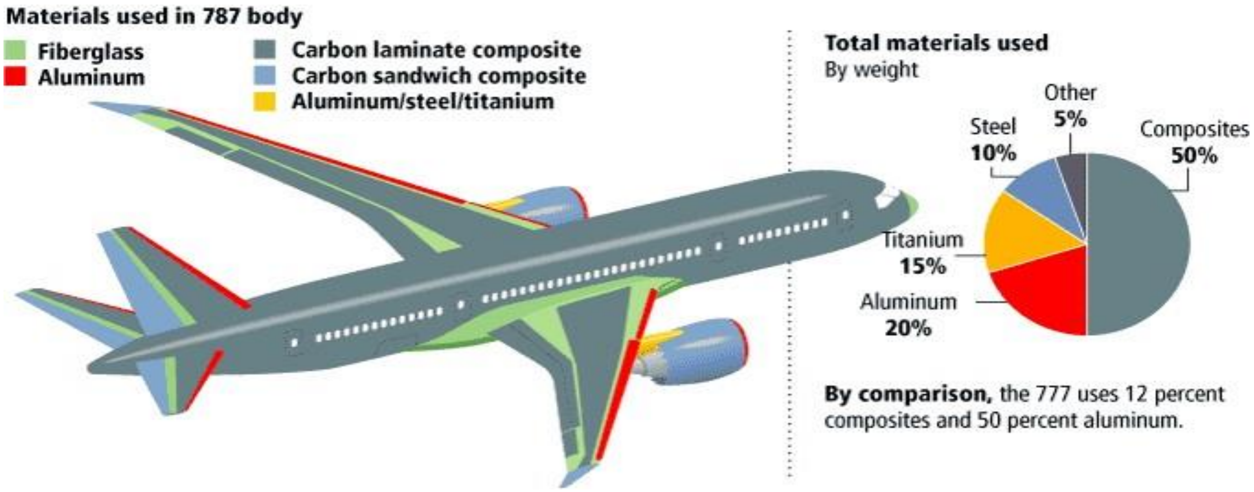


Fig. 1.24 Material used in boeing 787

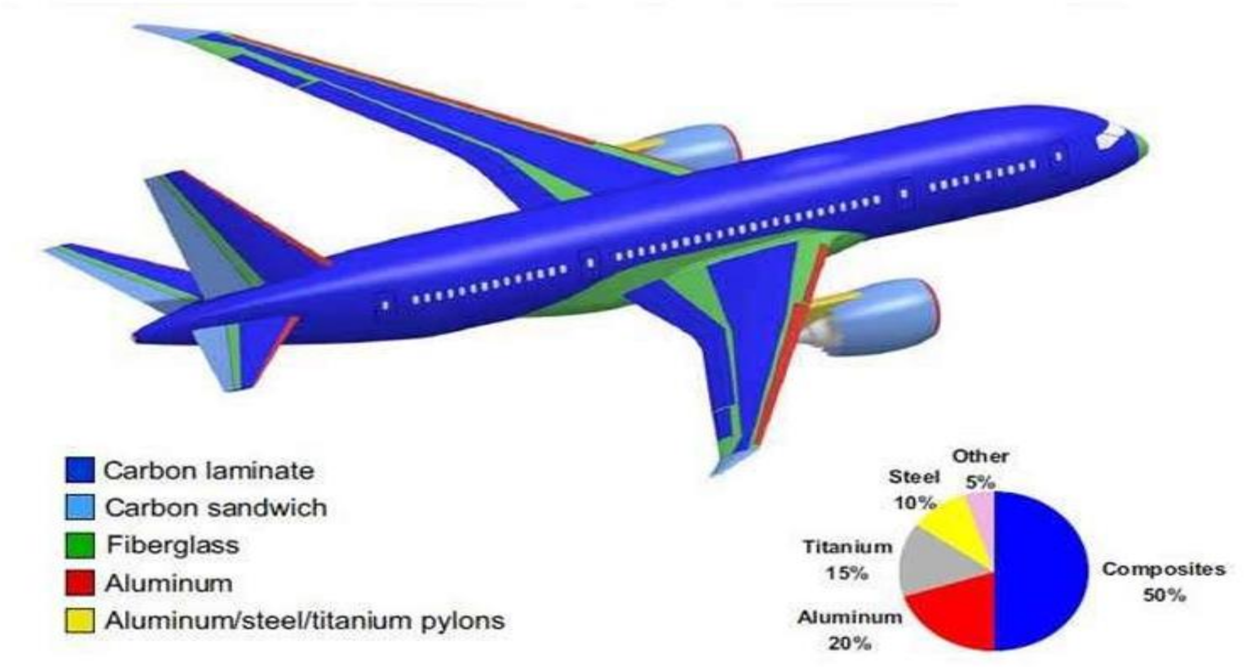


Fig. 1.25 Material used in boeing 787

Airbus A380

Components that uses composite structure are:

1. Horizontal Stabilizer
2. Vertical Fin

3. Radom
4. Wing Fairings
5. Wing Box
6. Belly Fairings
7. Engine Cowlings
8. Engine fairings

Wing box, made of CFRP, has reduced weight up to one and a half tones.

Glare: - Glass reinforcement aluminium

In 1979, a pilot project was started to manufacture carbon fiber fin box assemblies for the A300/A310 aircraft. A highly mechanized production process was established to determine if high material cost could be offset by increased manufacturing efficiency. Although material costs were 35% greater than a comparable aluminum structure, total manufacturing costs were lowered 65 to 85%. Robotic assemblies were developed to handle and process materials in an optimal and repeatable fashion.

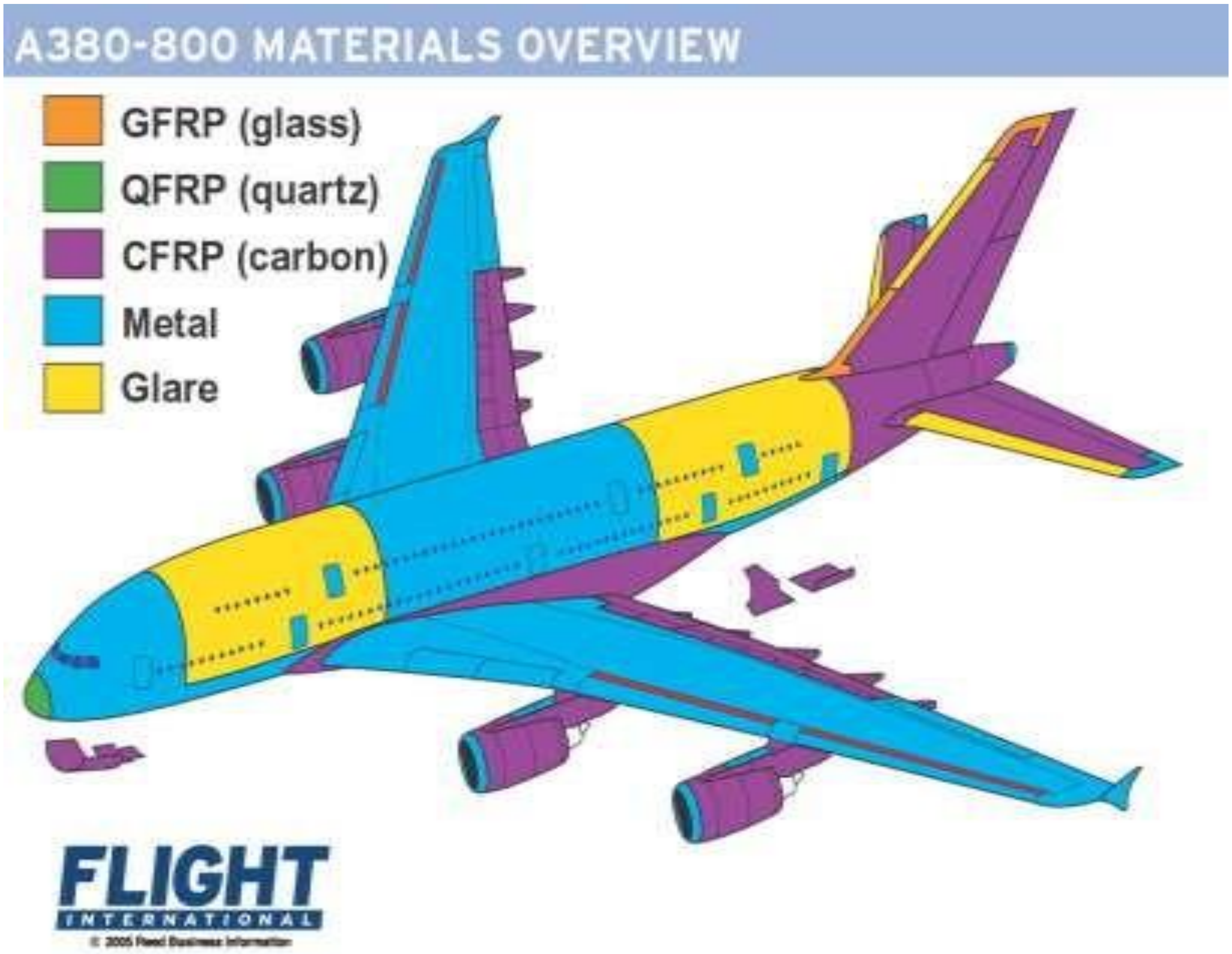


Fig. 1.26 Material used in airbus-A380

BOMBER B-2 AIRCRAFT

B-2 Bomber is mostly made of carbon/epoxy materials. The reduction in weight was about 40000 to 50000 pounds.

Design material was specially designed to absorb radar waves.

The B-2 derives much of its stealth qualities from the material properties of composites and their ability to be molded into complex shapes. Each B-2 contains an estimated 40,000 to 50,000 pounds of advanced composite materials. According to Northrop, nearly 900 new materials and processes were developed for the plane.

Fig. 1.27 Bomber B-2 aircraft

LCA (TEJAS) HAL

LCA stands for Light Combat Aircraft which is basically use of composite materials in its structure.

Components which are made of composite material are:

- Nose
- Wing upper surface and leading edge
- Exit Nozzle

Weight is reduced by 21%

NAVY FIGHTER AIRCRAFT (F-18A)

The wing skins of the F-18A represented the first widespread use of graphite/epoxy in a production aircraft. The skins vary in thickness up to one inch, serving as primary as well as secondary load carrying members. It is interesting to note that the graphite skins are separated from the aluminium framing with a fiberglass barrier to prevent galvanic corrosion. The carrier-based environment that Navy aircraft are subjected to has presented unique problems to the aerospace designer. Corrosion from salt water surroundings is exacerbated by the sulphur emission from the ship's exhaust stacks.

Fig. 1.28 Navy fighter aircraft (f-18a)

Osprey Tilt-Rotor (V-22)

The tilt-rotor V-22 is also a weight sensitive craft that is currently being developed by Boeing and Bell Helicopter. Up to 40% of the airframe consists of composites, mostly AS-4 and IM-6 graphite fibres in 3501-6 epoxy (both from Hercules). New uses of composites are being exploited on this vehicle, such as shafting and thick, heavily loaded components. Consequently, higher design strain values are being utilized.sd

Fig. 2.29 Osprey Tilt-Rotor (V-22)

Disadvantages of composite material: -

Use of composite is more challenging to design.

1. NDT test for composite material is much more difficult as compared to metals.
2. Delamination of layers.
3. High cost
4. Damage tolerance.
5. Need specialized repair techniques.

References:

1.Analysis and Performance of Fiber Composites – B.D. Agarwal, L.J. Broughtman and K. Chandrashekar, John Wiley & Sons.Inc.

2. Principles of Composite Material Mechanics, R.F. Gibson, CRC Press.

3. Prepregs and Autoclave Moulding, Dr.S.K. Malhotra,Comptec,Course Module,IIT Madras.

4. Vacuum Impregnation Methods, Dr. B.J.C. Babu, Comptec, Course Module,IITMadras.

5. Resin Transfer Moulding, N.G. Nair Comptec, Course Module, IIT Madras.

6. Filament Moulding of FRP, N.G. Nair, Comptec, Course Module, IIT Madras.

7. Hard layup for FRP Fabrication, N.G. Nair, Course Module, IIT Madras.

UNIT-III

Analysis and Strength of An Orthotropic Lamina: Strain relations and engineering constants, relation between engineering constants and stiffness coefficients, strength of an orthotropic lamina, failure theories,

ORTHOTROPIC MATERIALS: -

There are three mutually orthogonal planes of material property symmetry in an orthotropic material. Fiber-reinforced composites, in general, contain the three orthogonal planes of material property symmetry and are classified as orthotropic materials. The intersections of these three planes of symmetry are called the principal material directions.

The material behaviour is called as especially orthotropic, when the normal stresses are applied in the principal material directions. Otherwise, it is called as general orthotropic which behaves almost equivalent to anisotropic material.

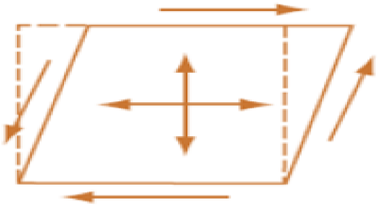
In material science and solid mechanics, orthotropic materials have material properties that differ along three mutually-orthogonal twofold axes of rotational symmetry. They are a subset of anisotropic materials, because their properties change when measured from different directions.

A familiar example of an orthotropic material is wood. In wood, one can define three mutually perpendicular directions at each point in which the properties are different. These are the axial direction (along the grain), the radial direction, and the circumferential direction. Because the preferred coordinate system is cylindrical-polar, this type of orthotropy is also called polar orthotropy. Mechanical properties, such as strength and stiffness, measured axially (along the grain) are typically better than those measured in the radial and circumferential directions (across the grain). These directional differences in strength can be quantified with Hankinson's equation.

There are nine independent elastic constants in the stiffness matrix as given below for an especially orthotropic material.

According to stress-strain relationship it is clear that normal stresses applied in one of the principal material directions on an orthotropic material cause elongation in the direction of the applied stresses and contractions in the other two transverse directions. However, normal stresses applied in any directions other than the principal material directions create both extensional and shear deformations.

$$\begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \tau_{23} \\ \tau_{31} \\ \tau_{12} \end{Bmatrix} = \begin{pmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{13} & C_{23} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{pmatrix} \begin{Bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ \gamma_{23} \\ \gamma_{31} \\ \gamma_{12} \end{Bmatrix}$$



Material behavior is represented in physical theories by constitutive relations. A large class of physical behaviors can be represented by linear material models that take the form of a second-order tensor. The material tensor provides a relation between two vectors and can be written as

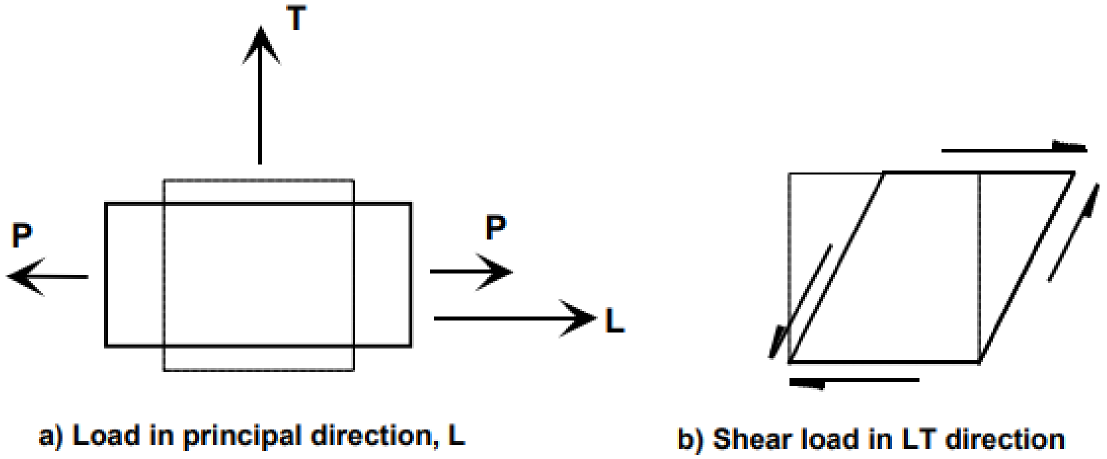
$$\mathbf{f} = \boldsymbol{K} \cdot \mathbf{d}$$

where d, f are two vector representation physical quantity and K is the second-order material tensor. If we express the above equation in terms of components with respect to an orthonormal coordinate system, we can write

$$f_i = K_{ij}\, d_j$$

$$\underline{\mathbf{f}} = \underline{\underline{\boldsymbol{K}}}\, \underline{\mathbf{d}} \implies \begin{bmatrix} f_1 \\ f_2 \\ f_3 \end{bmatrix} = \begin{bmatrix} K_{11} & K_{12} & K_{13} \\ K_{21} & K_{22} & K_{23} \\ K_{31} & K_{32} & K_{33} \end{bmatrix} \begin{bmatrix} d_1 \\ d_2 \\ d_3 \end{bmatrix}$$

In an orthotropic material there are two unique mutually orthogonal directions (called the principal material directions) in which tension load causes extension only parallel and perpendicular to the tensile load direction, and shear load causes shear strains only. The effects of extensional and shear loads in the principal directions on the strains in an orthotropic material are shown in Fig. 2 (a). The unstrained lamina is shown as dotted lines in this figure. The extensional load shown in Fig.2 (b) causes only extension in the longitudinal direction and contraction in the transverse direction.



a) Load in principal direction, L

b) Shear load in LT direction

Fig. 2 (a) (b) Orthotropic lamina loaded in principal directions or isotropic lamina loaded in any direction

Also, we have defined four stiffness constants [Q], which can be used to evaluate stresses in terms of strains. Additionally, we have defined four compliance constants [S], which relate strains and stresses. Relationships between components of [S] and [Q}have also been defined. However, neither components of [S] nor those of [Q] are easy to measure. Hence, there is a need to define a third set of constants, known as “engineering constants”, which may be determined experimentally. Isotropic materials have two independent engineering constants. These are; Young’s modulus (E), and Poisson’s ratio (ν). Similarly, we need four, easy to measure engineering constants for two dimensional orthotropic materials, which may be used to calculate elements of [Q] and [S] matrices.

TWO-DIMENSIONAL ORTHOTROPIC: -

A two-dimensional orthotropic linearly elastic lamina has four engineering constants. These are:

- **Longitudinal modulus (E_L):** If a unidirectional lamina is pulled in tension along its fiber length, then its longitudinal modulus is defined as:

$E_L = \sigma_L/\varepsilon_L$ ………………………………………………………………………A

- **Transverse modulus (E_T):** If a unidirectional lamina is pulled in tension across its fiber length, i.e. transversely, then its transverse modulus is defined as:

$E_T = \sigma_T/\varepsilon_T.$ …………………………………………………………………………… B

- **Shear modulus (G_{LT}):** If a unidirectional lamina is subjected to pure shear in L-T plane, then its shear modulus is defined as:

$G_{LT} = \tau_{LT}/\gamma_{LT}.$ ………………………………………………………………………C

- **Major Poisson's ratio (ν_{LT}):** It is the ratio of negative of transverse strain and longitudinal strain for a unidirectional lamina pulled in fiber direction. Mathematically:

$\nu_{LT} = -\varepsilon_T/\varepsilon_L.$ ……………………………………………………………………...D

Engineering constants are generalized young's moduli, poisons ratios, and shear moduli as well as some other behavioral constants. These constants re measured in simple tests such as uniaxial tension or pure shear tests.

Most simple material characterization tests are performed with a known load or stress. The resulting displacement or strain is then measured. The engineering constant are generally the slope of the stress-strain curve (e.g E = stress/strain) or the slope of a stress-strain curve (e.g poison ratio = transverse strain/ longitudinal strain). Thus, the components of the compliance (S_{ij}) matrix are determined more directly than those of the stiffness (C_{ij}) matrix. For and orthotropic material, the compliance matric components in terms of the engineering constants are

$$[S_{ij}] = \begin{bmatrix} \frac{1}{E_1} & -\frac{v_{21}}{E_2} & -\frac{v_{31}}{E_3} & 0 & 0 & 0 \\ -\frac{v_{12}}{E_1} & \frac{1}{E_2} & -\frac{v_{32}}{E_3} & 0 & 0 & 0 \\ -\frac{v_{13}}{E_1} & -\frac{v_{23}}{E_2} & \frac{1}{E_3} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{23}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{31}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{12}} \end{bmatrix}$$

Where,

E_1, E_2, E_3 = Youngs moduli in the 1, 2 and 3 directions

v_{ij} = Poissons ratio i.e the negative of the transverse strain inn the j-direction over the strain in the j-direction when stress is applied in the i-direction i.e

$v_{ij} = \epsilon_j / \epsilon_i$

G_{23}, G_{31}, G_{12} = shear modulii in the 2-3, 3-1, and 1-2 plane.

ORTHOTROPIC MATERIAL: -

For orthotropic materials, the relations between engineering constant are more complex. First, the product of a stress and the corresponding strain represents work done by the stress. The sum of work done by all stresses must be positive in order to avoid the creation of energy. This later condition provides the thermodynamic constraint on the values of the engineering constants.

This mathematically condition can be replaced by the following physical argument. If only one normal stress is applied at a time, the corresponding strain is determined by the diagonal elements of the compliance matrix. Thus the element must be positive,

$S_{11}, S_{22}, S_{33}, S_{44}, S_{55}, S_{66} > 0$ ……………1

Or, in terms of the engineering constants,

$E_1, E_2, E_3, G_{23}, G_{31}, G_{12} > 0$ …………….2

Similarly, under suitable constraints, deformation is possible in which only one extensional strain arises or is applied. Again, work is produced by the corresponding stress alone. Thus, because the work done is determined by the diagonal elements of the stiffness matrix, those elements must be positive, that is

$C_{11}, C_{22}, C_{33}, C_{44}, C_{55}, C_{66} > 0$ ……………......3

As for orthotropic material the matrix algebra is: -

$$C_{11} = \frac{1 - \nu_{23}\nu_{32}}{E_2E_3\Delta} \qquad C_{22} = \frac{1 - \nu_{13}\nu_{31}}{E_1E_3\Delta}$$

$$C_{12} = \frac{\nu_{21} + \nu_{31}\nu_{23}}{E_2E_3\Delta} = \frac{\nu_{12} + \nu_{32}\nu_{13}}{E_1E_3\Delta} \qquad C_{23} = \frac{\nu_{32} + \nu_{12}\nu_{31}}{E_1E_3\Delta} = \frac{\nu_{23} + \nu_{21}\nu_{13}}{E_1E_2\Delta}$$

$$C_{13} = \frac{\nu_{31} + \nu_{21}\nu_{32}}{E_2E_3\Delta} = \frac{\nu_{13} + \nu_{12}\nu_{23}}{E_1E_2\Delta} \qquad C_{33} = \frac{1 - \nu_{12}\nu_{21}}{E_1E_2\Delta} \qquad (2.36)$$

$$C_{44} = G_{23} \qquad C_{55} = G_{31} \qquad C_{66} = G_{12}$$

where

$$\Delta = \frac{1 - \nu_{12}\nu_{21} - \nu_{23}\nu_{32} - \nu_{31}\nu_{13} - 2\nu_{21}\nu_{32}\nu_{13}}{E_1E_2E_3} \qquad (2.37)$$

Then this above equation become,

$$(1 - \nu_{23}\nu_{32}) > 0 \qquad (1 - \nu_{13}\nu_{31}) > 0 \qquad (1 - \nu_{12}\nu_{21}) > 0 \qquad (2.47)$$

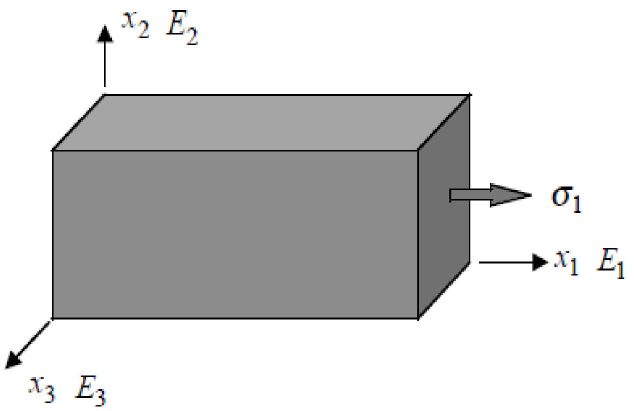
and

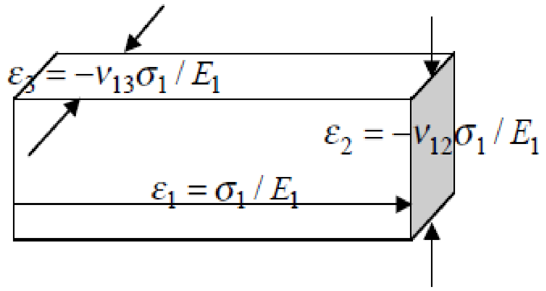
$$\overline{\Delta} = 1 - \nu_{12}\nu_{21} - \nu_{23}\nu_{32} - \nu_{31}\nu_{13} - 2\nu_{21}\nu_{32}\nu_{13} > 0 \qquad (2.48)$$

Now, above condition (equation 2.47) will be,

$$|\nu_{21}| < \sqrt{\frac{E_2}{E_1}} \qquad |\nu_{32}| < \sqrt{\frac{E_3}{E_2}} \qquad |\nu_{13}| < \sqrt{\frac{E_1}{E_3}} \qquad (2.51)$$

$$|\nu_{12}| < \sqrt{\frac{E_1}{E_2}} \qquad |\nu_{23}| < \sqrt{\frac{E_2}{E_3}} \qquad |\nu_{31}| < \sqrt{\frac{E_3}{E_1}}$$

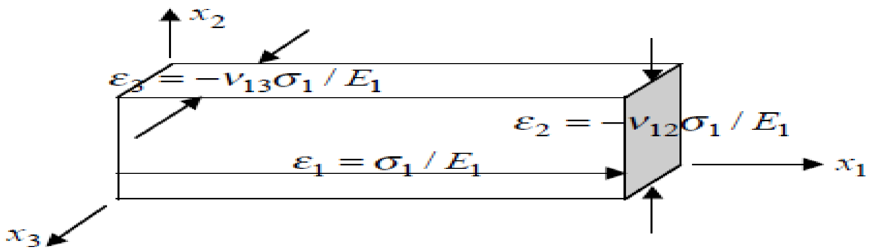




Definition:

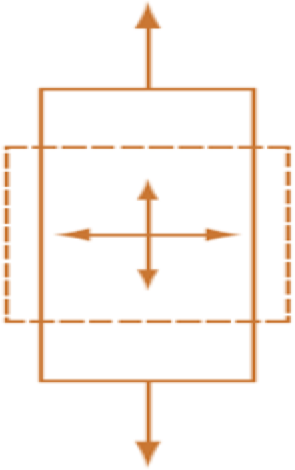
Elastic Modulus (E_1) = Stress/Strain = σ_1/ε_1

Poisson's Ratio (ν_{12}) = - Transverse strain/Applied strain = $-\varepsilon_2/\varepsilon_1$

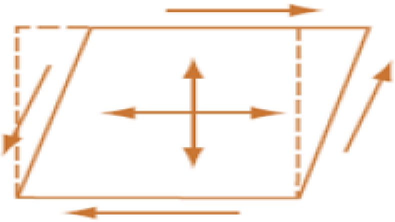


Normal Strains	Applied Stresses		
	σ_1	σ_2	σ_3
$in - x_1$	σ_1 / E_1	$-\nu_{21}\sigma_2 / E_2$	$-\nu_{31}\sigma_3 / E_3$
$in - x_2$	$-\nu_{12}\sigma_1 / E_1$	σ_2 / E_2	$-\nu_{32}\sigma_3 / E_3$
$in - x_3$	$-\nu_{13}\sigma_1 / E_1$	$-\nu_{23}\sigma_2 / E_2$	σ_3 / E_3

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



Specially Orthotropic



RELATIONSHIP BETWEEN ENGINEERING CONSTANTS AND ELEMENTS OF STIFFNESS CONSTANTS [Q] & COMPLIANCE (ELASTICITY) CONSTANTS [S] MATRICES: -

Consider an orthotropic lamina under arbitrary state of stress such that:

– Stress in fiber direction is σ_L

– Stress in transverse direction is σ_T

– Shear stress in L-T plane is τ_{LT}

• Such a lamina will exhibit strains due these stresses. These strains are:

– ε_L: Strain in the fiber direction

– ε_T: Strain in transverse direction

– γ_{LT}: Shear strain in L-T plane

• If, the lamina is stressed only in the longitudinal direction (i.e. σ_T, and τ_{LT} are zero) then, using we can write:

– $\sigma_L = Q_{11}\,\varepsilon_L + Q_{12}\,\varepsilon_T$

$-\sigma_T = Q_{12}\,\varepsilon_L + Q_{22}\,\varepsilon_T$

This above equation comes from below matrix :-

$$\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \tau_{23} \\ \tau_{31} \\ \tau_{12} \end{Bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & Q_{13} & 00 & 00 & 00 \\ Q_{12} & Q_{22} & Q_{23} & 00 & 00 & 00 \\ Q_{13} & Q_{23} & Q_{33} & 00 & 00 & 00 \\ 00 & 00 & 00 & Q_{44} & 00 & 00 \\ 00 & 00 & 00 & 00 & Q_{55} & 00 \\ 00 & 00 & 00 & 00 & 00 & Q_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \gamma_{23} \\ \gamma_{31} \\ \gamma_{12} \end{Bmatrix}$$

Solving for strains we get:

$\varepsilon_L = Q_{22} / (Q_{11}\,Q_{22} - Q^2_{12})\,\sigma_L$

$\varepsilon_T = Q_{12} / (Q_{11}\,Q_{22} - Q^2_{12})\,\sigma_L$

- Rearranging these equations, we get:

$\sigma_L/\varepsilon_L = (Q_{11}\,Q_{22} - Q^2_{12})/Q_{22}$

$\sigma_L/\varepsilon_T = -(Q_{11}\,Q_{22} - Q^2_{12})/Q_{12}$

- Recognizing the definitions of longitudinal modulus, and major Poisson's ratio from Eqs. A, and D respectively, and comparing those with above equations, we can write:

$E_L = (Q_{11}\,Q_{22} - Q^2_{12})/Q_{22}$ (Eq. E)

$\nu_{LT} = Q_{12}/Q_{22}$ (Eq. F)

- And similarly, we can also write:

$E_T = (Q_{11}\,Q_{22} - Q^2_{12})/Q_{11}$ (Eq. G)

$GLT = Q_{66}$

Similarly, engineering constants can also be used to define elements of compliance matrix. The methodology for developing these relations is very similar to one used earlier to develop.

- Here we directly write the resulting equations.

$S_{11} = 1/E_L$ ……. (Eq. H)

$S_{22} = 1/E_T$ ……… (Eq. I)

$S_{12} = -\nu_{LT} /EL = -\nu T_L /E_T$ …… (Eq. J)

$S_{66} = 1/G_{LT}$ ……. (Eq. K)

STRENGTH OF AN ORTHOTROPIC LAMINA: -

The strength characteristics of an orthotropic lamina are just as important a building block in the description of laminates as the stiffness characteristics. As review, from previous studies, the central issue ere is that principle stresses and strains are the largest values irrespective of direction or orientation; however, direction of stresses or strain has, by definition, absolutely no significant for isotropic materials. because of orthotropy, the axes of principle stress might not be the stress governing the design.

