



UNIT 1: Introduction

ME 434: Composite Materials

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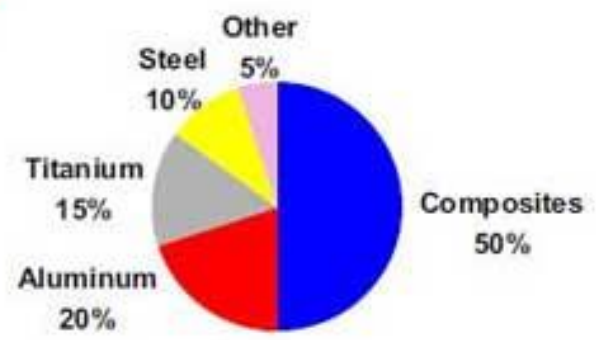
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Department of Mechanical Engineering

Tezpur University



- Carbon laminate
- Carbon sandwich
- Fiberglass
- Aluminum
- Aluminum/steel/titanium pylons



Primary (load-carrying) structures

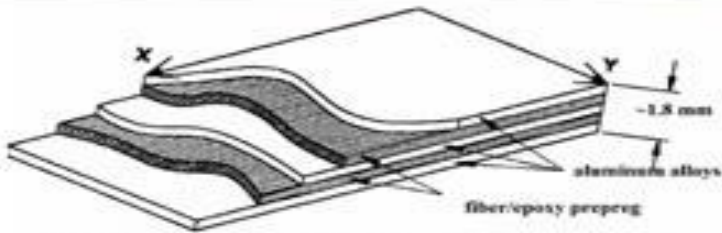
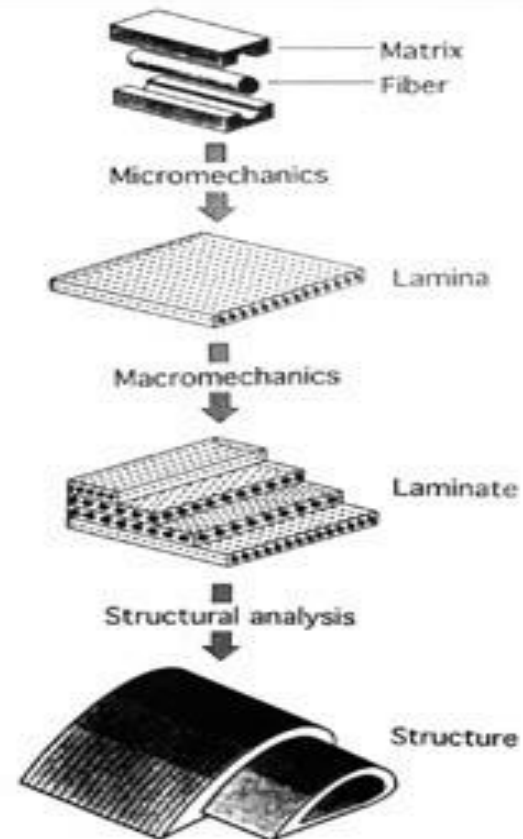
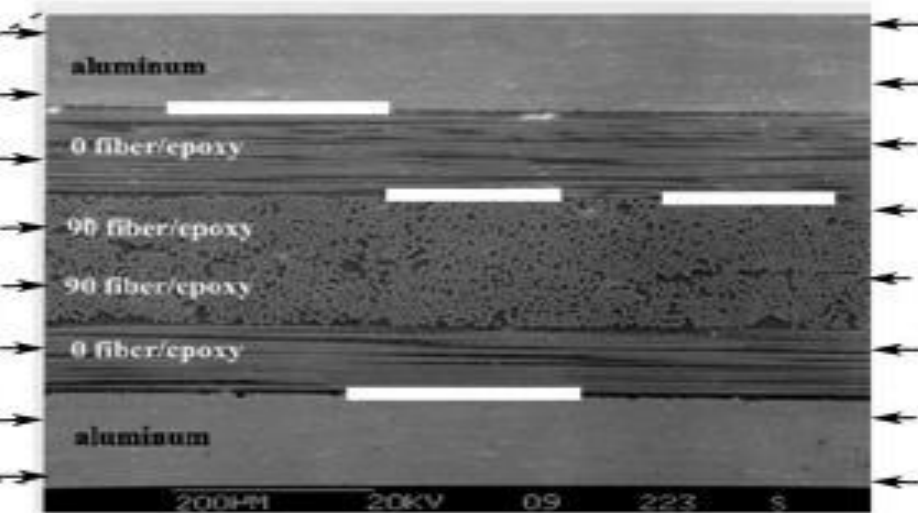


Fig. 2. Configuration of continuous fiber/epoxy hybrid composite (3/2 lay-up).





F-15 Eagle
Early 1970s
2% Composites



AV-8B Harrier
Early 1980s
27% Composites



F/A-18 Hornet
Mid-1970s
10% Composites



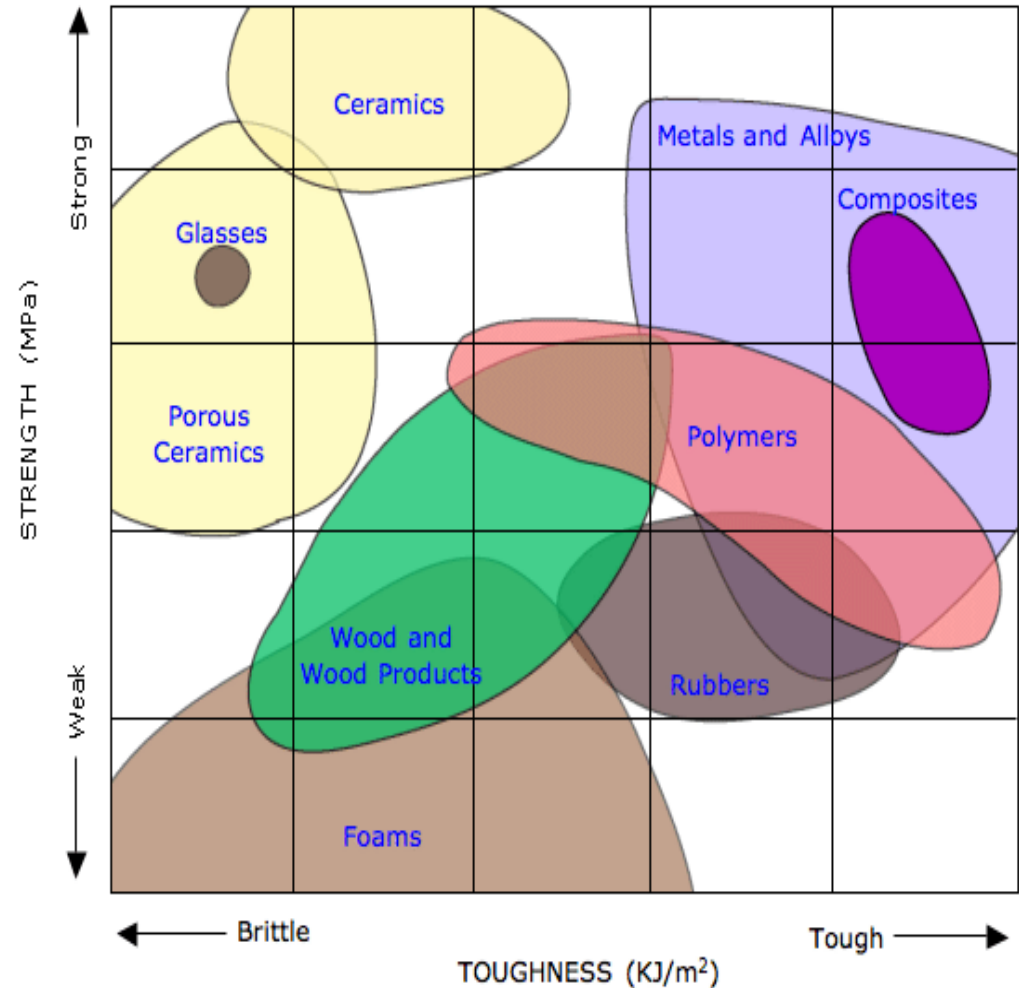
F/A-18 E/F Hornet
Late 1990s
21% Composites

Introduction

Definition: combination of two or more materials that results in better properties than those of the individual components used alone.

In contrast to metallic alloys, each material retains its separate chemical, physical, and mechanical properties.

- The two constituents are a **reinforcement** (or filler) and a **matrix**.
- The main advantages of composite materials are their high strength and stiffness, combined with low density, when compared with bulk materials, allowing for a weight reduction in the finished part and in some cases, low cost



Introduction

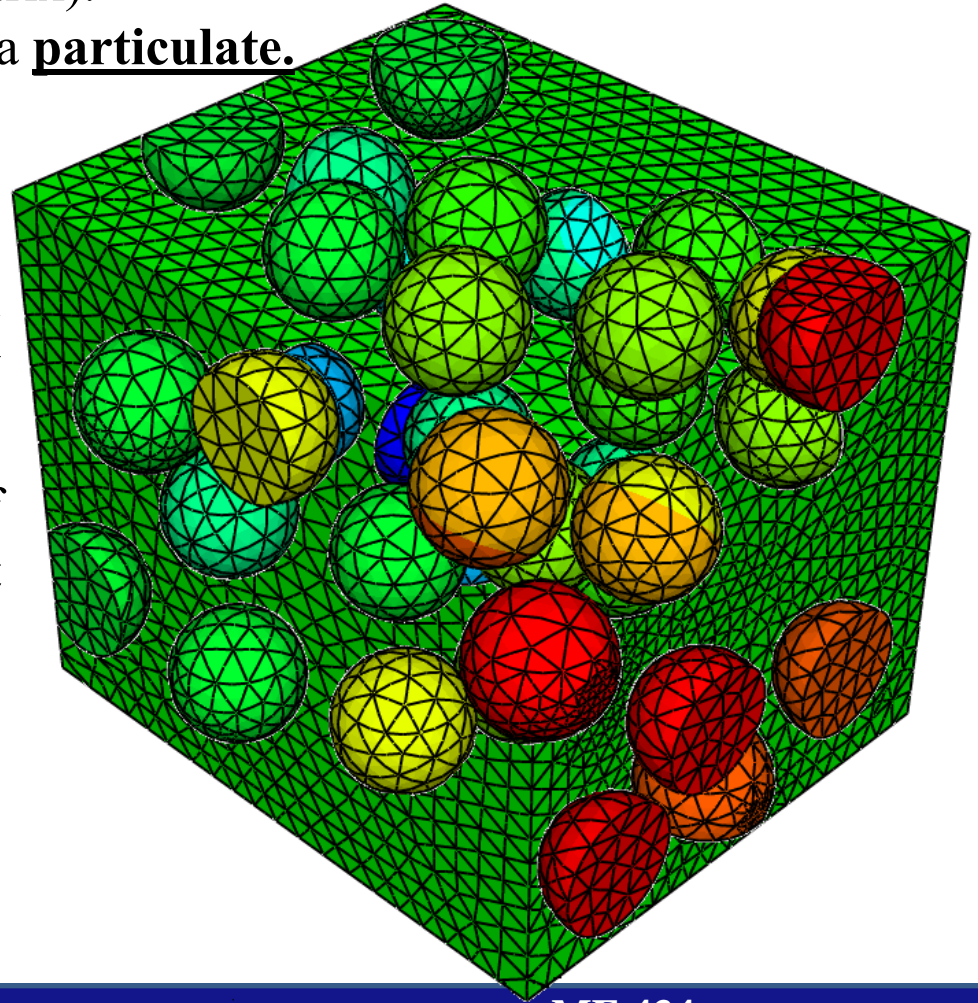
Reinforcing phase:

The reinforcing phase provides the strength and stiffness (in most cases, it is harder, stronger, and stiffer than the matrix).

