# Mechanics of Fiber Reinforced Polymer Composite Structures

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## Lecture - 02
## Composite Materials - Classification

Welcome to the second lecture of the first module of the course “Mechanics of fiber reinforced polymer composite structures”. As mentioned in the last lecture, the objective of the first module has been to understand in general what a composite material is and with little more details on fiber reinforced polymer composites. Even though the course is actually on the mechanics of fiber reinforced polymer composites structures, but before we actually discuss in details the mechanics of fiber reinforced polymer composite structures, it is important that we understand what is a composite material in general, how composite materials are classified, and what is a fiber reinforced polymer composite in particular and what are the different terminologies. With that background, it will be convenient to discuss the mechanics of fiber reinforced polymer composite structures with a better appreciation.

As a part of module one, in the first lecture we understood –m

- What is a composite material— Definition, how it is actually different from alloys?
- Genesis of modern composites.
- Advantages and limitations of composites.
- Different applications of composite materials.

In today's lecture, we will discuss classifications and types of the composite materials in brief and we will have a little more detailed discussion on the fiber reinforced polymer composites and different terminologies that will be used with respect to the mechanics of fiber reinforced polymer matrix composites as the course progresses.

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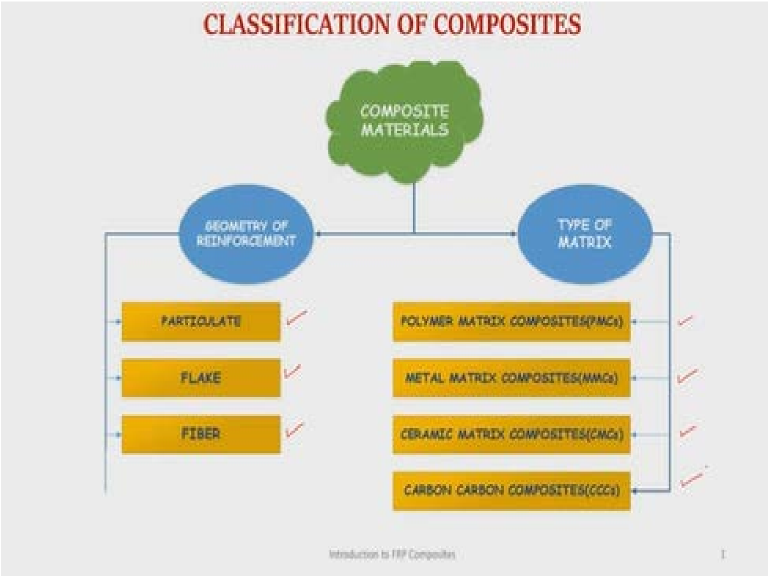


In our last lecture, we have discussed that composite materials actually consist of two phases. One is the **reinforcement phase**, other is the **matrix phase**. The reinforcement phase is the discontinuous phase and the matrix phase is the continuous phase. We also understood their functions where the reinforcement is basically the main load bearing member and the matrix actually acts as a binder which embeds the reinforcements.

**Classifications:**

Depending upon the geometry of the reinforcement and depending upon the type of matrix materials used, the composites are accordingly classified. For a given matrix material, depending upon the geometry of the reinforcement the composite could be

- Particulate composites— where the reinforcements are like particles.
- Flake composites— where the reinforcement shape is like flake
- Fiber composites— where the reinforcements are actually fibers

Similarly, for a given reinforcement depending upon the matrix materials used, the composites could be

- Polymer matrix composites or PMCs – where the matrix material is a polymer
- Metal matrix composites or MMCs – where the matrix material is a metal
- Ceramic matrix composites or CMCs – where matrix material is a
- Carbon-carbon composites or CCCs – carbon fibers are used with carbon as the matrix.

With reference to the classifications above, when the reinforcement if FIBER and the matrix is a POLYMER, this leads to what is known as FIBER REINFORCED POLYMER (FRP) COMPOSITES First we will discuss in brief all these types of composites in brief before we discuss in details the actually go to the FRP composites.

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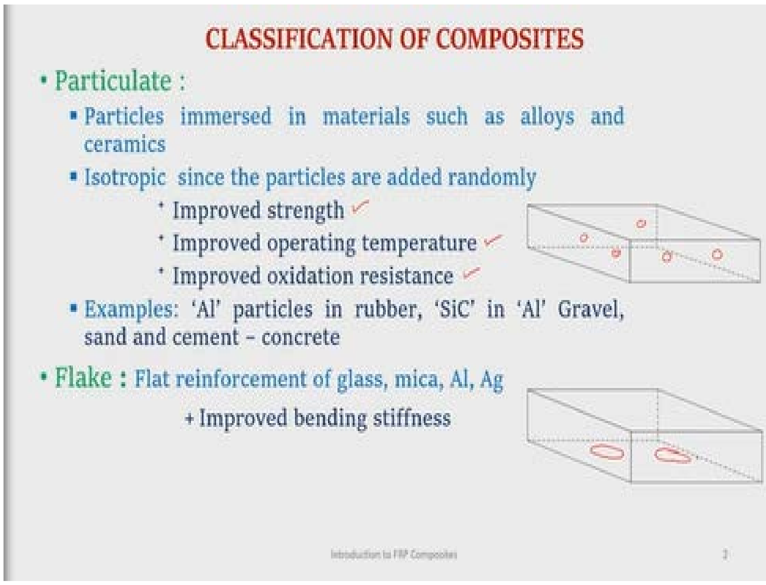


**Particulate Composites**

In particulate composites reinforcements in the form of particles are actually impregnated in materials such as alloys and ceramics. For example, aluminium particles in rubber or silicon carbide in aluminium or a very common example like gravels in sands and cement which makes concrete. In all these cases, the reinforcements are in the form of particles and since the particles are actually spaced randomly, they show isotropic behaviour in their properties. The advantages of particulate composites are –

- improved strength
- improved operating temperature (depending upon the kind of particle)
- improved oxidation resistance

**Flake Composites**

In flake composites, glass, mica, aluminium, silver etc in the form of flakes are used as reinforcements. Advantage of such flake composites is that when reinforced with flakes the bending stiffness increases. In the case of a say, plates with lower stiffness materials, providing flakes below the neutral axis will lead to improved bending stiffness and strength

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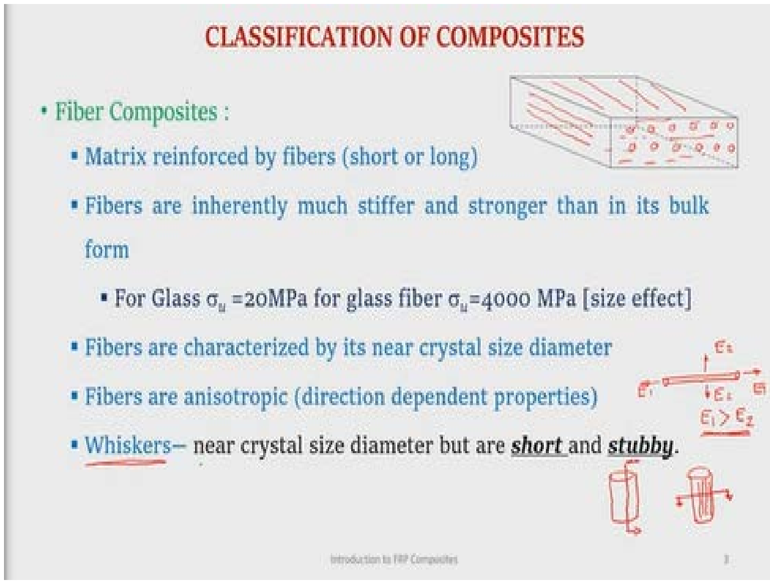