For a lamina stresses in its own plane, there are three fundamental strength if the lamina has equal strengths in tension and compression:

X = axial or longitudinal strength (1- direction)

Y = Transverse strength (2 – direction)

S = shear strength (in 1-2 coordinated)

The directions of each of these strength in figure 3; obviously, the strength results from independent application of the respective stresses $\sigma_1, \sigma_2, \tau_{12}$.

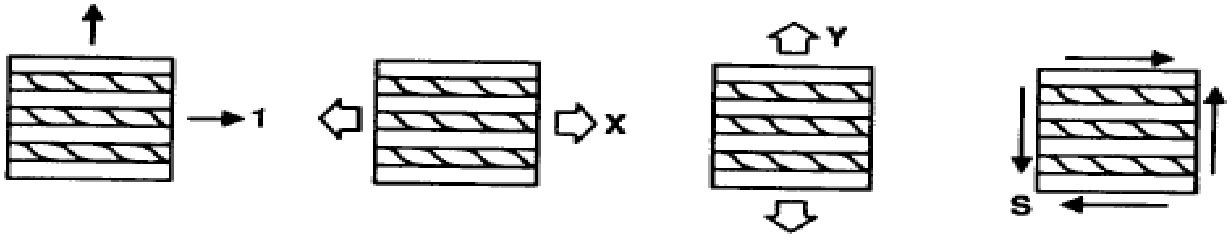


Fig. 3 Fundamental strength for a unidirectionally reinforcement lamina

That the principal stresses are not of interest in determining the strength of an orthotropic lamina is a following example. Consider the lamina with unidirectional fibers in fig. 3. Say that the hypothetical strength of the lamina in the 1-2 plane are

$X = 50{,}000$ psi (350 MPa)

$Y = 1{,}000$ psi (7MPa)

$S = 2{,}000$ psi (14 MPa)

The stiffness would also be high in the 1- direction and low in the 2- direction as is easily imagined on the physical basis of the fiber orientation. Now, the plane 1-2, the stresses are: -

$$\sigma_1 = 45{,}000 \text{ psi (315 MPa)}$$
$$\sigma_2 = 2{,}000 \text{ psi (14 MPa)}$$
$$\tau_{12} = 1{,}000 \text{ psi (7 MPa)}$$

Then, obviously the maximum principle stress is lower than the largest strength. However, σ_2 is greater than Y, so the lamina must fail under the imposed stresses. The key observation is that strength is a function of orientation of stresses relative to the principal material coordinates of an orthotropic lamina. In contrast, for an isotropic material, strength is independent of material orientation relative to the imposed stresses.

If the material has different properties in tension and compression as do most composite materials, then the following strength are required;

X_t = axial or longitudinal strength in tension

X_c = axial or longitudinal strength in compression

Y_t = transverse strength in tension

Y_c = transverse strength in compression

S = shear strength

The shear strength in the principle material coordinates is seen to be independent of differences in tensile and compression behavior, as it must be by definition of a pure shear stress. That is, the shear stress, whether "positive" or "negative" has the same maximum value in principal material coordinates for materials the exhibits different behavior in tension than in compression.

However, the maximum value of shear stress in other than principal material coordinates depends on the sign of the shear stress. For example, at 45º to the principal material axes, positive and negative shear stresses result in normal stresses of opposite signs on the fibers as in fig. 4. There, for positive shear stress, tensile stresses results in the fiber direction, and compression stresses arises perpendicular to the fibers.

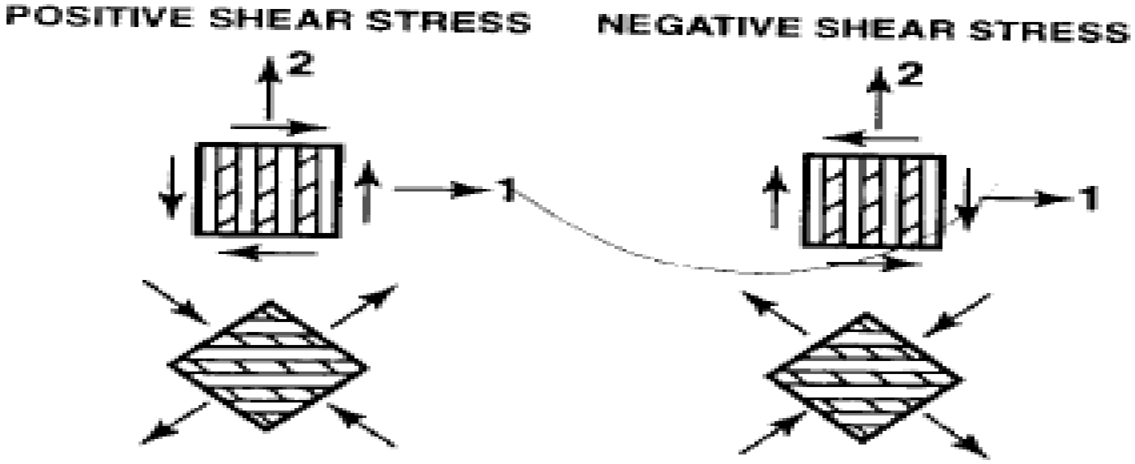


Fig. 4 Shear stress in principal material coordinates

For negative shear stress, compressive shear exist in the fiber direction and tensile stresses occurs transverse to the fibers. However, both the normal strengths and normal stiffnesses for the material are different for the material are different under tension loading than under compression loading. Thus, the apparent shear strengths and shear stresses applied at 45º to the principal material coordinates.

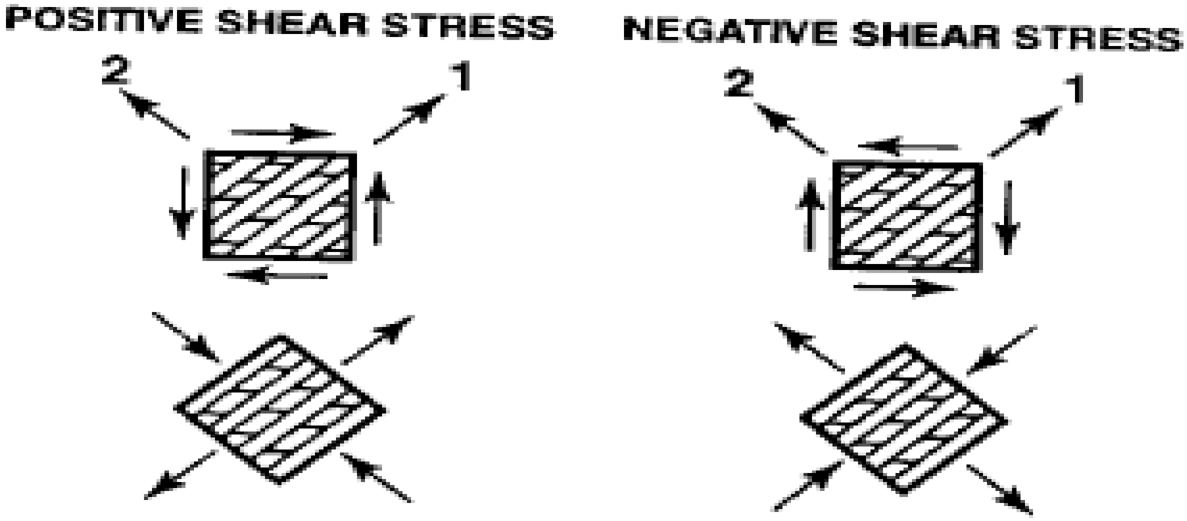


Fig. 6 Shear stress at 45º to principal material coordinates

The foregoing example is but one of the difficulties encountered in analysis of orthotropic materials with different properties in tension and compression.

Experimental determination of strength and stiffness: -

For orthotropic materials, certain basic experiments can be performed to measure the properties in the principal material coordinates. The experiments, if conducted properly, generally reveal both the strength and stiffness characteristics of the material. Recall that the stiffness characteristics are

E_1 = Youngs modulus in the 1- direction

E_2 = Youngs modulus in the 2- direction

$\upsilon_{12} = - \epsilon_2 / \epsilon_1$ for $\sigma_1 = \sigma$ and all other stresses are zero

$\upsilon_{21} = - \epsilon_1 / \epsilon_2$ for $\sigma_2 = \sigma$ and all other stresses are zero

G_{12} = shear modulus in 1-2 coordinates

Where only three of E_1, E_2, υ_{12}, υ_{21} are independent, and the strength characteristics are

X = axial or longitudinal strength (1- direction)

Y = Transverse strength (2 – direction)

S = shear strength (in 1-2 coordinated)

Where X and Y can have different values in tension and compression.

Several experiments will now be described from which the foregoing basic stiffness and strength information can be obtained. For many, but not all, composite materials, the stress- strain behavior is linear from zero load to the ultimate or fracture load. Such linear behavior is typically for epoxy-glass composite material.

A key element in the experimental determination of the stiffness and strength characteristics of lamina is the imposition of a uniform stress state in the specimen.

Before we examine any specific tests, we need to examine the testing or measurement process itself. Thus, we must,

- Understand the purpose of the test
- Visualize the expected results
- Know opportunities for error

We would probably agree on the following criteria for a good test specimen:

1. The highest stress must occur in the gage section (region of smallest cross-sectional area) so, that failure occurs in the gage section.
2. A uniform stress field must exist over the entire gage-section volume to eliminate volume-based statistical failure effects.
3. The specimen material and the test procedure must be represented of the indended application fom the standpoint of:-
    a. Fabrication
    b. Size effect (the characterstics dimensions of the specimen i.e thickness)
    c. Environment (the loading rate, moisture content and temperature of the specimen)

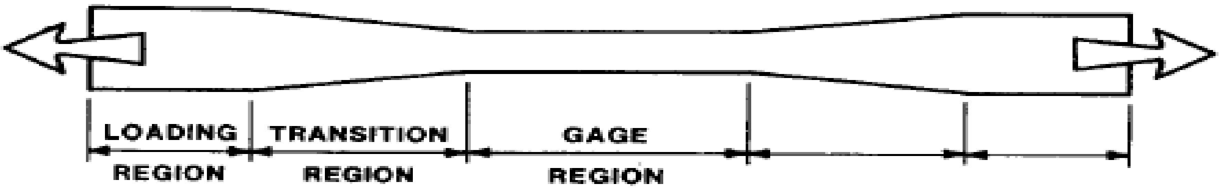
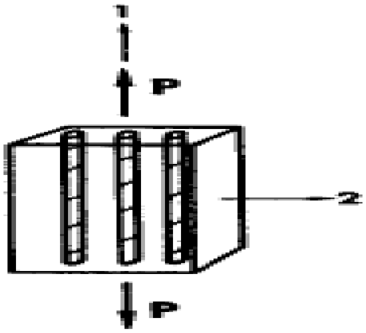


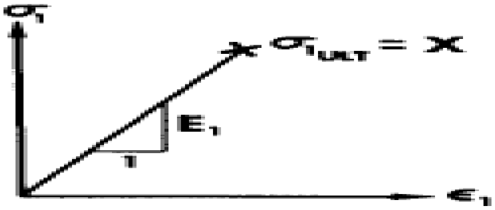
Fig. 7 Test specimen region of concern

First, consider uniaxial tension loading in the 1- direction on a flat piece of unidirectionally reinforcement lamina where only the gage section is fig. 8. The specimen thickness is not just one lmina, but several laminae all of which are the same orientation. The strain ϵ_1 and ϵ_2 are measured so,

$$\sigma_1 = \frac{P}{A} \qquad E_1 = \frac{\sigma_1}{\varepsilon_1} \qquad \nu_{12} = -\frac{\varepsilon_2}{\varepsilon_1} \qquad X = \frac{P_{ult}}{A}$$

Where A is the gage section cross-sectional area perpendicular to the applied load and P_{ult} is the ultimate load on the specimen.





As the second major measurement, consider uniaxial tension loading in the 2- direction on a flat piece of unidirectionally reinforced lamina as fig. 8. As in the first experiment, ϵ_1 and ϵ_2 are measurement as

$$\sigma_2 = \frac{P}{A} \qquad E_2 = \frac{\sigma_2}{\varepsilon_2} \qquad \nu_{12} = -\frac{\varepsilon_1}{\varepsilon_2} \qquad Y = \frac{P_{ult}}{A}$$

Where again A is the cross-sectional area of the gage section and P_{ult} is the ultimate load on the specimen.

The stiffness properties should satisfy the reciprocal relations

$$\frac{\nu_{12}}{E_1} = \frac{\nu_{21}}{E_2}$$

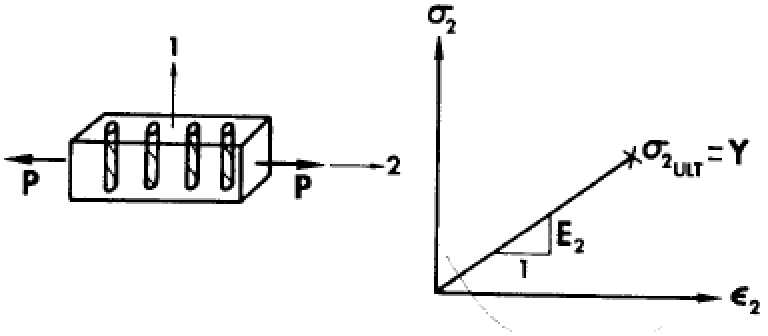


Fig. 9 Uniaxial loading in the 2- direction

As the third major measurement to try to determine the remaining properties G_{12} and S, consider uniaxial tension loading at 45° to the 1-direction on a flat piece of lamina.

$$E_x = \frac{P/A}{\varepsilon_x}$$

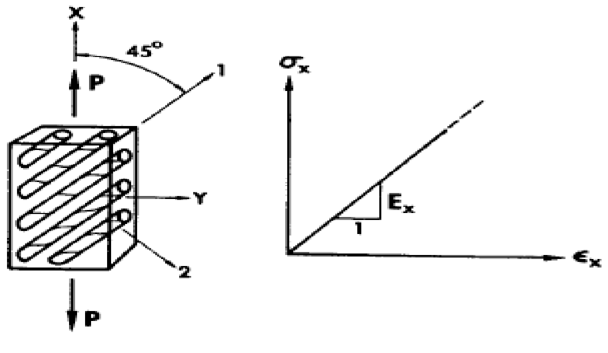


Fig. 10 Uniaxial loading at 45° to the 1-direction

FAILURE THEORIES: -

Similarly, for 2-D orthotropic materials, we evaluate allowable stress field in context of five different strengths of material measured with respect to its principal material directions.

These are:

– Longitudinal tensile strength (σ_{LU})

– Lateral or transverse tensile strength (σ_{TU})

– Longitudinal compressive strength (σ'_{LU})

– Lateral or transverse compressive strength (σ'_{TU})

– In-plane shear strength (τ_{LTU})

• These material strength parameters for an orthotropic lamina are its fundamental material properties.

Similar to isotropic materials, several theories have been developed to predict failure in orthotropic materials. Some of the more widely used theories are based on maximum stress, maximum strain, and maximum work.

• **Maximum Stress Theory**: As per this theory, failure will occur once stresses measured with respect to principal material axes, exceed their respective allowable limits. Thus, for failure at least one of the following conditions must be violated.

For tensile loads:

$\sigma_L < \sigma_{LU}$, $\sigma_T < \sigma_{TU}$, $\tau_{LT} < \tau_{LTU}$.

For compressive loads:

$\sigma_L < \sigma'_{LU}$, $\sigma_T < \sigma'_{TU}$.

• One limitation of this theory is that different modes of potential failure do not interact with each other.

Maximum Strain Theory: As per this theory, failure will occur once strains measured with respect to principal material axes, exceed their respective allowable limits. Thus, for failure, at least one of the following five conditions must be violated.

For normal tensile strains the conditions are:

$\varepsilon_L < \varepsilon_{LU}$, $\varepsilon_T < \varepsilon_{TU}$, $\gamma_{LT} < \gamma_{LTU}$.

And if normal strains are compressive, then failure criteria are:

$\varepsilon_L < \varepsilon'_{LU}$, $\varepsilon_T < \varepsilon'_{TU}$. (Eq. A)

- If material is linearly elastic, then Eq. 24.15 can be re-written as:

$\varepsilon_L < \sigma_{LU} /E_L$, $\varepsilon_T < \sigma_{TU} /E_T$, $\gamma_{LT} < \tau_{LTU}/G_{LT}$.

$\varepsilon_L < \sigma'_{LU} /E_L$ $\varepsilon_T < \sigma'_{TU} /E_T$. (Eq. B)

- Predictions from maximum stress and maximum strain theories are very similar, with minor differences being attributable to role of Poisson's ratio. This is true for linear elastic materials. For non-linear elastic materials, Eq. B should not be used, and significant difference should be expected between results from these two theories.

Tsai Hill or Ma Tsai-Maximum Work Theory: As per this theory, failure occurs when the following inequality condition is violated.

$(\sigma_L /\sigma_{LU})^2 - (\sigma_L /\sigma_{LU}) (\sigma_T /\sigma_{TU}) + (\sigma_T/\sigma_{TU})^2 + (\tau_{LT} /\tau_{LTU})^2 < 1$ (Eq. C)

- Here, if normal stresses are compressive then compressive strength should be used in the equation. Also, if the lamina is subjected to unidirectional normal stress, then above equation can be simplified as:

$(\cos 2\theta/\sigma_{LU})^2 - (\cos\theta \sin\theta/\sigma_{LU})^2 + (\sin 2\theta /\sigma_{TU})^2 + (\cos\theta \sin\theta/\tau_{LTU})^2 < (1/ \sigma x)^2$ (Eq. D)

- Unlike maximum stress and strain theories, Eq. C provides a single criterion for predicting failure. It also accounts for interaction between different strengths of the material. Predictions of strength from this theory are slightly lesser than those from maximum stress and maximum strain theories.

- All the theories discussed till so far work only for a lamina subjected to bi-axialstress state and not for tri-axial stress state.

Unit-4 (Chapter-2)

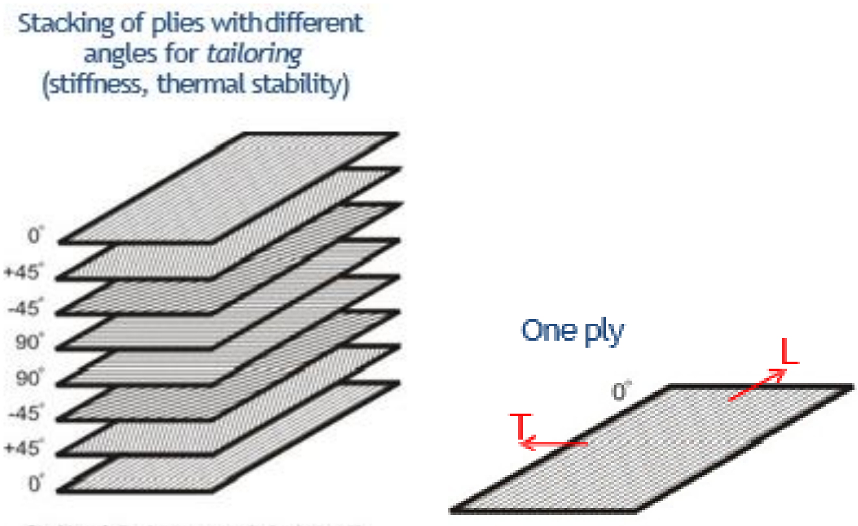
Analysis of laminated composites, laminate orientation code, stress and strain variation in a laminate, properties of symmetric, cross ply angle-ply and quasi isotropic analysis of laminate after initial failure, hygrothermal behaviour of laminates. Thermal and moisture expansion coefficients, transports properties, mass diffusion.

ANALYSIS OF A LAMINATED COMPOSITE: -

One very significant advantage offered by composites is that their properties can be tailor-made; layer-by-layer, to meet specific functional requirements. Further, each layer can be itself engineered by altering selection of fiber materials, having a mix of fibers, changing their orientation, using matrix material with appropriate properties, and controlling fiber volume fraction. Analytical models developed thus far help us calculate fairly accurately mechanical properties of each lamina. These models allow variability of properties of fibers and matrices, volume fractions, and fiber orientation.

The next step in this journey is to develop a theoretical construct which will help us predict the mechanical response of a laminate, i.e. a collection of laminae, stacked up and bonded together. Each lamina in this stack-up may have different properties. The 1st step for predicting the response of a laminate involves developing stress-strain relations for a composite plate.

The transverse properties of unidirectional composites are unsatisfactory for most practical applications. The goal of this chapter is to analyses the stacking sequence in order to achieve adequate anisotropic properties.



Stacking of plies into a composite laminate with different angles of the fibre reinforcement

One individual ply with fibre reinforcement

Fig. 1 Stacking of plies with different angles for *tailoring* (stiffness, thermal stability)

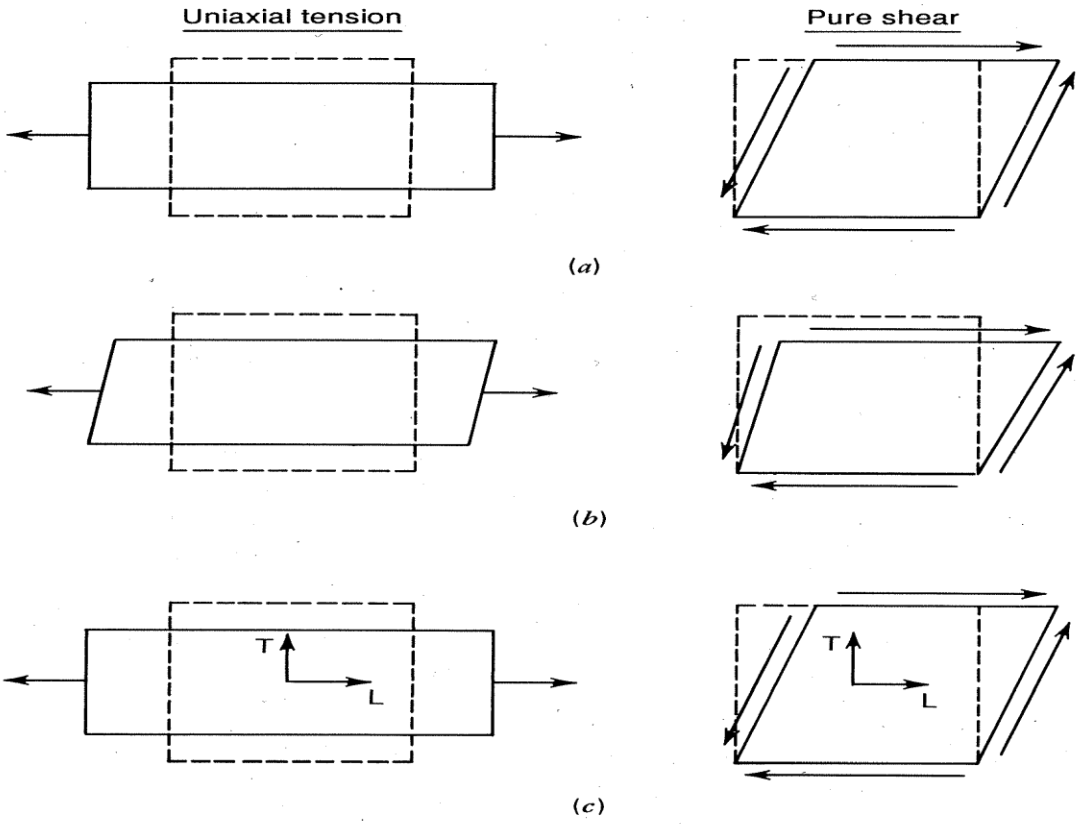
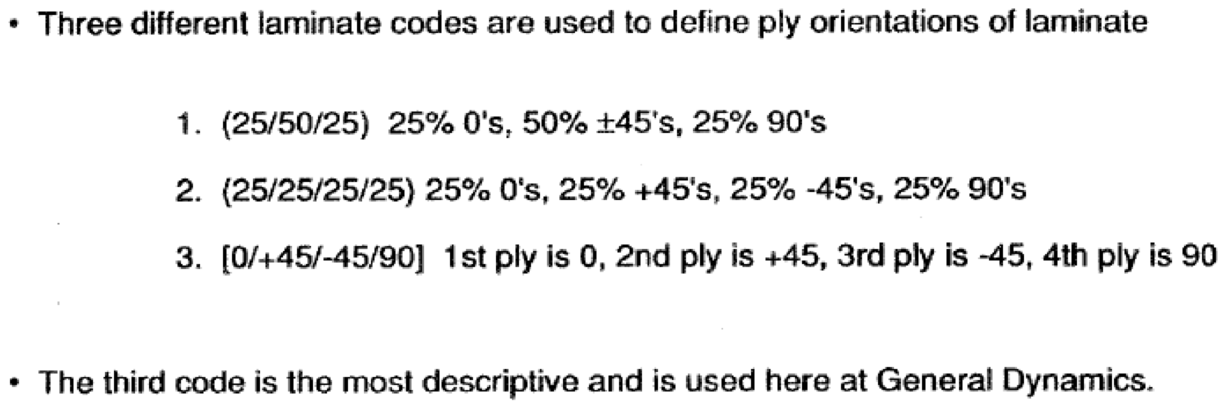


Figure 5.1. Deformation behavior of materials—response to uniaxial tension and pure shear: (*a*) isotropic material; (*b*) anisotropic and generally orthotropic material; (*c*) specially orthotropic material.

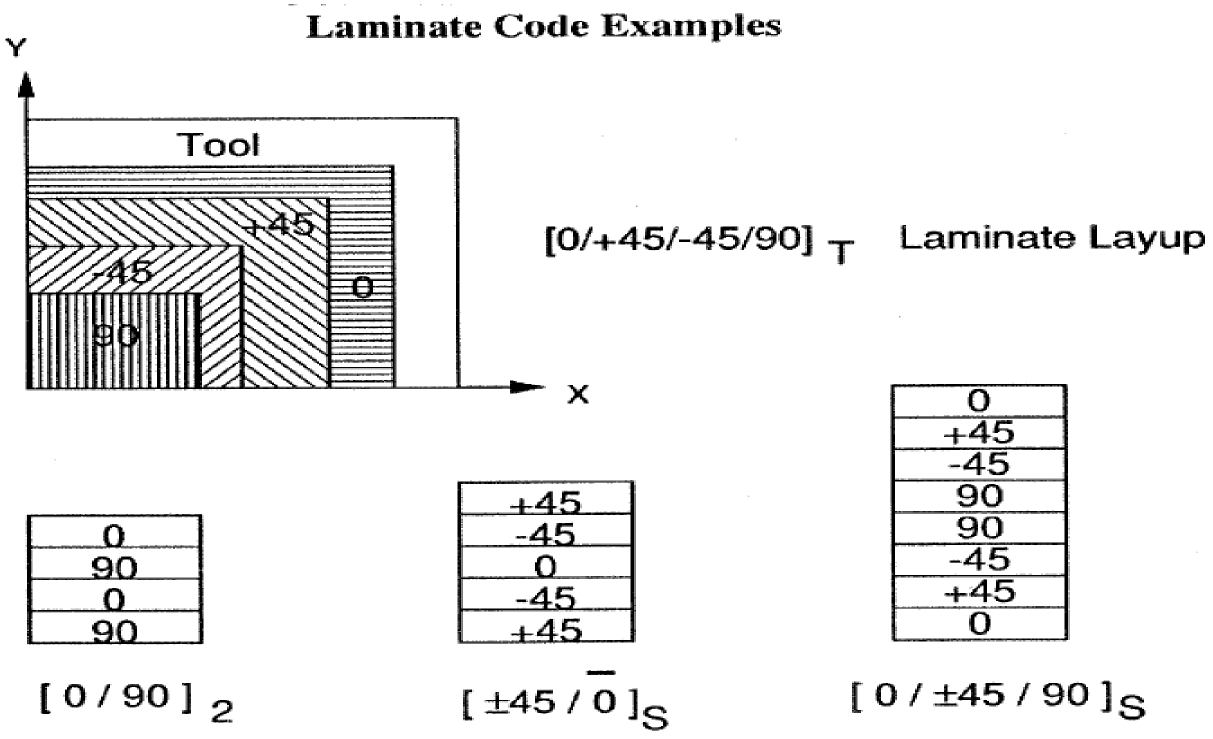
LAMINATE CODES



- Three different laminate codes are used to define ply orientations of laminate

1. (25/50/25) 25% 0's, 50% ±45's, 25% 90's
2. (25/25/25/25) 25% 0's, 25% +45's, 25% -45's, 25% 90's
3. [0/+45/-45/90] 1st ply is 0, 2nd ply is +45, 3rd ply is -45, 4th ply is 90

- The third code is the most descriptive and is used here at General Dynamics.



STRAIN RELATION IN A LAMINATE

Before developing an understanding about variation of strains in a laminate, we will make certain assumptions about it. These are:

Laminates are manufactured so that they act as *single-layer* materials. In typical applications, such a response from the laminate is required so that its overall strength and stiffness can be maximized.

The requirement of “single-layer materials” necessitates that the adhesive bond between two adjacent layers is perfect in the sense it has:

- Almost zero thickness
- No shear deformation - Thus, adjacent lamina cannot slip over each other.

The assumption of “single-layer material” also implies that displacements are continuous across the bond between two adjacent layers.

Laminates are thin in the sense their overall thickness is significantly smaller other dimensions of the laminate. Consider Fig. 25.1. The figure shows how a section of laminate, taken in *x-z direction*, appears after deformation due to application of forces. Here, *z*, is the thickness direction on reference coordinate system.