The reinforcement is usually a **fiber** or a **particulate**.

Particulate composites:

- Dimensions approximately equal in all directions (spherical, platelets, or any other regular or irregular geometry).
- Tend to be much weaker and less stiff than continuous fiber composites, but usually much less expensive.
- Particulate reinforced composites usually contain less reinforcement (up to 40 to 50 volume % due to processing difficulties and brittleness).

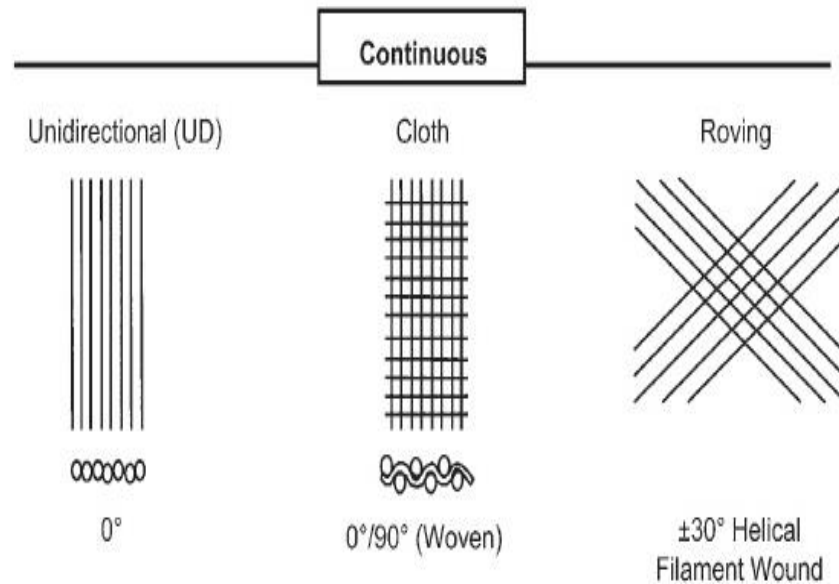




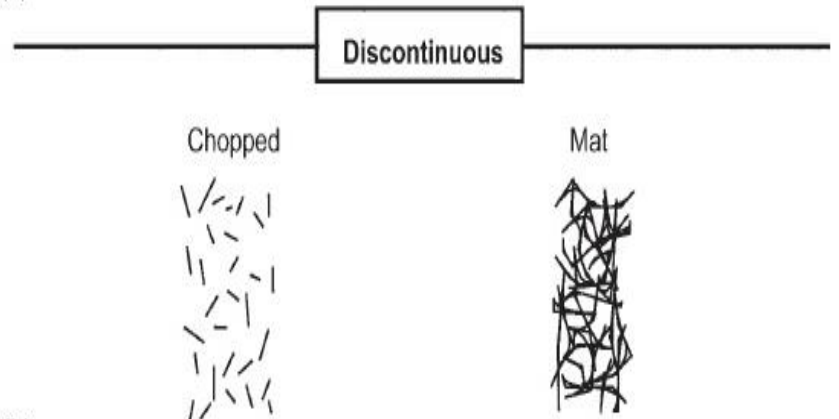
Fiber composites:

- A fiber has a length that is much greater than its diameter (l/d ratio - *aspect ratio* which can vary greatly).
- Continuous fibers have long aspect ratios, while discontinuous fibers have short aspect ratios.
- Continuous-fiber composites normally have a preferred orientation (unidirectional, woven cloth, and helical winding; Fig. 1.1a) while discontinuous fibers have a random orientation (chopped fibers and random mat; Fig. 1.1b).
- Continuous-fiber composites are often made into laminates by stacking single sheets of continuous fibers in different orientations to obtain the desired strength and stiffness properties with fiber vol % up to 60-70%.
- Fibers produce high-strength composites because of their small diameter; they contain far fewer defects (normally surface defects) compared to the material produced in bulk. Generally, smaller the diameter of the fiber, the higher its strength, but often the cost increases as the diameter decreases.
- Smaller-diameter high-strength fibers have greater flexibility and easy to fabricate (weaving or forming over radii).
- Typical fibers include glass, aramid, and carbon.

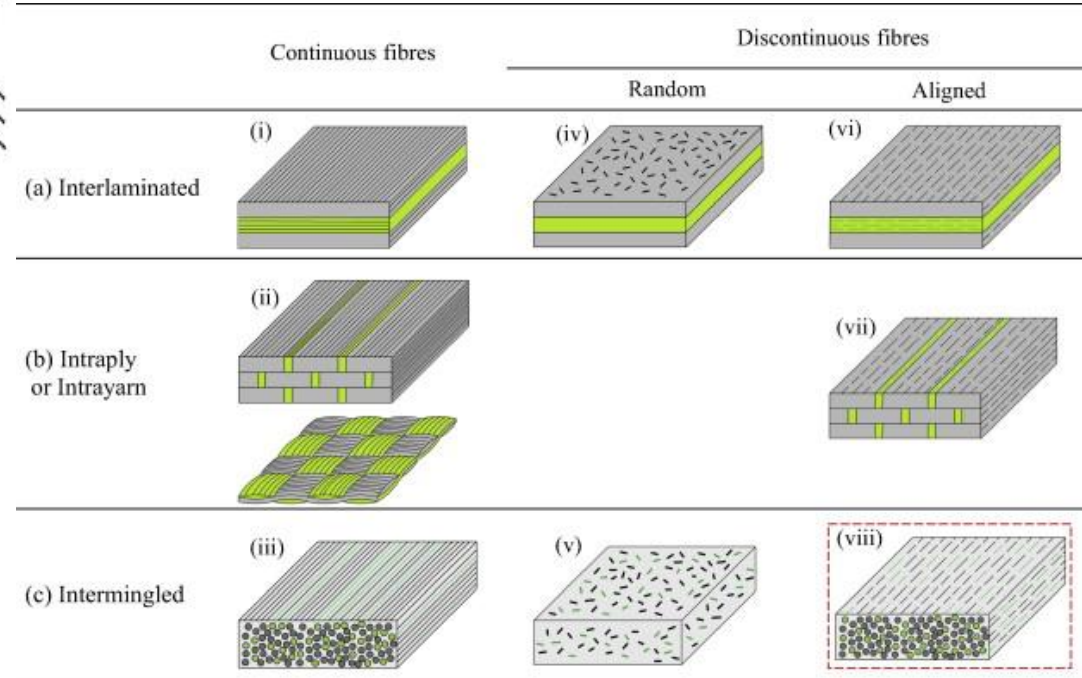
Introduction



(a)



(b)



Hemp Fiber

Non-Woven Mat



Finished Door

Pre-Finished Door



(a)



(b)



(c)

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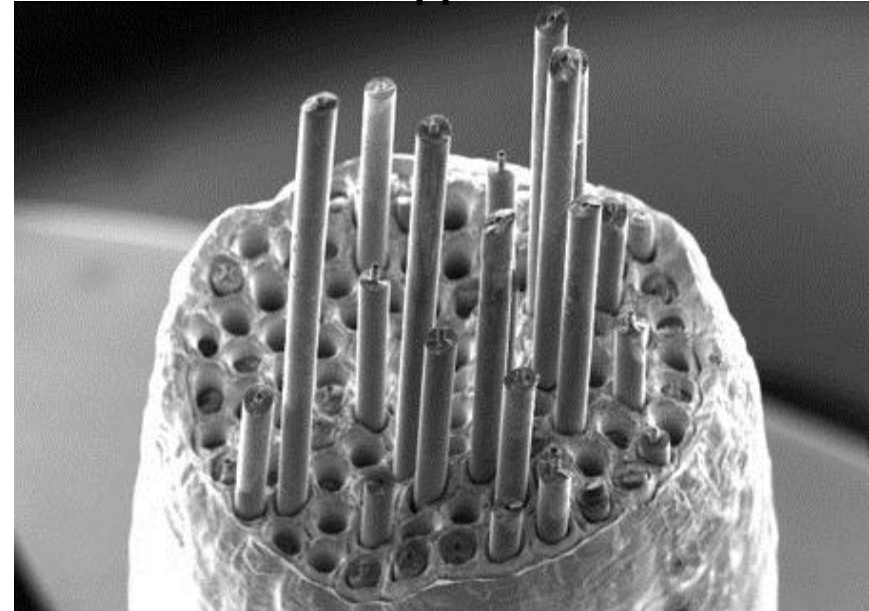
(Composite Materials)

Introduction

Matrix Phase:

- The continuous phase is the matrix, made of polymer, metal, or ceramic. Polymers have low strength and stiffness, metals have intermediate strength and stiffness but high ductility, and ceramics have high strength and stiffness but are brittle.
- The matrix (continuous phase) performs several functions – maintaining the fibers in the proper orientation and spacing, and protecting them from abrasion and the environment.
- In polymer and metal matrix composites that form a strong bond between the fiber and the matrix, the matrix transmits load to the fibers through shear loading at the interface.
- In ceramic matrix composites, the objective is often to increase the toughness rather than the strength and stiffness; therefore, a low interfacial strength bond is desirable.

Silicon Carbide - Copper Metal Matrix



Properties of composites

- The type and quantity of the reinforcement determine the final properties of composites.
- Highest strength and modulus are obtained with continuous-fiber composites.
- Practical limit of about 70 vol.% reinforcement can be added to form a composite. At higher percentages, there is too little matrix to support the fibers effectively.
- Discontinuous-fiber composites are normally random in alignment, which dramatically reduces their strength and modulus but are less costly than continuous-fiber composites.
- Hence, continuous-fiber composites are used where higher strength and stiffness are required (but at a higher cost), and discontinuous-fiber composites are used where cost is important and strength and stiffness are less important.