**Fiber Composites**

In fiber composites, the matrix is reinforced by fibers. The fibers could be short or long fibers. In our last lecture, we discussed that the fiber diameters are of the order of microns and size effect with reference to why fibers are inherently much stronger and stiffer than its bulk form. In addition, it is important to note that the fibers are anisotropic, meaning the properties are direction dependent. Suppose if we consider a fiber, its strength and stiffness in the axial direction will be more compared to its strength and stiffness in the transverse direction. Considering a fiber, if its stiffness in the longitudinal direction is $E_1$ and the stiffness in the transverse direction is $E_2$, then, $E_1 > E_2$. A common example is a bamboo, which is a fibrous structure where the fibers are aligned along the longitudinal direction. If we want to split it into two parts in the transverse section it is not that easy. But at the same time suppose if we want to split it in the longitudinal section we can do it with less effort compared to that required to split the same into two parts along a transverse section. This is due to the fact that the bamboo fibers are very strong and stiff in the axial direction but in transverse direction. So, it becomes much easier to split the bamboo along the longitudinal axis and it is difficult to cut the bamboo in the transverse section (REF to the Fig. in SLIDE).

In a fiber composite (REF to the Fig. SLIDE),  if we take a transverse cross section, we can clearly see the fibers in the cross section embedded in the matrix confirming to the  characteristics of the composites that we can actually distinctly see the two faces by naked eye. We have shown fibers here as continuous long fibers, but it can be short fiber also.

Sometimes the term whisker is also used. A whisker is also like a fiber but is much shorter and stubby.

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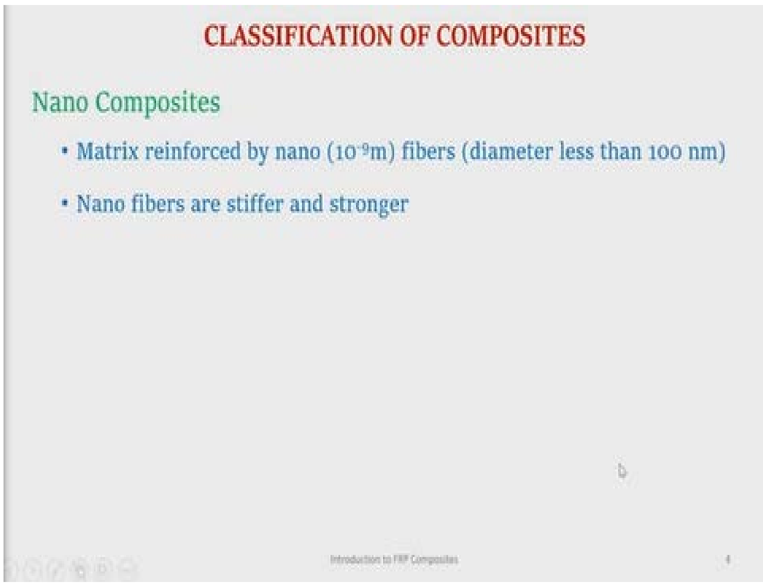
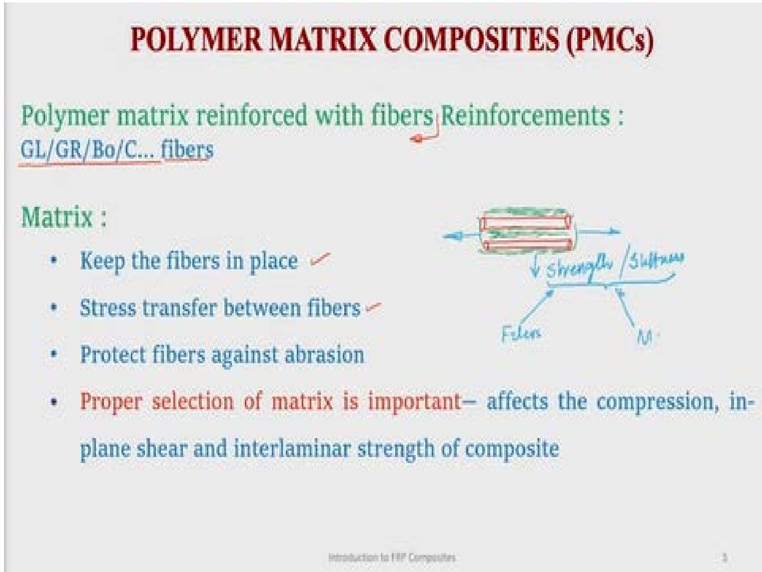



And in the recent past, nano composites are also used where the matrix is actually enforced by nanofibers. Nano means the dimensions are of the order of $10^{-9}$meter and diameter less than 100 nanometre is considered to be nano fibers. Nano fibers are even stronger and stiffer compared to conventional fibers. For example, the Young's modulus of carbon nano tubes (CNTs) could be as high as 1TPa. **(Refer Slide Time: 10:03)**




**Polymer matrix composites (PMCs)**

When the matrix material is polymeric it is called polymer matrix composite. In polymer matrix composites, the matrix is a polymer and reinforcements could be fibers such as glass, graphite, boron, carbon fibers. As discussed earlier, in a fiber reinforced polymer composites, the fibers are the main load bearing members and the functions of the matrix as binder are

- to act as binder and keep the fibers in place
- stress transfer between the fibers –

  the stress from one fiber is transferred to the next fiber by the matrix. That means when a load is applied the matrix actually acts as a medium which transfers the stress between the fibers. It is more so important in the event of fiber breakage. Because the strengths of the fibers are statistically distributed, during loading the weakest fiber will break first. However,, the existence of matrix between the broken fiber and the adjacent intact fiber prevents the whole broken fiber to become by efficient transfer of the stresses.
- protects the fiber against aberrations.

In view of the above functions of the matrix, proper selection of the matrix in a composite is extremely important to achieve the desired objectives of the composite. In addition, the type of matrix material used influences especially, the compression, strength, the in plane shear strength and the interlinear strength of the composites. We have already discussed that the strength and stiffness of a composite is actually decided by the strengths and stiffness of the fiber and the matrix and their relative proportions where the longitudinal strength and stiffness are dominated by the strength, stiffness and relative proportion of the fiber.

That is among the properties of the composite, some of the properties are actually fiber dominated and some of the properties are actually matrix dominated, that is some of the properties are influenced significantly by the matrix whereas some are significantly influenced by the fibers. Fibers are very strong and stiff in the longitudinal direction and therefore, the longitudinal strength and stiffness of a composite is actually decided by fibers properties and the role of matrix properties is insignificant there.