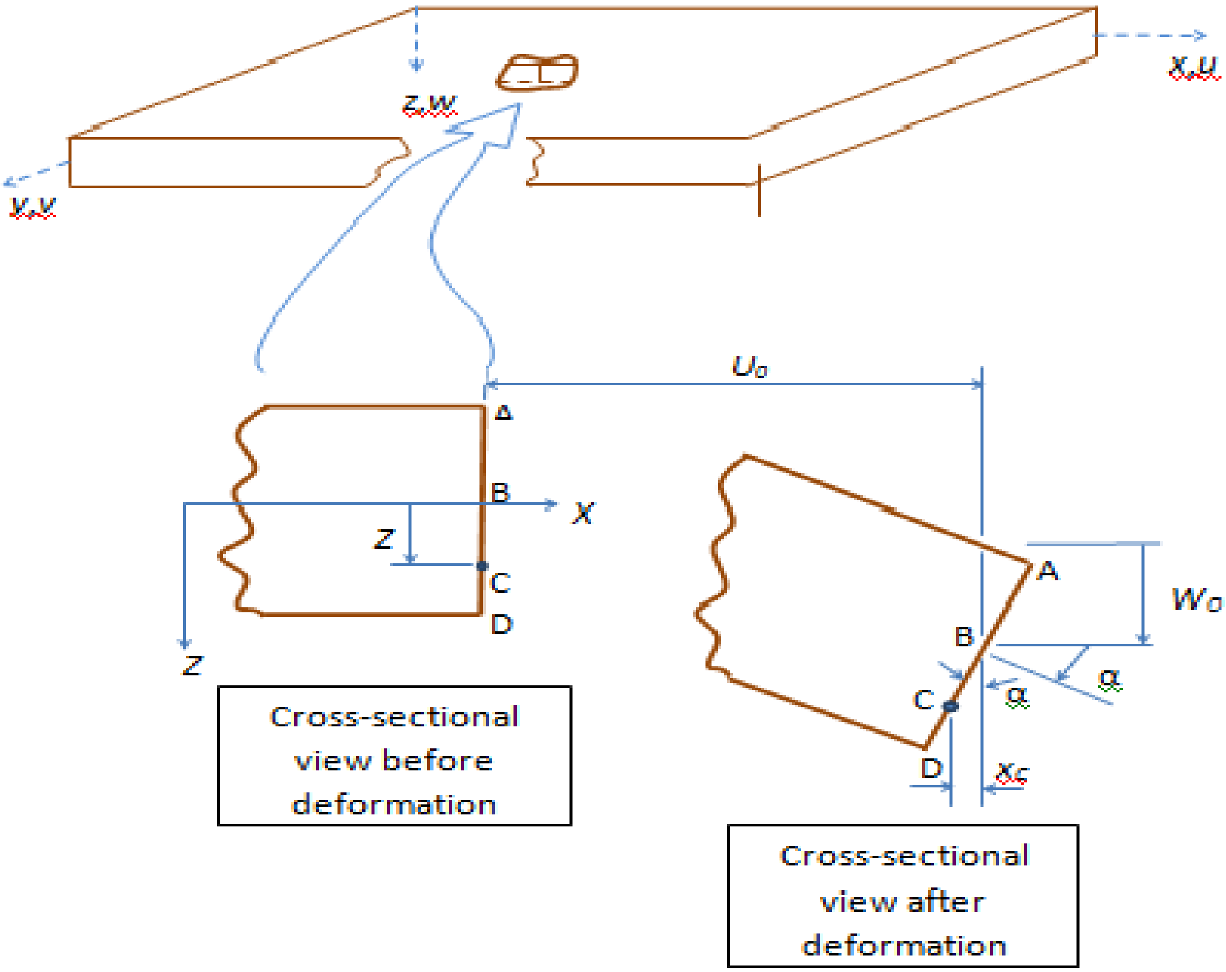


Fig. 25.1: Deformation of a Laminate as Viewed in *x-y* Plane

The lower left-side portion of Fig. 25.1 is a view of un-deformed laminate. The lower right-side portion of Fig. 25.1 shows the deformed state of laminate's section.

In the un-deformed section, line ABCD, is perfectly straight and normal to mid-plane of the laminate. This line is assumed to remain straight and normal to mid-plane even after getting deformed. This implies that:

- Out-of-plane shear strains γ_{xz}, and γ_{yz}, are zero.
- There is no inter-laminar shear or slipping.
- Further, it is assumed that the length of line ABCD remains same after deformation. This in turn implies that strain in z direction, ε_{zz}, is zero.

- The lower left-side portion of Fig. 25.1 is a view of un-deformed laminate. The lower right-side portion of Fig. 25.1 shows the deformed state of laminate's section.

- In the un-deformed section, line ABCD, is perfectly straight and normal to mid-plane of the laminate. This line is assumed to remain straight and normal to mid-plane even after getting deformed. This implies that:

  - Out-of-plane shear strains γ_{xz}, and γ_{yz}, are zero.

  - There is no inter-laminar shear or slipping.

- Further, it is assumed that the length of line ABCD remains same after deformation. This in turn implies that strain in z direction, ε_{zz}, is zero.

- Further, due to deformation of plate, point B undergoes translation by amount u^o, v^o, and w^o, in x, y, and z directions, respectively. Also, the line ABCD rotates about B by an angle α in the z plane. Figure 25.1 does not show v_o displacement explicitly because the figure is a side view of the laminate undergoing deformation.

- Thus, displacement of point C, which is z distance away from mid-plane is:

$$u(x,y,z) = u^o(x,y) - z\cdot\alpha(x,y) = \; = u^o - z\,\frac{\partial w_o}{\partial x} \qquad \text{(Eq. 1)}$$

In Eq. 1, we use the fact that α is partial differential of w^o in x-direction.

- Also, for small displacements, following relations hold for strains.

$$\epsilon_{xx} = \frac{\partial u}{\partial x}$$
$$\epsilon_{yy} = \frac{\partial v}{\partial y}$$
$$\gamma_{xy} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}$$

…. (Eq. 2)

- Now, using definitions for u, and v, in above strain definitions, we get:

$$\varepsilon_{xx}(x,y,z) = \frac{\partial u^o(x,y)}{\partial x} - z\frac{\partial^2 w^o(x,y)}{\partial x^2}$$

$$\varepsilon_{yy}(x,y,z) = \frac{\partial v^o(x,y)}{\partial y} - z\frac{\partial^2 w^o(x,y)}{\partial y^2}$$

$$\gamma_{xy}(x,y,z) = \frac{\partial u^o(x,y)}{\partial y} + \frac{\partial v^o(x,y)}{\partial x} - 2z\frac{\partial^2 w^o(x,y)}{\partial x \partial y}$$

………………………………. (Eq. 3)

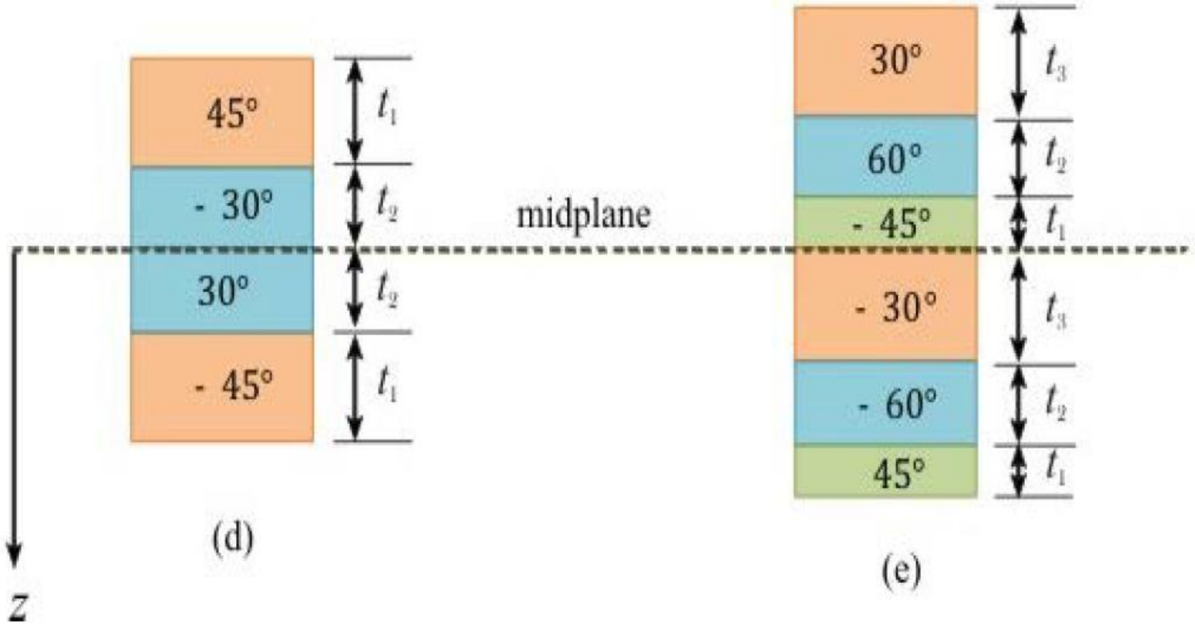


Figure 5.6: Classification of laminates examples (a) Symmetric laminate (b) Cross-ply laminate (c) Angle-ply laminate (d) Anti-symmetric laminate and (e)

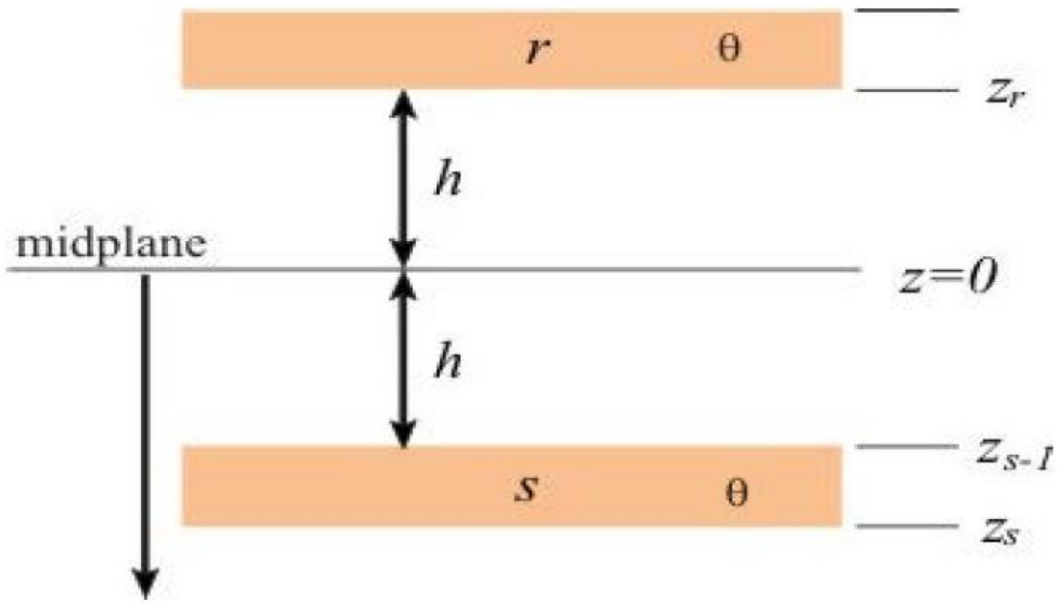


Figure 5.7: Coordinates for a pair of symmetric layers

And, mid-surface curvatures are defined as:

$$\begin{Bmatrix} k_x \\ k_y \\ k_{xy} \end{Bmatrix} = \begin{Bmatrix} \frac{\partial^2 w^o}{\partial x^2} \\ \frac{\partial^2 w^o}{\partial y^2} \\ 2\frac{\partial^2 w^o}{\partial x \partial y} \end{Bmatrix}$$

…………………………..(Eq. 4)

In Eq. 4, the last term represents twist curvature of mid-surface of composite laminate. Equations 1-4 are valid only for plates and not for shells. Equation 3 shows that strains vary linearly over the thickness of a composite plate, with the average strain computed over plate's thickness equaling mid-plane strain.

STRESSES IN A LAMINATE

If one were able to compute mid-plane strains and curvature of the plate, then predicting stresses over the laminate's thickness is simply a matter of multiplying these strains with stiffness constants using strain-stiffness relations on a layer-by-layer basis.

Thus, stresses in k^{th} layer of the laminate may be calculated using following relations.

$$\begin{Bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \tau_{xy} \end{Bmatrix} = \begin{bmatrix} \underline{Q}_{11} & \underline{Q}_{12} & \underline{Q}_{16} \\ \underline{Q}_{12} & \underline{Q}_{22} & \underline{Q}_{26} \\ \underline{Q}_{16} & \underline{Q}_{26} & \underline{Q}_{66} \end{bmatrix} \left\{ \begin{Bmatrix} \epsilon_{xx}^{0} \\ \epsilon_{yy}^{0} \\ \gamma_{xy}^{0} \end{Bmatrix} + z \begin{Bmatrix} k_{x} \\ k_{y} \\ k_{xy} \end{Bmatrix} \right\} \qquad \text{……………………(Eq. 5)}$$

Since $[\underline{Q}]$ matrix varies discontinuously between two adjacent layers, variation of stresses between two layers need not be linear, or even continuous. Thus, stresses are discontinuous between two adjacent layers, even though strain varies linearly across entire laminate thickness. However, over the thickness of a single lamina, stress variation is linearly continuous.

ANGLE AND CROSS-PLY LAMINATES

Angle-Ply Laminates:

A laminate is called angle-ply laminate if it has plies of the same thickness and material and are oriented at $+\theta$ and $-\theta$. **For example** $[45/-45/-30/30]$ is shown in Figure 5.6(c).

For angle-ply laminates the terms $A_{16} = A_{26}$ are zero. This can be justified by that fact that $\overline{Q}_{16}$ and $\overline{Q}_{26}$ have the term mn. Due to this term $\overline{Q}_{16}$ and $\overline{Q}_{26}$ have opposite signs for layers with $+\theta$ and $-\theta$fibre orientation. Since the thicknesses and materials of these layers are same, by the definition the terms $A_{16} = A_{26}$ are zero for the laminate.

For angle-ply laminates the following relations are very useful in computing [A], [B] and [C].

$$\begin{aligned} \overline{Q}_{11}(+\theta) &= \overline{Q}_{11}(-\theta), & \overline{Q}_{22}(+\theta) &= \overline{Q}_{22}(-\theta) \\ \overline{Q}_{12}(+\theta) &= \overline{Q}_{12}(-\theta), & \overline{Q}_{66}(+\theta) &= \overline{Q}_{66}(-\theta) \\ \overline{Q}_{16}(+\theta) &= -\overline{Q}_{16}(-\theta), & \overline{Q}_{26}(+\theta) &= -\overline{Q}_{26}(-\theta) \end{aligned}$$

Angle-ply laminates have an abitary number of layers (n). each ply has the same thickness and is the same material. The plies have alternating fiber orientations of +θ and -θ. An angle-ply laminates can be either symmetric or antisymmetric, and $[\overline{Q}]$ is fully populated.

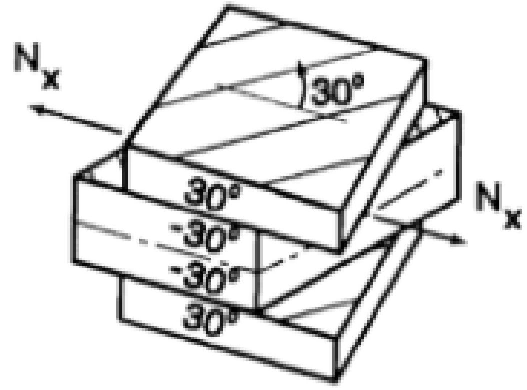


Fig. 2 Angle -ply laminate

An angle-ply laminates in this section has N unidirectionally reinforced (orthotropic) layers of the same material with principle material directions alternatingly oriented at +α and -α to the laminate x-axis. The odd-numbered layers are at -α, and even- numbered layers are at +α. Consider the special, but practical, case where all layers are same thickness, that is regular angle-ply laminates. More general angle-ply laminates have no such conditions on fiber orientation or laminate thickness. for example, an angle-ply laminates could be [45º @t/ 60º @t/60º @t/45º @t], wherein the fiber orientations do not alternate and the laminate thicknesses are not the same, however, this laminate is clearly a symmetric angle-ply laminate.

$$A_{ij} = \sum_{k=1}^{N} (\bar{Q}_{ij})_k (z_k - z_{k-1})$$

$$B_{ij} = \frac{1}{2} \sum_{k=1}^{N} (\bar{Q}_{ij})_k (z_k^2 - z_{k-1}^2)$$

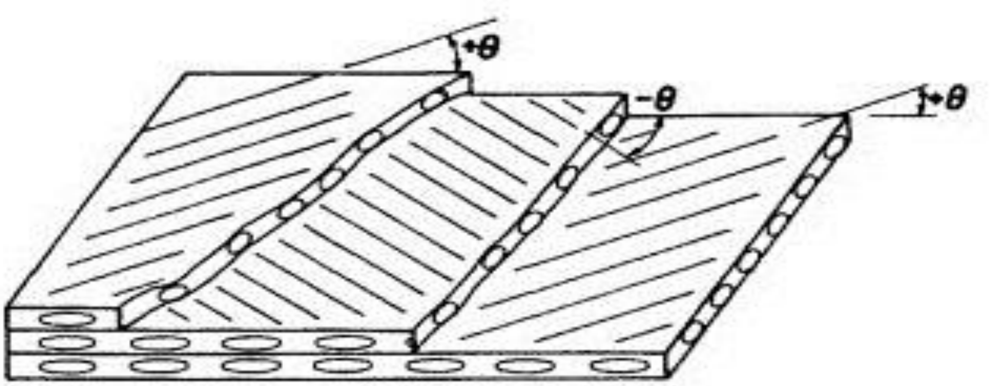
$$D_{ij} = \frac{1}{3} \sum_{k=1}^{N} (\bar{Q}_{ij})_k (z_k^3 - z_{k-1}^3)$$

…………………………………………………….(Eq. 1)

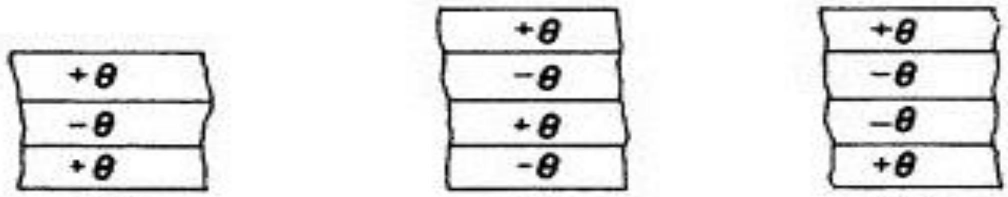
can be expressed in terms of N, $\bar{Q}_{ij}$, and t for laminates with and even number of layers and with and odd number of layers. In both cases $\bar{Q}_{ij}$ is calculated for -α and

$$\begin{aligned} \bar{Q}_{11+\alpha} &= \bar{Q}_{11-\alpha} & \qquad \bar{Q}_{66+\alpha} &= \bar{Q}_{66-\alpha} \\ \bar{Q}_{12+\alpha} &= \bar{Q}_{12-\alpha} & \qquad \bar{Q}_{16+\alpha} &= -\bar{Q}_{16-\alpha} \\ \bar{Q}_{22+\alpha} &= \bar{Q}_{22-\alpha} & \qquad \bar{Q}_{26+\alpha} &= -\bar{Q}_{26-\alpha} \end{aligned}$$

……………………………………(Eq. 2)



a) TYPICAL ANGLE - PLY LAMINATE



(b) SYMMETRIC UNBALANCED

(c) UNSYMMETRIC BALANCED

(d) SYMMETRIC BALANCED

CROSS - SECTIONAL VIEWS OF VARIOUS TYPES OF ANGLE - PLY LAMINATES

Fig. 3 Angle-ply laminates

Symmetric Laminates:

A laminate is called symmetric when the material, angle and thickness of the layers are the same above and below the mid-plane. For example, laminate [30, 45, 0] is shown in Figure 4(a). For symmetric laminates the matrix B is zero. This can be proved as follows:

Consider two layers r and s which have the same material, angle and thickness and are located symmetrically with respect to the mid-plane as shown in Figure 4. For these layers we can write the relation about the reduced stiffness matrix entries as

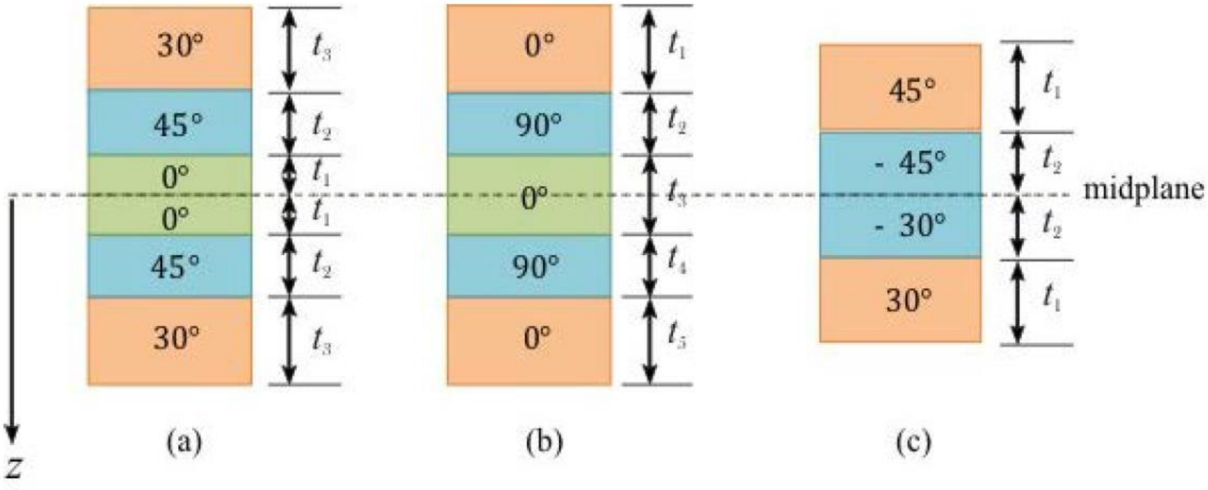


Fig. 4 Symmetric laminates

CROSS-PLY LAMINATES:

A laminate is called cross-ply laminate if all the plies used to fabricate the laminate are only 0° and 90°.

For example, is shown [0/90/0/90/0] in Figure.

- Values of terms A_{16}, A_{26}, B_{16}, B_{26}, D_{16}, and D_{26} are zero.
- Shear and extensional responses are not coupled.
- Bending and twisting responses are not coupled.

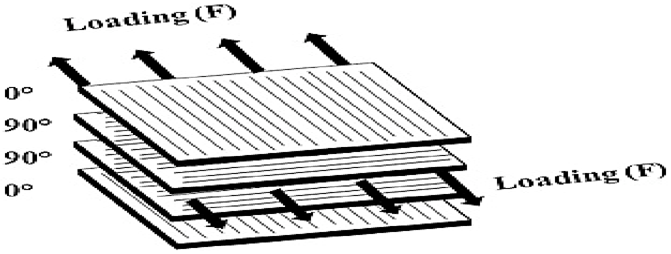


Fig. 5 Cross-ply laminates

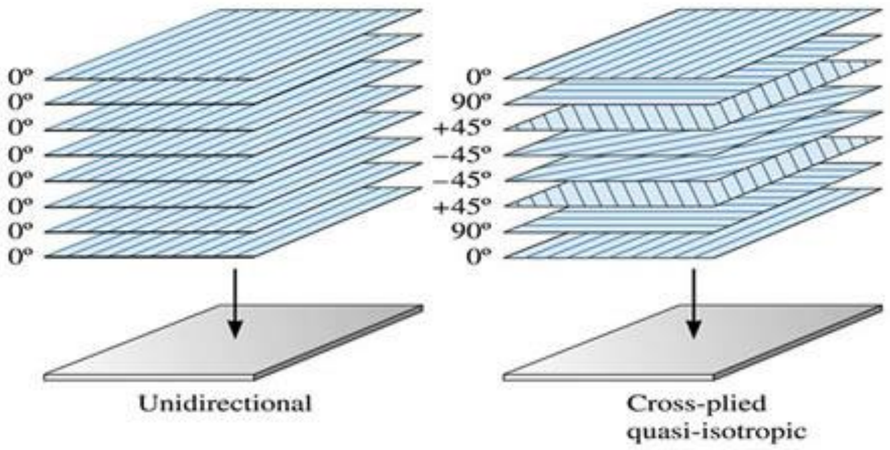


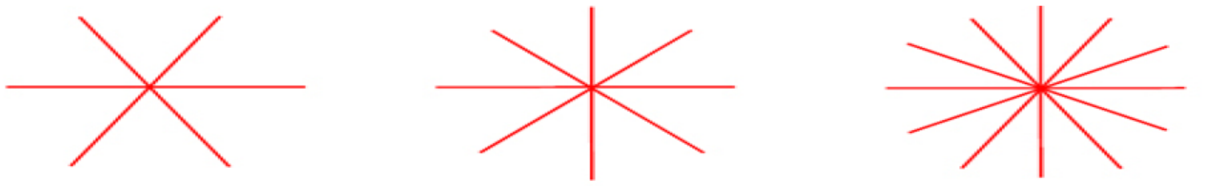
Fig. 6 Difference between unidirectional and cross-ply laminates

QUASI-ISOTROPIC LAMINATES: -

A laminate is called quasi-isotropic when its extensional stiffness matrix behaves like an isotropic material. This requires that $A_{11} = A_{22}$, $A_{16} = A_{26} = 0$. Further, this extensional stiffness matrix is independent of orientation of layers in laminate. This requires a laminate with $N \geq 3$, equal thickness layers and N equal angles between adjacent fibre orientations. The N equal angles, $\Delta\theta$ between the fibre orientations in this case can be given as

$$\Delta\theta = \frac{\pi}{N}$$

The quasi-isotropic laminate with this construction for N=3, 4 and 6 will have fibre orientations as shown in below figure.

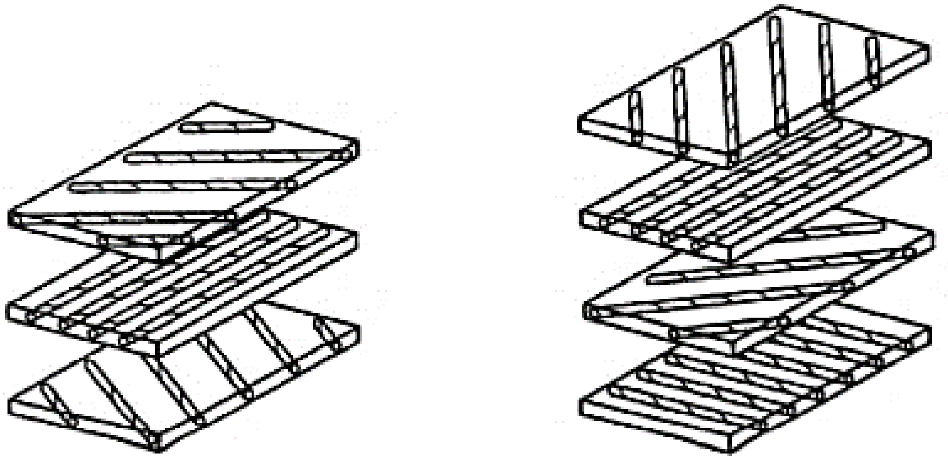


$N = 3\ (\Delta\theta = 60°)$ $N = 4\ (\Delta\theta = 45°)$ $N = 6\ (\Delta\theta = 30°)$

Figure 5.8: Fibre orientations in a typical quasi-isotropic laminates

It should be noted that the isotropy in these laminates is in-plane only. The matrices *B* and *D* may not behave like an isotropic material. Hence, such laminates are quasi-isotropic in nature.

Some examples of quasi-isotropic laminate are: $[0/\pm 60]_S$, $[0/\pm 45/90]_S$.



$[+60°/0°/-60°] \equiv \frac{\pi}{3}$ $[-45°/0°/+45°/90°] \equiv \frac{\pi}{4}$

Figure 4-21 Unbonded View of Simple Quasi-Isotropic Laminates

The term quasi-isotropic laminates is used to describe laminates that have isotropic extensional stiffnesses (the same in all directions in the plane of the laminates). As background, to the definition, recall that the term isotropic is a material property whereas laminate stiffnesses are a function of both material properties and geometry.

In this case, a quasi-isotropic laminate is taken to mean equal extensional stiffnesses in all in-plane direction of the laminate i.e

$$\overline{A}_{ij} = A_{ij} \quad A_{11} = A_{22} \quad A_{12} = \nu A_{11} \quad A_{66} = \frac{1-\nu}{2} A_{11} \quad A_{16} = A_{26} = 0$$

The layers of a laminate can be arranged in such a way that the laminate will behave as an isotropic layer under in-plane loading. Actually, the laminate is not isotropic (that is why it is called a quasi-isotropic laminate) because under transverse (normal to the laminate plane) loading and under interlaminar shear its behavior is different from that of an isotropic (e.g., metal) layer.