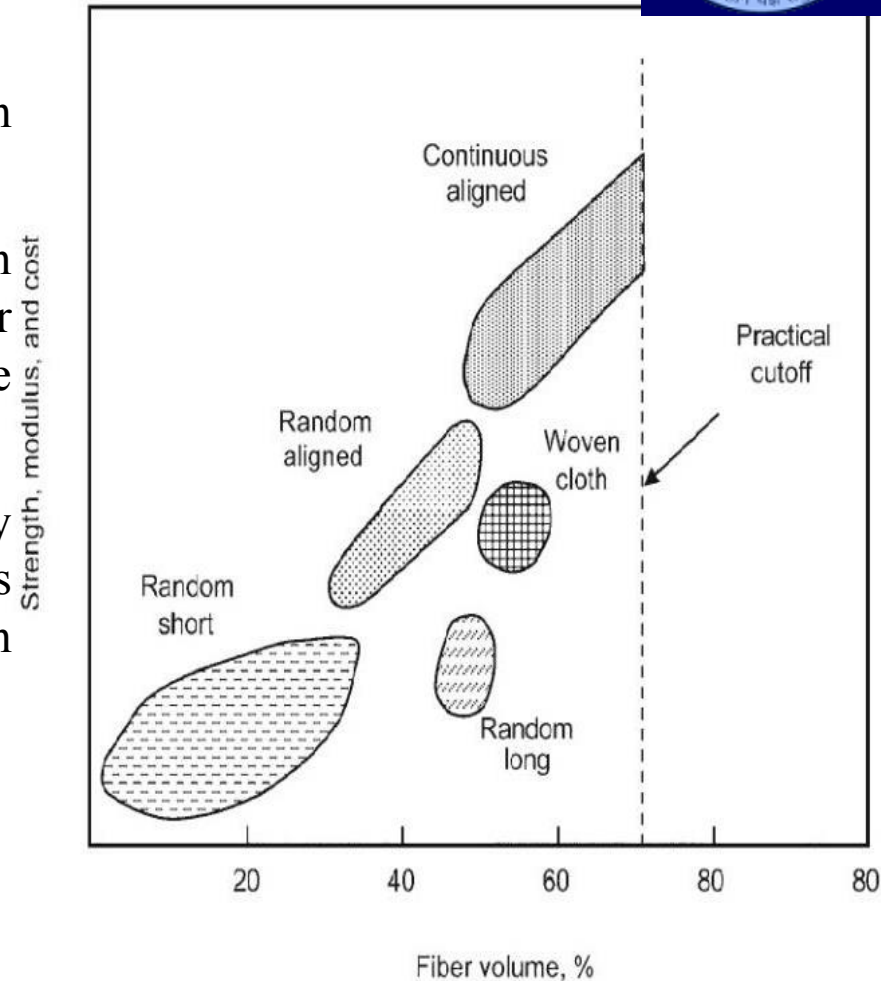


Fig. 1.2 Influence of reinforcement type and quantity on composite performance

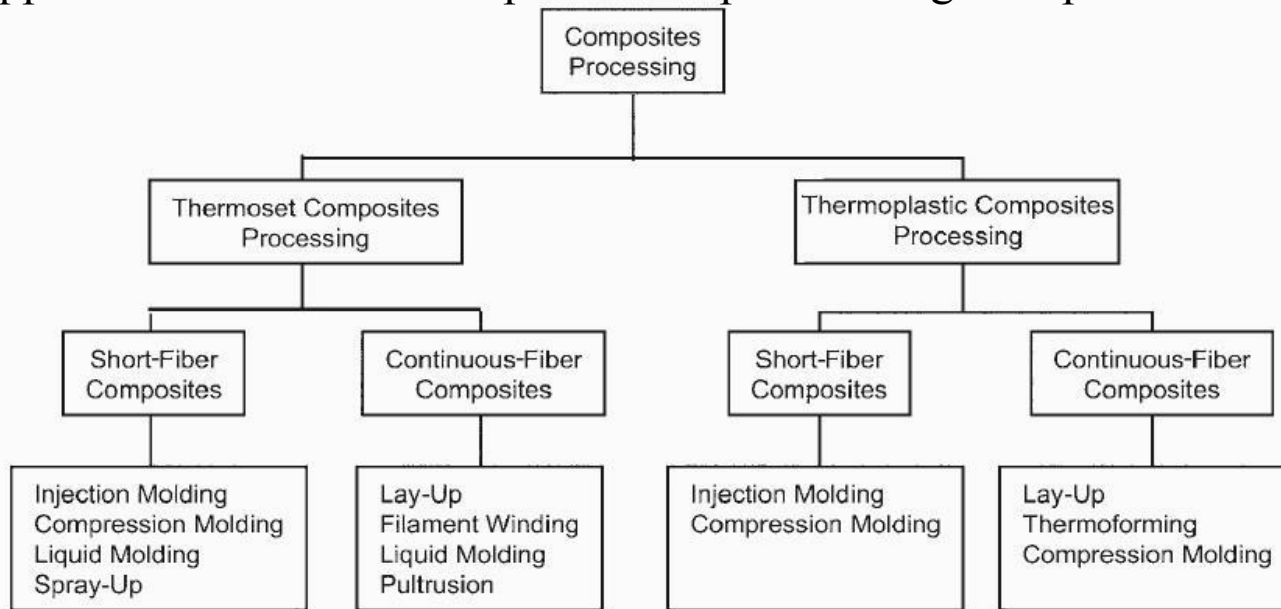


Processing of composites

Both the reinforcement type and the matrix affect processing.

Polymer composites: Two types of polymer matrices are shown: thermosets (a low-viscosity resin that reacts and cures during processing, forming an intractable solid – cannot be reprocessed by heating again) and thermoplastics (high-viscosity resin that is processed by heating it above its melting temperature – can be reprocessed).

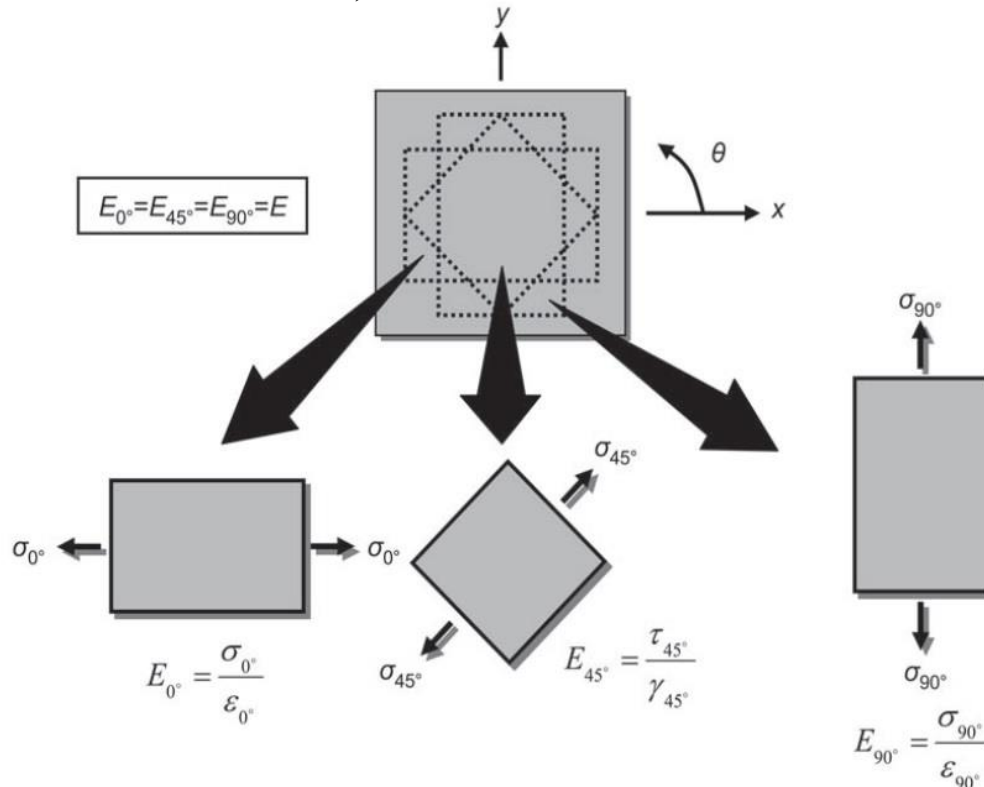
Metal and Ceramic composites: Metal and Ceramic matrix composites require very high temperatures and sometimes high pressures for processing, they are normally much more expensive than polymer matrix composites. However, they have much better thermal stability, a requirement in applications where the composite is exposed to high temperatures.



Isotropic, Anisotropic, and Orthotropic Materials

Materials can be classified as either isotropic or anisotropic.

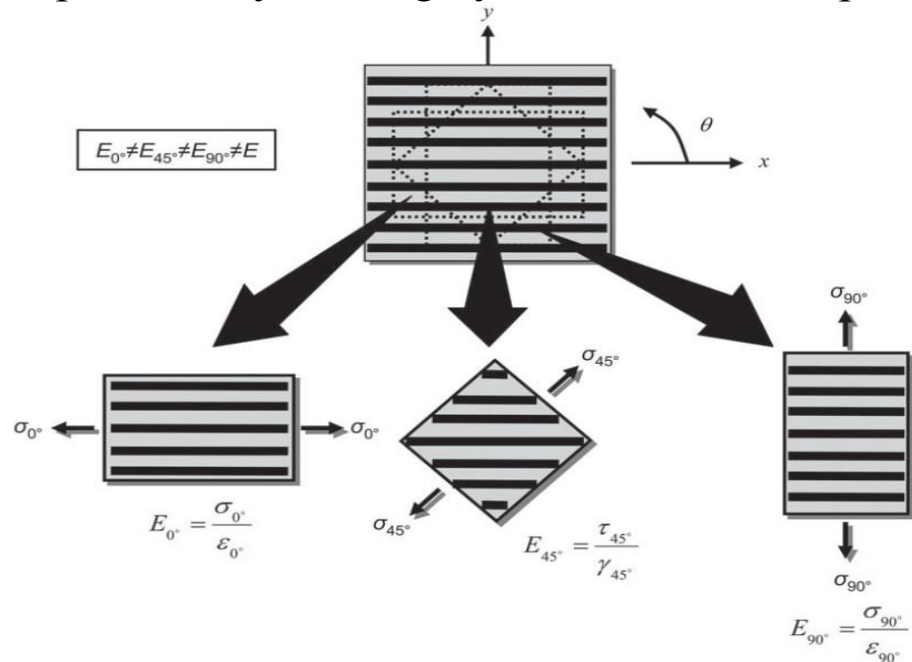
- Isotropic materials have the same material properties in all directions, and normal loads create only normal strains. Here properties (modulus of elasticity, as ultimate strength, Poisson's ratio, thermal expansion coefficient etc) are independent of direction within the material. If the material is loaded along its 0° , 45° , and 90° directions, the modulus of elasticity (E) is the same in each direction ($E_{0^\circ} = E_{45^\circ} = E_{90^\circ}$).



Isotropic, Anisotropic, and Orthotropic Materials

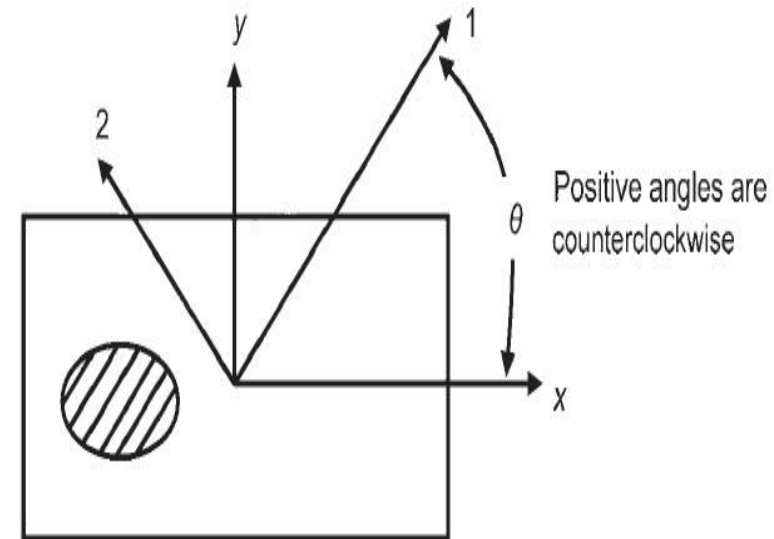
Materials can be classified as either isotropic or anisotropic.

- Anisotropic materials have different material properties in all directions. There are no material planes of symmetry and normal loads create both normal strains and shear strains. It has properties that vary with direction within the material. The moduli of elasticity are different in each direction ($E_{0^\circ} \neq E_{45^\circ} \neq E_{90^\circ}$).
- Bulk materials, such as metals and polymers are normally treated as isotropic materials, while composites are treated as anisotropic. However, even bulk materials such as metals can become anisotropic — for example, if they are highly cold worked to produce grain alignment in a certain direction.