But on the other hand, the transverse strength and stiffness of the composite is matrix dominated. Similarly, the longitudinal competition strength of a composite is actually decided by what is the compression strength of the matrix as the fibers are very thin and long with a very high aspect ratio.

Similarly, the interlaminar shear strength and in plane shear strength are influenced by the matrix. Therefore, depending upon the design requirement depending upon what is the kind of strength and stiffness required it is important that we make a judicious choice of the matrix.

In polymer matrix composites, there are two types of polymers; one is thermoset polymers and thermoplastic polymers.

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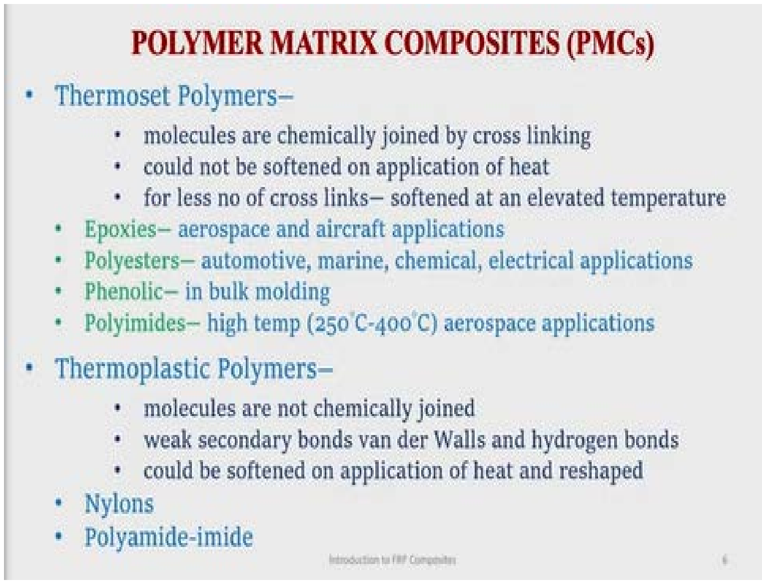


While the choice of such polymers is decided by the design requirements of the composite, we shall not discuss the details of the chemistry involved and will briefly discuss the characteristics of those polymers.

**Thermoset polymers** are those where the molecules are chemically joined by crosslinking and therefore they do not get softened on application of heat. However, in some cases where the number of cross links is less, maybe at an elevated temperature they could get soften. Examples are

Epoxies— epoxies are extensively used in aerospace and aircraft applications

Polyesters— are used in automotive, marine, chemical and electrical applications

Phenolic—are used for bulk molding applications and

Polyimides— are specially used for high temperature and aerospace applications.

Therefore, thermoset polymers could be used in comparatively higher operating temperature range. On the other hand **Thermoplastic polymers** are those where the molecules are actually not chemically joined but are connected by weak secondary bonds like van der Walls and hydrogen bonds. As a result, they could be softened on application of heat and could be reshaped. For example, thermoplastic polymers or nylons polyamide imide.

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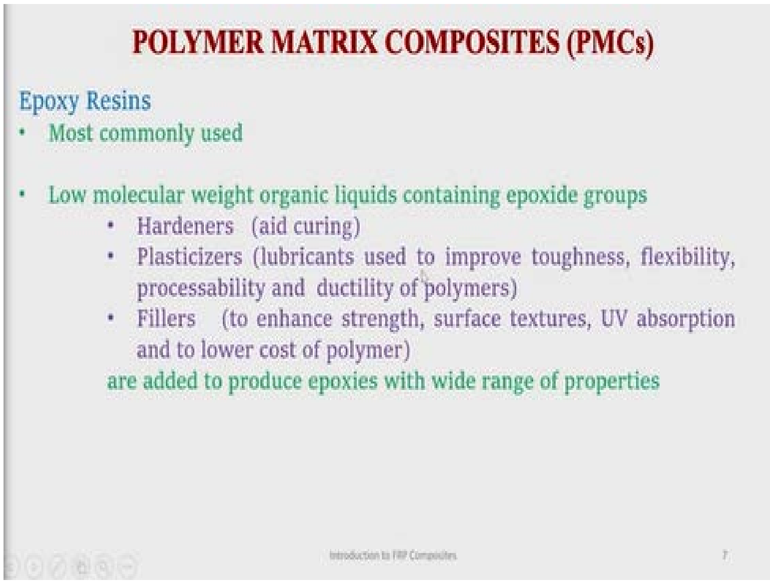


Among the polymer matrix, epoxy resins are the most commonly used and are actually low molecular weight organic liquids containing epoxide groups. With epoxy resins, hardeners, plasticizers and fillers are added to obtain different range of properties. Hardeners actually aid in curing of the composite whereas the plasticizers enhance the toughness, flexibility and ductility of the polymer. Addition of fillers improves the strength and surface texture and lowers the cost. Some of the important properties of the composites are significantly influenced by the matrix properties. Epoxies being available in a wide range of properties, depending upon the design requirements or the functional requirements of the composite, we may select the appropriate matrix.

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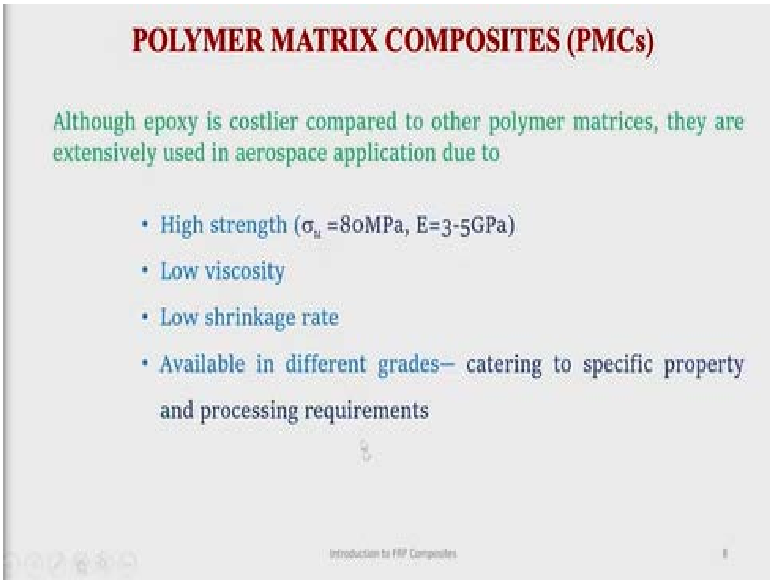

Epoxy is costlier compared to other polymers but even then, they are extensively used in aerospace applications mainly because of their strength, stiffness, low viscosity, low shrinkage and more importantly because they are available in different grades catering to different properties and process requirements. It is available almost in 20 different grades having different properties which cater to a wide range of design requirement of the composites. Ultimate tensile strength of a typical epoxy is around 80MPa and the Young's modulus is around 3 - 5 GPa.