To derive the conditions that should be met by the structure of a quasi-isotropic laminate, consider in-plane loading with stresses σ_x , σ_y , and τ_{xy} that are shown in Fig. 7 and induce only in-plane strains ε^0_x, ε^0_y , and γ^0_{xy}. Taking $\kappa_x = \kappa_y = \kappa_{xy} = 0$ we, introducing average (through the laminate thickness h) stresses as

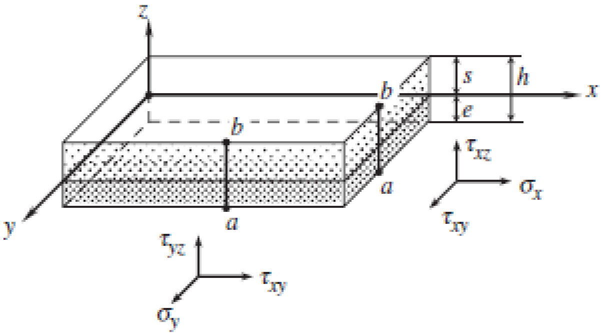


Fig. 7 An element of a generalized layer

$$N_x = B_{11}\varepsilon_x^0 + B_{12}\varepsilon_y^0 + B_{14}\gamma_{xy}^0 + C_{11}\kappa_x + C_{12}\kappa_y + C_{14}\kappa_{xy}$$

$$N_y = B_{21}\varepsilon_x^0 + B_{22}\varepsilon_y^0 + B_{24}\gamma_{xy}^0 + C_{21}\kappa_x + C_{22}\kappa_y + C_{24}\kappa_{xy}$$

$$N_{xy} = B_{41}\varepsilon_x^0 + B_{42}\varepsilon_y^0 + B_{44}\gamma_{xy}^0 + C_{41}\kappa_x + C_{42}\kappa_y + C_{44}\kappa_{xy}$$

$$M_x = C_{11}\varepsilon_x^0 + C_{12}\varepsilon_y^0 + C_{14}\gamma_{xy}^0 + D_{11}\kappa_x + D_{12}\kappa_y + D_{14}\kappa_{xy}$$

$$M_y = C_{21}\varepsilon_x^0 + C_{22}\varepsilon_y^0 + C_{24}\gamma_{xy}^0 + D_{21}\kappa_x + D_{22}\kappa_y + D_{24}\kappa_{xy}$$

$$M_{xy} = C_{41}\varepsilon_x^0 + C_{42}\varepsilon_y^0 + C_{44}\gamma_{xy}^0 + D_{41}\kappa_x + D_{42}\kappa_y + D_{44}\kappa_{xy}$$

……………………..(Eq. 1)

Where,

$$C_{11}\kappa_x + C_{12}\kappa_y + C_{14}\kappa_{xy}$$

$$C_{21}\kappa_x + C_{22}\kappa_y + C_{24}\kappa_{xy}$$

$$+ C_{41}\kappa_x + C_{42}\kappa_y + C_{44}\kappa_{xy} = h$$ …………………………………………………...(Eq. 2)

$$\sigma_x = N_x/h, \quad \sigma_y = N_y/h, \quad \tau_{xy} = N_{xy}/h$$

……………………………………......(Eq. 3)

we can write the first three equations of Eqs. 2 in the following form,

$$\sigma_x = \overline{B}_{11}\varepsilon_x^0 + \overline{B}_{12}\varepsilon_y^0 + \overline{B}_{14}\gamma_{xy}^0$$

$$\sigma_y = \overline{B}_{21}\varepsilon_x^0 + \overline{B}_{22}\varepsilon_y^0 + \overline{B}_{24}\gamma_{xy}^0$$

$$\tau_{xy} = \overline{B}_{41}\varepsilon_x^0 + \overline{B}_{42}\varepsilon_y^0 + \overline{B}_{44}\gamma_{xy}^0$$

……………………………………………………..(Eq. 4)

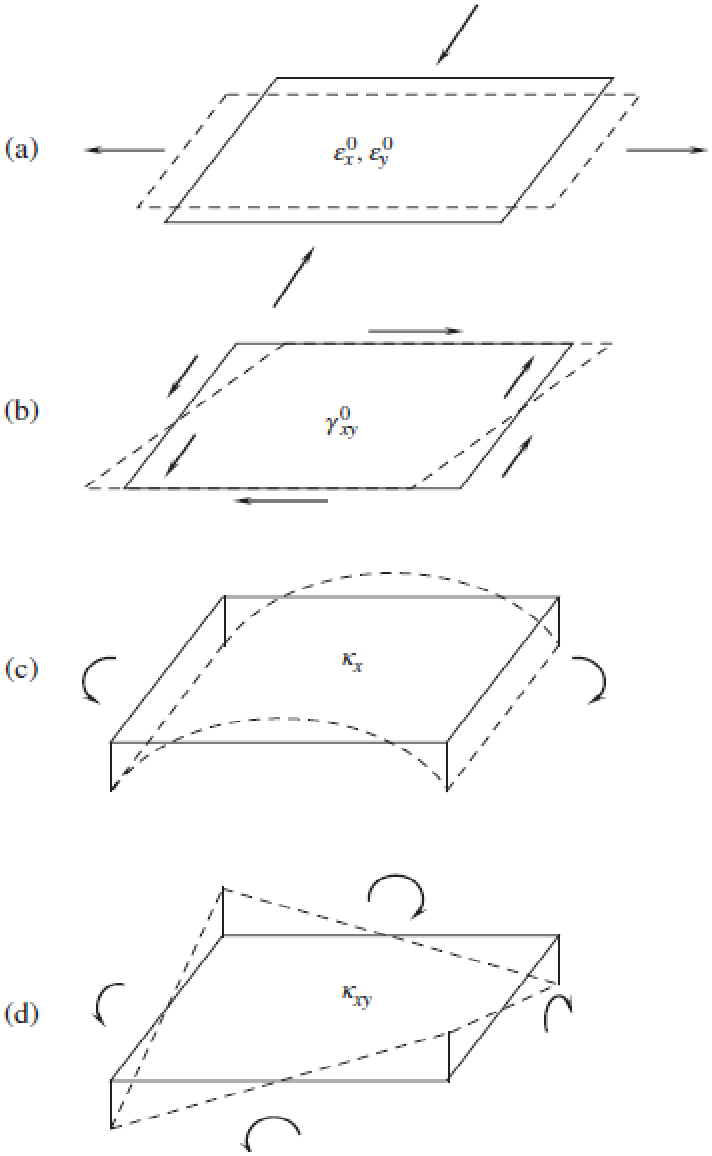


Fig. 8. Basic deformations of the layer: (a) in-plane tension and compression ($\varepsilon^0{}_x$, $\varepsilon^0{}_y$); (b) in-plane shear ($\gamma^0{}_{xy}$), (c) bending (κ_x); (d) twisting (κ_{xy}).

in which, in accordance with

$$\overline{B}_{mn} = \sum_{i=1}^{k} A_{mn}^{(i)} \overline{h}_i, \quad \overline{h}_i = h_i / h$$

………………………………………………………(Eq. 5)

where, h_i is the thickness of the ith layer normalized to the laminate thickness and A_{mn} are the stiffness coefficients. For an isotropic layer, the constitutive equations analogous to Eqs. 4 are,

$$\sigma_x = \overline{E}\left(\varepsilon_x^0 + \nu\varepsilon_y^0\right), \quad \sigma_y = \overline{E}\left(\varepsilon_y^0 + \nu\varepsilon_x^0\right), \quad \tau_{xy} = G\gamma_{xy}^0$$

……………………………(Eq. 6)

Where,

$$\overline{E} = \frac{E}{1-\nu^2}, \quad G = \frac{E}{2(1+\nu)} = \frac{1}{2}(1-\nu)\overline{E}$$

……………………………………………(Eq. 7)

Comparing Eqs. (4) and (6), we can see that the shear–stretching coefficients of the laminate, i.e., $B_{14} = B_{41}$ and $B_{24} = B_{42}$, should be equal to zero. As this equation is balanced equations i.e., it should be composed of 0◦, ±φi (or φi and π − φi), and 90◦ layers only. Since the laminate stiffness in the x- and the y-directions must be the same, we require that $B_{11} = B_{22}$.

$$\sum_{i=1}^{k} \cos 2\phi_i = 0$$

As can be checked by direct substitutions, for k = 1 this equation is satisfied if $\varphi_1 = 45^\circ$ and for k = 2 if $\varphi_1 = 0$ and $\varphi_2 = 90^\circ$. Naturally, such one- and two-layered materials cannot be isotropic even in one plane. So, consider the case k ≥ 3, for which the solution has the form

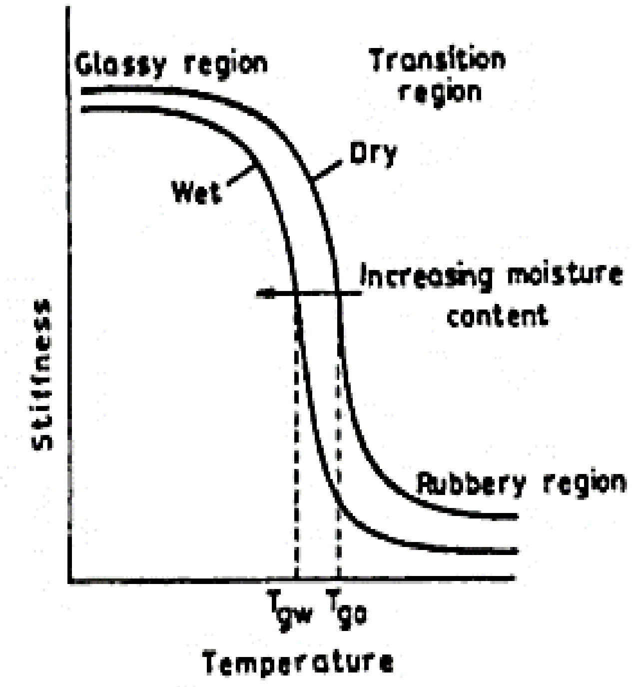
$$\phi_i = (i-1)\frac{\pi}{k}, \quad i = 1, 2, 3, \ldots, k$$

HYGRO-THERMAL EFFECTS IN LAMINATE

The first effect of temperature Known as thermal effects. The second is the effect of moisture absorption from the atmosphere known as hygroscopic effects. The combined effect of temperature and moisture is known as hygrothermal effect. Hygrothermal effects induce a dimensional change of laminate. But due to the mismatch of the properties of the constituents of the laminate, its free movement is inhibited. As a result of which deformation and corresponding stresses are setup.

There are two principal effect of changes in hygrothermal environment on the mechanical behavior of polymer composites.

1. Matrix dominated properties such as stiffness and strength under transverse, off-axis and shear loading are altered. Increased temperature causes a gradual softening of the polymer matrix material upto a point. If the temperature is increased beyond the so-called “glass transistion” region, however, the polymer become too soft for use as a structural material.



T_g - glass transition temperature T_{go} - dry T_g T_{gw} - wet T_g

Fig. 9 Variation of stiffness with temperature for a typical polymer

2. Hydrothermal expansion or contractions change the stress or strain distribution of the composite. Increased temperature and moisture content causing swelling or contraction of the matrix is resisted the fibres and residual stresses developed in the composite.

EFFECT OF HYGROTHERMAL FORCES ON MECHANICAL BEHAVIOUR

Hygrothermal effect are most pronounced in matrix dominated properties, as fibres are least influenced by environment. The effect of temperature on matix dominated properties of composites such as transverse strength and in plane shear as fig. 10 and 11 respectively for carbon/epoxy composites. Increase of temperature decrease the transverse modulus at a uniform rate and the ultimate strain at failure is the same at all three temperatures.

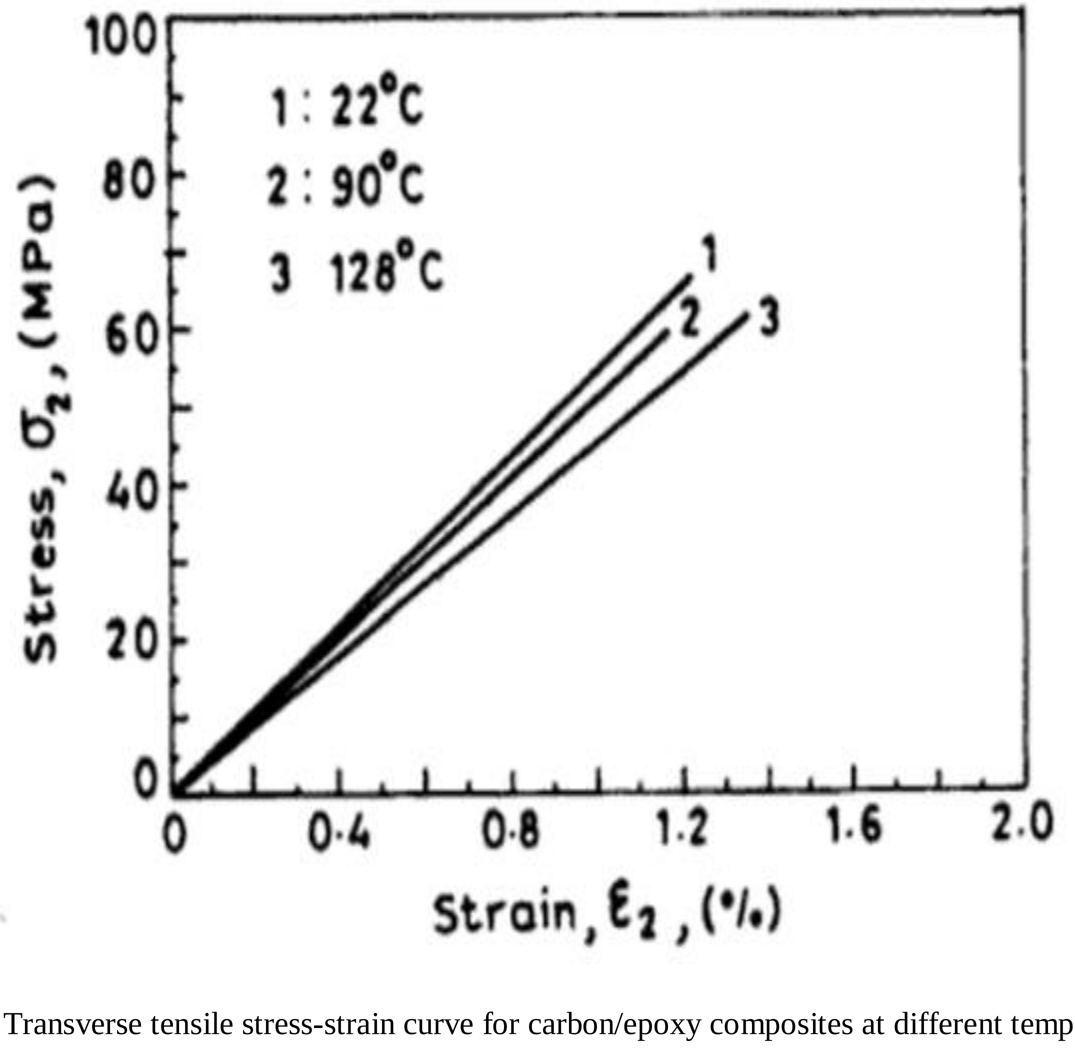


Fig. 9 Transverse tensile stress-strain curve for carbon/epoxy composites at different temperature

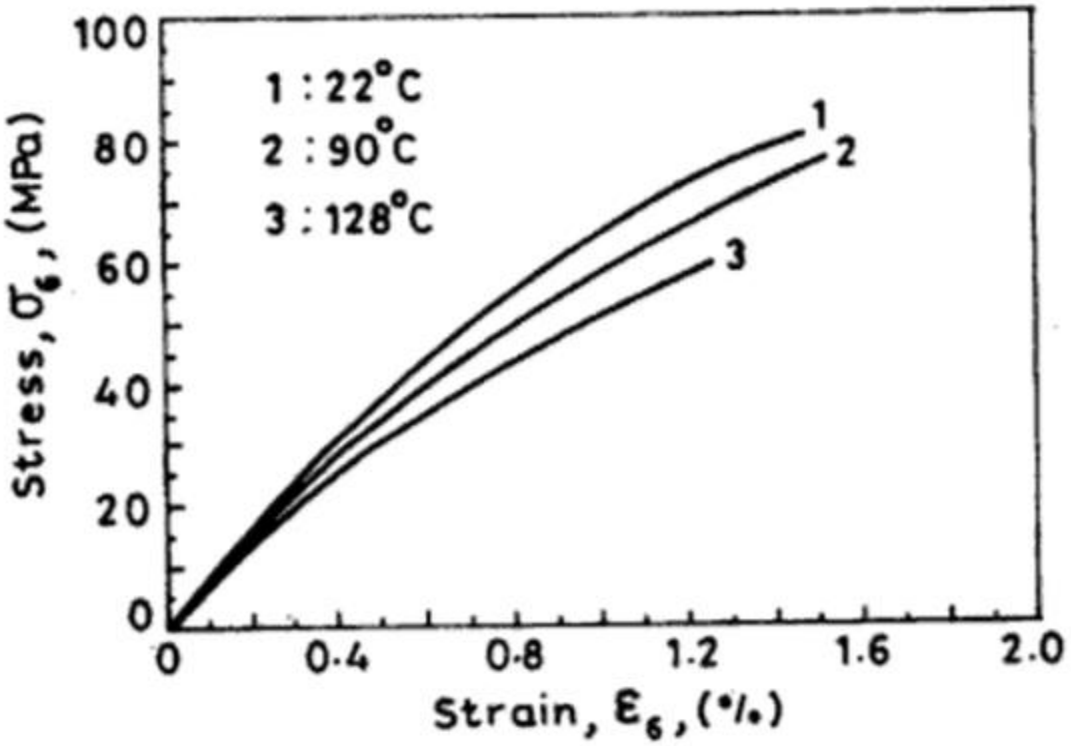


Fig. 10 In plane shear stress-strain curve for unidirectional carbon/epoxy composites at varying temperature

HYGROTHERMAL BEHAVIOR OF COMPOSITE LAMINATES

Composite materials can absorb moisture and expand in the same way that they expand due to temperature.We can use the same kind of analysis to deal with stresses that arise from both. In this course we will focus on thermal behavior.The effect of temperatures on composite laminates is more pronounced than on metals because of large disparity in coefficient of thermal expansion.

Effect of mismatch

Graphite/epoxy typical thermal expansion coefficients are $\alpha_1 = 0.02 \times 10^{-6}/\ ^{\circ}C$, $\alpha_2 = 22.5 \times 10^{-6}/\ ^{\circ}C$. A $200^{o}C$ drop in temperature will produce a strain of -0.0045 in the transverse direction, and almost nothing in the fiber direction.

In a 0/90 laminate the fibers in one ply will not allow the matrix in the other ply to shrink by more than a fraction of the -0.0045 strains. This will eat up a substantial part of the load carrying capacity. For cryogenic conditions (e.g. liquid hydrogen tanks) the temperature drop is more than doubled, and the laminate can fail just due to thermal loads.

Thermal deformation

If ply can expand or contract due to hygrothermal effects, only strains, but no stresses. Stress free expansion strain in a unidirectional layer (fig. 11)

Fig. 11 Thermal deformation

Strains and stresses

1. “Free” strains: -

$$\begin{Bmatrix} \varepsilon_1^F \\ \varepsilon_2^F \\ \gamma_{12}^F \end{Bmatrix} = \begin{Bmatrix} \alpha_1 \\ \alpha_2 \\ 0 \end{Bmatrix} \Delta T + \begin{Bmatrix} \beta_1 \\ \beta_2 \\ 0 \end{Bmatrix} \Delta C$$

2. Hooke’s law when total strains are different from free strains.

$$\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{Bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_1^t - \varepsilon_1^F \\ \varepsilon_2^t - \varepsilon_2^F \\ \gamma_{12}^t \end{Bmatrix}$$

$(0/90)_s$ laminate

- Stress-free expansion of layers

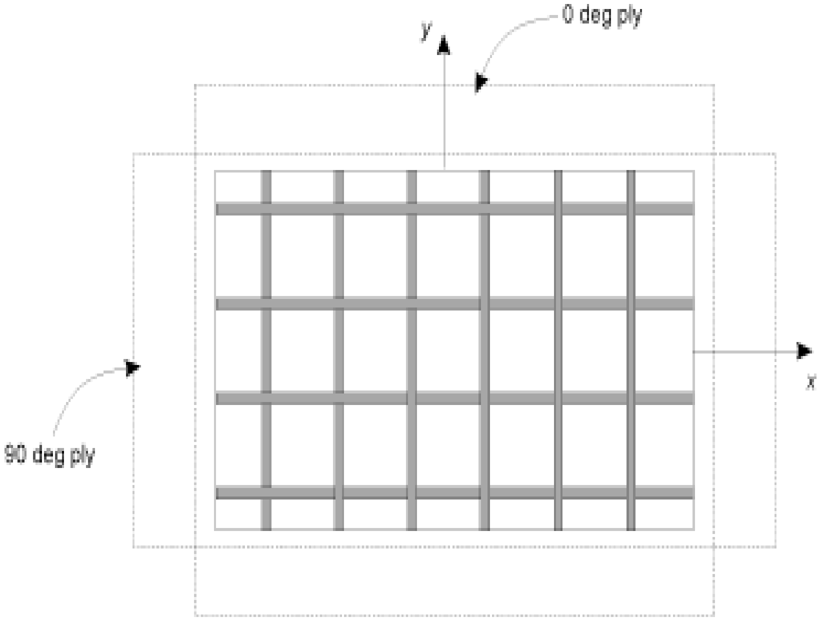


Fig. 12 Stress free expansion

Hygrothermal laminate coefficient of thermal expansion

The derivation of laminate coefficients of thermal expansion is dealt here for symmetric laminates. This is because there is no extension-bending coupling due to the fact that for symmetric laminates [B] = 0.

Let us derive the expression for the coefficient of thermal expansion for laminate. Let us define the coefficient of thermal expansion for laminate, $[\overset{\times}{\overset{\times}{\alpha}}]$, as the laminate mid-plane strain, [ϵ(0)], to the per unit uniform change in temperature, ΔT. Thus,

$$\{\alpha^*\} = \frac{\{\epsilon^{(0)}\}}{\Delta T}$$

……………………………………1

Now for symmetric laminates with pure thermal loading, we have,

$$\{\epsilon^{(0)}\} = [A]^{-1}\{N^{(T)}\}$$

……………………………2

Combining Equation (1) and Equation (2), we get

$$\{\alpha^*\} = \frac{[A]^{-1}\{N^{(T)}\}}{\Delta T}$$

.,……………………...…….3

Thermal strains for an orthotropic material in (L,T) frame: (no thermal shear in L-T frame)

$$\boxed{\begin{aligned} \varepsilon_L^T &= \alpha_L\,\Delta T \\ \varepsilon_T^T &= \alpha_T\,\Delta T \end{aligned}}$$

……………………………………..…4

For a uniform temperature change the equivalent thermal force is given as: -

$$\{N^{(T)}\} = \Delta T \int_{-H}^{H} \overline{[Q]}^k \{\alpha\}_{xy}^k \, dz$$

………………....5

Thus, the laminate coefficient of thermal expansion becomes,

$$\{\alpha^*\} = [A]^{-1} \int_{-H}^{H} \overline{[Q]}^k \{\alpha\}_{xy}^k \, dz$$

……………..….6

Where, $t_k = z_k - z_{k-1}$ is the thickness of kth lamina.

From these figures it is seen that these coefficients vary from positive to negative values. Further, it is observed that the coefficient of thermal expansion depends upon stacking sequence. This fact is very important from laminate designing point of view where it is used in an environment with large thermal gradient. One can choose a laminate sequence for which a coefficient of thermal expansion is zero.

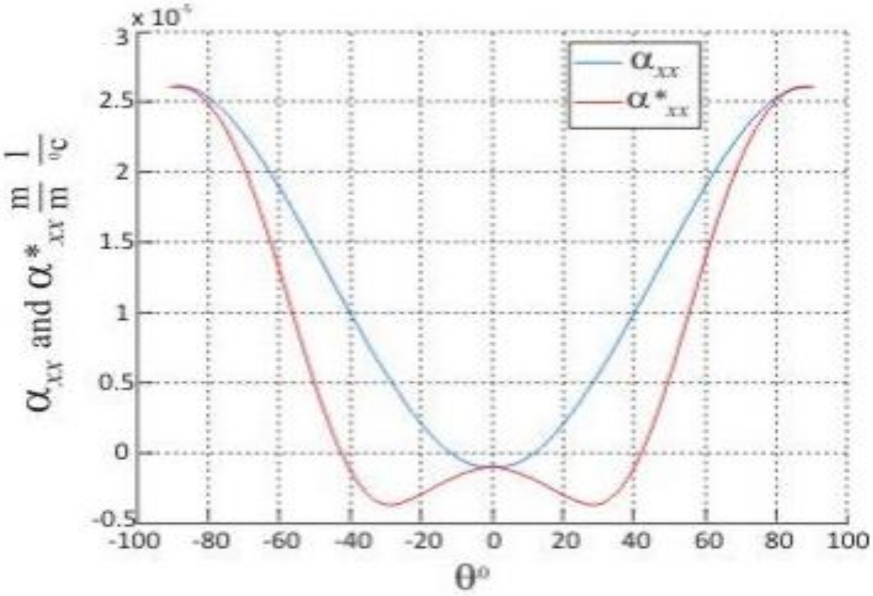


Fig. 12 Variation of $[\alpha]_{xx}$ for lamina and of $[\overset{*}{\alpha}_{xx}$ for [+-θ] laminate

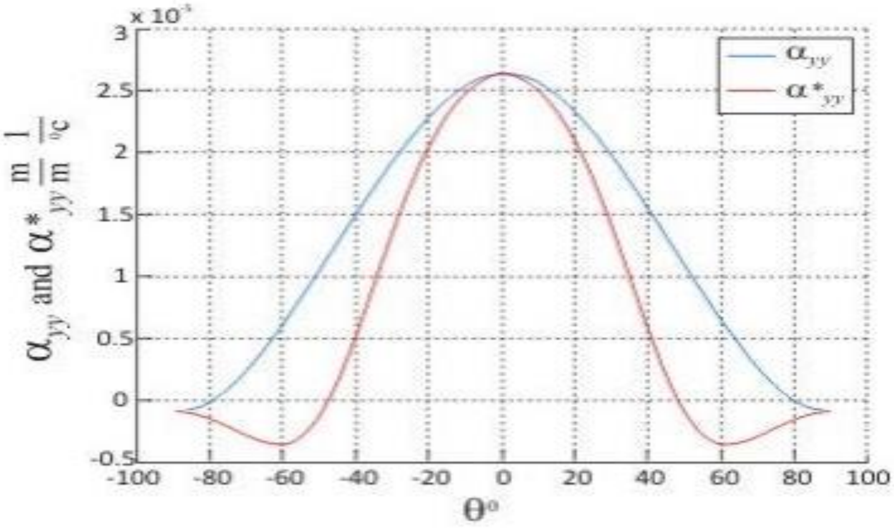


Fig. 13 variation of $[\alpha]_{yy}$ for lamina and of $[\overset{*}{\alpha}_{yy}$ for [+-θ] laminate

LAMINATE COEFFICIENTS OF HYGRAL EXPANSION

Here we derive the laminate coefficients hygral expansion, $\{\beta^{\times}\}$, for symmetric laminates. Let us define the coefficient of hygral expansion for laminate as laminate mid-plane strains to the per percentage change in moisture absorption. Thus,

$$\{\beta^*\} = \frac{\{\epsilon^{(0)}\}}{\Delta M}$$

…………………………………………………1

For symmetric laminates with hygral loads alone, we can write,

$$\{\epsilon^{(0)}\} = [A]^{-1}\{N^{(H)}\}$$

……………………………….……….2

Combining Equation (1) and Equation (2), we get,

$$\{N^{(H)}\} = \Delta M \int_{-H}^{H} [Q]^{k} \{\beta\}_{xy}^{k}\, dz$$

……………………………….3

Thus, the laminate coefficient of hygral expansion becomes,

$$\{\beta^*\} = [A]^{-1} \int_{-H}^{H} [Q]^{k} \{\beta\}_{xy}^{k}\, dz$$

……………………..……4

It is known that the $[Q]^k$ and $[\beta]^k_{xy}$ are constant in each lamina in thickness direction. Thus, the integration over thickness can be simplified as summation over laminae thicknesses as

$$\{\beta^*\} = [A]^{-1} \int_{-H}^{H} [Q]^{k} \{\beta\}_{xy}^{k}\, dz$$

…………………………….………5

Combining Equation (5) and Equation (6) we can get the effective hygral force as

$$\{N^{(H)}\} = [A]\,\{\beta^*\}\,\Delta M$$

……………………………….6

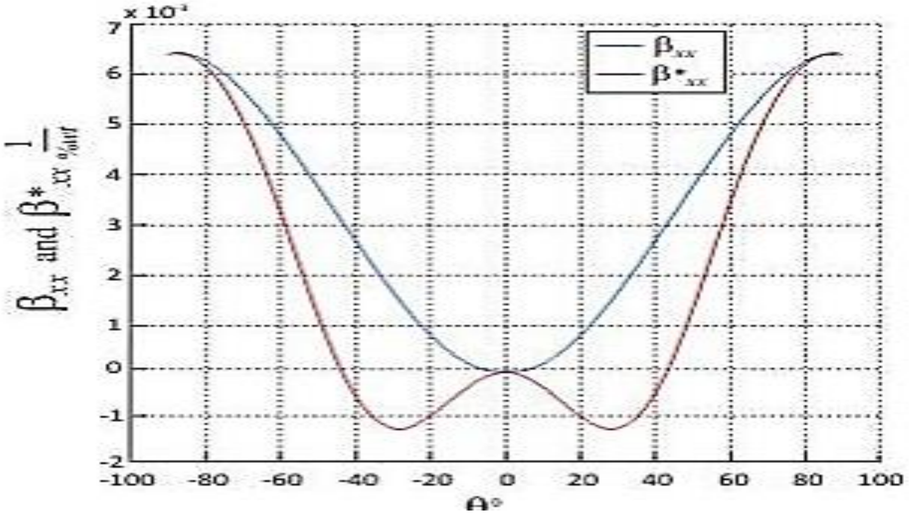


Fig. 14 Variation of $[\beta]_{xx}$ for lamina and of $[\beta^{\times}_{xx}$ for [+-θ] laminate

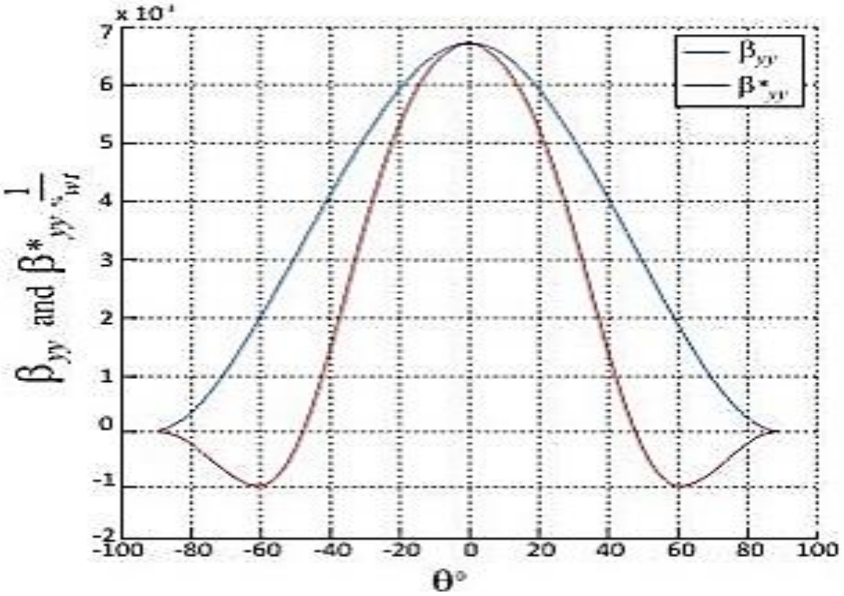


Fig. 15 variation of $[\beta]_{yy}$ for lamina and of $[\beta^{\times}_{yy}$ for [+-θ] laminate

Changes in moisture concentration are responsible for swelling of the matrix material Moisture-induced strains in orthotropic material in (L-T) frame:

$$\boxed{\begin{array}{l}\varepsilon_L^H = \beta_L \, \Delta C \\ \varepsilon_T^H = \beta_T \, \Delta C\end{array}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 7$$

MASS DIFFUSION

Effect that are similar to temperature variations i.e expansion and degradation of properties, can also be caused by moisture. Moisture absorption is governed y ficks law , which is analogous to Fourier's law equation, for thermal conductivity i.e

$$q_W = -D\frac{\partial W}{\partial n} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..8$$

In which q_w is the diffusion flow through a unit area of surface with normal n, D is the diffusivity of the material whose moisture absorption is being considered, and W is the relative mass moisture concentration in the material, i.e.,

$$W = \frac{\Delta m}{m} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.9$$

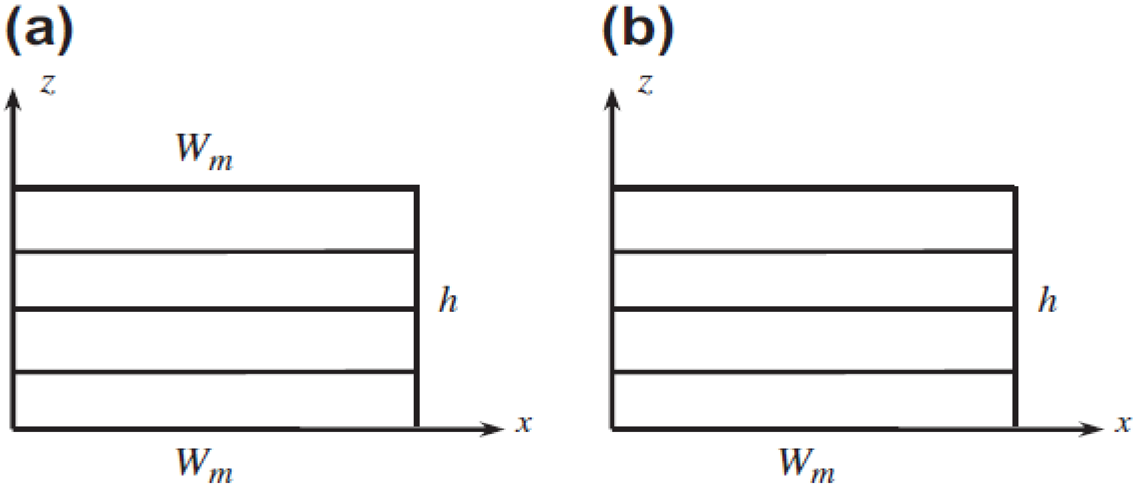


Fig. 16 Composite material exposed to moisture on (a) both surfaces z ¼ 0 and z ¼ h, and (b) on the surface z ¼ 0 only.