Isotropic, Anisotropic, and Orthotropic Materials

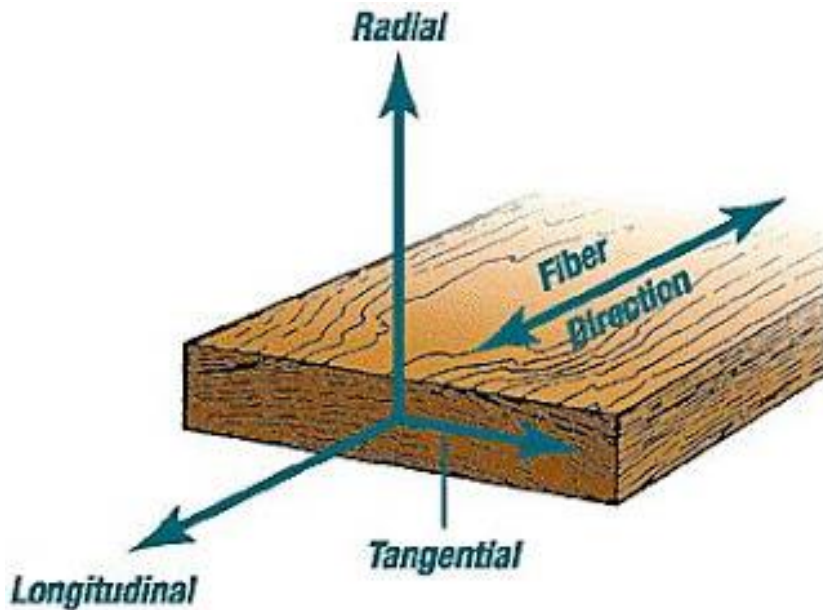
- Consider the unidirectional fiber-reinforced composite ply (*lamina*). The coordinate system used to describe the ply is labeled the *1-2-3 axes*. In this case, the 1-axis is defined to be parallel to the fibers (0°), the 2-axis is defined to lie within the plane of the plate and is perpendicular to the fibers (90°), and the 3-axis is defined to be normal to the plane of the plate. The 1-2-3 coordinate system is referred to as the *principal material coordinate system*.
 - If the plate is loaded parallel to the fibers (axis 1 or 0° direction), the modulus of elasticity E_{11} approaches that of the fibers.
 - If the plate is loaded perpendicular to the fibers (axis 2 or 90° direction), E_{22} is much lower, (less stiff matrix). Since $E_{11} \gg E_{22}$ and the modulus varies with direction within the material, the material is anisotropic.



Ply coordinate system:
 1-axis is parallel to the fiber direction.
 2-axis is perpendicular to the fiber direction.
 3-axis is normal to the plane of the ply.

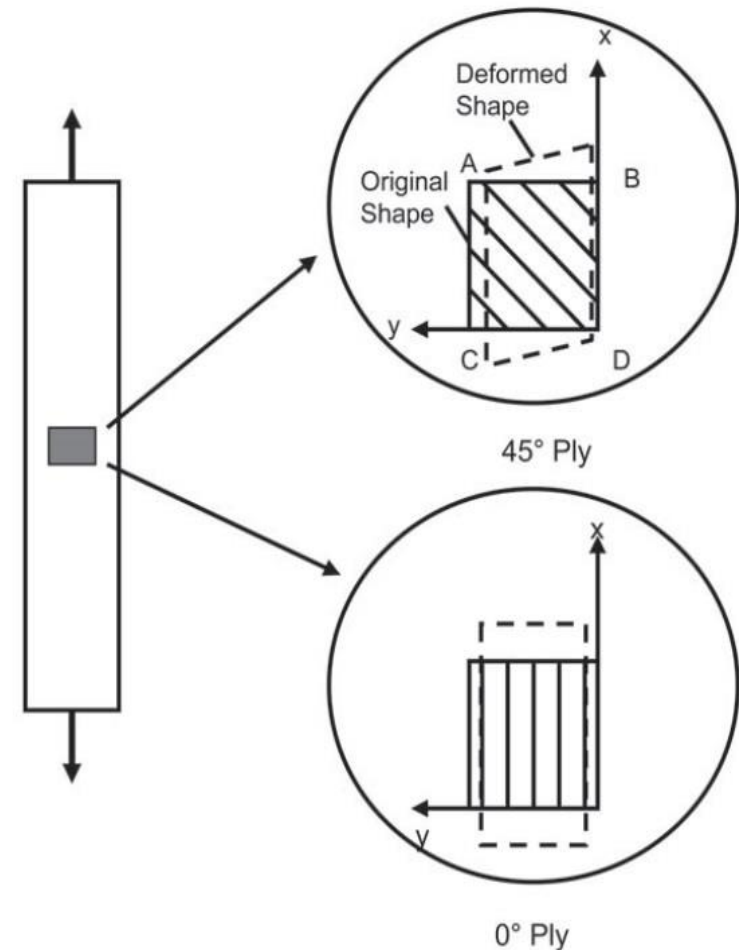
Isotropic, Anisotropic, and Orthotropic Materials

Orthotropic composites are a subclass of anisotropic materials. Orthotropic materials have properties that are different in three mutually perpendicular directions (three planes). They have three mutually perpendicular axes of symmetry, and a load applied parallel to these axes produces only normal strains. However, loads that are not applied parallel to these axes produce both normal and shear strains. Therefore, orthotropic mechanical properties are a function of orientation. e.g. wood (3 directions – longitudinal, circumferential and radial)



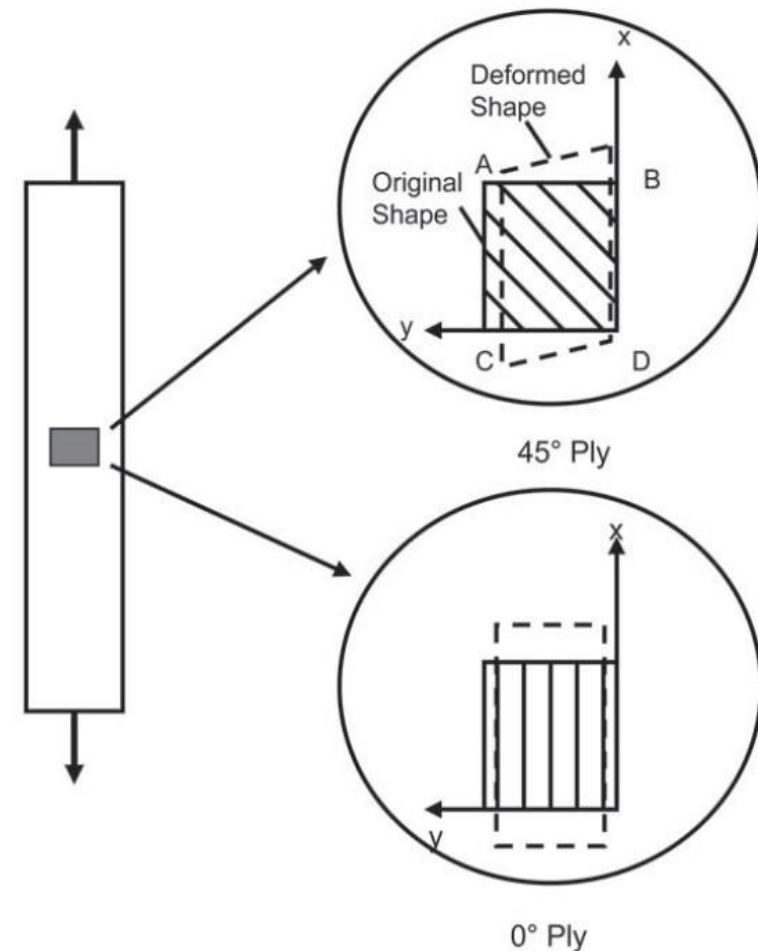
Isotropic, Anisotropic, and Orthotropic Materials

- Consider the unidirectional composite shown in the upper portion of Fig., where fibers are oriented at 45° w. r. t. x -axis.
- Consider small, isolated square element which is initially square; the fibers are parallel to diagonal AD and perpendicular to BC of the element.
- When a tensile stress is applied, the square element deforms.
- Because the stiffness is higher along diagonal AD than along diagonal BC, the length of diagonal AD is not increased as much as that of diagonal BC. Therefore, the initially square element deforms into the shape of a parallelogram. Because the element has been distorted into a parallelogram, a shear strain γ_{xy} is induced as a result of coupling between the axial strains e_{xx} and e_{yy} .



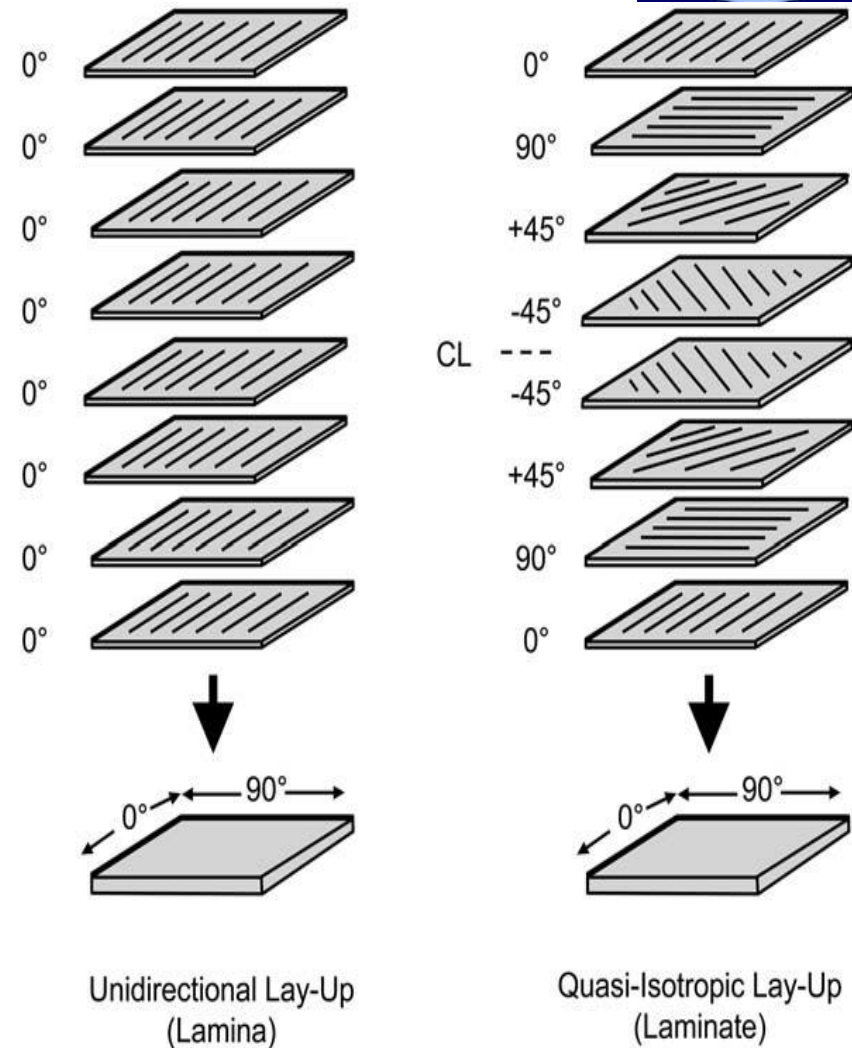
Isotropic, Anisotropic, and Orthotropic Materials

- If the fibers are aligned parallel to the direction of applied stress, as in the lower portion of the Fig, coupling between e_{xx} and e_{yy} does not occur.
- In this case, the application of a tensile stress produces elongation in the x -direction and contraction in the y -direction, and the distorted element remains rectangular.
- Therefore, the coupling effects exhibited by composites occur only if stress and strain are referenced to a non-principal material coordinate system.
- Thus, when the fibers are aligned parallel (0°) or perpendicular (90°) to the direction of applied stress, the lamina is known as a *specially orthotropic lamina* ($\theta = 0^\circ$ or 90°). A lamina that is not aligned parallel or perpendicular to the direction of applied stress is called a *general orthotropic lamina* ($\theta \neq 0^\circ$ or 90°).