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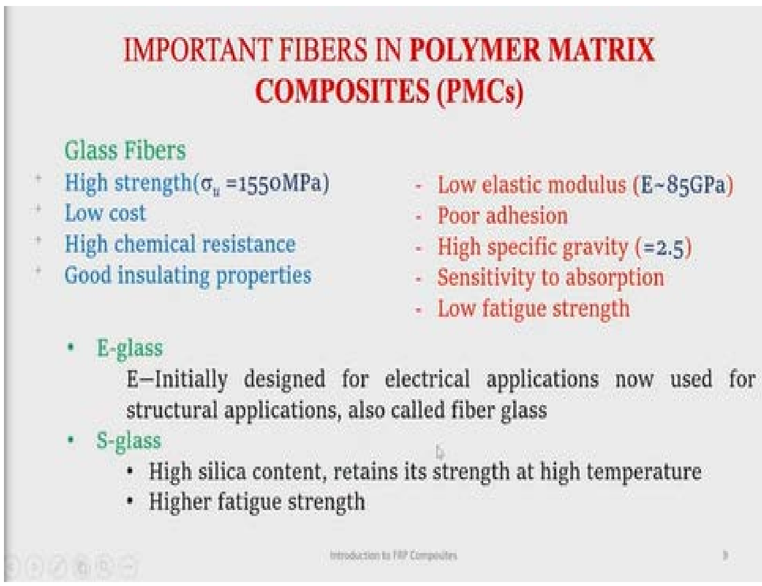


Having discussed different types of polymers which are used as matrix in polymer matrix composites, let us discuss the commonly used fibers in fiber reinforced polymer matrix composites.

**Glass Fibers—** are one of the most commonly used fibers in FRP composites and the advantages and limitations of glass fibers are

**Advantages—**

High strength (1550MPa)

Low cost

High chemical resistance

Good insulating properties

**Limitations—**

Lower elastic modulus (85GPa)

Poor adhesion

Higher specific gravity (2.5)

Low fatigue strength

Sensitive to absorption

**E glass—** Also known as fiber glass. E actually stands for electrical applications because initially it was designed for electrical applications though nowadays these are also used for structural application.

**S glass—** is glass with high silica content and as a result it retains its strength at a higher temperature and it has a higher fatigue strength.

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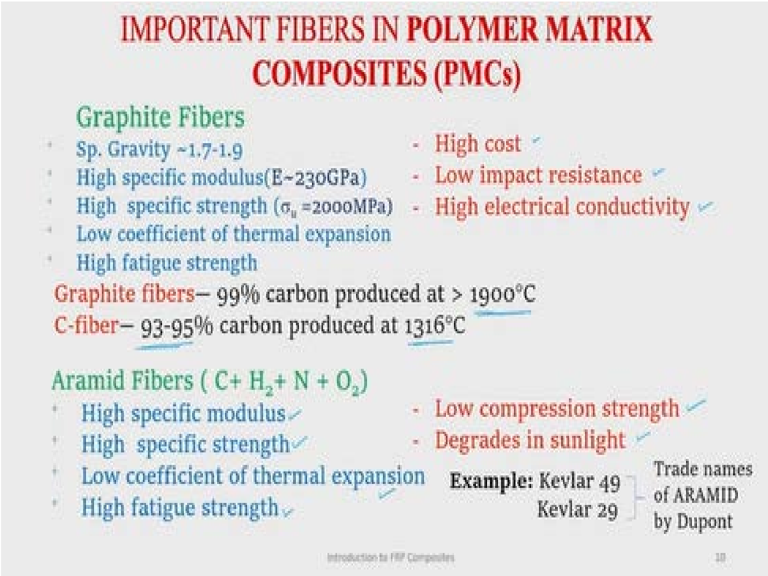


**Graphite Fibers** are also used in FRP composites for high strength applications and the advantages and limitations of glass fibers are

**Advantages—**

Lighter compared to glass fibers (specific gravity=1.7-1.9)

Higher specific modulus (E=230 GPa) –could lead to lighter composites with similar stiffness

Higher specific strength ($\sigma_u$=2000 MPa) –could lead to lighter composites with similar strength

Low coefficient of thermal expansion— as a result it can have a better dimensional stability in a wide range of operating temperature

Higher fatigue strength

**Limitations—**

Higher cost

Higher electrical conductivity

Low impact resistance

What is the difference between graphite fibers and carbon fibers? Graphite fiber has 99% carbon and produced at a 1900°C and carbon fiber contains 93-95% of carbon and produced at 1316°C.

**Aramid fibers—** mixture of carbon, hydrogen nitrogen and oxygen.

**Advantages—**

higher specific modulus

higher specific strength

low coefficient of thermal expansion

high fatigue strength.

**Limitations—**

lower compression strength

degrades in sunlight.

The commercial name of aramid fiber is Kevlar 49 and Kevlar 29 manufactured by Dupont. Have better impact resistance and are used for bullet proof vests.

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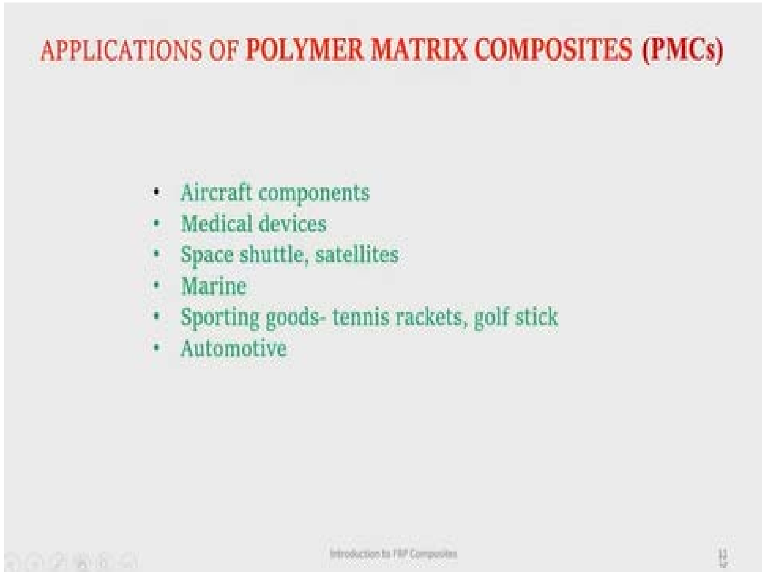


**Applications:**

Aircraft components— rudders, elevators, landing gears, panels, floors

Medical devices— lightweight face mask, implants

Space shuttle— bay doors, manipulator arms

Satellites—

Marine—boats

Sporting goods— golf club, tennis racquate

Automotive—leaf spring, body

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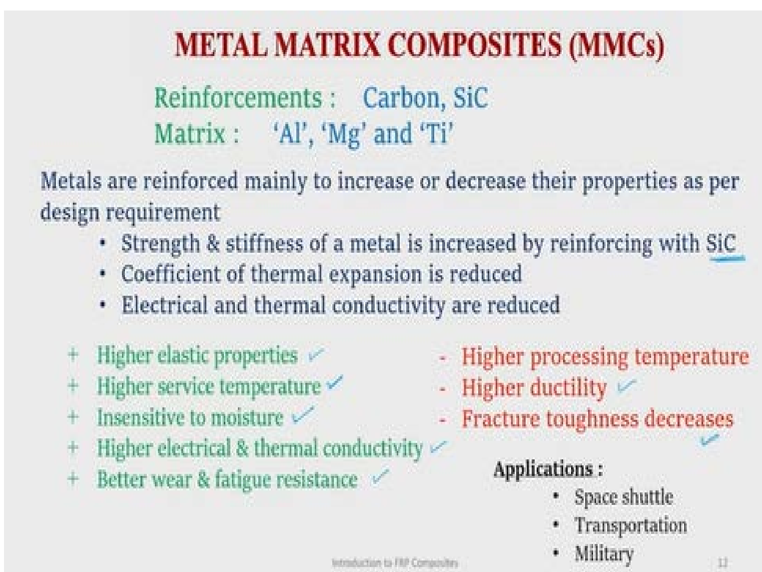

Having discussed FRP composites in little details let us now look into the other types of composites very briefly.