Where, Dm is the increase in the mass of a unit volume material element due to moisture absorption and m is the mass of the dry material element. Moisture distribution in the material is governed by: -

$$\frac{\partial}{\partial n}\left(D\frac{\partial W}{\partial n}\right)=\frac{\partial W}{\partial t}$$ ……………………………………………17

Consider a laminated composite material shown in Fig. 17 for which n coincides with the z-axis. Eq. (2) for moisture diffusion, there is a difference in principle between these problems. This difference is associated with the diffusivity coefficient D, which is much lower than the thermal conductivity l of the same material. As is known, there are materials, e.g., metals, with relatively high l and practically zero D coefficients. Low D-value means that moisture diffusion is a rather slow process.

To simplify the problem, we can neglect the possible variation of the mass diffusion coefficient D over the laminate thickness, taking D ¼ constant for polymeric composites. Then, Eq. (3) reduces to

$$D\frac{\partial^2 W}{\partial z^2}=\frac{\partial W}{\partial t}$$ ………………………………………………18

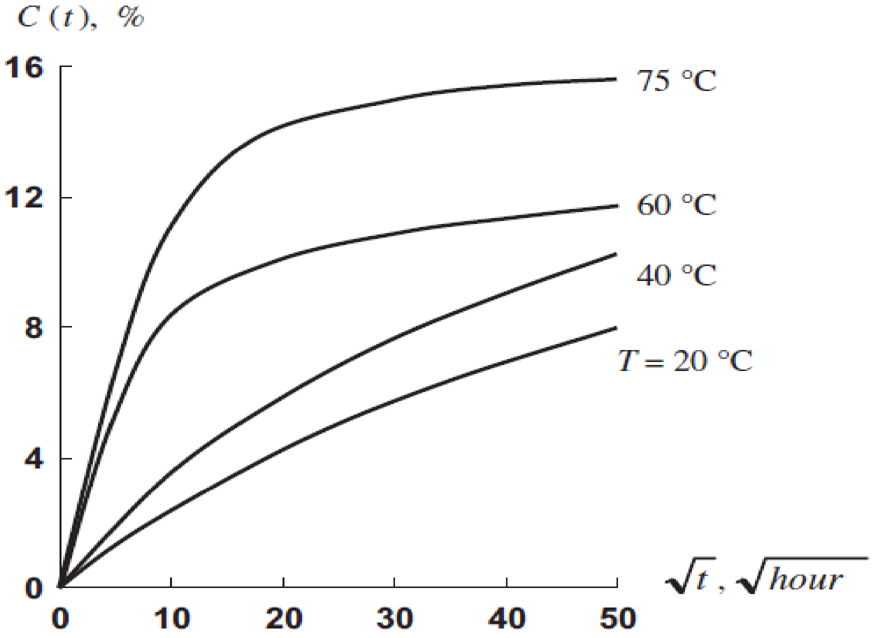


Fig. 18 Moisture content as a function of time and temperature for aramid-epoxy composite

UNIT -5

Maintenance of Composites: Assessment and Repair – Classification of damage, Inspection Methodology, Repair operation, Repair procedures. Types of Repairs – Repair failures, Typical repair procedures Delaminations, Damage to laminate structures, Repair to sandwich structures, Repair to Honycomb structures, lightning protection, painting the composite part, Quality control.

MAINTAINANCE OF COMPOSITES

Aircraft Structure Repair: -

Aviation composites utilize an assortment of materials which may include fiberglass, carbon fiber or aramid. These materials are very durable and versatile and also provide corrosion and fatigue benefits. Even with their great benefits they still do wear down and can get damaged over time. Our aircraft composite maintenance technicians classify damage or fatigue, determine necessary repair procedures and aircraft structure repair time.

Advanced Aircraft Composite Repair Technology: -

When it comes to composites in aviation we know the importance of safety and keeping your fleet flying. By never losing sight of the pressures placed on cost control, Delta TechOps expands your MRO capabilities without the enormous capital investment. Delta TechOps provides the highest quality services for the greatest overall value by continually upgrading cutting-edge technology to lead the industry with the latest advances in aircraft composite repair.

Composite Repair Technical Support & Services

Delta TechOps offers comprehensive technical support and a wide range of in-shop and on-wing services to evaluate failures, recommend preventative actions and assist with component reliability. Check out some of our composite maintenance support capabilities below.

1. Visual inspection
2. Damage assessments – Point of Impact Damage and Load Path Damage
3. Inspection
4. Repair

5. Overhaul

DAMAGE ASSESSMENT

Damage to composites is often hidden to the eye. Where a metal structure will show a “dent” or “ding” after being damaged, a composite structure may show no visible signs of damage, and yet may have delaminated plies or other damage within Impact energy affects the visibility, as well as the severity, of damage in composite structures. High and medium energy impacts, while severe, are easy to detect. Low energy impacts can easily cause “hidden” damage.

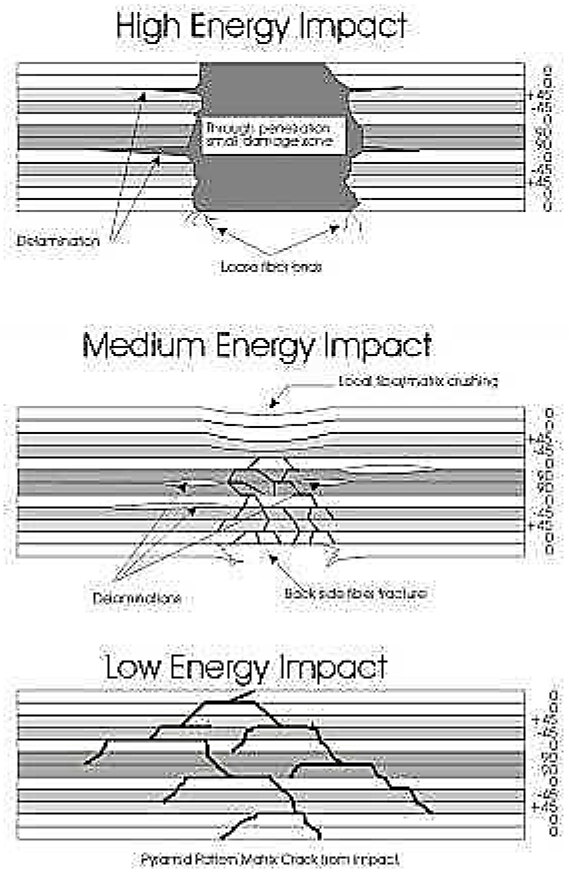


Fig. 1 high energy, medium energy and low energy impact

There are a variety of non-destructive inspection techniques available to help determine the extent and degree of damage. Each has its own strengths and weaknesses, and more than one method may be needed to produce the exact damage assessment required. The following table provides a basic comparison between the non-destructive inspection techniques. 'A' indicates damage where the technique scores well, and 'C' indicates damage where the technique is not so good.

ASSESSMENT OF COMPOSITE MATERIAL DAMAGE

The task of repair begins when you determined that the structure has been damaged and that the damage is sufficient to require the structure to be repaired. The existence of damage may be obvious, such as a skin penetration, a gouge, or a dent. Con-aversely, the proper identification and classification of the damage may be difficult. Because of the brittle, elastic nature of composite laminate materials, for example, the fibers may break upon impact, but then spring back, leaving little visible indication of damage. There are three distinct steps involved in damage assessment. The first step is to locate the damage. The second step is to evaluate the defect to determine such information as the defect type, depth, and size. This information is important because the method of repair will vary, depending on this information. The third step is to re-evaluate, after defect removal (as applicable), the area being repaired.

INSPECTION METHODOLOGY

1. Non-destructive inspection-present damage detection: -

Throughout the years, NDI has been the most important tool used in order to assess the condition of the aircraft structure. NDI inspections are being accepted as part of procedures during major aircraft inspection tasks such as the C-checks, Heavy maintenance visit (HMV) or during defect findings. Rectification of the damage has to be accompanied by task completion documentations when the certificate of release to service (CRS) is issued. The improvement in NDI technology has allowed inspection to e tailored to the materials used, the operational conditions and the level of difficulties. However, and autonomous NDI is privileged to large aircraft manufacturing or assembly due to its high cost in obtaining certification, implementing the system and training for competent human capital.

Laminated composite materials, on the other hand, can have a wide varying set of material properties based on the chosen fibers, matrix, on other hand, can have a wide varying set of material properties based on the chosen fibers, matrix and manufacturing process. This makes modelling for composites more complex, often involving non-linear and hybridization of materials such as fiber, matrix, core.

2. Visual inspection method

Perhaps the most natural form of evaluating composite structure is by visual inspection. There are several variants of this method existing at various levels of sophistication, from the use of a static optical or scanning electron microscope to optical examination by eye over the structure. While microscope can be a useful method to optical examination by eye over the structure. While microscopy can be a useful method to obtain detailed information such as micro-crack counting or the delamination area, it can only be used in the laboratory therefore requiring that any given section must be removed from the larger structure. Visual inspections on particular structures are perhaps the simplest and least expensive method; they are relatively fast and capable of detecting relevant impact damages. However, any damages which have occurred in the su-laminate layer or on the other side of the surface are difficult to detect by eye and may require additional equipment such as a flash light, a magnifying glass. In addition, visually, the eyes alone can only determine very little detail about the damage mechanism or its severity. While this method can potentially provide some useful data for damage detection, on a largescale structure this process would prove inefficient and ineffective as determined by campbell.

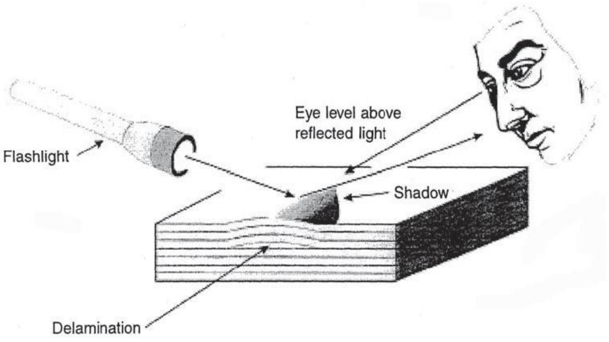


Fig. 1 Visual inspection. (Courtesy of Abaris Training Resources Inc.)

Advantages of Visual Inspection:

- No expensive equipment is required.

- Airworthiness design philosophy is such that most damage that is of concern is capable of being found visually.

Disadvantages of Visual Inspection:

- Large areas are time consuming to inspect.

- Inspectors have difficulty in maintaining concentration over large areas.

- Composites may have extensive nonvisible damage (NVD). This is particularly important in the case of nonvisible delamination. The critical failure mode of composites is often in compression, and any damage that reduces compression performance is unwelcome.

3. TAP TEST METHOD

This is the most well-known, vibration-based method specifically used on composite structures, the inspection uses a small metallic shape like coin which is then lightly tapped on the suspected structure. The change in sound between defective and defect-free regions indicates the presence of damage. However, the sensitivity of the method decreases with a defect depth of 1mm under the skin or the sub laminate area. In addition, the inspection only provides a rough dimension of the damaged section and is limited by approved certified personnel. Advanced equipment that digitally records the thudding sounding and displays it has replaced the coin tap test. The digital tap test captures the tapping sound made by the tap hammer connected to a unit which translates the tapping energy to sound energy. The sound energy is displayed as a numerical value. During inspection, the tap hammer is tapped at the adjacent area or on a reference specimen for a baseline reading. A tap test, as shown in Fig. 2, may be performed using a coin of modest weight or even a thick steel washer of approximately 25 mm (1 in.) diameter and approximately 2.5 mm (0.1 in.) thick. Inspection techniques, other than visual, do not come cheaper than this

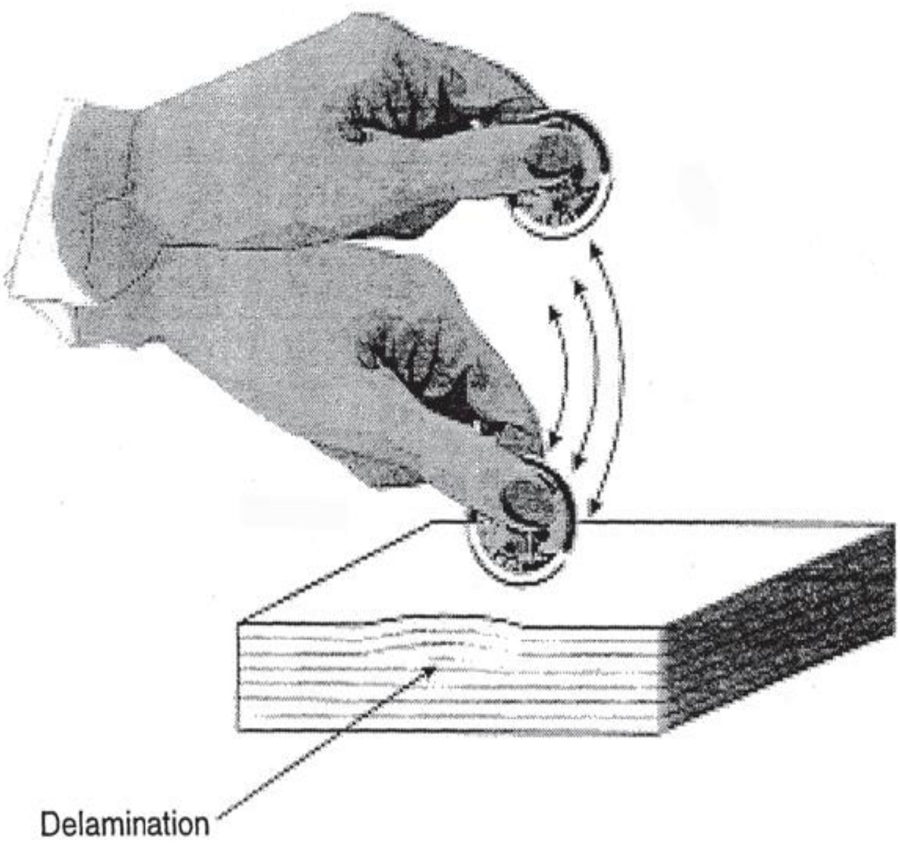


Fig. 2 Tap testing method

The method has now been automated, at much greater expense, and with somewhat greater accuracy. Three automated versions are now made. The earliest is aptly called the “Woodpecker,” which is of Japanese design. Since the first edition of this book went to print, two more automated tap test methods have been designed. These are the Wichitech RD3, which is a hand-held device developed by Boeing and licensed to Wichitech, and the CATT (Computer Aided Tap Test), developed by Iowa State University and licensed to Advanced Structural Imaging Inc., which has an automatic tapping carriage to eliminate any effects due to the human operator. All of the automated methods have the advantage that they can produce a print of the damaged area, which is both useful and a permanent record of the damage found. The tap test method may also be described as “audiosonic” because it operates in the normal human hearing range. In contrast, ultrasonic methods operate outside the human hearing frequency band.

The tap test method is well loved and widely used because, in the cheaper form, it is simple and available to everyone. All that is required is to tap gently on the suspect surface. Areas of good bond will sound clear and of a higher frequency than disbonded areas, which give a dull sound of lower frequency. By tapping at intervals of approximately 6 mm (0.25 in.), the damaged area can be mapped effectively. If approximately 12 mm (0.5 in.) are cut away beyond this to provide a margin of safety, then this is probably sufficient for fairings and nonstructural items. For these items, the method is often sufficient by itself, especially for initial damage assessment, although it is wise to use more sophisticated methods as a backup to ensure that all the damage has been cut away before commencing repairs to more significant parts. The method is especially useful on sandwich structure with honeycomb core. It also works on a solid laminate if the first few layers are delaminated, but it cannot detect defects deeper in the laminate.

Advantages of the Tap Test:

- No expensive equipment is required, at least not for the simple version.
- A tap test provides a quick initial method of investigating the extent of a defect.
- A tap test can be used to detect delamination, disbond, and severe moisture ingress.

Disadvantages of the Tap Test:

- It is impractical to cover large areas effectively because it is difficult for an inspector to maintain concentration.
- A tap test is highly subjective.
- A tap test cannot locate small defects (e.g., voids or minor moisture ingress).
- A tap test cannot be used on locations covered by protective coatings and sealants.
- The sonic response is a function of material properties, laminate composition, thickness, shape, and component construction.

4. X-ray inspection methods

X-ray techniques relies on recording the difference in x-ray absorption rates through the surface of a structure. These methods are implemented either in real-time digitally, or by taking static radiography, where areas of different permeability or density are differentiated by the magnitude of x-ray exposure to the media on the opposite side of the surface after a predetermined excitation time. To accentuate damaged regions with cracks or delmination, a liquid penetrant is often applied to the area to be examined. While these techniques are relatively inexpensive and simple to implement and interpret, they require large and closely equipment that is difficult to use on large structural components without removing them from the vehicle. Other laminations include tier inability to detect defects in thin laminate structures, orientation variations, hybrid materials and image quality indicator. The greatest challenge to using x-ray in a vehicle inspection application is that all of these methods require access to both sides of the surface in order to emit and collect the x-ray radiations.

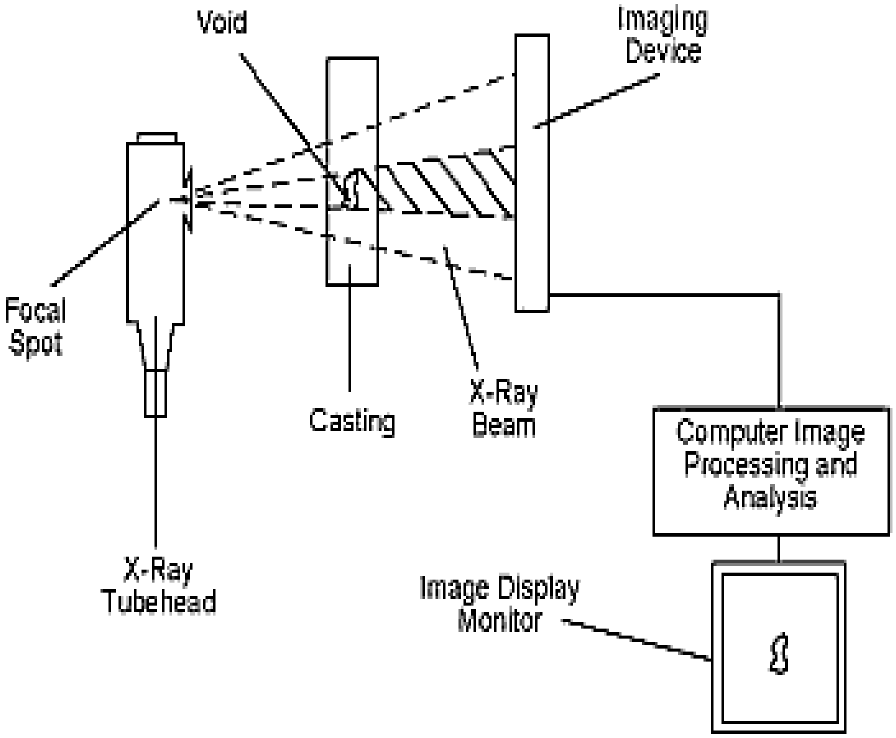


Fig. 3 X-ray inspection techniques

Advantages of X-Ray Methods:

- X-ray inspection may be used to detect transverse cracks, inclusions, honeycomb core damage, honeycomb moisture ingress (water as shallow as 10% of the cell depth), porosity, and delamination (if a radio opaque penetrant is used).

When used with a radio opaque penetrant and a radio opaque fiber system, x-ray inspection may provide an accurate picture of damage in a complex structure.

- Stereographic use allows some depth resolution (e.g., 15° source tilt gives +1 mm [0.04 in.] depth resolution, and 8° source tilt gives +10 mm [0.4 in.] depth resolution).

- The x-ray technique may be used to measure fiber volume fraction (Vf) and fiber alignment when material characteristics allow (e.g., GRP).

Disadvantages of X-Ray Methods:

- Considerable safety protection is required when this technique is in use. The hangar area requires evacuation, thus imposing a downtime penalty on the production plan.

- The equipment is not easily portable.

- The usefulness of the equipment is limited by access.

- The use of penetrants contaminates the component. Organic pentrants are affected by moisture, which may alter the recorded results. Halogen-based penetrants may result in stress corrosion.

5. ULTRA SONIC METHODS

Another commonly implemented NDI techniques is ultrasonic testing, most often referred to a A-, B- and C- scans. The method uses an ulltrasoonic signal and measures the attenuations of the signals using stress waves on the inspected structure. The stress waves are mechanical waves or vibrations in which for composites the compatible frequency range is between 1 to 10 MHz. there are two modes of operation which are pulse echo and through transmission. A pulse eco uses a single transducer which behaves as a transmitter and receiver. Alternatively, through transmission of the ultrasonic waves is achieved by the use of a couplant such as liquid and water but these couplant may contaminate the structure further if the couplant is seeping through the unseen damage. Newer techniques, such as non-conact couplant uses air to transmit the waves, but more confident results are required for the method to be used on the current NDI for aircrafts.an A- scan refers to a single point measurement of density, a B- scans measures these variations along a single line, and a C- scan is a collection of B- scans forming a surface countour plot. The C- scans has been common practice in the aerospace industry since the introduction of composite parts to this field.

Wavelength l = c/f

where

c = Velocity of ultrasound

f = Frequency

Although the use of ultrasonic inspection has more accurate results compared to other method dicussed above but are limited to laminated structure only.

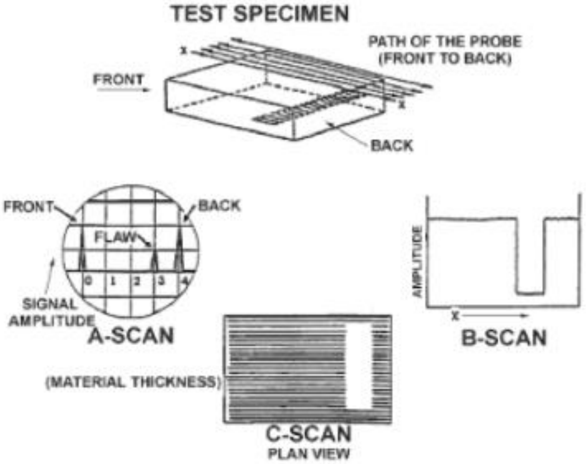


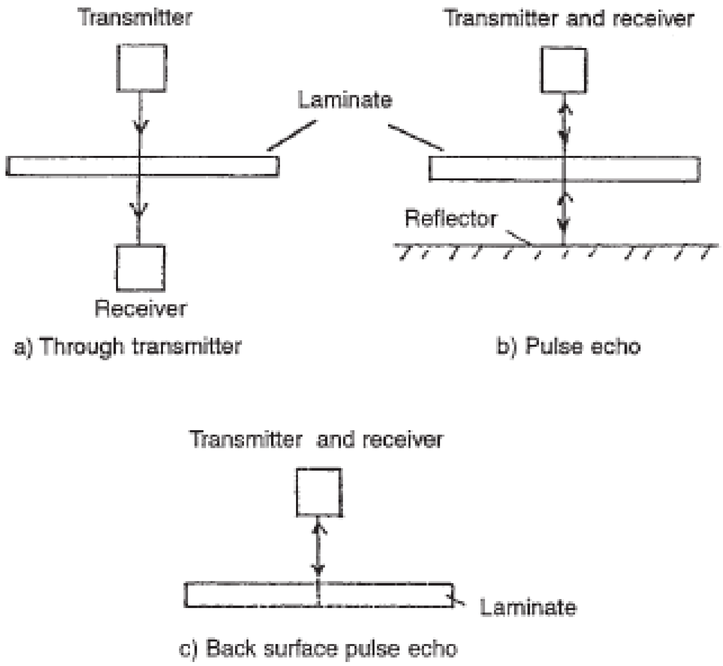
Figure 4 Typical scanning method for ultrasonic inspection (Downloaded from http://www.engineersedge.com/inspection/ultrasonic.htm).

Two modes of operation are normally used (Fig. 4):

1. Pulse echo mode using a single transducer

2. Through-transmission mode using two transducers

In either case, the transducer(s) must be coupled to the structure via a liquid or solid medium because of the severe impedance mismatch between air and solid materials.

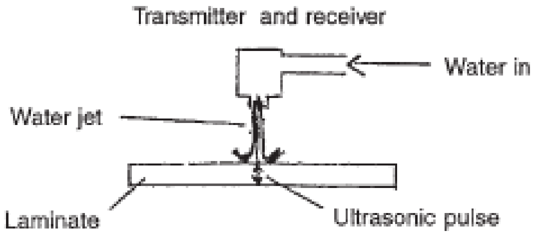


a) Through transmitter

b) Pulse echo

c) Back surface pulse echo

Ultrasonic testing



Water jet probe

Fig. 4 (b) Diagram of ultrasonic inspection methods.

Using a pulse-echo technique, only the top face-to-core bond can be inspected reliably according to one source. By using through-transmission mode, top and bottom bonds can be inspected in a single test. The same basic equipment may be used with either water or gel coupling. Several types of measurement are possible.

The "A" Scan is the display normally seen on the screen of the ultrasonic test set and gives the time history of the echoes received by the receiving transducer.

In the "B" Scan presentation, the vertical axis is the time axis of the "A" Scan, the presence of echoes being indicated by intensity variations. The horizontal axis gives position information, building an image of the component cross section.

If the amplitude of a particular echo is monitored at each point on the surface of the work, a "C" Scan can be produced. Measurements at each point are taken using a scanning mechanism, which produces a plan of the defect positions but gives no information about their depth. This method is often used by manufacturers using the through-transmission mode and water jet coupling and has the advantage that a permanent record can be printed.

If necessary, this printout could be compared with another scan taken after some period of service or when the possibility of damage was suspected.

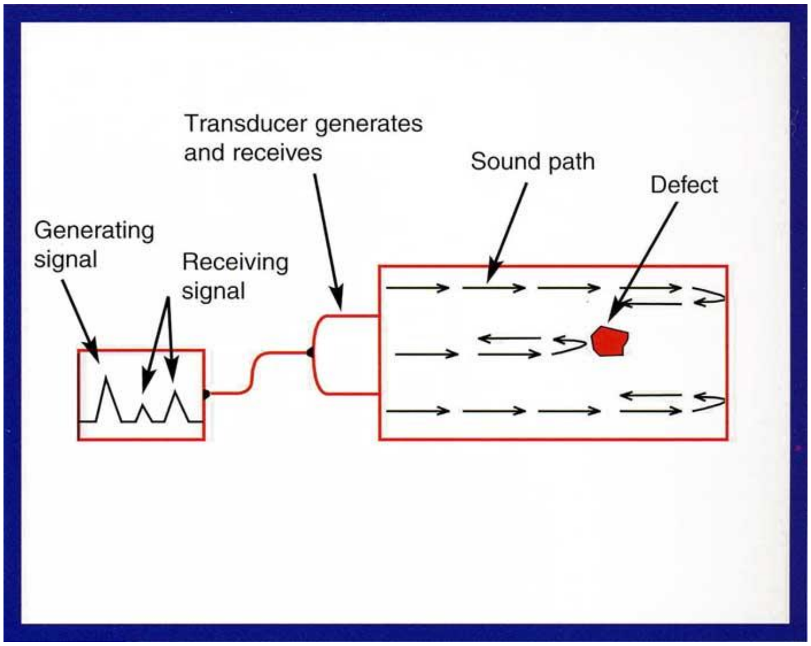


Fig. 5 Ultrasonic testing

Advantages of the Ultrasonic Technique:

- This technique may be used to detect many defects, such as defects in the plane of the sheet, delamination, voids, foreign objects, moisture, disbonding, and cracks perpendicular to the plane of the sheet if the transmitter and receiver are located at an angle with respect to the plane of the composite surface. This technique also may be used to detect delamination between sandwich panel core and skin laminate.

- This method can also indicate the depth of a defect in a laminate.

- The technique is flexible because it may be used in a local portable form or to cover large areas, such as "C" Scan, providing a map of defect locations in a part.

- If focused transceivers are used in conjunction with "C" Scan and suitable computing equipment, a three-dimensional image of the composite component and its defects can be built. (Focused transceivers allow some depth resolution.)

Disadvantages of the Ultrasonic Technique:

- A couplant must be used between the transceiver and component. This may be in the form of a gel, or water in the case of "C" Scan and may contaminate the specimen.

- "C" Scan requires component removal from the aircraft.

- The pulse-echo technique allows detection of damage from only one side of the component.

- The through-transmission technique requires access to both sides of the specimen and is best suited to the production environment.

TYPES OF REPAIRS IN COMPOSITE

1. Cosmetic

A superficial, non-structural filler is used to restore a surface to keep fluids out until a more permanent repair is made. This type of repair will not regain any strength and is used only where strength is unimportant. Due to high shrinkage, cosmetic repairs may start to crack after a relatively short time in service.

Fig. 6 Cosmetic repair

2. Resin Injection

This type of repair can be effective in limited instances, where the delamination is restricted to one ply. However, not much strength is regained, and the primary benefit is that it is quick and cheap. At best, this type of repair can hope to slow the spread of delamination and is generally considered a temporary measure.

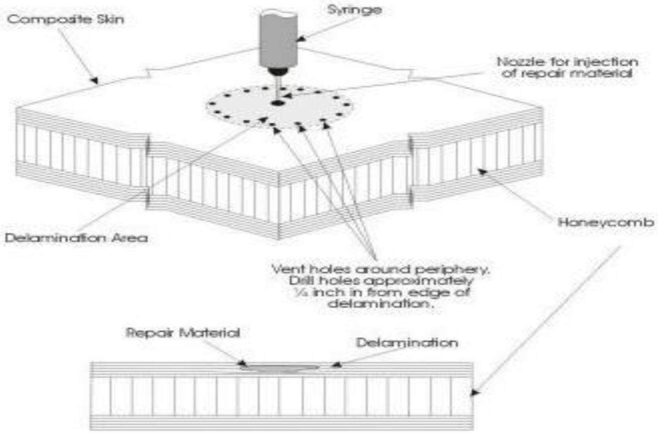


Fig. 7 Resin injection

3. Semi-structural Plug/Patch

This type of repair can regain some strength. The mechanically-fastened plug (i.e. core plug) and patch repair can be especially effective where thick solid laminates are used, since they take bolt loads well.

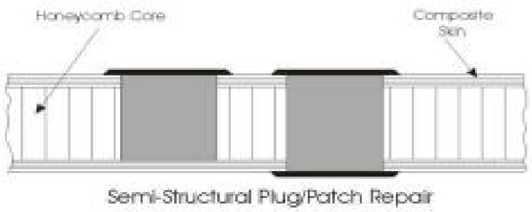


Fig. 8 Semi-structural Plug/Patch

4. Structural Mechanically–fastened Doubler

Full structural repairs using bolted doublers can be used in heavily loaded solid laminates. This is often the only practical means of repairing such structures. However, such repairs are not aerodynamically smooth, and may cause "signature" problems in structures where low-observability by radar is required. They also leave the original damage and simply attempt to transfer loads around the damage. Finally, they can create stress concentrations at their corners and edges.