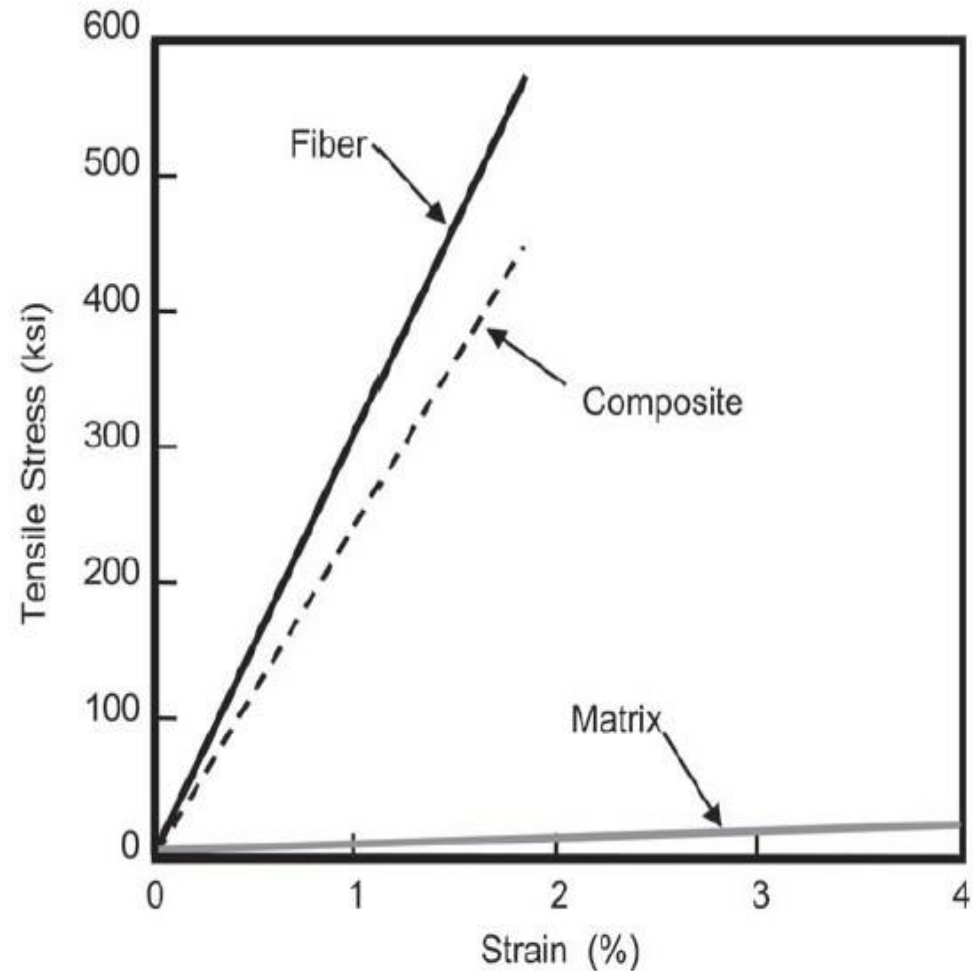
Laminates:

- When there is a single ply or a lay-up in which all of the layers or plies are stacked in the same orientation, the lay-up is called a *lamina*.
- Unidirectional (0°) laminae are extremely strong and stiff in the 0° direction. However, they are very weak in the 90° direction because the load must be carried by the much weaker polymeric matrix.
- When the plies are stacked at various angles, the lay-up is called a *laminated*.
- Continuous-fiber composites are normally laminated materials in which the individual layers, plies, or laminae are oriented in different directions that will enhance the strength in the respective load direction.



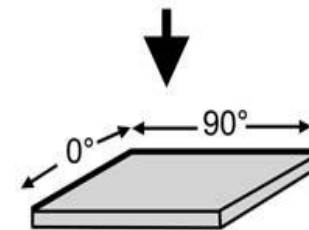
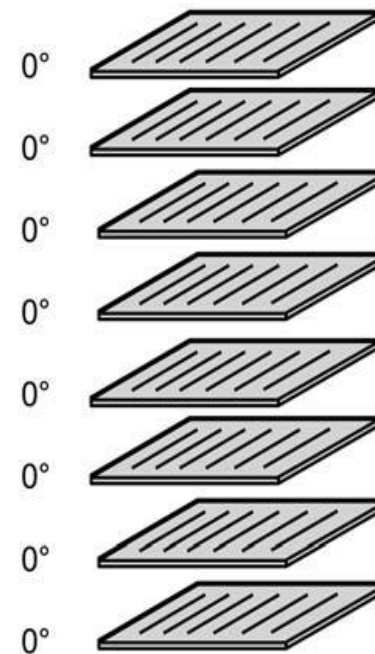
Laminates:

- While a high-strength fiber can have a tensile strength of 3500 MPa or more, a typical polymeric matrix normally has a tensile strength of only 35 to 70 Mpa.
- **In a unidirectional lamina, the longitudinal tension and compression loads are carried by the fibers, while the matrix distributes the loads between the fibers in tension and stabilizes the fibers and prevents them from buckling in compression.**
- **The matrix is also the primary load carrier for inter-laminar shear (i.e., shear between the layers) and transverse (90°) tension.**

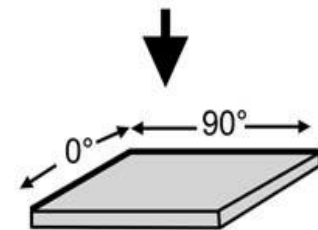
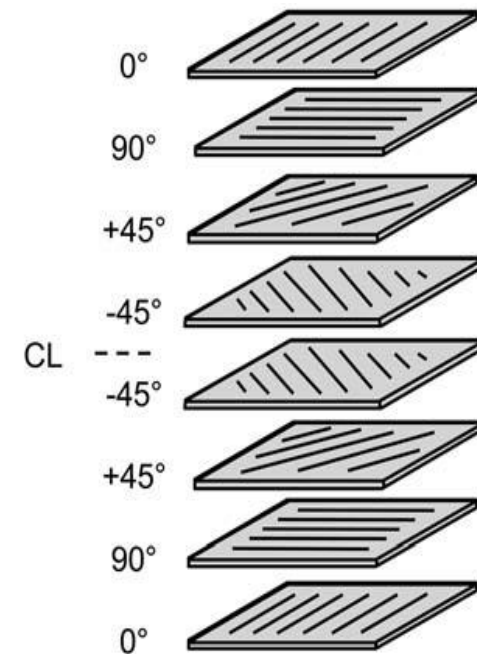


Laminates:

- Because the fiber orientation directly impacts mechanical properties, it seems logical to orient as many of the layers as possible in the main load-carrying direction.
- While this approach may work for some structures, it is usually necessary to balance the load-carrying capability in a number of different directions, such as the 0° , $+45^\circ$, -45° , and 90° directions.
- A balanced laminate having equal numbers of plies in the 0° , $+45^\circ$, -45° , and 90° degrees directions is called a *quasi-isotropic laminate*, because it carries equal loads in all four direction.



Unidirectional Lay-Up
(Lamina)



Quasi-Isotropic Lay-Up
(Laminate)

Fundamental Property Relationships:

When a **unidirectional continuous-fiber lamina or laminate** is loaded in a direction parallel to its fibers (0° or 11 -direction), the longitudinal modulus E_{11} can be estimated from its constituent properties as per the *rule of mixtures*:

$$E_{11} = E_f V_f + E_m V_m$$

Where, E_f is the fiber modulus, V_f is the fiber volume percentage, E_m is the matrix modulus, and V_m is the matrix volume percentage.

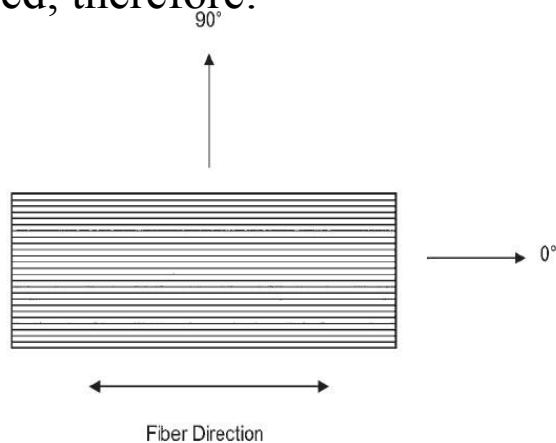
The longitudinal tensile strength s_{11} also can be estimated by the rule of mixtures:

$$s_{11} = s_f V_f + s_m V_m$$

Where, s_f and s_m are the ultimate fiber and matrix strengths, respectively. Because the properties of the fiber dominate for all practical volume percentages, the values of the matrix can often be ignored; therefore:

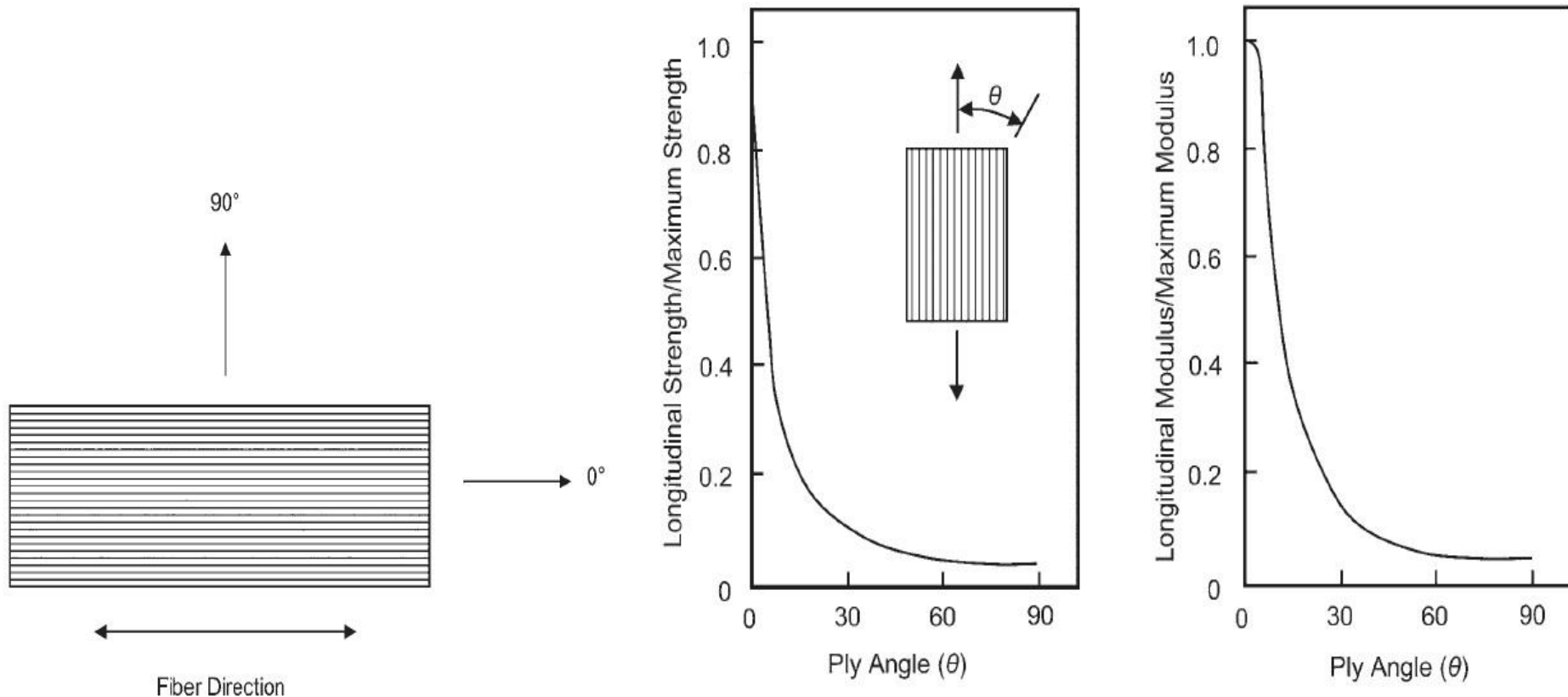
$$E_{11} \approx E_f V_f$$

$$s_{11} \approx s_f V_f$$



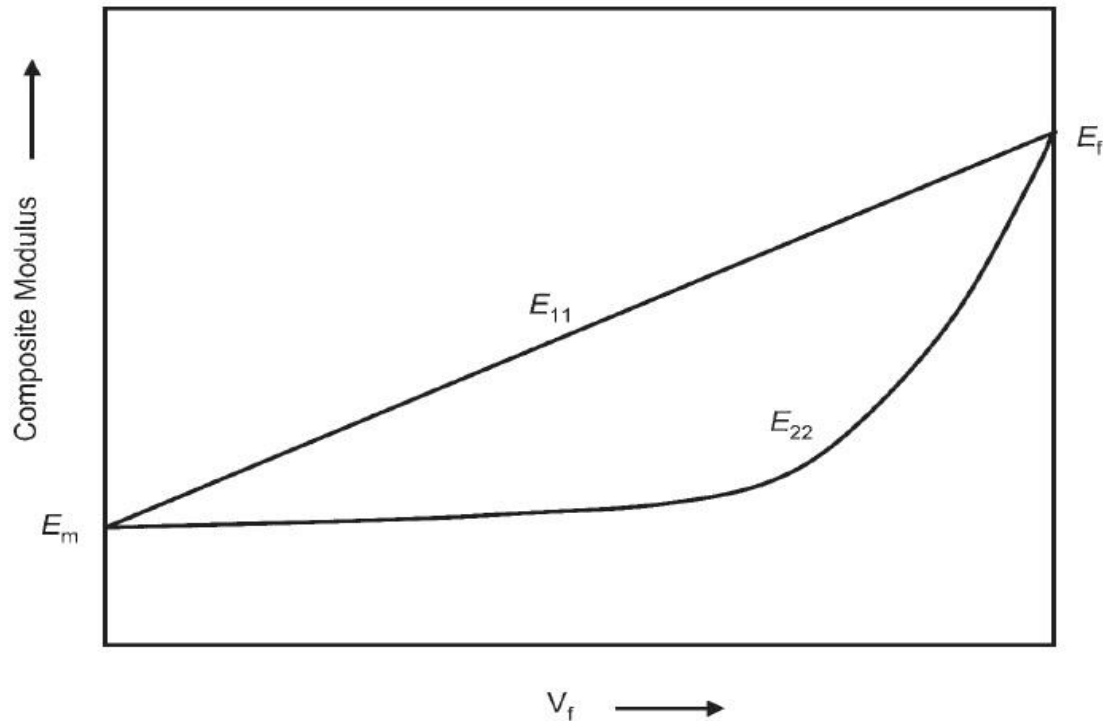
Fundamental Property Relationships:

Figure shows the dominant role of the fibers in determining strength and stiffness. When loads are parallel to the fibers (0°), the ply is much stronger and stiffer than when loads are transverse (90°) to the fiber direction. There is a dramatic decrease in strength and stiffness resulting from only a few degrees of misalignment from 0° .



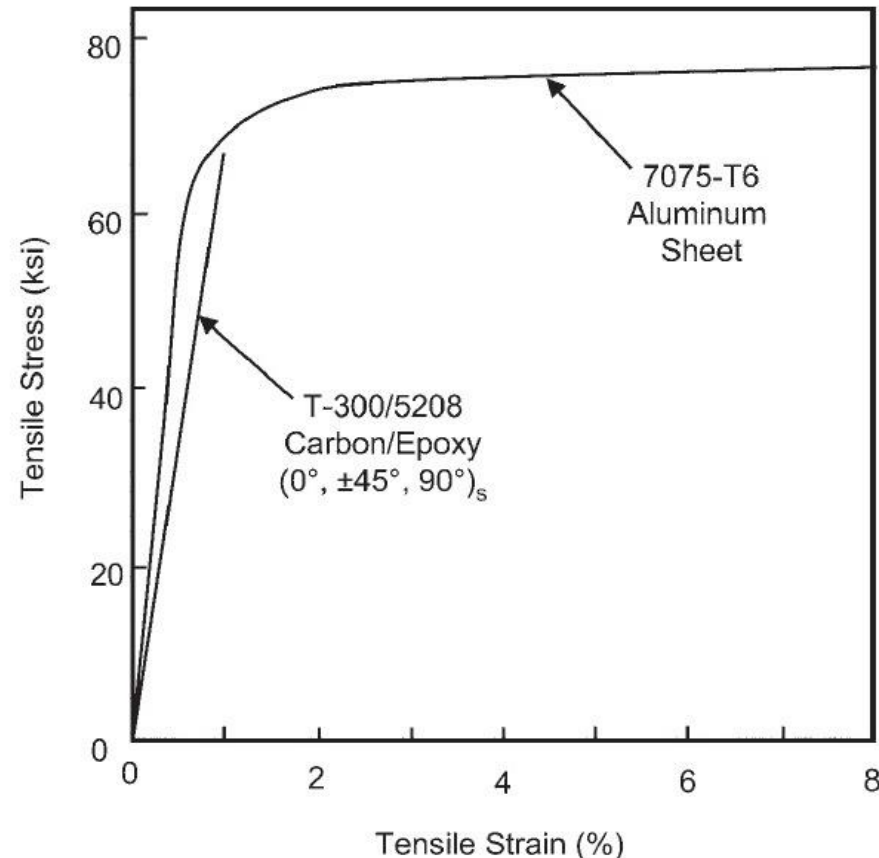
Fundamental Property Relationships:

Figure shows the variation of modulus as a function of fiber volume percentage. When the fiber percentage is zero, the modulus is essentially the modulus of the polymer, which increases up to 100 percent (where it is the modulus of the fiber). At all other fiber volumes, the E_{22} or 90° modulus is lower than the E_{11} or zero degrees modulus, because it is dependent on the much weaker matrix.



Composites vs. Metals:

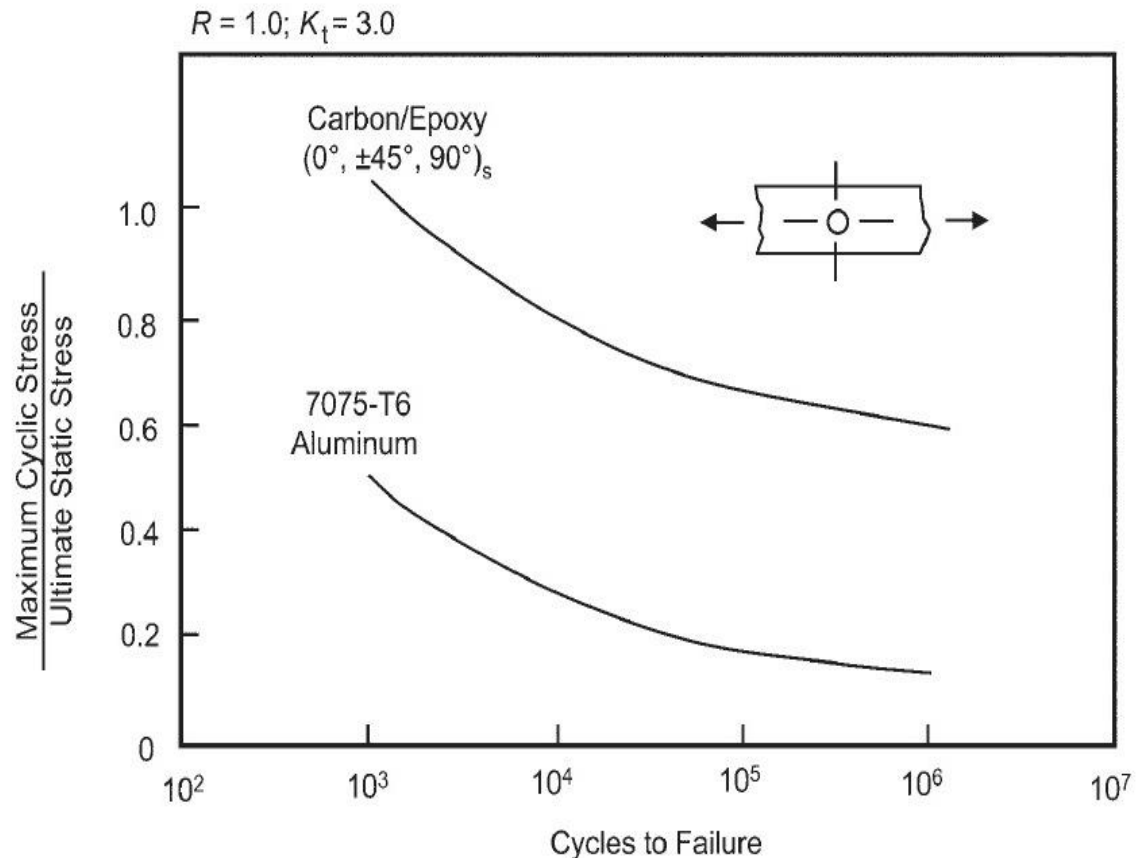
- Composites are highly anisotropic, their strength and stiffness directionally variable, depending on the orientation of the reinforcing fibers. Properties are high in the direction of orientation of fibers while properties other than this direction are (at least for polymer matrix composites) are comparatively low in strength and stiffness.
- Metals have reasonable ductility, continuing to elongate or compress considerably when they reach a certain load (through yielding) without picking up more load and without failure. Two important benefits of this ductile yielding are that (1) it provides for local load relief (from stress concentration) by distributing excess load to the adjacent part of the structure under static loading; (2) provides great energy-absorbing capability (indicated by the area under a stress-strain curve). As a result, when impacted, a metal structure typically deforms but does not actually fracture. In contrast, composites are relatively brittle.