**<u>Metal matrix composites</u>**

In metal matrix composites

the commonly used reinforcements are— carbon and silicon carbide and

the matrix is of course metal— it could be aluminium, magnesium or titanium.

Here the metals are reinforced mainly to increase or decrease their properties as per the design requirements. For example, whereas the strength and stiffness of a metal could be increased by reinforcing with silicon carbide, the coefficient of thermal expansion will be reduced and electrical and thermal conductivity are also reduced. Therefore, depending upon what are the requirements, appropriate reinforcements, metal matrix and their relative proportions are chosen.

**Advantages of metal matrix composites over polymers composites —**

higher elastic properties

higher service temperature—polymers have limitations on the maximum temperature

insensitive to moisture—polymers being porous are sensitive to moisture and it might degrade by absorbing moisture.

higher electrical and thermal conductivity

better and fatigue resistance.

**Limitations—**

much higher processing temperature during fabrication

more ductile and fracture toughness is actually is reduced by the reinforcement.

**Applications—**

space shuttle

transportation and

military applications.

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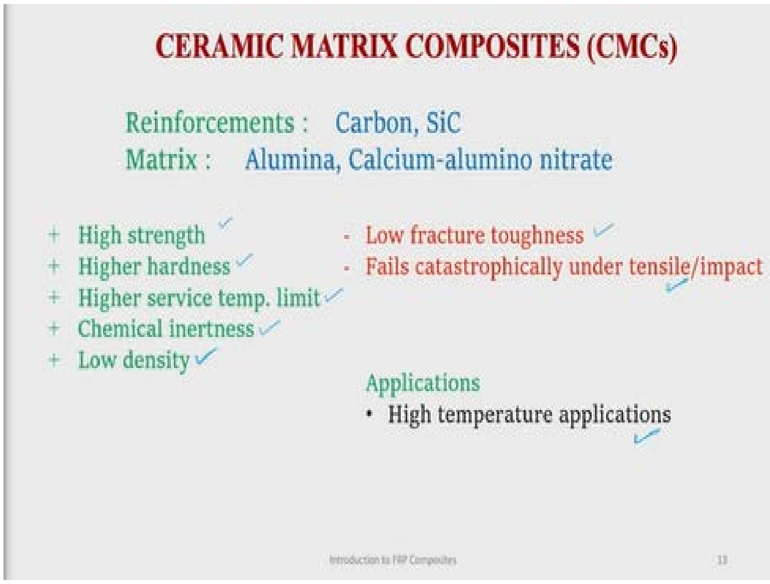


**Ceramic matrix composites (CMCs)**

Main reinforcements are— carbon and silicon carbide and

the matrix are ceramics— alumina or calcium aluminium nitride.

**Advantages**

higher strength

higher hardness

higher service temperature limit—ceramics can withstand much more temperature compared to polymer matrix composites

chemically inert and

low density— leads to more specific strength and stiffness and as a result it will be lighter.

**Limitations**

Low fracture toughness—under impact it fails catastrophically, low impact resistance

**Applications**

CMCs are mainly used for high temperature applications like ceramic tiles are actually used in space shuttle as during re-entry the temperature goes very high and the ceramic tiles are actually used there.

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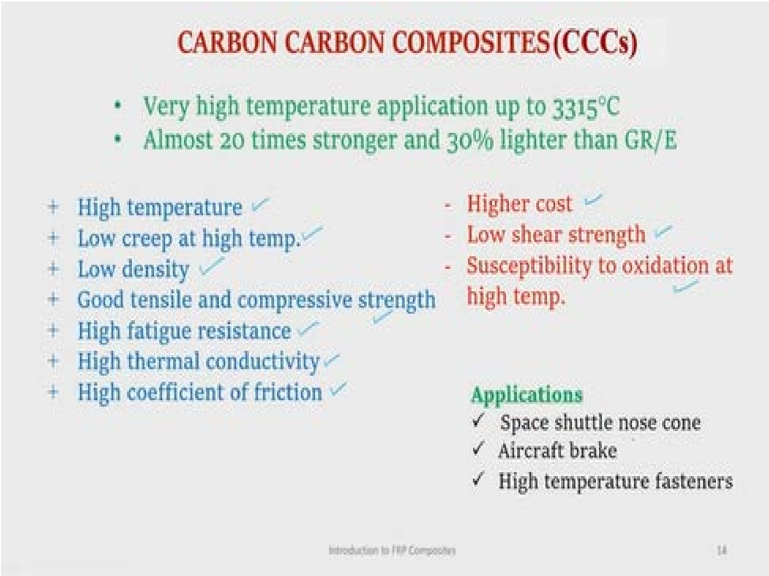


**Carbon carbon composites (CCCs)**

These are actually used for very high temperature applications up to 3300°C and are almost 20 times stronger and 30 times lighter than graphite epoxy.

**Advantages**

high temperature

low creep at high temperature

low density

good tensile and compression strength

high fatigue resistance

high thermal conductivity

high coefficient of friction.

**Limitations**

Higher cost

Low shear strength

Susceptible to oxidation at high temperature

**Applications**

The space shuttle nose cone is made up of this carbon carbon composites because during re-entry it experiences very high temperature and carbon carbon composite can withstand that temperature.

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Choice of appropriate manufacturing process of FRP composites is extremely important as it influences the quality of the product and hence the properties of the final component. Some of the commonly used manufacturing processes are

**Filament winding—**fibers are made wet with resin by drawing through a resin bath and wounf over a mandrel to form a filament wound composite.

**Autoclave forming—**prepregs with resins are stacked in an autoclave and are cured at specified temperature and pressure.

**Resin transfer molding—**preforms are put into the mold and a low viscosity resin is injected and finally cured at a particular pressure and temperature

We shall not discuss the details of manufacturing processes in this course and the details of the same could be found in most of the texts on composite materials.

In the early days of composites hand layups were used where the laminae are actually put one over the other and pressure is applied by rolling a heavy roller by hand and finally, they are cured to get the component. But, there are many disadvantages and of course it is time consuming.