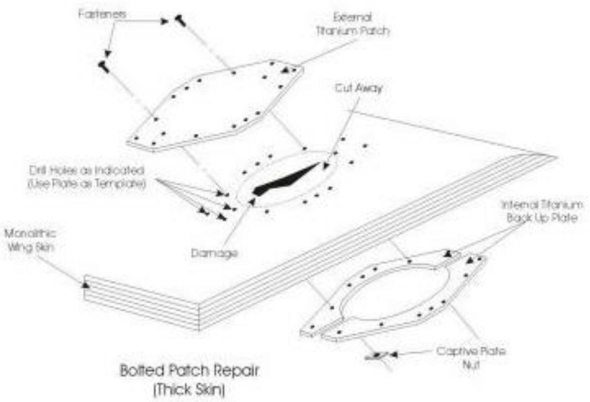


Fig. 9 Structural Mechanically–fastened Doubler

5. Structural Bonded External Doubler

Bonded external doublers are often used to perform repairs to lightly loaded thin laminate structures. This type of repair is especially common using wet lay-up materials. They may be room-temp or high-temperature cured, depending on the matrix resin system used. These repairs can regain a significant portion of the original strength of the structure—or even full strength—although with a significant stiffness and weight penalty in many cases. This type of repair is generally easy, relatively quick and does not require the highly developed skills of flush structural repairs.

6. Structural Flush Repair

This repair restores full structural properties by forming a joint between the prepared repair area and the repair patch. The repair patch is made by replacing each ply of the composite laminate that has been removed from the damage area. The size of the repair patch should fit exactly the area prepared for repair, except for a final cosmetic or sanding layer, which is often slightly larger to allow for sanding down to achieve a smooth and/or cosmetic surface.

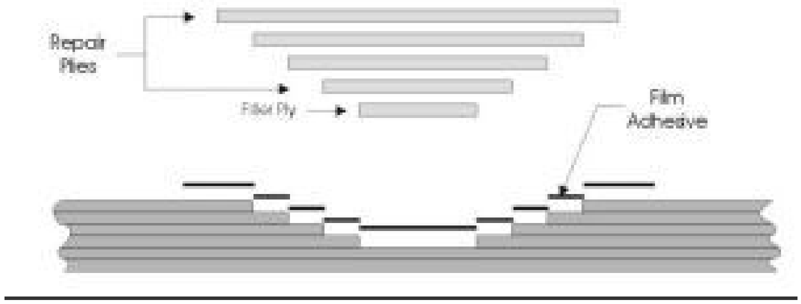


Fig. 10 Structural Flush Repair

TYPICAL REPAIR PROCEDURE

1. Selection of The Repair Method: -

The repair design is often driven by engineering requirement other than stress analysis. These design drivers include the following:

a. Availability of repair facilities, including tools, equipment and materials, and the level of repair authorization.
b. The types of damage found has significant influence on the structural design of the repair. This would be analysis with the indication of degradation in material due to cracks, delamination and holes.
c. Repairs done on or off the aircraft will involve a certain level of compromise between adequate strength/stiffness restoration and aircraft down-time and labour cost.
d. Accessibility of the damaged area influences design simplicity and repair scheme application methods.

2. Repair Criteria

The basic of the repair design follows a logical repair criterion. The parameters of the repair criteria are listed in below table.

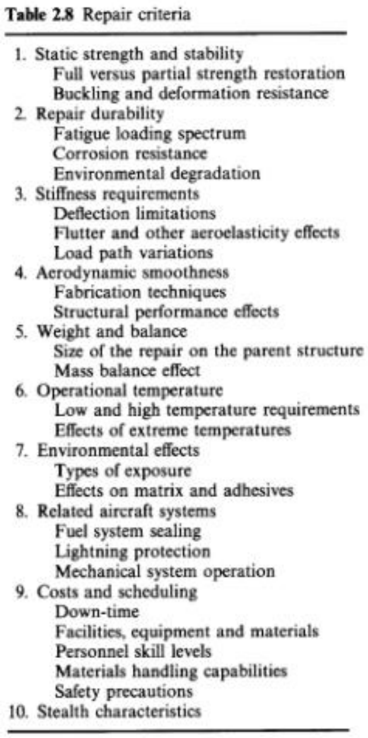


Table 2.8 Repair criteria

1. Static strength and stability
   - Full versus partial strength restoration
   - Buckling and deformation resistance
2. Repair durability
   - Fatigue loading spectrum
   - Corrosion resistance
   - Environmental degradation
3. Stiffness requirements
   - Deflection limitations
   - Flutter and other aeroelasticity effects
   - Load path variations
4. Aerodynamic smoothness
   - Fabrication techniques
   - Structural performance effects
5. Weight and balance
   - Size of the repair on the parent structure
   - Mass balance effect
6. Operational temperature
   - Low and high temperature requirements
   - Effects of extreme temperatures
7. Environmental effects
   - Types of exposure
   - Effects on matrix and adhesives
8. Related aircraft systems
   - Fuel system sealing
   - Lightning protection
   - Mechanical system operation
9. Costs and scheduling
   - Down-time
   - Facilities, equipment and materials
   - Personnel skill levels
   - Materials handling capabilities
   - Safety precautions
10. Stealth characteristics

3. GENERIC REPAIR DESIGNS

There are four basic levels of generic repair design:

a. Non-structural or cosmic repairs. Filling and sealing the damaged area where damage significance is minor, but environmental protection is necessary, is a cosmetic or non-structural repair. A typical cosmetic repair is as shown in below

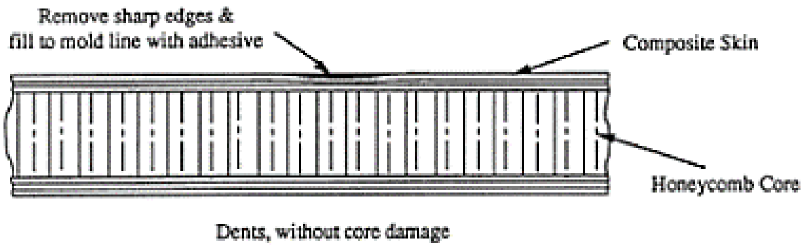


Fig. 11 Cosmetic repairs (Unstructured)

b. Semi-structural repairs. Filling the internal cavity with an adhesive form or honeycomb core replacement and applying a doubler patch to the damaged area is a semi-structural repair as shown in fig. the doubler patch can be either non-load bearing, load bearing or have some intermediate load carrying capacity.

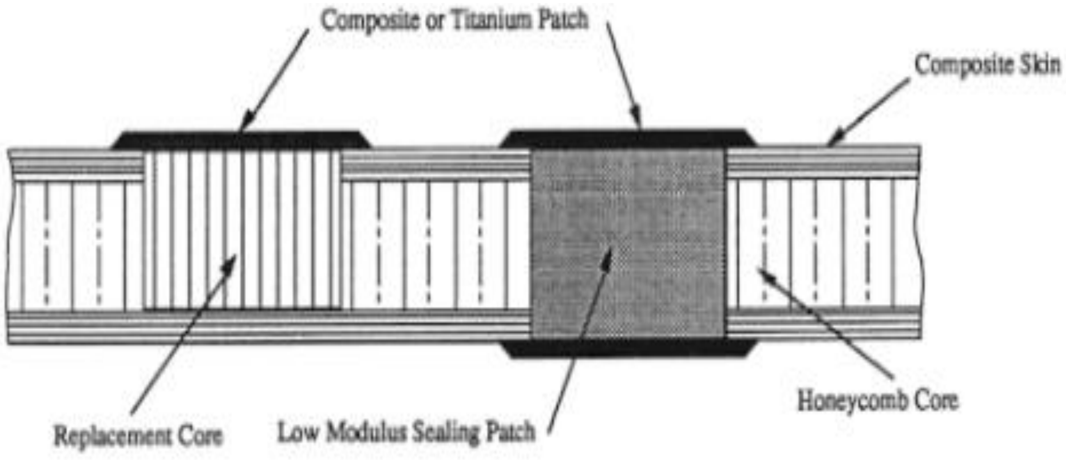
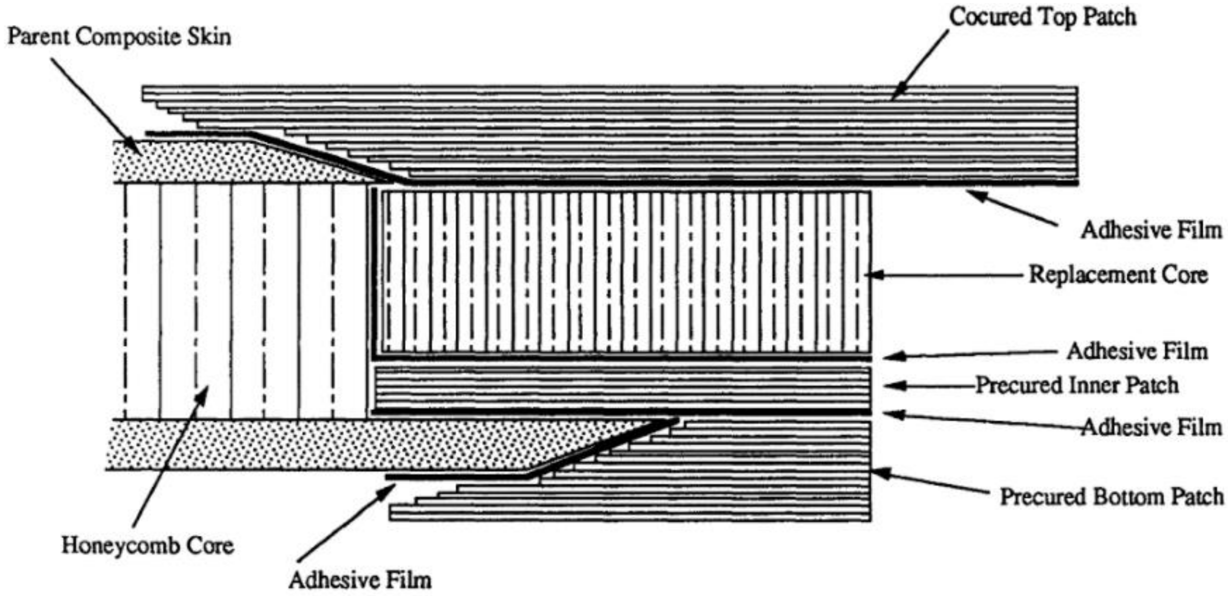


Fig. 12 Semi-structural plug/patch repairs

c. Adhesively bonded structural repair. A flush patch adhesively bonded over the damaged area as shown in fig., is a major structural repair utilizing a scarf or stepped-lap joint. The flush is generally application to thin skin structures only.
d. Mechanically fastened structural repairs. Another structural repair is the bolted patch. This is used on primarily thick structural components as shown in fig.



Fig, 13 Flush bonded patch repairs

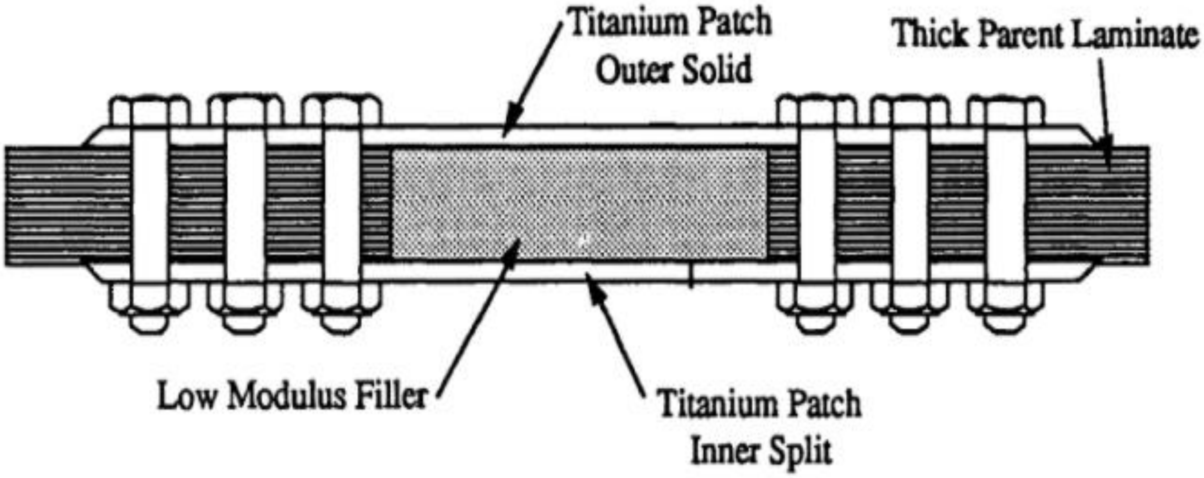


Fig. 14 bolted patch repairs

4. SWELLING AND DELAMIATION

The repair scheme is to adhesively bond a doubler patch over the delaminaed region. The required repair scheme is to stiffen the delaminated region by an adhesively bonded patch. Determination of the patch stiffness is based on the analysis as in below equation, but here the stiffness of the sublaminate and patch needs to be such that the critical bucking load is greater than the applied design allowable load.

$$E_p = \frac{E_{\mathrm{lam}} h}{t_p}$$

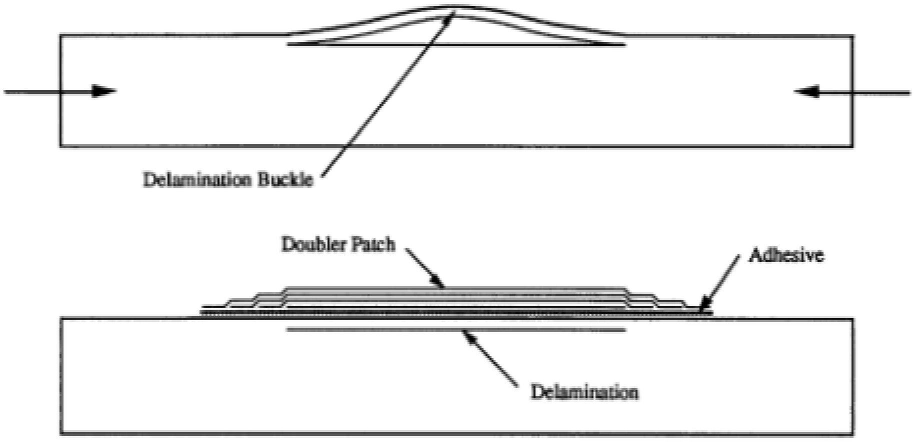


Fig. 13 Swelling and delamination composite

C. Edge delamination repairs. With an edge delamination the first requirement of the repair scheme is to seal the edge from further moisture absorption. Again, a low viscous resin is used. Local in-plane stiffening of the edge is more difficult since the out-of-plane forces which causes delamination growth are still present. The most effective repair design is to simply reinforce the out-of-plane stresses are much lower than in-plane, a fattener or thin capping patch is all that is required. The capping patch is made from titanium foil or composite cross-ply of thickness about 1mm and overlap length on the upper and lower surface extending 25mm beyond the depth of the delamination.

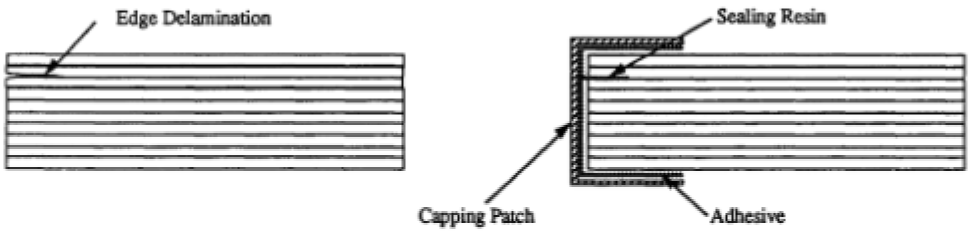


Fig. 14 Out-of-plane reinforcing capping patch over edge delamination

5. HOLES

Three fundamental repairs are required for holes. These are classified as low, moderate and full-strength restoration, and depend on the degree of strength loss in the structure.

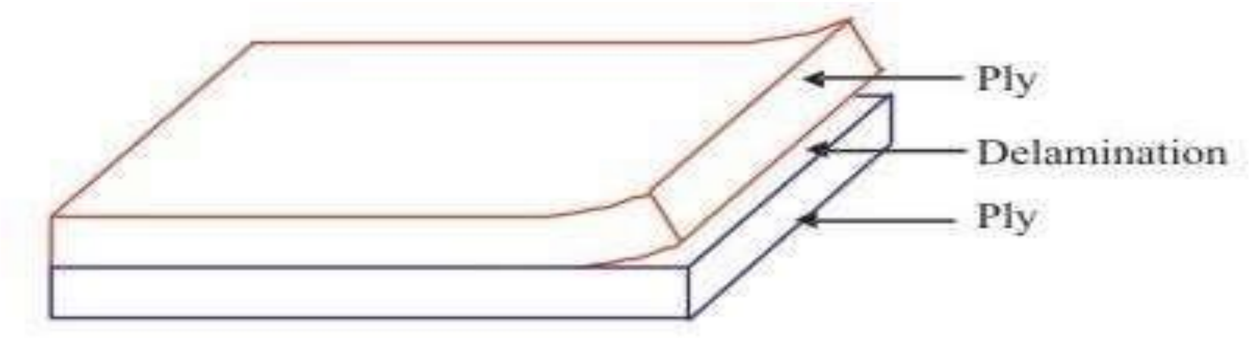
a. Low strength restoration hole repairs. When the hole in the laminate has minimal strength degradation the general repair is a plug/patch scheme.
b. Moderate strength restoration hole repairs. When damage analysis of a hole indicates that there is moderate strength degradation, i.e. the current level of damage tolerance is significantly reduced, but catastrophic failure would only occur with severe overload, then a plug and structural doubler patch is recommended in fig. 13

DELAMINATION

Delamination is a mode of failure for composite materials and steel. In laminated materials, repeated cyclic stresses, impact, and so on can cause layers to separate, forming a mica-like structure of separate layers, with significant loss of mechanical toughness. Delamination also occurs in reinforced concrete structures subject to reinforcement corrosion, in which case the oxidized metal of the reinforcement is greater in volume than the original metal. The oxidized metal therefore requires greater space than the original reinforcing bars, which causes a wedge-like stress on the concrete. This force eventually overcomes the relatively weak tensile strength of concrete, resulting in a separation (or delamination) of the concrete above and below the reinforcing bars.

Fiber pull-out (another form of failure mechanism) and delamination can occur, in part, due to weak adhesive bonding between the fibers and the polymer matrix.

Delamination failure may be detected in the material by its sound; solid composite has bright sound, while delaminated part sounds dull, reinforced concrete sounds solid, whereas delaminated concrete will have a light drum-like sound when exposed to a dragged chain pulled across its surface. Bridge decks in cold climate countries which use de-icing salts and chemicals are commonly subject to delamination and as such are typically scheduled for annual inspection by chain-dragging as well as subsequent patch repairs of the surface. Other nondestructive testing methods are used, including embedding optical fibers coupled with optical time domain reflectometer testing of their state, testing with ultrasound, radiographic imaging, and infrared imaging.



Separation of adjacent layers due to weakening of interface layer between them.

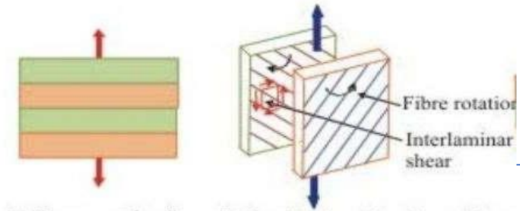
<u>Causes of delamination</u>: -

<u>1. Manufacturing Defects</u>

a. Improper laying of laminae
b. Insufficient curing temperature; pressure and duration of curing
c. Air pockets and inclusions

<u>2. Loading Generating Transverse Stresses</u>

The interface is weaker in transverse strength as compared to the layers. Hence, its failure is dominated by the transverse stresses.



(a) Transverse loading (b) Interlaminar shear by axial loads in off-axis laminate (c

3. Laminate Geometry

1. Free edges

The free edges of the laminate have very high transverse normal and shear stresses. It is shown that significant interlaminar stresses are induced in regions near the laminate free edges.

2. Notch

Notch in the laminates acts like an external crack giving rise to high three-dimensional stress state in the vicinity of the notch

3. Cut- out

The cutout boundaries act like free edges leading to significant transverse stresses.

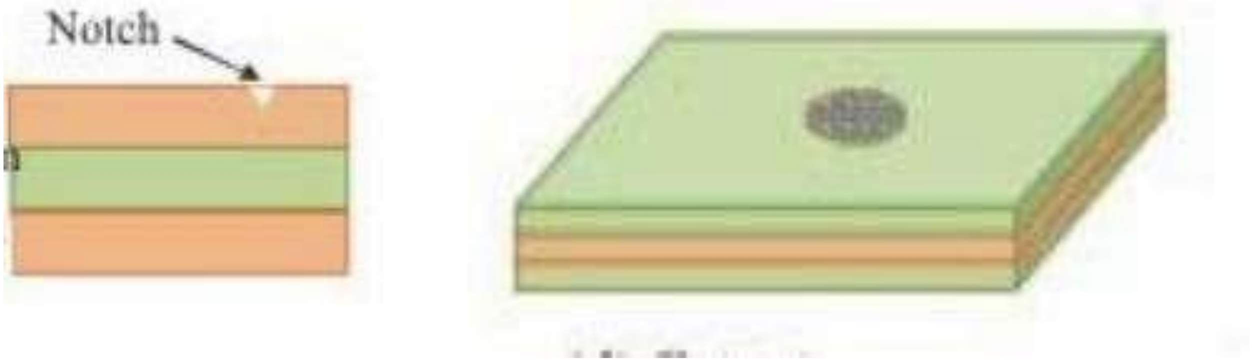


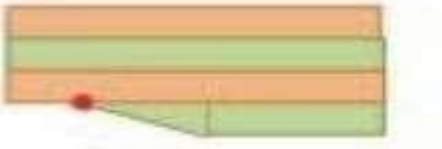
Fig. a. Notch b. Cut-out

4.Bounded joint

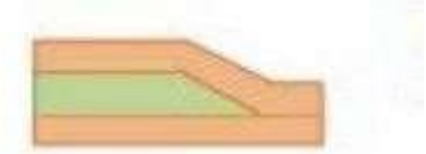
Improper bonding leads to weaker joints. When such weak joints are subjected to serve loading conditions delamination can occur.

5.Ply drop

The region of ply termination acts like a region of high stresses for neighboring laminae which can be a reason for delamination of the plies adjacent to the ply drop region.



(f) Bonded joint



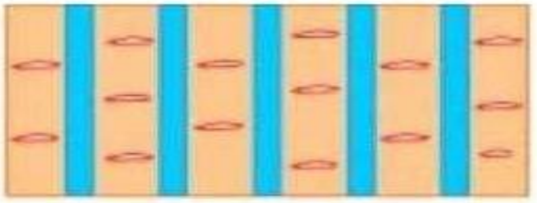
e) Ply drop/termination

EFFECTS OF DELAMINATION: -

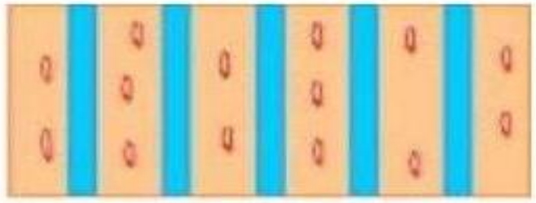
1. Reduces the strength and stiffness

2. It causes stress concentration in load bearing plies and a local instability leading to a further growth of delamination which results in a compressive failure of the laminate.

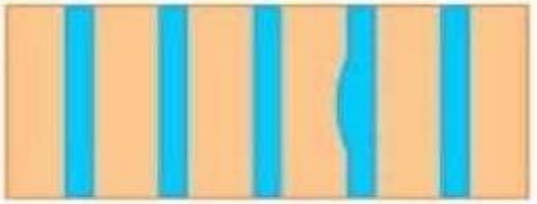
Matrix cracking



(a) Matrix Cracking



(b) Matrix Cracking



(c) Matrix Interface Cracking

Matrix cracks are developed due to stress in the matrix exceeds the strength of the matrix

Causes of matrix cracking

Two types of matrix cracks

The cracks are either perpendicular or parallel to the fibre direction.

> In the first type, the cracks are developed when axial stress in the lamina is tensile in nature.

>In the second type, the cracks are developed when the inplane transverse stress in the lamina is tensile in nature.

DAMAGE TO LAMINATE STRUCTURES: -

Laminated composites have an important application in modern aeronautical structures. They have extraordinary properties, like high strength, stiffness and lightweight. Nevertheless, a serious obstacle to more widespread use of those materials is their sensitivity to impact loads. As a consequence of that, impact damage initiation and growth are appearing in them. Failures that occur in laminated composite structures can be intralaminar and interlaminar. To date a lot of models for impact damages in laminates have been developed with higher or lower accuracy.

The laminated composites are increasingly used in load-carrying structures due to the number of advantages over conventional materials, especially in aircraft structures. They have exceptional characteristics such as: high specific strength and stiffness, low density, good fatigue performance, resistance to corrosion and high temperatures, ability to create complex shapes. For implementation of composite materials in aviation, the most important feature is their behaviour on dynamic loads and resistance to fatigue.

The failure of composite laminates involves sequential accumulation of various types of intra- and inter-laminar damages, which gradually lead to the loss of the laminate’s load-carrying capacity. The main damage mechanisms that appear in composite laminates, are those associated with matrix and fibre. Generally, it is difficult to simulate numerically or analytically, the behaviour of those systems under impact loads because of the complexity of damage mechanisms. Predicting damage in laminated composite aircraft components due to impact events such as runway debris, hail, bird, is an area of on-going research. To reduce certification and development costs, computational methods are required by the aircraft industry to be able to predict structural integrity of composite structures under high velocity impacts from hard objects, such as metal fragments, stone debris and from soft or deformable bodies such as birds, hailstones and tyre rubber. Key issues are the development of suitable constitutive laws for modelling composites in-ply, determination of composites parameters from dynamic materials tests, materials laws for deformable impactors, and the efficient implementation of the materials models into finite element (FE) codes.

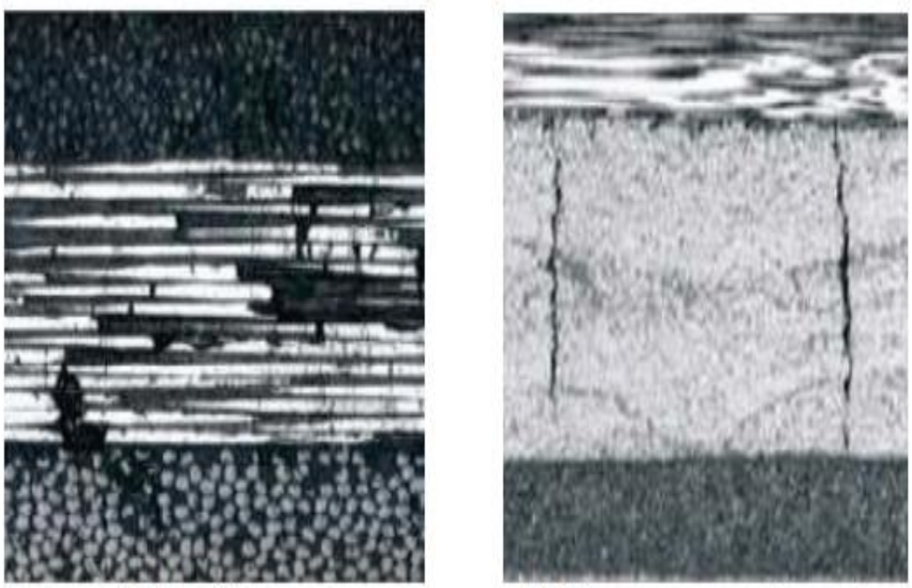
Impact damages in composite laminates

The energy absorbed during impact process is often very large. That energy is mainly dissipated by a combination of matrix damage, fibre fracture and fibre matrix debonding. These facts lead to the significant reductions in the load-carrying capabilities in such structures. In ballistic impacts (short contact between impactor and target) the damage is localized and clearly visible by external inspection, while low velocity impact involves long contact time between impactor and target, which produces global structure deformation with undetected internal damage at points far from the contact region.

Damages in composites are different from those in metals. Composite failure is a progressive accumulation of damage, including multiple damage modes and complex failure mechanisms. Impact on the structure has a dynamic nature and therefore it is necessary to take into account the effects arising from inertia and spreading voltage waves in the material. Often the material response is highly nonlinear and large deformations occur.

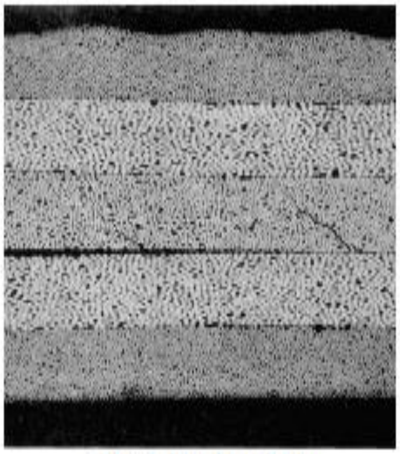
The most common damage mechanisms in laminated composites are: fibre fracture, transverse matrix crack and delamination. Those mechanisms are clearly presented in Fig 15.

Damage mechanisms in composite laminates can be studied theoretically following two approaches. Using the continuum damage mechanics approach, different types of damage are accounted for via the damage tensor. By the application of the damage micromechanics approach, stress analysis of the damaged composite structure is carried out in the explicit presence of damage. Transverse low velocity impact on the laminated composites induces intra-ply matrix cracking and interplay delamination.



a) Fiber fracture

b) Transverse matrix crack



c) Delamination

Fig. 15 Different types of defects corresponding to different directions

Structure of polymer matrix composites (PMC) is made of matrix and fibre. As an impact response in those materials some damages are occurring over time in certain phases. Damage observed during the initial stages of the failure process is the intralaminar damage in the form of matrix cracks. Matrix cracking is initiated long before the laminate loses its load-carrying capacity. It gradually reduces the stiffness and strength of the laminate.