Composites vs. Metals:

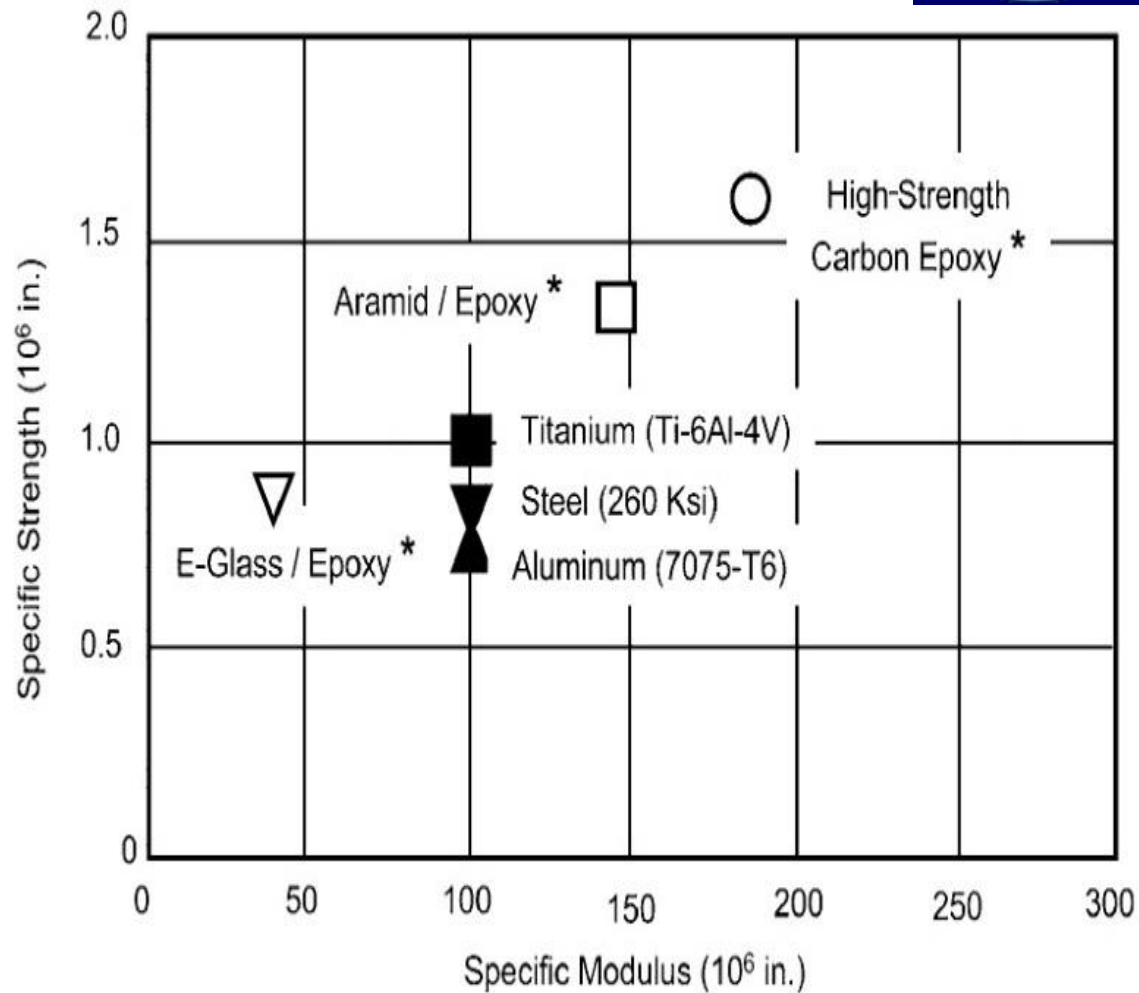
- The ability of composites to withstand cyclic loading is far superior to that of metals, in contrast to the poor composite static strength when it has damage or defects. requirement.
- is typically much higher than the fatigue

Figure shows a comparison of the normalized notched specimen fatigue response of a common 7075-T6 aluminum aircraft metal and a carbon/epoxy laminate. The fatigue strength of the composite is much higher relative to its static or residual strength. The static or residual strength requirement for composite structures



Advantages of composites:

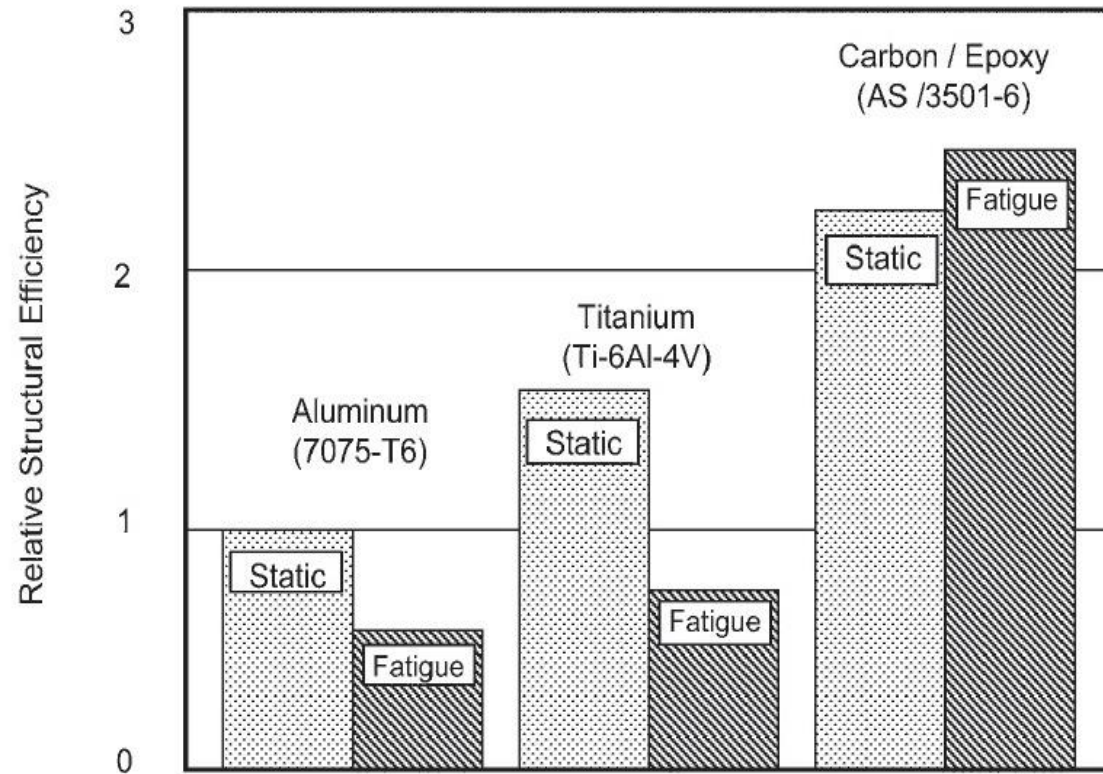
- lighter weight, the ability to tailor the lay up for optimum strength and stiffness, improved fatigue life, corrosion resistance, and, with good design practice, reduced assembly costs due to fewer detail parts and fasteners.
- The specific strength (strength/weight) and specific modulus (modulus/weight) of high strength fibers (especially carbon) are higher than those of other comparable aerospace metallic alloys. This translates into greater weight savings (25-45%) resulting in improved performance, greater payloads, longer range, and fuel savings.



* $[\pm 45^\circ, 0^\circ 90^\circ]_s$

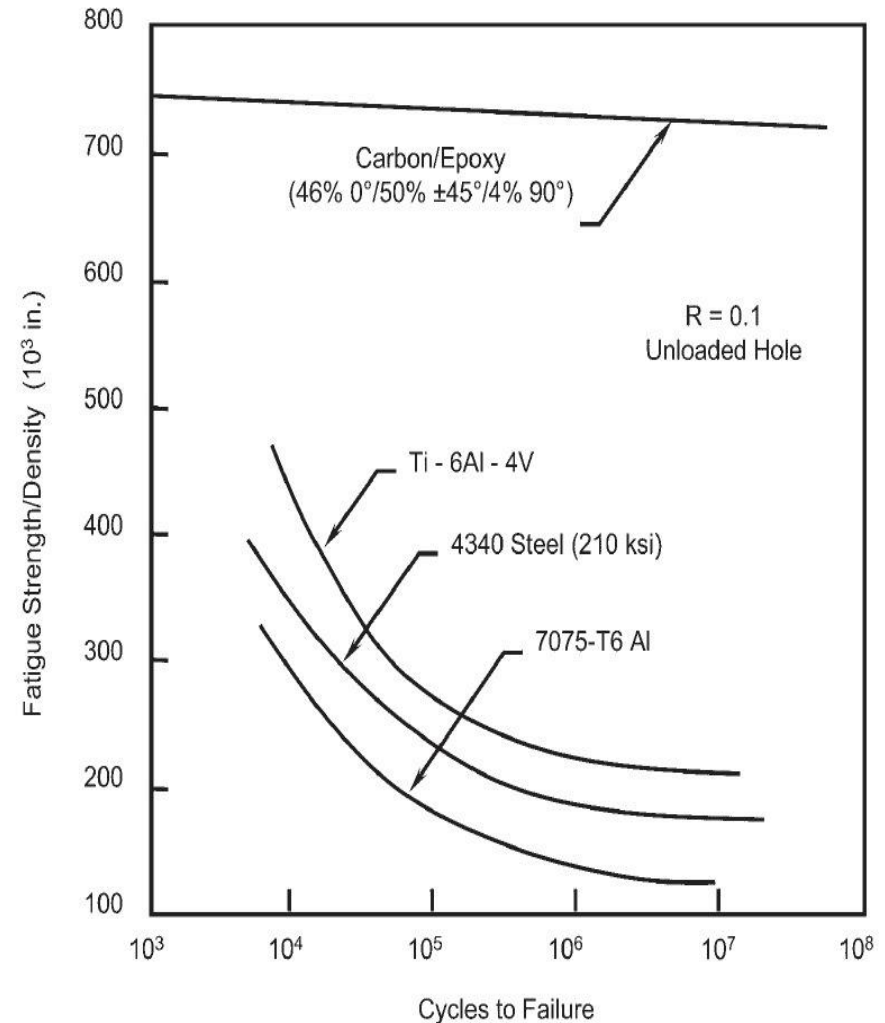
Advantages of composites:

- Figure compares the overall structural efficiency of carbon/epoxy, Ti-6Al-4V, and 7075-T6 aluminum.
- Composites do not corrode and they don't get tired [fatigue]. Corrosion of aluminum alloys is a major cost and a constant maintenance problem for both commercial and military aircraft. The corrosion resistance of composites in a marine environment can result in major savings.



Advantages of composites:

- Fatigue resistance of composites compared to high strength metals is shown in Fig. As long as reasonable strain levels are used during design, fatigue of carbon fiber composites should not be a problem.



Advantages of composites:



- Directional tailoring capabilities to meet the design requirements. The fibre pattern can be laid in a manner that will tailor the structure to efficiently sustain the applied loads.
- Improved dent resistance is normally achieved. Composite panels do not sustain damage as easily as thin gage sheet metals.
- Assembly cost consists of 50 % of the cost of an airframe. Composites reduce the amount of assembly labor and the number of required fasteners. Detail parts can be combined into a single cured assembly either during initial cure or by secondary adhesive bonding.
- It is easier to achieve smooth aerodynamic profiles for drag reduction. Complex double-curvature parts with a smooth surface finish can be made in one manufacturing operation.
- Composites offer improved torsional stiffness. This implies high whirling speeds, reduced number of intermediate bearings and supporting structural elements. The overall part count and manufacturing & assembly costs are thus reduced.