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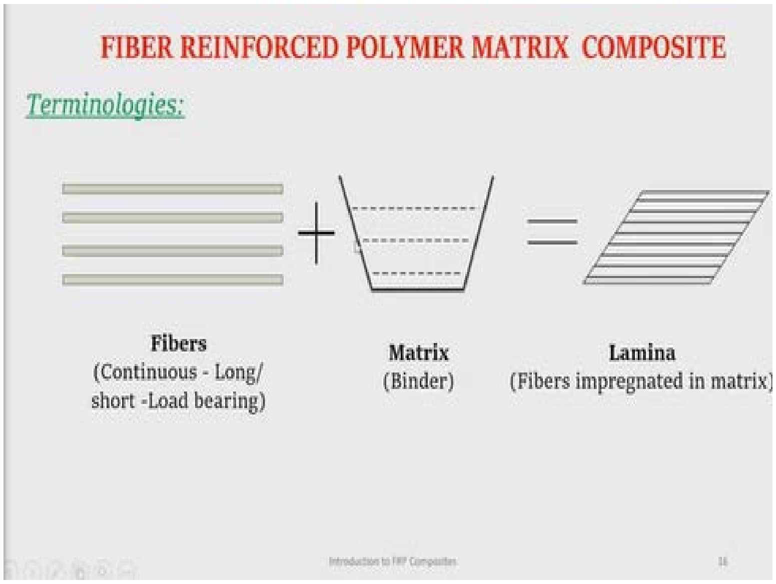


**Mechanics of FRP Composites—** important terminologies and overview of this course

Fibers as reinforcements when mixed with polymers as matrix make FRP composites. Most basic element where a large number of fibers are mixed with polymer matrix is called a **LAMINA**. Lamina as shown is a thin sheets where a large number of fibers are actually impregnated in the matrix with certain proportions maybe say 50% fibers and 50% matrix. Lamina is sometimes also called a ply. Thickness of a typical lamina is in the range of 0.1-0.5 mm. Lamina could be unidirectional or bi-directional. Since it is very thin, a lamina by itself can't be a structural components and large number of laminae are stacked together to provide a meaningful thickness suitable to be used as a component.

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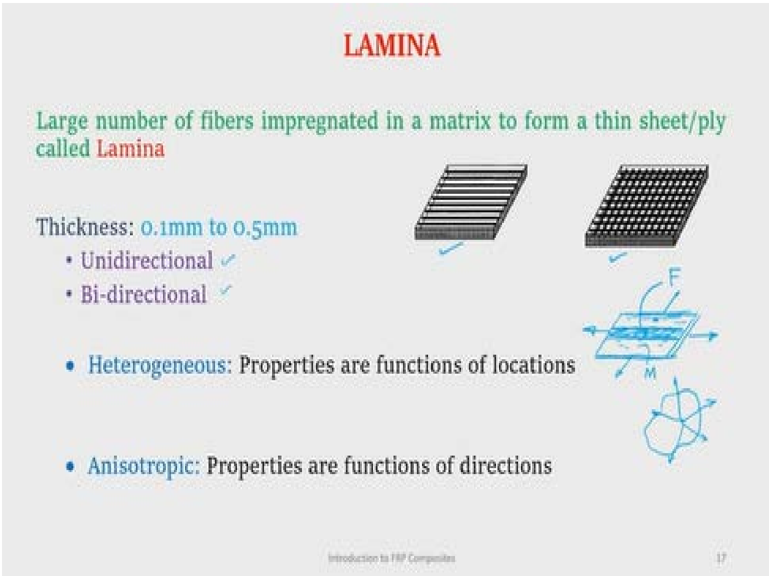

Lamina could be unidirectional or bi-directional. In unidirectional lamina, all the fibers are in one particular direction whereas in bi-directional lamina, fibers are in two perpendicular directions. Depending upon the requirements both unidirectional, bi directional lamina are used.
Another important aspect is that lamina is **heterogeneous** and **anisotropic**.

**Heterogeneous** means properties at a point are functions of location of that point. For example, if choose a point in a lamina at random and if the point happens to be on a fiber, its properties will be different than those of a point which lies on a matrix.

**Anisotropic** means properties at a point are dependent on the direction. Considering a lamina, the fibers are very strong and stiff in the longitudinal direction. Therefore, the lamina when loaded along the longitudinal direction, the strength and stiffness will be far higher compared to those in the other direction. Therefore, it is anisotropic.

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Laminae are available in the form of **Prepregs** which are readymade tapes made of fibers in polymer matrix. This comes as a roll available in stands with varying width. Depending upon the requirements, the laminae will be cut from this prepregs with different widths and different angles.

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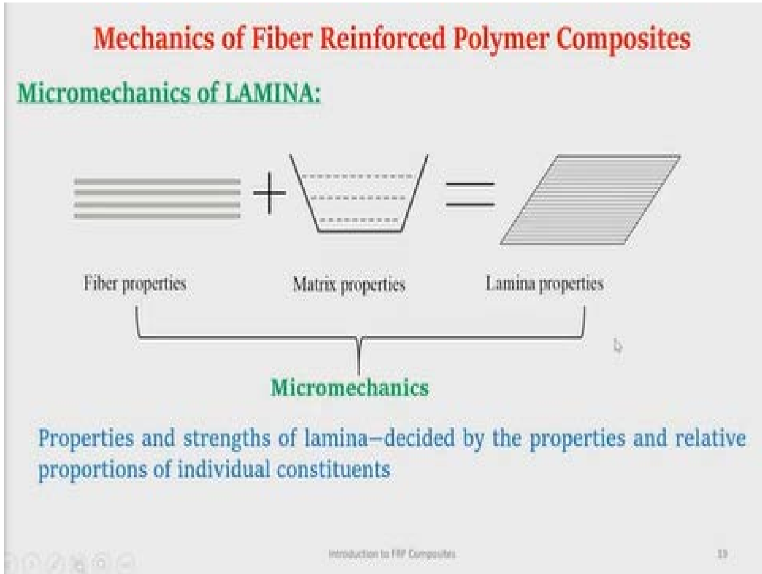


Since this course is on mechanics of fiber reinforce polymer composites, having understood the basic ingredients of fiber reinforce polymeric composites ie. the fibers and the polymer matrix, it is important to understand different aspects of mechanics of such fiber reinforced polymer matrix (FRP) composites along with important terminologies used.

**Micromechanics of Lamina**

FRP composites being made of fibers and matrix mixed at a particular proportion, it is understood that the properties of the composites will be decided by the properties of the constituents ie. the properties of fiber and the properties of matrix. Therefore, the stiffness and and strength of a lamina will be decided by what are the corresponding stiffness and strengths of the matrix and the fibers and the relative proportions of fibers and the matrix in the lamina.

In micromechanics we shall study how the properties (strengths, elastic moduli, coefficients of thermal expansion etc) of the lamina are actually influenced by the properties of fibers and the matrix and their relative proportions in the lamina. Say for example if we have two laminae of made from same fiber and matrix but one has fiber volume of 20% and the other has a fiber volume of 60%, their properties will be different. Therefore, in micromechanics the objective is to develop mathematical expressions for estimating the properties of a lamina in terms of the properties of fibers and matrix and their relative proportions and to understand the influence of important factors on the properties of the lamina.