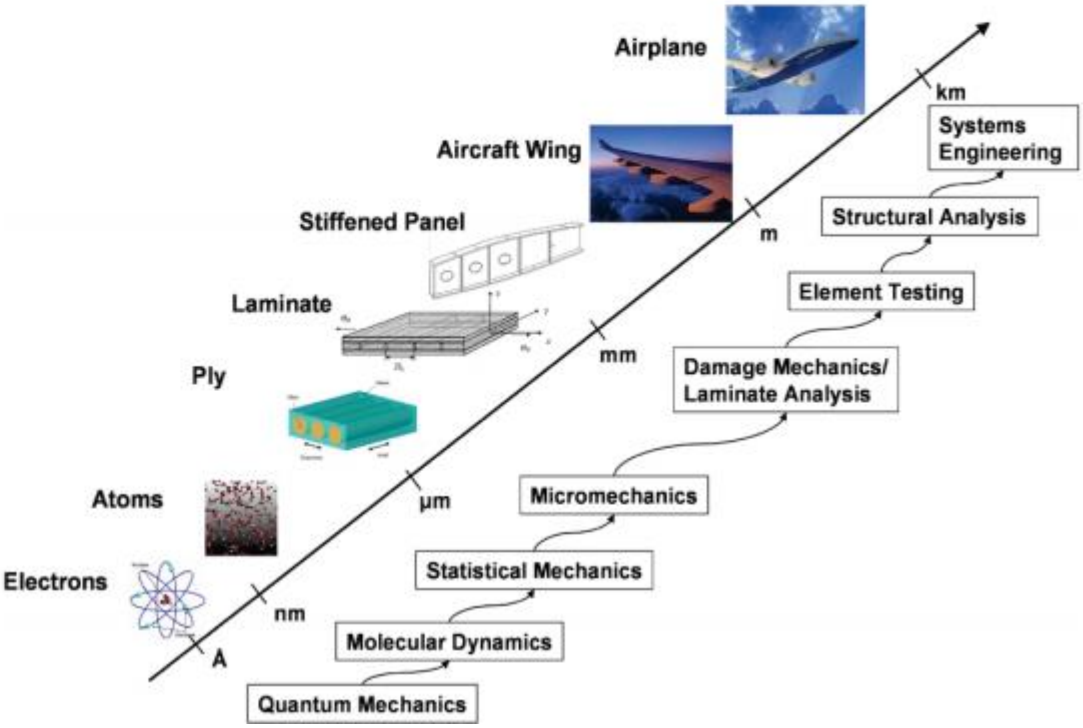


Fig. 17 Hierarchy of structural scales in damage modelling of aircraft composite materials

Multiscale modelling of damage The damage in composite laminates occurs due to different mechanisms. Some of them (fibre fracture, matrix crack and delamination) are already presented in Fig. 16. In the section below it will be addressed as the multiscale modelling damage in composite materials. To fully understand the underlying phenomena of structure degradation and characterize its effect on material performance, it is essential to link the two scales: the length scale at which these processes take place (the "micro" scale), and the length scale at which we use the material (the structural or "macro" scale). In reality these two scales may be different from each other and may require consideration of in-between scales (also known as "meso" scale). The process of linking material behavior at these different scales is termed as the "multiscale modelling". In Fig. 17 is described the hierarchy of all possible length scales (structural scales) involved in multiscale materials modelling (damage modelling). Another issue, particular to multiscale damage modelling, is that the total damage may be due to multiple damage mechanisms, whose length scales might be quite different from one another. Moreover, these length scales may evolve as loading is increased. The microstructural configuration and driving forces for damage initiation and progression determine the length scales of damage. Thus, the length scales of damage and their hierarchy are not fixed but are subject to evolution as a function of loading.

Damage Mechanisms in Fibrous Composites:

The damage mechanisms in a fibrous composite are broadly categorized as:

1. Micro-level damage mechanisms

2. Macro-level damage mechanisms and

3. Coupled micro-macro-level damage mechanisms

The local level mechanisms are further subcategorized based on constituent level as

i. Fibre level damage mechanisms

ii. Matrix level damage mechanisms and

iii. Coupled fibre-matrix level damage mechanisms

A. *Micro-level Damage Mechanisms:*

First, we will look at the micro-level mechanisms in detail as follows:

a) *Fibre Level Damage Mechanisms:*

The fibre failure mode is considered to be the most catastrophic mode of failure in laminates. This is because the fibre is the load carrying constituent. The failure of fibres can take place due to various stress components. The damage mechanisms for fibre are explained below in detail.

1) *Fibre Fracture/Breaking:*

The fibre breaks into two or more pieces along its length when the axial tensile stress (or strain) in the fibre exceeds the axial strength (or maximum allowable strain) of the fibre. This kind of fracture occurs in brittle fibres. Such fractures are more catastrophic in nature than other modes of fibre failure.

The fibre fracture may also take place in shearing when the shear stress or strain exceeds the maximum allowable stress or strain. The fibre fracture is depicted in Figure 18(a).

2) *Fibre Buckling or Kinking:*

This type of failure occurs when the axial load on the fibre is compressive in nature. The axial compressive stress causes the fibre to buckle. This form of fibre failure is also called as fibre kinking.

The critical stress at which the kinking takes place is function of material properties of fibre and matrix properties and the distribution of fibres in the matrix. In general, the fibre kinking first starts at the site of fibre misalignment or local defects as show in fig 18 (b)

3) *Fibre Bending:*

The bending of fibre can take place under flexural load. The bending of fibres also depends upon the properties of fibre and matrix along with the fibre arrangement.

The fibre bending is shown in Figure 18(c).

4) *Fibre Splitting:*

The fibre fails in this mode when the transverse or hoop stresses in the fibre exceeds the maximum allowable value. Further, this can also happen when these stresses in the interface/interphase region (region in matrix very close to the fibre) exceed the maximum allowable stress. The fibre splitting is elucidated in Figure 18(d).

5) *Fibre Radial Cracking:*

The hoop stresses can also cause the radial cracking of the fibre. This type of cracking is seen in some of the fibres. The radial cracking of a fibre is shown in Figure 18(e).

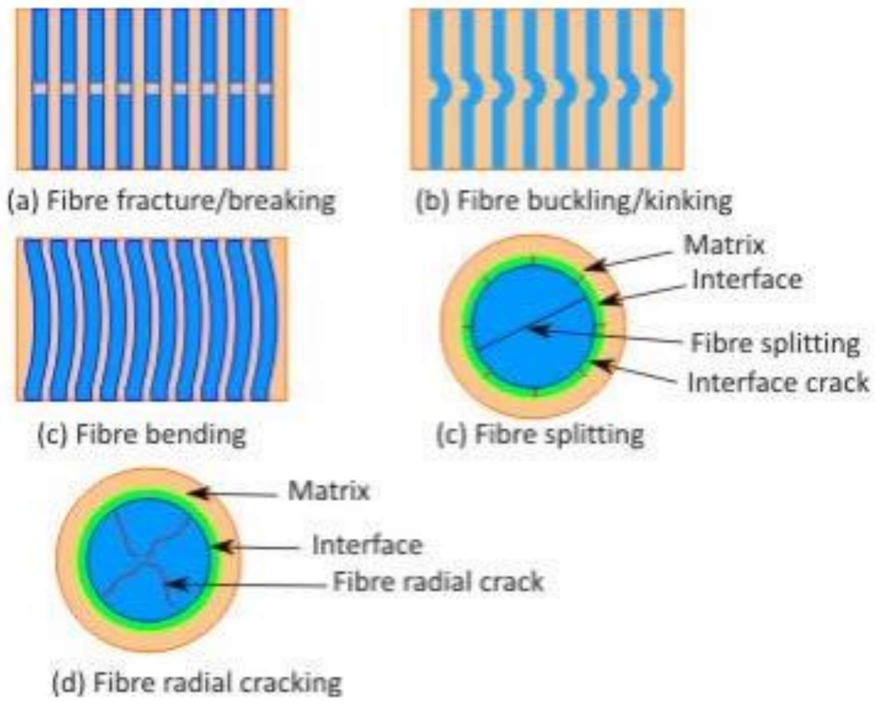


Fig. 18 Fiber level damage mechanism

b) *Matrix Level Damage Mechanisms:*

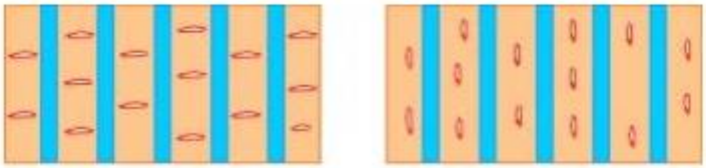
There are two main damage mechanisms in matrix. These are: Matrix cracking and fibre interfacial debonding. These are explained below.

1) *Matrix Cracking:*

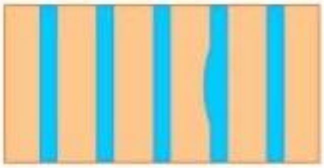
When the stress in the matrix exceeds the strength of the matrix, matrix cracks are developed. There are two types of matrix cracks that are developed in a unidirectional lamina. The cracks are either perpendicular or parallel to the fibre direction. In the first type, the cracks are developed when axial stress in the lamina is tensile in nature. In the second type, the cracks are developed when the inplane transverse stress in the lamina is tensile in nature.

2) *Fibre Interfacial Cracking:*

When the in-plane transverse stresses in matrix are tensile in nature, the weaker interface between fibre and matrix is broken. A crack in the matrix region at this location is initiated. This crack grows along the fibre length. This leads to the debonding of the interphase between fibre and matrix. This mode of damage is also called “transverse fibre debonding”. This damage is shown in Figure 19(c).



(a) Matrix Cracking (b) Matrix Cracking



(c) Matrix Interface Cracking

Fig.19 Matrix-level damage mechanisms

c) *Coupled Fibre-Matrix Level Mechanisms:*

1) *Fibre Pullout:*

The fibre pullout takes place when the bonding between fibre and matrix is weakened and the fibres are subjected to tensile stresses. If the fibres are already broken then the fibres just slide through the matrix and come out of it. This phenomenon is called fibre pullout. The fibre pullout is shown in Figure 20 (a).

2) *Fibre Breakage and Interfacial Debonding:*

When the fibres break the interface close to the tip of broken fibre, acts as a site of stress concentration. The interface may then fail, leading to debonding of the fibre from matrix. The fibre breakage leading to interfacial debonding is shown in Figure 20(b).

3) *Transverse Matrix Cracking:*

The interface failure causing debonding (as in fibre breaking and interfacial debonding in above case) from the matrix may act like as a stress concentration site for the in-plane transverse tensile stress. When this stress exceeds the limiting stress in matrix, it leads to through thickness transverse crack in the matrix.

The through thickness transverse matrix cracking is shown in Figure 20(c).

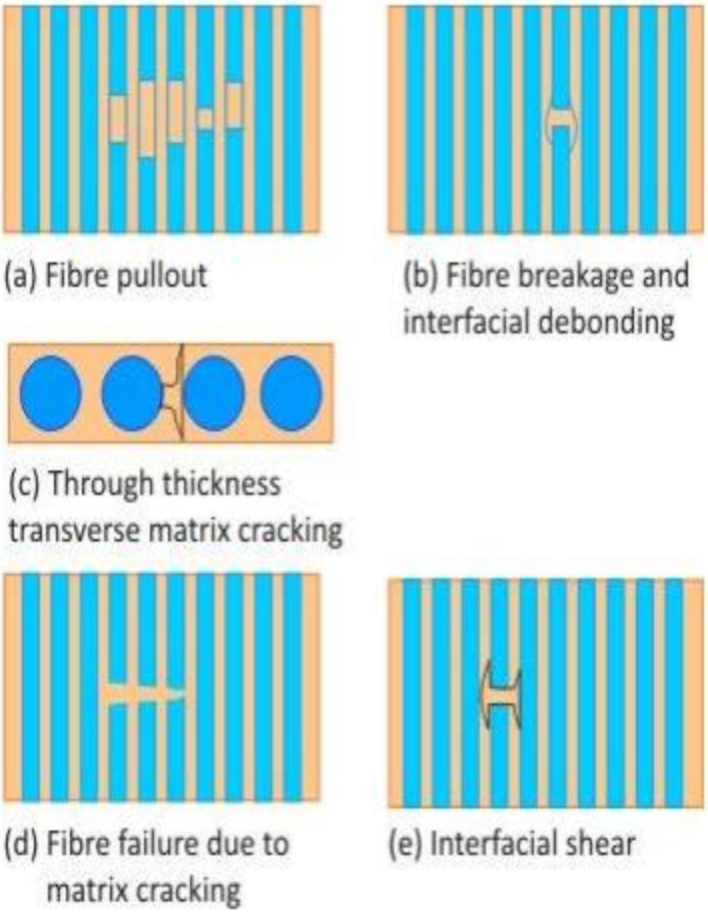


Fig. 20 Fibre-matrix coupled failure mechanisms

REPAIR OF SANDWITCH STRUCTURE

A large proportion of current aerospace composite components are light sandwich structures that are susceptible to damage and are easily damaged. Because sandwich structure is a bonded construction and the face sheets are thin, damage to sandwich structure is usually repaired by bonding. Repairs to sandwich honeycomb structure use similar techniques for the most common types of face sheet materials, such as fiberglass, carbon, and Kevlar®. Kevlar® is often repaired with fiberglass.

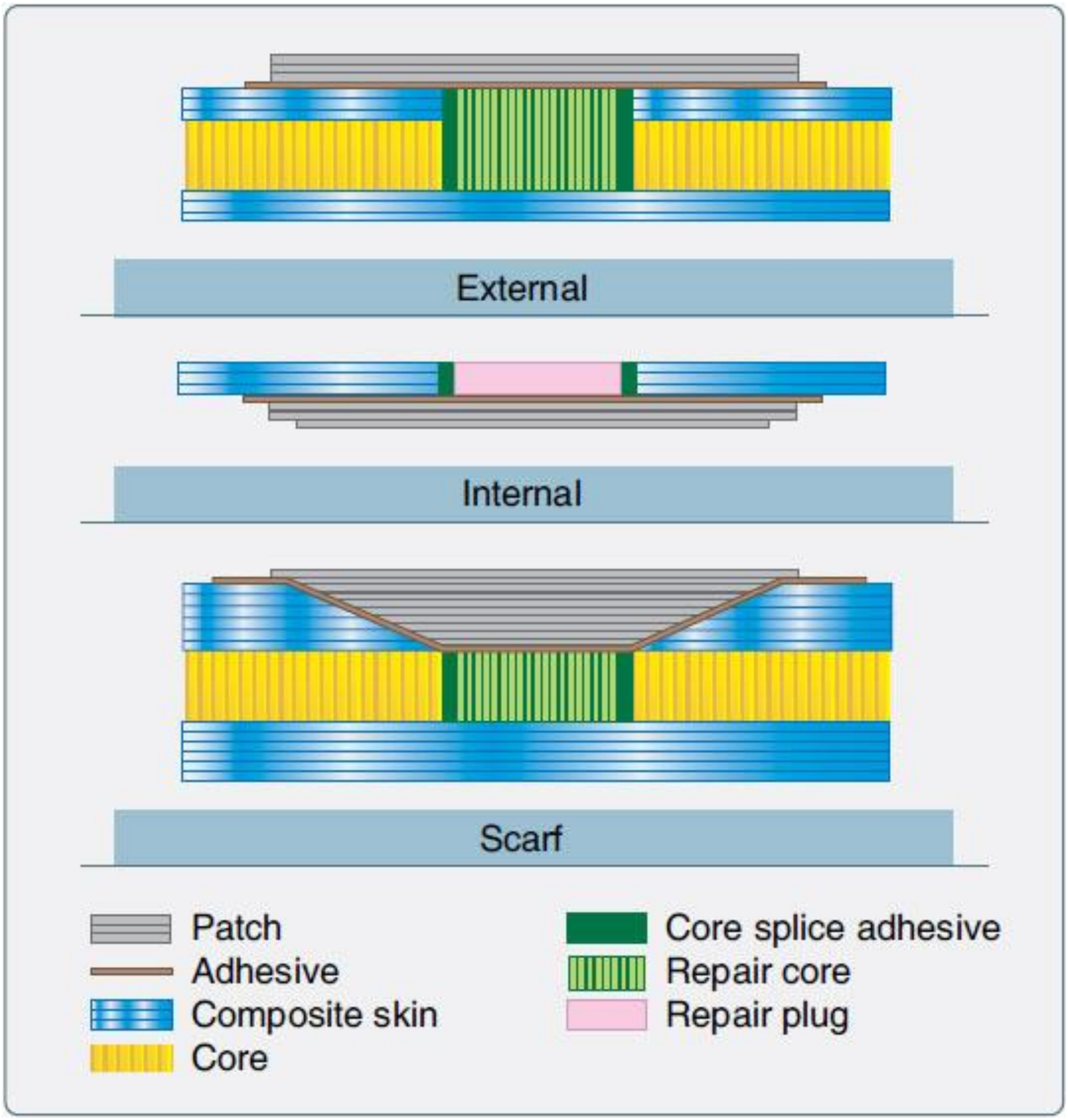


Fig. 21 Typical repairs for honeycomb sandwich structure

Damage Classification in sandwitch structure

A temporary repair meets the strength requirements, but is limited by time or flight cycles. At the end of the repair's life, the repair must be removed and replaced. An interim repair restores the required strength to the component. However, this repair does not restore the required durability to the component. Therefore, it has a different inspection interval and/or method. A permanent repair is a repair that restores the required strength and durability to the component. The repair has the same inspection method and interval as the original component.

Sandwich Structures

Minor Core Damage (Filler and Potting Repairs) :-

A potted repair can be used to repair damage to a sandwich honeycomb structure that is smaller than 0.5 inches. The honeycomb material could be left in place or could be removed and is filled up with a potting compound to restore some strength. Potted repairs do not restore the full strength of the part.

Potting compounds are most often epoxy resins filled with hollow glass, phenolic or plastic microballoons, cotton, flox, or other materials. The potting compound can also be used as filler for cosmetic repairs to edges and skin panels. Potting compounds are also used in sandwich honeycomb panels as hard points for bolts and screws. The potting compound is heavier than the original core and this could affect flight control balance. The weight of the repair must be calculated and compared with flight control weight and balance limits set out in the SRM.

<u>Damage Requiring Core Replacement and Repair to One or Both Faceplates</u>

Step 1: Inspect the Damage

Thin laminates can be visually inspected and tap tested to map out the damage. Thicker laminates need more in-depth NDI methods, such as ultrasonic inspection. Check in the vicinity of the damage for entry of water, oil, fuel, dirt, or other foreign matter. Water can be detected with X-ray, back light, or a moisture detector.

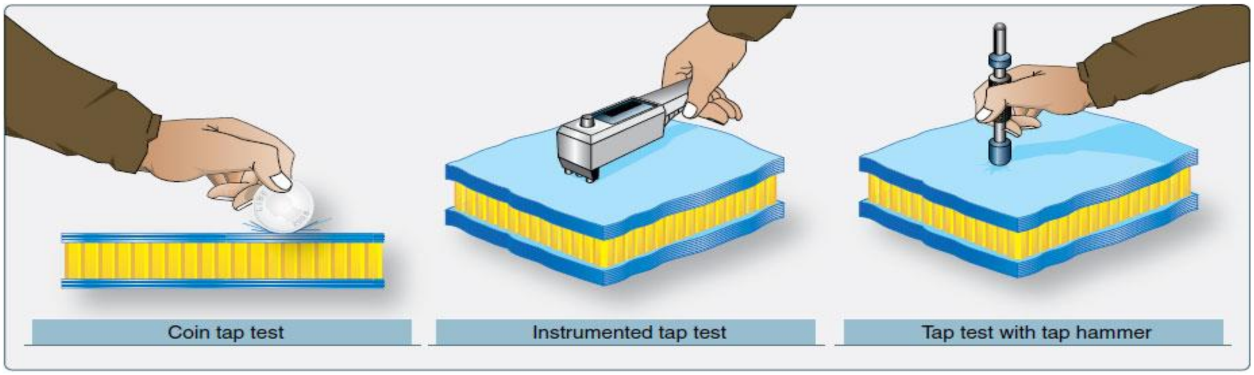


Fig. 22 Inspect the Damage

Step 2: Remove Water from Damaged Area

Water needs to be removed from the core before the part is repaired. [Figure 7-56] If the water is not removed, it boils during the elevated temperature cure cycle and the face sheets blow off the core, resulting in more damage. Water in the honeycomb core could also freeze at the low temperatures that exist at high altitudes, which could result in disbonding of the face sheets.

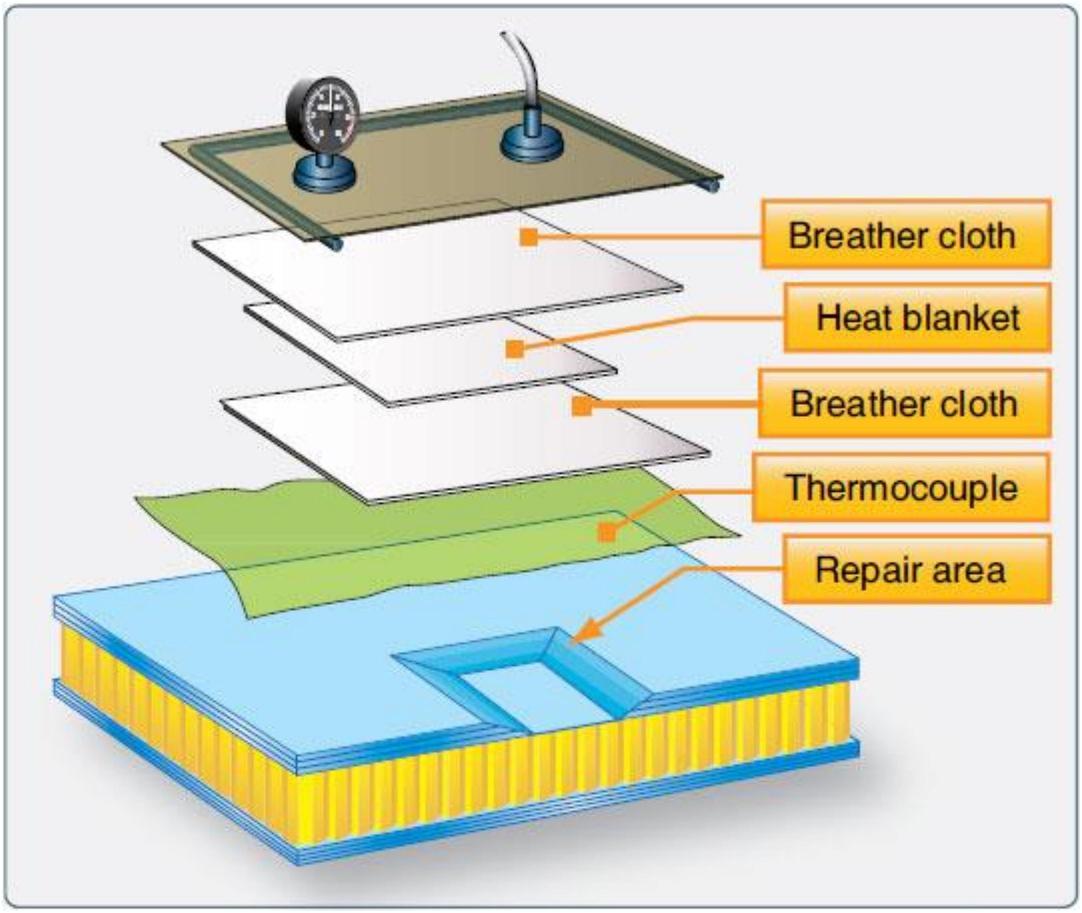


Figure 23. Vacuum bag method for drying parts.

Step 3: Remove the Damage

Trim out the damage to the face sheet to a smooth shape with rounded corners, or a circular or oval shape. Do not damage the undamaged plies, core, or surrounding material. If the core is damaged as well, remove the core by trimming to the same outline as the skin.

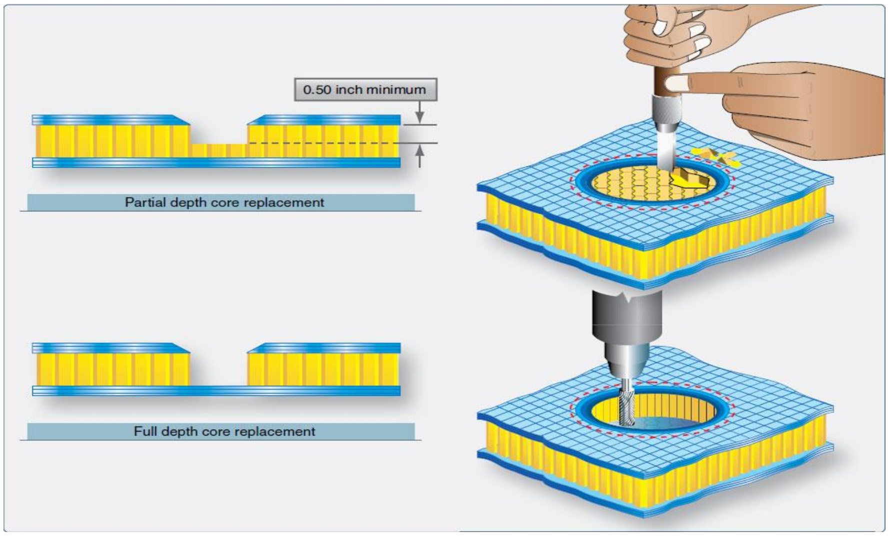


Figure 24. Core damage removal.

Step 4: Prepare the Damaged Area

Use a flexible disk sander or a rotating pad sander to taper sand a uniform taper around the cleaned up damage. Some manufacturers give a taper ratio, such as 1:40, and others prescribe a taper distance like a 1-inch overlap for each existing ply of the face sheet. Remove the exterior finish, including conductive coating for an area that is at least 1 inch larger than the border of the taper. Remove all sanding dust with dry compressed air and a vacuum cleaner. Use a clean cloth moistened with approved solvent to clean the damaged area.

Figure 25. Taper sanding of repair area.

Step 5: Installation of Honeycomb Core (Wet Layup)

Use a knife to cut the replacement core. The core plug must be of the same type, class, and grade of the original core. The direction of the core cells should line up with the honey comb of the surrounding material. The plug must be trimmed to the right length and be solvent washed with an approved cleaner.

For a wet layup repair, cut two plies of woven fabric that fit on the inside surface of the undamaged skin. Impregnate the fabric plies with a resin and place in the hole. Use potting compound around the core and place it in the hole. For a prepreg repair, cut a piece of film adhesive that fits the hole and use a foaming adhesive around the plug. The plug should touch the sides of the hole. Line up the cells of the plug with the original material. Vacuum bag the repair area and use an oven, autoclave, or heat blanket to cure the core replacement. The wet layup repair can be cured at a room temperature up to 150 °F. The prepreg repair must be cured at 250 °F or 350 °F.

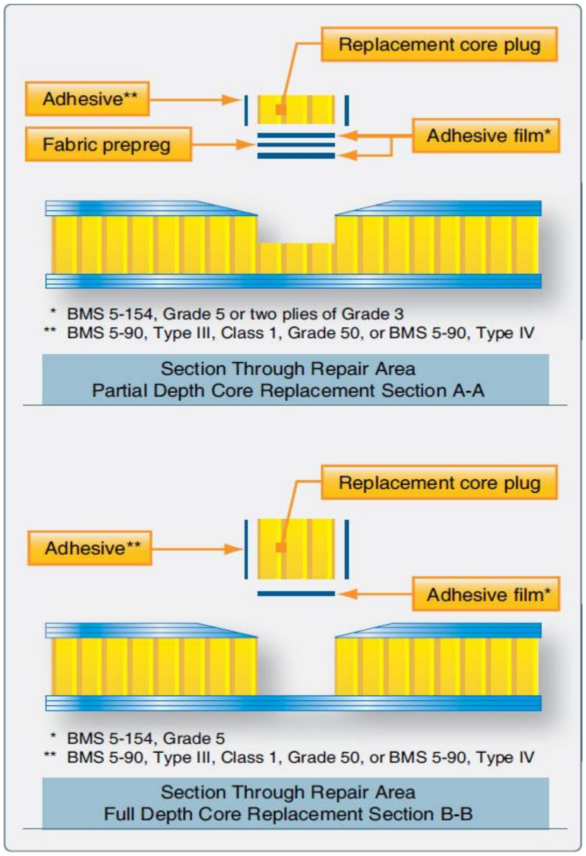


Fig. 25 Core replacement.

Step 6: Prepare and Install the Repair Plies

Consult the repair manual for the correct repair material and the number of plies required for the repair. Typically, one more ply than the original number of plies is installed. Cut the plies to the correct size and ply orientation. The repair plies must be installed with the same orientation as that of the original plies being repaired. Impregnate the plies with resin for the wet layup repair, or remove the backing material from the prepreg material. The plies are usually placed using the smallest ply first taper layup sequence.

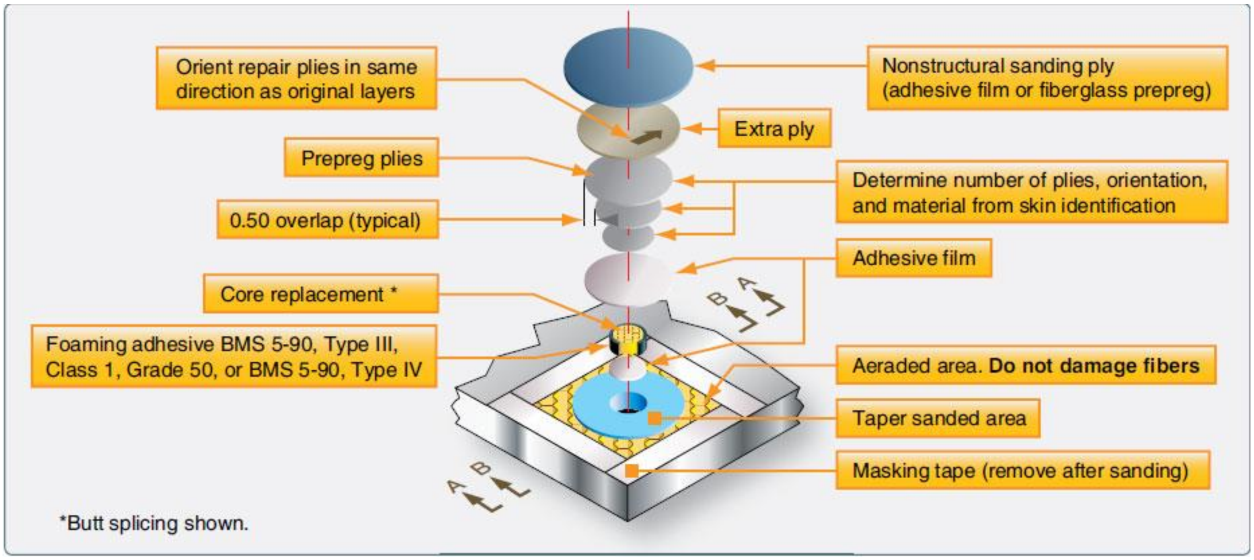


Figure 26. Repair ply installation.

Step 7: Vacuum Bag the Repair

Once the ply materials are in place, vacuum bagging is used to remove air and to pressurize the repair for curing. Refer to Figure 27 for bagging instructions.

Step 8: Curing the Repair

The repair is cured at the required cure cycle. Wet layup repairs can be cured at room temperature. An elevated temperature up to 150 °F can be used to speed up the cure. The prepreg repair needs to be cured at an elevated cure cycle. Parts that can be removed from the aircraft could be cured in a hot room, oven, or autoclave. A heating blanket is used for on-aircraft repairs.

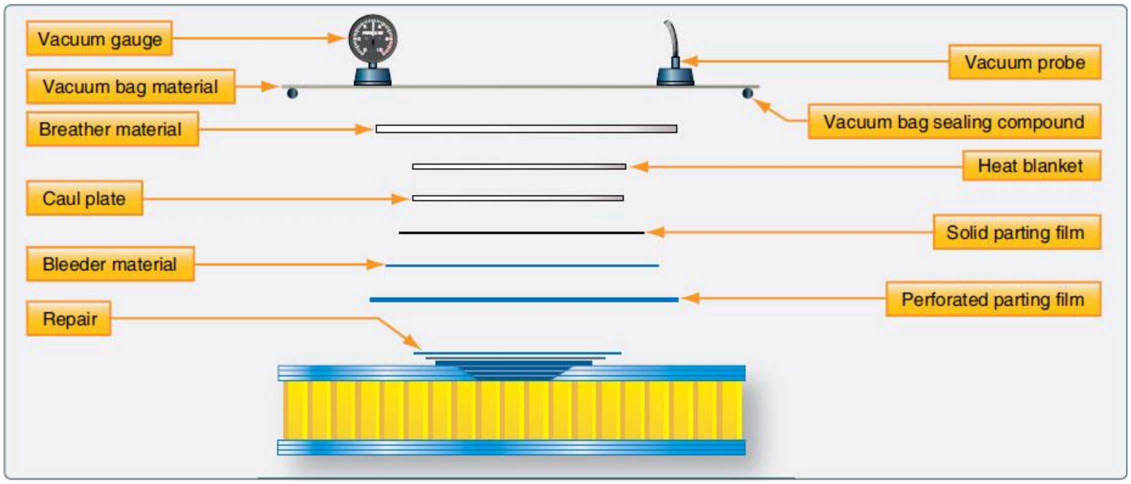


Figure 27. Vacuum processing.