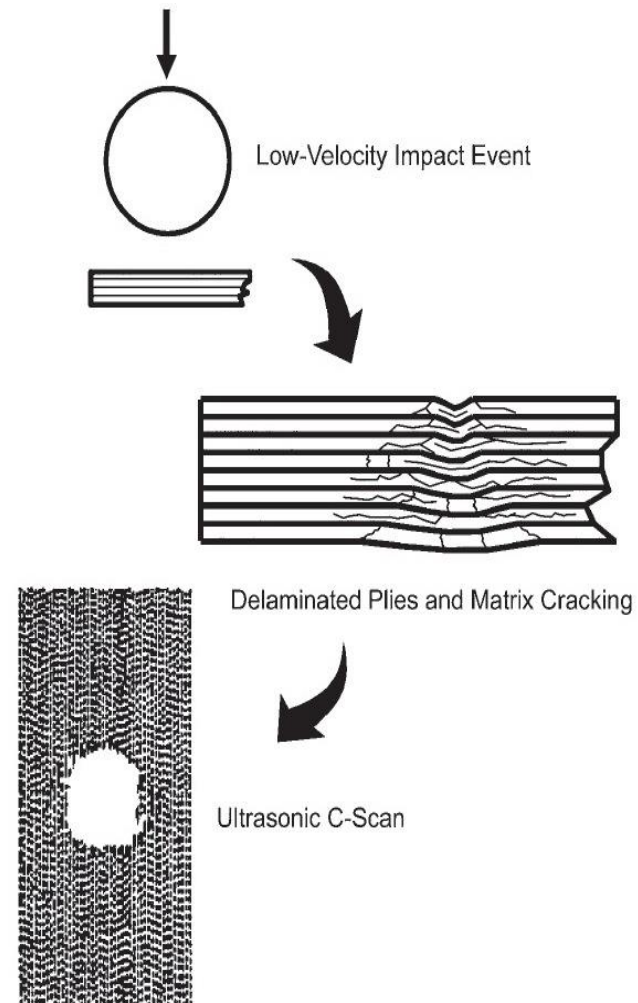
Advantages of composites:



- Thermoplastics have rapid process cycles, making them attractive for high volume commercial applications that traditionally have been the domain of sheet metals. Moreover, thermoplastics can also be reformed.
- Unlike metals, thermoplastics have indefinite shelf life.
- Composites are dimensionally stable i.e. they have low thermal conductivity and low coefficient of thermal expansion. Composite materials can be tailored to comply with a broad range of thermal expansion design requirements and to minimize thermal stresses.
- Close tolerances can be achieved without machining. Material is reduced because composite parts and structures are frequently built to shape rather than machined to the required configuration, as is common with metals.
- Excellent heat sink properties of composites, especially Carbon-Carbon, combined with their lightweight have extended their use for aircraft brakes.
- Improved friction and wear properties.

Disadvantages of composites:

- High raw material costs.
- Adverse effects of both temperature and moisture.
- Composites are more brittle than wrought metals and thus more easily damaged.
- Transverse properties may be weak. Poor strength in the out-of plane direction where the matrix carries the primary load (they should not be used where load paths are complex, such as with lugs and fittings).
- Susceptibility to impact damage and delamination or ply separations.
- Greater difficulty in repairing them compared to metallic structures.
- The major cost driver in fabrication for a composite part using conventional hand lay-up is the cost of laying up or collating the plies. This cost is generally 40 to 60 % of the fabrication cost, depending on part complexity.





- Fabrication and assembly costs. Assembly cost is a major cost $\sim 50\%$ of total part cost. As previously stated, one of the potential advantages of composites is the ability to cure or bond a number of detail parts together to reduce assembly costs and the number of required fasteners.
- Temperature has an effect on composite mechanical properties. Typically, matrix-dominated mechanical properties decrease with increasing temperature. Fiber-dominated properties are somewhat affected by cold temperatures, but the effects are not as severe as those of elevated temperature on the matrix-dominated properties.
- Composites are susceptible to delamination (ply separations) during fabrication, during assembly, and in service.



Applications of composites:

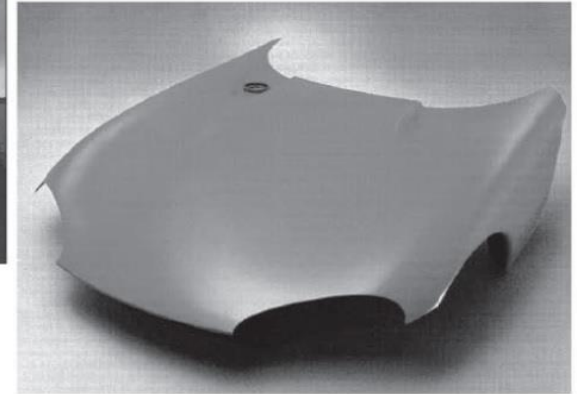
- Applications include aerospace, transportation, construction, marine goods, ~~sporting~~ goods, and more recently infrastructure.
- High-performance but more costly continuous-carbon-fiber composites are used where high strength and stiffness along with light weight are required, and much lower-cost fiberglass composites are used in less demanding applications where weight is not as critical.
- In military aircraft, low weight is of prime importance for performance and payload reasons, and composites often approach 20 - 40 % of the airframe weight. Hence, helicopters have incorporated glass fiber-reinforced rotor blades for improved fatigue resistance (carbon-fiber composites). Also used in military aircraft (continuous-carbon-fiber composites), small and large commercial aircraft (decrease weight and increase fuel performance) e.g. 50 % composite airframe for the Boeing 787.

Applications of composites:

- Composites are also used extensively in both weight-critical reusable and expendable launch vehicles and satellite structures. Weight savings due to the use of composite materials in aerospace applications generally range from 15 to 25 %.
- The major automakers are increasingly turning to composites to help them meet performance and weight requirements, thus improving fuel efficiency e.g. glass fibers, (durability and weight savings over metal). For high-performance Formula 1 racing cars, where cost is not an impediment, most of the chassis, including the monocoque, suspension, wings, and engine cover, is made from carbon fiber composites.



Composites are used in both trucks and cars to reduce weight and increase fuel efficiency.



Recreational vehicles have long used fiberglass composites, mostly for its durability and weight savings over metal.



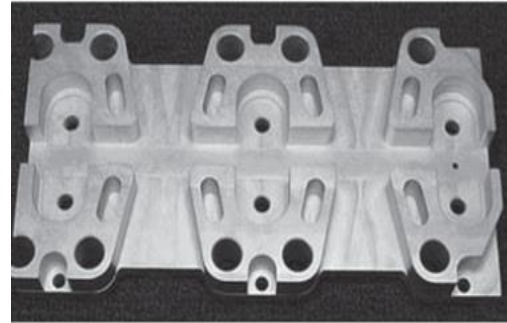
Applications of composites:

- Corrosion is a major headache and expense for the marine industry. Composites help minimize these problems, primarily because they do not corrode like metals or rot like wood. Hulls of boats ranging from small fishing boats to large racing yachts are routinely made of glass fibers and polyester or vinyl ester resins.
- Masts are frequently fabricated from carbon fiber composites.
- Fiberglass filament-wound SCUBA tanks are another example of composites improving the marine industry.
- Jet skis and boat trailers often contain glass composites to help minimize weight and reduce corrosion. More recently, the topside structures of many naval ships have been fabricated from composites.

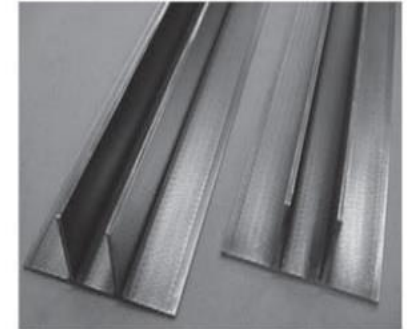


Applications of composites:

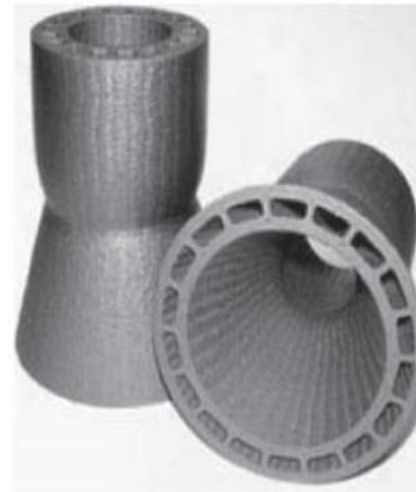
- In construction, pultruded fiberglass rebar is used to strengthen concrete, and glass fibers are used in some shingling materials.
- The blades for large wind turbines are normally made of composites to improve electrical energy generation efficiency.
- Tennis racquets (glass composites), golf club shafts (carbon composites). Lighter, stronger skis, surfboards and snow boards composites.
- Although metal and ceramic matrix composites are normally very expensive and are used where high temperatures are involved.



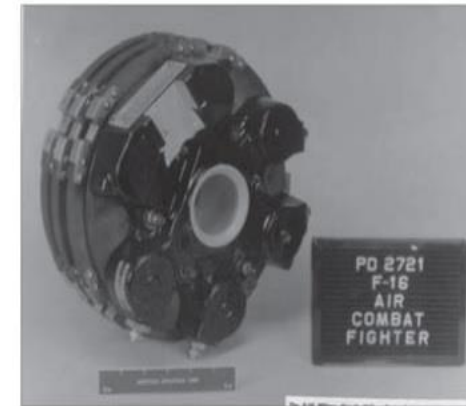
Metal Matrix Composite
Electronic Components



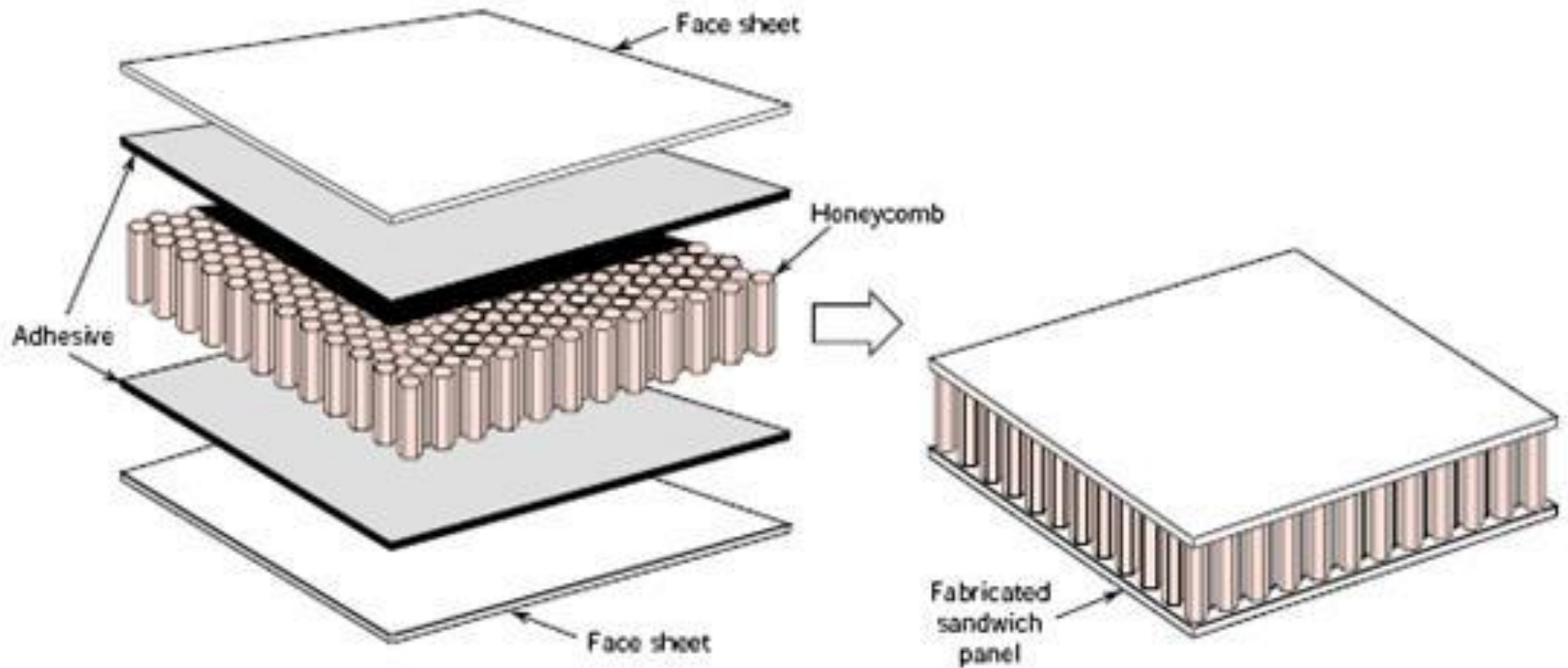
Metal Matrix Composite
Structural Components



Ceramic Matrix Ceramic
Exhaust Nozzles



Carbon-Carbon Brakes



Honeycomb structure (used in space shuttle)