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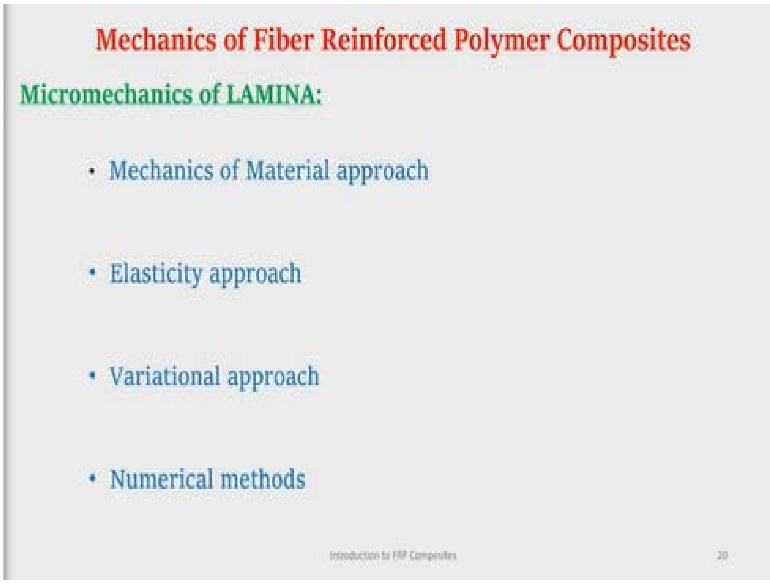


While there are different approaches in micromechanics, the efficacy of a particular method depends on how well those estimates correlate with the experimental observations.

**Mechanics of materials approach**

It is the most simple approach where the basic principles of strength of materials are used with a number simplified assumptions to establish simple expressions where the properties of the composite is expressed in terms of the properties of the matrix and the fiber and the relative proportions.

**Elasticity approach**

Elasticity approach is slightly more rigorous compared to mechanics to material approach where the equilibrium equations, the compatibility conditions and the boundary conditions are used to derive closed form analytical expressions for properties of the lamina in terms of the properties of the fiber and the properties of the matrix.

**Variational approach**

Here the energy principles like principles are actually used to determine the properties of the composites in terms of the properties of the fiber and the properties of the matrix. Additionally, the lower and upper bounds of the properties of a composite in terms of the properties of the fiber and the matrix are also established.

**Numerical approach**

Powerful numerical techniques like FEM, FDM are also used to determine the effective properties of a lamina in terms of the properties of fiber and the properties of the matrix.

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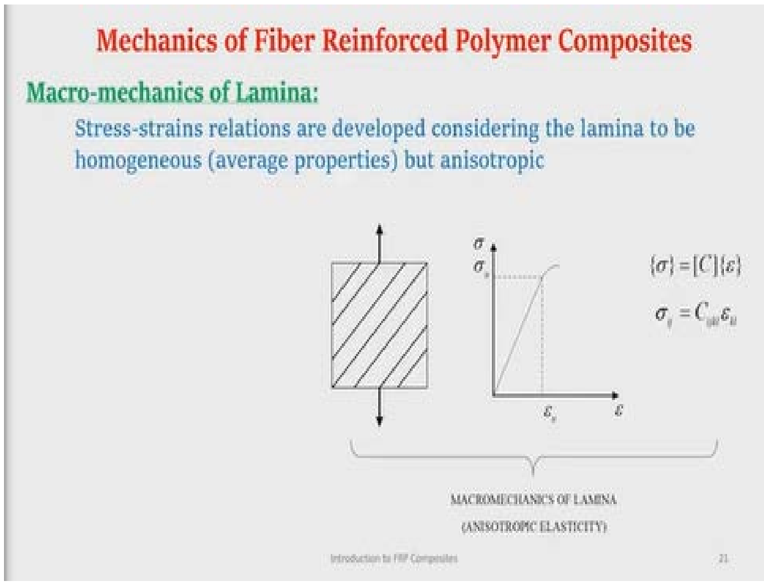


**<u>Macromechanics of Lamina</u>**

In macromechanics of a lamina, stress strain relationship for laminae are developed in terms of the lamina properties. In macromechanics, the lamina is considered to be homogenous ie the lamina is represented by its effective average properties and the fact that the lamina is made of two different materials is not heeded to. However, those average properties of a lamina are actually functions of properties of constituent fibers and matrix and their relative proportions and are determined either experimentally or using micromechanical relations. Therefore, in macromechanics of lamina, we would know subjected to a load what the response of a lamina is or subjected to stress what will be the strain, what is the constitutive relation what are the engineering constants, what are the different failure criteria etc for a lamina. But, even though the lamina is considered to be homogeneous, nevertheless, it is anisotropic and is treated as anisotropic in macromechanics of a lamina. Therefore, in macromechanics of a lamina, we shall also study briefly the anisotropic elasticity.

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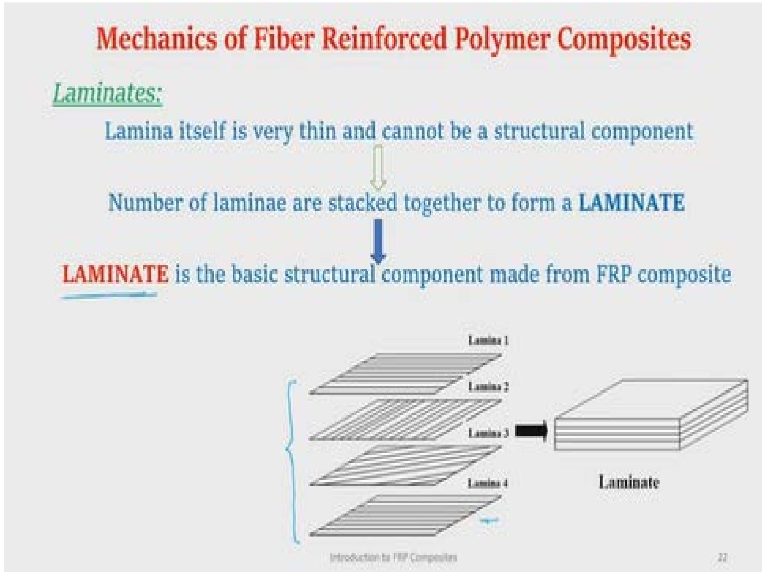


## Macromechanics of a Laminate

We understood that a lamina by itself is very thin and definitely cannot be a structural component by itself. Therefore, a large number of laminae are actually stacked together to form what is called a Laminate as shown in the figure. Actually the laminae are stacked one over the other and resins are supplied and is cured at a particular pressure and temperature to form a laminate. Thus, we get a laminate which is having the desired thickness, stiffness and strength. What kind of laminae, how many laminae and the sequence of stacking etc are decide by what is the required strength and stiffness of the laminate. Laminate is the basic structural component made from FRP composite.