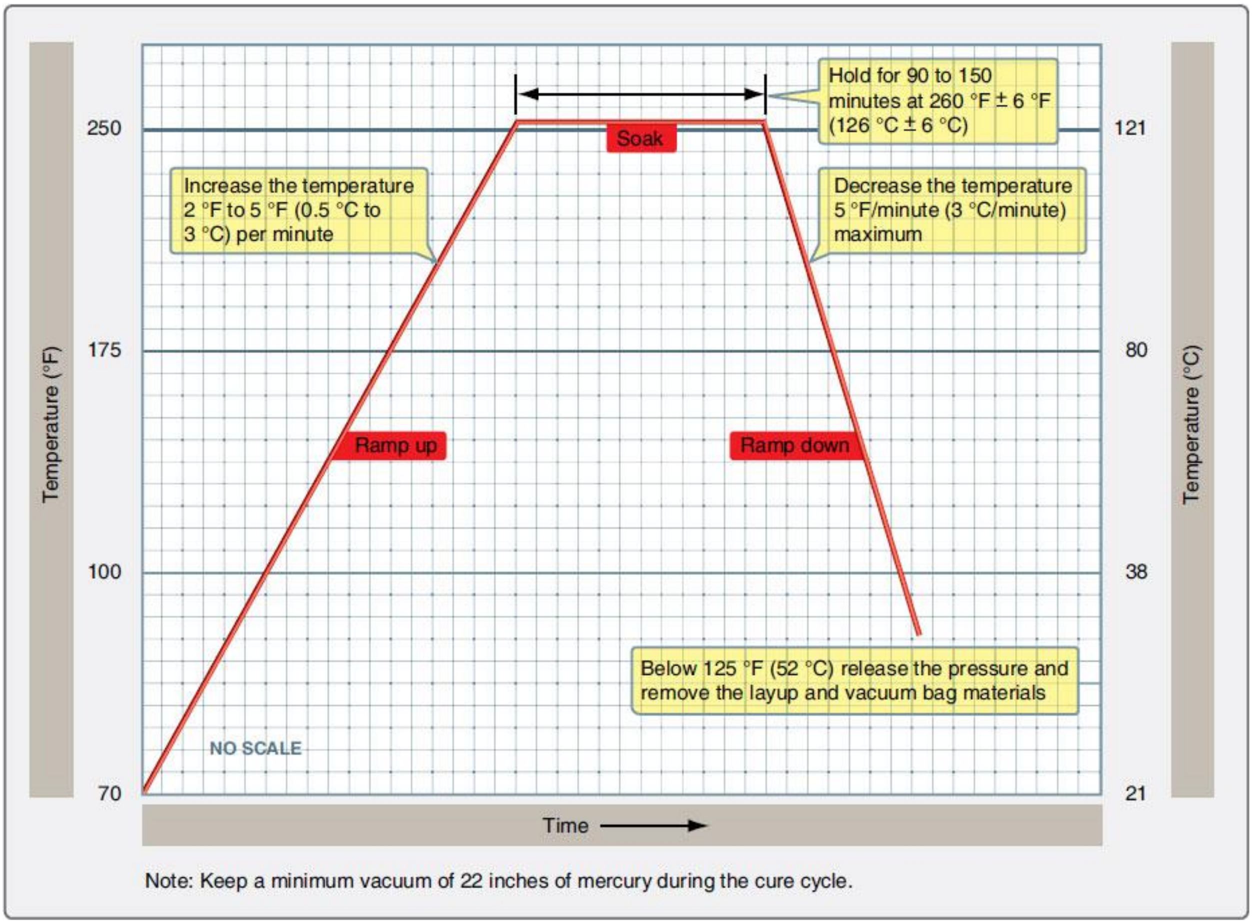


Fig. 28 Curing graph

REPAIR OF HONEYCOMB STRUCTURE

A process for the repair of a honeycomb structure which comprises a honeycomb bonded to at least one surface layer wherein a replacement for a damaged piece of the structure is, bonded to the honeycomb structure by means of a adhesive material.

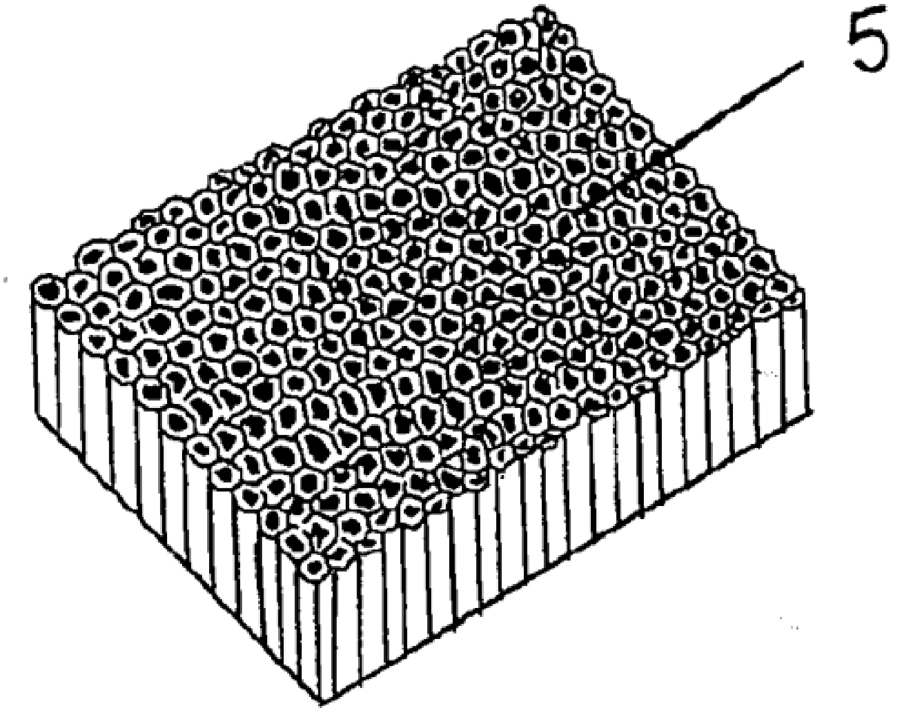


Fig. 29 Honeycomb structure

1. The present invention relates to improvements in or relating to composite structures and in particular honeycomb structures and more particularly to the bonding together of two honeycomb structures. In a preferred embodiment the invention provides a simple technique for the repair of hon eycomb structures. Honeycomb structures are widely used as lightweight materials to provide strength particularly intrans portation vehicles Such as aircraft, motor vehicles, trains, boats, ships and in aerospace.
2. Honeycomb structures are typically made from two skins or facing panels which enclose the honeycomb which may be of any lightweight material aluminum or impregnated paper are the preferred materials.

3. One difficulty with composite structures and in par ticular honeycomb structures is that they are difficult to repair. For example, with a composite structure an impact at a single point on the surface of a structure can be transmitted within the structure to cause distortion and perhaps breakage over a large area and/or to some depth within the structure. It is however important that the structure can be repaired to provide the same strength and performance as the original article and the repair must Support applied loads and transmit applied loads across the repaired area. Various techniques have been proposed for the repair of composite structures, including honeycomb structures. One method involves cutting out the damaged area and replacing it with filler plies which are then bonded to the exposed surface of the laminate. This method suffers from the disadvantages that the repaired structure is generally thicker and heavier than the original structure and good adhesion between the replacement material and the original structure is difficult to achieve. Other methods include careful and precise cutting away of the dam aged area to provide a tapered surface so that each ply of the structure can be replaced individually. This is an extremely laborious and complicated procedure to perform.
4. There is therefore a need for a simple and effective method for the repair of composite structures which mini mizes the increase in weight caused by the repair, which repairs the structure of the composite structure that has been damaged and which can return the structure to its original strength.
5. We have now found that foam able adhesive material are particularly useful for bonding together composite structural materials and, in particular they are particularly useful for the bonding of replacement pieces of honeycomb structures for repair purposes.
6. The present invention therefore provides the use of a foamable adhesive material for the bonding together of honeycomb structures.
7. In a preferred embodiment of the invention the foamable adhesive material is a material that foams and cures under the application of heat.
8. Inafurther preferred embodiment the invention pro vides for the repair of composite honeycomb structures which comprise a honeycomb bonded to at least one Surface layer whereby a replacement for a damaged piece of the structure is bonded to the honeycomb

structure and is also bonded to a replacement piece of the Surface layer by means of a foamable adhesive material.

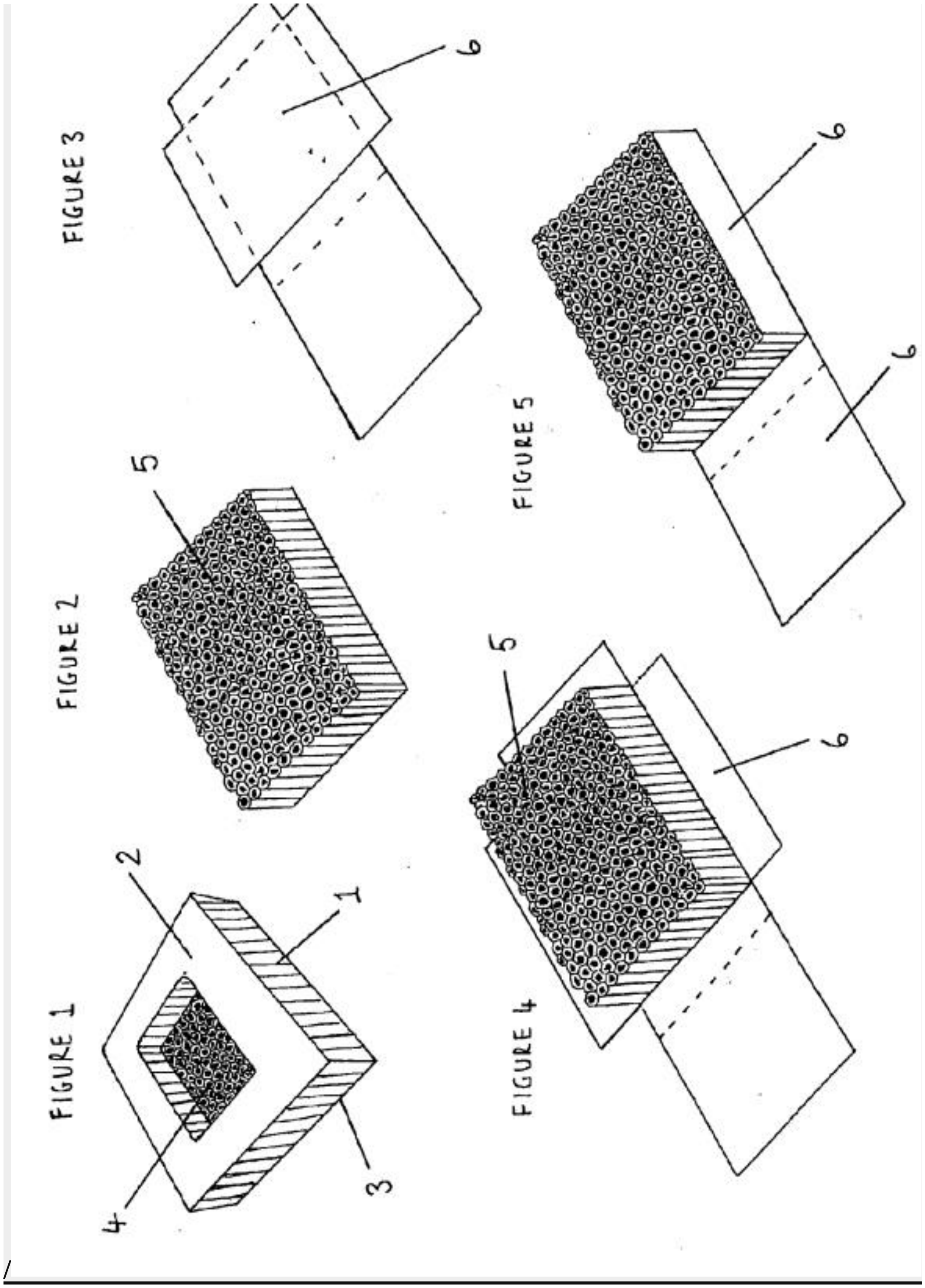


Fig. 30 Different axis of honeycomb structure

The Material

The foam able material used in the present invention is typically selected so as to be activatable under a desired condition. As used herein, activatable means that the material softens (e.g., melts), cures, expands, foams or a combination thereof upon exposure to a condition or upon the combination of particular chemicals (e.g., 2-component materials).

In a preferred embodiment, the material has a post cure glass transition temperature that is greater than any temperatures to which the material may be exposed while in its intended environment of use (e.g., in an airplane or automotive vehicle). Exemplary post-cure glass transition temperatures may be greater than about 80 degrees Celsius and more preferably greater than about 100 degrees Celsius. Other desired characteristics of the material might include good adhesion retention and degradation resistance particularly in adverse environments such as highly variable temperature environments, high dynamic activity environments, combinations thereof or the like. For particular embodiments (e.g., where damping or sound absorption is desired), the material may stay in a softer or goopy state or it may become more Solid particularly if it has a lower post-cure glass transition temperature.

The material may beathermoplastic, a thermoset or a blend thereof. According to one embodiment, the material is as an epoxy-containing material, an ethylene-containing polymer, an acetate or acrylate containing polymer, or a mix ture thereof, which when compounded with appropriate ingredients (typically a blowing agent, a curing agent, and perhaps a filler), typically expands, cures or both in a reliable and predictable manner upon the application of heat or another activation stimulus. Thus, according to one preferred embodiment, an exemplary material may be a heat-activated and/or epoxy-based resin having foamable characteristics. Of course, the material may be activated by other conditions or stimuli. Generally, it is contemplated that, particularly for higher expansion materials, the activatable material may include or be based upon an elastomer (e.g., rubber), an acetate, an acrylate or combinations.

Epoxy Resin

Epoxy resin is used herein to mean any of the conventional dimeric, oligomeric or polymeric epoxy materials containing at least one epoxy functional group. The polymer-based materials may be epoxy containing materials having one or more oxirane rings polymerizable by a ring opening reaction. It is contemplated that the activatable material can include up to about 80% of an epoxy resin or more. Typically, the activatable material includes between about 5% and 60% by weight epoxy resin and still more typically between about 10% and 30% by weight epoxy resin. 0028. The epoxy may be aliphatic, cycloaliphatic, aromatic or the like. The epoxy may be supplied as a solid (e.g., aspellets, chunks, pieces or the like) or a liquid (e.g., an epoxy resin). The epoxy may include an ethylene copolymer or terpolymer that may possess an alpha-olefin. As a copolymer or terpolymer, the polymer is composed of two or three different monomers, i.e., Small molecules with high chemical reactivity that are capable of linking up with similar molecules. Preferably, an epoxy resin is added to the activatable material to increase adhesion properties of the material. One exemplary epoxy resin may be a phenolic resin, which may be a novalac type or other type resin. Other preferred epoxy containing materials may include a bisphenol-A epichloro hydrin ether polymer, or a bisphenol-A epoxy resin which may be modified with butadiene or another polymeric additive. Elastomeric Material.

Activatable materials used in the present invention, particularly when used in structures for Sound reduction (e.g., Sound attenuation and or sound absorption), insulation or both, will typically include a substantial amount of elastomeric or rubber material, which can be one elastomer or a mixture of several different elastomers. When used, the elastomeric material is typically at least about 5%, more typically at least about 14%, even more typically at least 25% by weight of the activatable material and the elastomeric mate rial is typically less than about 65%, more typically less than about 45% and even more typically less than about 35% by weight of the activatable material.

Blowing Agent

One or more blowing agents may be added to the activatable material. Such blowing agents can assist in forming cellular or foamed activated materials, which typically have a lower density and/or weight. In addition, the material expansion that can be caused by the blowing agents can help to improve sealing capability, Substrate wetting ability, adhesion to a Substrate, acoustic damping, combinations thereofore the like.

The blowing agent may be a physical blowing agent or a chemical blowing agent. For example, the blowing agent may be a thermoplastic encapsulated solvent that expands upon exposure to a condition Such as heat. Alternatively, the blowing agent may chemically react to liberate gas upon exposure to a condition Such as heat or humidity or upon exposure to another chemical reactant.

Curing Agent

One or more curing agents and/or curing agent accelerators may be added to the activatable material. Amounts of curing agents and curing agent accelerators can, like the blowing agents, vary widely within the activatable material depending upon the type of cellular structure desired, the desired amount of expansion of the activatable material, the desired rate of expansion, the desired structural properties of the activatable material and the like. Exemplary ranges for the curing agents or curing agent accelerators present in the activatable material range from about 0.001% by weight to about 7% by weight. 0040 Typically, the curing agents assist the activatable material in curing by crosslinking of the polymers, epoxy resins or both. It can also be desirable for the curing agents to assist in thermosetting the activatable material. Useful classes of curing agents are materials selected from aliphatic or aromatic amines or their respective adducts, amidoamines, polyamides, cycloaliphatic amines, (e.g., anhydrides, poly carboxylic polyesters, isocyanates, phenol-based resins (such as phenol or cresol novolak resins, copolymers such as those of phenol terpene, polyvinyl phenol, or bisphenol-A formal dehyde copolymers, bishydroxyphenyl alkanes or the like), sulfur or mixtures thereof. Particular preferred curing agents include modified and unmodified polyamines or polyamides such as triethylenetetramine, diethylenetriamine tetraethyl enepentamine, cyanoguanidine, dicyandiamides and the like. An accelerator for the curing agents (e.g., a modified or unmodified urea such as methylene diphenyl bis urea, an imidazole or a combination thereof) may also be provided for preparing the activatable material.

LIGHTNING PROTECTION

Lightning strikes are a serious problem during operation of aircraft due to the increasing applicability of polymeric composites in aircraft structures and the weak electrical conducting properties of such structures. In composite structures, lightning strikes may cause extended damage sites which require to be appropriately maintained and repaired leading to increased operational costs. In order to overcome this problem various lightning strike protection solutions have been developed. Some of them are based on the immersion of metallic elements and particles while others use novel solutions such as intrinsically conductive polymers or other types of highly conductive particles including carbon nanotubes and graphene.

Changes occurring over the last decades in design philosophy of many aircraft structures, in particular the application of fibre-reinforced composites with a polymeric matrix in the exterior fuselage, allowed the strength-to-mass ratio to be significantly increased, which resulted in the possibility of achieving higher speeds and manoeuvrability while keeping fuel consumption at a lower level. However, the usage of polymeric composites in manufacturing aircraft structures resulted in one drawback with respect to the lightning phenomena. Since polymers applied are dielectrics, the lightning strike events occurring during aircraft operation cause serious damage to such structures. This, in turn, requires expensive repairing and testing, and obviously, grounding the aircraft for the period of up to 6 working days, leading to increased operational costs. A lightning striking a structure made of polymeric composite initiates numerous accompanying phenomena, which additionally intensify structural degradation and disintegration. Lightning strikes usually occur during take-off and landing of an aircraft as well as during passing through the storm clouds . Lightning usually strikes a geometrically extremal point of an aircraft (like radome, wing tips, etc.) and travels through the structure along the shortest path, which is additionally the most conductive one, to exit at another geometrically extremal point.

In order to overcome the problems caused by lightning strikes affecting composite elements, various lightning strike protection (LSP) solutions have been developed over the last decades. From a variety of LSP solutions one can mention several groups: coatings of metallized sprays or paints, impregnation of metallic meshes and foils as well as solutions based on dispersion of metallic particles, graphite and carbon nanostructures.

This is an important issue having serious safety implications and repair needs. Two reports mention this problem. One of these is unusual and needs special consideration because it raises the possibility of a composite part acting as an electrical capacitor. The report states, *“Sandwich design with carbon and Kevlar or glass skins and aluminum honeycomb core using the carbon as the outer skin and Kevlar or glass next to the honeycomb acts as a capacitor and attracts lightning strikes. This possibility should be investigated for safety reasons because aluminum honeycomb is being used due to its lower cost. It cannot be used in direct contact with carbon in damp or wet environments because of the corrosion risk”*

Proposed Solutions:

- Do not use aluminum core.
- Improve electrical grounding.
- Improve lightning protection.

The extent of the hazard will depend on the following factors:

- Thickness of the CFC skins
- Density, thickness, and ribbon direction of the aluminum honeycomb
- The nature of the CFC interface bond
- The position of the component in the aircraft

Insulated Honeycomb Panels: Nomex honeycomb panels with CFC skins present less of a problem, as the core is of insulating or high-resistance material. The current is generally confined to the CFC skins.

Nature of Lightning Damage: From tests on several aluminum alloys and Nomex cored honeycomb panels, the following effects were reported:

- In contrast to solid CFC plates, the application of erosion-resistant polyurethane paint drastically increased damage area and depth.
- In some cases, only minimal damage was found at the attachment point; however, a larger area of damage was found on the opposite side of the sandwich. This effect has been observed on radomes in which a small burn on the outside of 6 mm (1/4 in.) diameter may indicate a 450-mm (18-in.) diameter area of disbond of skin from the honeycomb on the inside.

In cases where no exterior damage was experienced, interior interlaminar shear failure was discovered on cutting through the test specimen at the attachment point.

Comparing the skin damage area with that of the core in the case of Nomex sandwich plates, the zone was found to be similar. In the case of aluminum honeycomb, the area of damage was at least twice the extent of the outside skin damage.

A bank of experience in this subject should now be used. Some past occurrences have shown the following:

1. Induced currents have resulted in the release of bombs and drop tanks by military aircraft. Drop tanks have been blown from aircraft.

2. Radomes have been blown forward and completely lost from aircraft when no lightning protection was fitted. The pressure generated inside the radome, as a result of the temperature generated as the lightning struck the radar antenna, has been sufficient to fracture all the latches. In other cases, pieces of skin of 0.093 m2 (1 ft2) or larger have been blown away.

3. On light aircraft, control bearings have been welded solid, resulting in the loss of the aircraft and crew.

4. On a medium-sized jet airliner with carbon fiber elevators, several cases occurred of spar damage that could have been more serious. In these cases, several points of interest were noted:

The elevator hinge bearings and the main pivot arm bearing felt gritty when operated by hand. The current involved had tried to weld each ball to its race.

The jumper lead that was supposed to carry the current had been fractured, presumably by inductive forces. The current had flowed along the carbon fiber spar, through a bolt and out over the aluminum flame-sprayed coating on the outside.

The spar was locally delaminated and required a hot-bonded repair. The aluminum flame-sprayed coating was burned, and parts of the skin required repair. The bolt had received an instantaneous spark-eroded undercut of about 0.5 mm (0.02 in.).

5. Composite fuselages do not naturally provide as much electromagnetic interference (EMI) shielding as aluminum fuselages. Sufficient shielding must be provided, by other means if necessary, to avoid catastrophic interference with automatic flight controls, radio, radar, and navigation equipment.

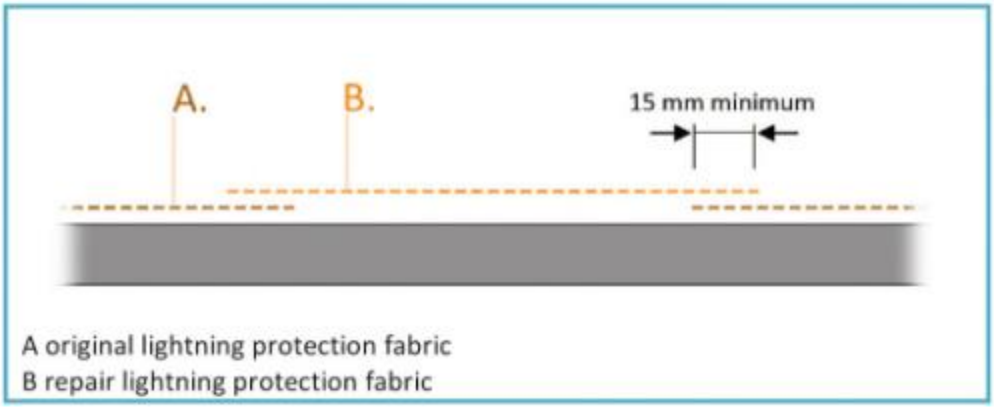


Fig. 31 Lightning process

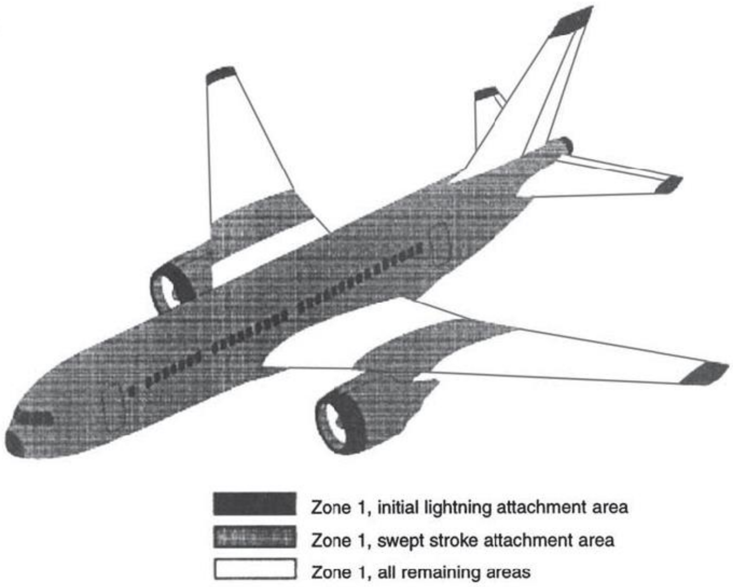


Fig. 32 Different zones of lightning effect in aircraft

1. Remove the paint system until the lightning protection fabric (grit 220-440).
2. Remove dust with a vacuum cleaner and clean with solvent.
3. Apply the repair metal fabric and brush with resin.

4. Press (vacuum bag) and cure.
5. Restore paint system.

PAINTING THE COMPOSITE MATERIAL

Painting is a good way to restore or change the color of the composite after the original finish has faded. The best methods of painting depend on the type of materials in the composite. Following are step-by-step instructions for painting some of the most common composites.

Painting Fiber Cement Composites: -

1. Use a pressure washer to clean. Wait two-four hours for the cement composite to dry.
2. Apply a primer.
3. Wait two hours or so for the primer to dry.
4. Apply the paint same way you applied the primer. Wait about two hours for the paint to dry.

Painting Wood Composites: -

1. For exterior wood composites, use a pressure washer with a low-pressure tip to clean. Wait two hours for the composite to dry.
2. For interior wood composites, dust with a broom.
3. Using a roller, coat with an acrylic latex primer. Use a paintbrush for any areas you can't reach with a roller.
4. Wait two hours or so for the primer to dry.
5. Use satin or semi-gloss latex paint on interior wood composites. Use acrylic enamel on wood composites inside the house. Apply acrylic latex paint the same way you applied the primer. Wait four hours until dry.

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2. For interior wood composites, dust with a broom.
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Painting Composite Decking

1. Mix one-part bleach with three parts waters.
2. Using rags, a roller, or a brush, apply the bleach solution liberally to all surfaces.
3. After half an hour, scrub the surfaces.
4. Rinse off the solution and residue.
5. Using very fine sandpaper (220 grit) lightly sand all the surfaces.
6. Wash off dust and dirt with a household detergent or commercial cleaner made for cleaning composite decks.
7. Rinse thoroughly.
8. If you are going to paint the deck, prime with an exterior latex stain-blocking primer made for plastic materials. Do not prime if you plan to stain the deck instead of painting it.
9. For painting, use a high-quality latex floor and deck paint in a satin or semi-gloss finish. For staining, use a high-quality acrylic latex solid color deck stain recommended for composite decking.

Painting Fiberglass Composites

1. Fill holes or imperfections with fiberglass putty. Smooth out the putty with a putty knife. Let it cure completely.
2. Sand with heavy sandpaper (100 grit) to remove excess putty or any paint. After the composite is fairly smooth, switch to 800 grit sandpaper and sand until the composite is very smooth. You can use an orbital sander or sand by hand.
3. Use a dry rag and acetone to remove dust, grease, and debris.

4. Apply a primer. Most primers work on fiberglass, but it's a good idea to double check with the paint store on the best one to use. Wait two hours or so until the primer is dry.
5. Spray or use a brush to apply the final coat of paint. Wait until the paint is dry.
6. Apply another coat of paint or apply the clear coat. Always use a clear coat after the last coat of paint; it will seal the paint and help protect the paint from the elements.

QUALITY CONTROL

The term advanced aerospace composites typically refer to those materials that are made by binding high-strength and high-stiffness continuous fibres with various types of polymeric resins and consolidating the resulting bimaterial (composite) into finished parts under a prescribed cycle of temperature and pressure. The quality control process begins with controlling the raw materials used to form such advanced composites, namely, the fibres and the resin. The overall manufacturing process for advanced composites begins with the processing of fibres and resins from raw materials to obtain resins and fibres of the quality required for aerospace end-product applications. This means that the processed fibres have to meet certain minimum requirements to qualify in terms of their strength and stiffness, as well as their ability to maintain these required properties in the presence of adverse conditions such as exposure to extreme temperatures, moisture and chemicals. Similarly, the processed resins must meet certain minimum requirements to qualify, mainly in terms of their high-strength, modulus, toughness, low shrinkage, good chemical resistance, minimal curing volatility and overall ease of processing.

Material quality control

Constituent materials control

In the case of aerospace composite materials, the manufacturer will typically specify constituent material requirements which define, among others, material inspection procedures and supplier controls that ensure that the constituent materials used in the manufacturing of a composite structure meet the engineering requirements of the original equipment manufacturer. The tests conducted by the composites manufacturer to verify the properties and performance of the received constituent materials must be standardized to ensure that production parts are manufactured with materials that have properties equivalent to those generated from the tests conducted to establish the design allowable for this particular part or component.

Resins quality control

Resins, or what is more commonly referred to as the matrix material in a composite, are to be produced with the highest quality assurance standards in order to qualify as constituent raw materials in advanced aerospace composites. Many parameters affect resins quality and hence the performance and long-term durability of the composite. These include their chemical composition, physical state and morphology and the presence of impurities and contaminants. Finally, various test standards exist for the determination of glass transition temperature of resins, such as the one described in ASTM E1356.

Fibres quality control

Various fibre types are used in advanced aerospace composites, the most common of which are Carbone graphite fibres which are made predominately from the carbonization of polyacrylonitrile (PAN). These have highly anisotropic morphology leading to a high variability in their moduli values ranging anywhere from 100 to 800 GPa in the axial fibre direction, and around 10e30 GPa in the transverse direction.