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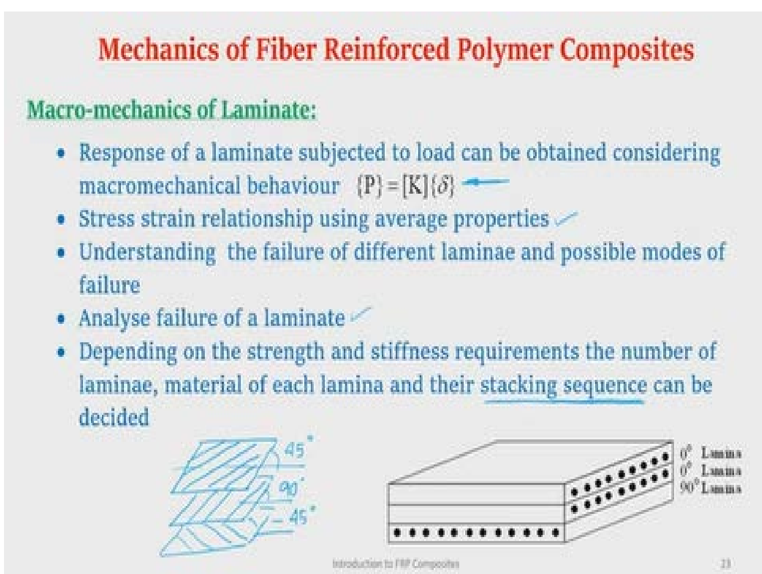

Since laminate is the basic structural component in FRP composite structures, it is important to understand the mechanics of a laminate to understand the behaviour of components made from FRP composites. Therefore, in macromechanics of laminates, we shall discuss the response of laminates subjected to load, constitutive relations, effective engineering properties of laminates etc.. Now, since a laminate is made form number of laminae stacked together, therefore, the response of a laminate subjected to loads will be decided by the behaviour of the constituent laminae or in other words, the stiffness and strengths of a laminate will be decided by the stiffness and strengths of the constituent laminae. Based on the macromechanics of lamina, macromechanics of laminates will be developed. Here each lamina is considered to be homogeneous and represented by its average providers that is why it is macro mechanical analysis of laminate.

As already discussed, depending upon the strength and stiffness requirements the number of lamina, material of each lamina and the stacking sequence in a laminate are decided. A laminate could have laminae with each lamina having fibers oriented in different directions. As shown in the figure, suppose, with respect to the global x-axis, successive laminae may have fibers oriented at say $0^\circ$, $90^\circ$, $+45^\circ$, $-45^\circ$, $-45^\circ$, $+45^\circ$, $90^\circ$, $0^\circ$. This is called stacking sequence and is written as $[0^o/90^o/+45^o/-45^o/-45^o/+45^o/90^o/0^o]$ and suppose each lamina is made of glass fiber and epoxy matrix, it is written as $[0^o/90^o/+45^o/-45^o/-45^o/+45^o/90^o/0^o]$ Glass/Epoxy.

A laminate is not necessarily always made from a single type of lamina like what is described above. Again depending upon the strength and stiffness requirements, it may be a single material laminate or a hybrid laminate. If the laminae are made from different materials like $[0^o{}_{Kev}/90^o{}_{Gr}/+45^o{}_{Gr}/-45^o{}_{Gr}/-45^o{}_{Gr}/+45^o{}_{Gr}/90^o{}_{Gr}/0^o{}_{Kev}]$, it is called inter-ply hybrid laminate. In some other cases, where, in a single lamina there are different types of fibers are used, it is called intra-ply hybrid laminate.

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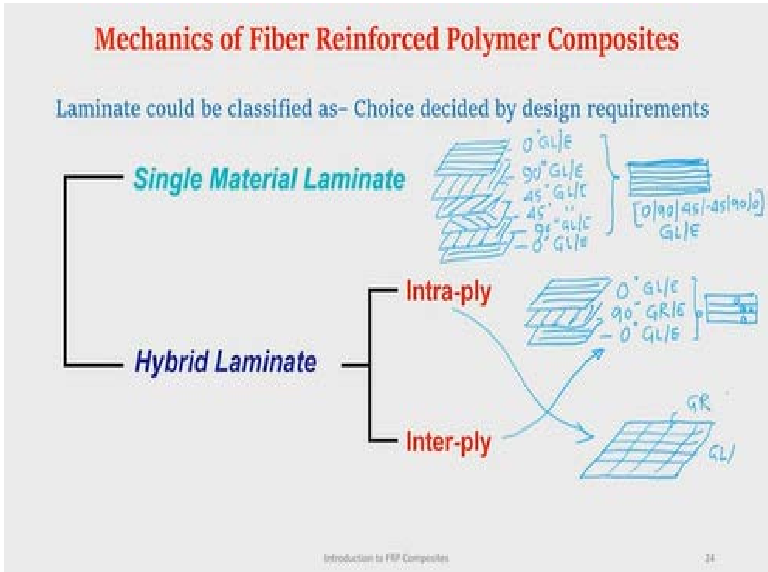


Again whether we will go for a single material laminate or whether we will choose a hybrid laminate is decided by what are the strength and stiffness requirements. For example, sometimes the outer layer of a laminate is actually provided with Kevlar to provide better resistance to impact.

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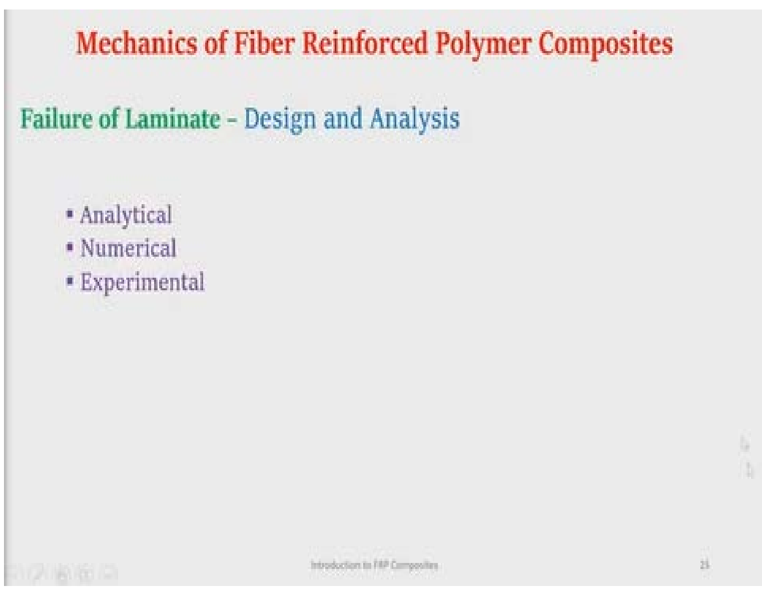


## <u>Failure of Laminate</u>

The stress relationships are obtained using the average properties then we try to understand the failure of different lamina and possible modes of failure. Now because the laminate consists of large number of lamina therefore behaviour of each lamina will actually decide the behaviour of the laminate and the failure of each lamina has to be understood to understand the failure of the laminate. In failure of laminate, we shall study how to estimate the failure load of a laminate by applying the failure criteria to individual lamina which we discussed in macromechanics of lamina. Here, we shall discuss in details the failure of laminates, and how to design and analyse a laminate. Again, there are several approaches to study the failure of laminates, it could be analytical, it could be numerical, it could be experimental. In analytical we use the knowledge of macromechanics and micromechanics of lamina along with principles of solid mechanics or elasticity are used to assess the failure of laminates. In experimental, the laminate is loaded following certain standards to obtain the failure loads. In numerical approach, finite element methods are extensively used to analyse the failure or the design of a particular laminate.

In today's lecture we understood different types of laminates and a brief introduction to the mechanics of FRP composites structures in general and the contents of this course in particular. We shall discuss all these in details in the respective modules.