Mechanics of Fiber Reinforced Polymer Composite Structures
Prof. Debabrata Chakraborty
Department of Mechanical Engineering
Indian Institute of Technology, Guwahati

Lecture - 01
Composite Materials - Introduction

Good afternoon. Welcome to the course of mechanics of fiber reinforced polymer composite structures. Today we will start module one, and today's is the first lecture. In module one, there will be two lectures.

(Refer Slide Time: 00:51)

FOCUS OF Module 1 (Lectures 1 and 2)

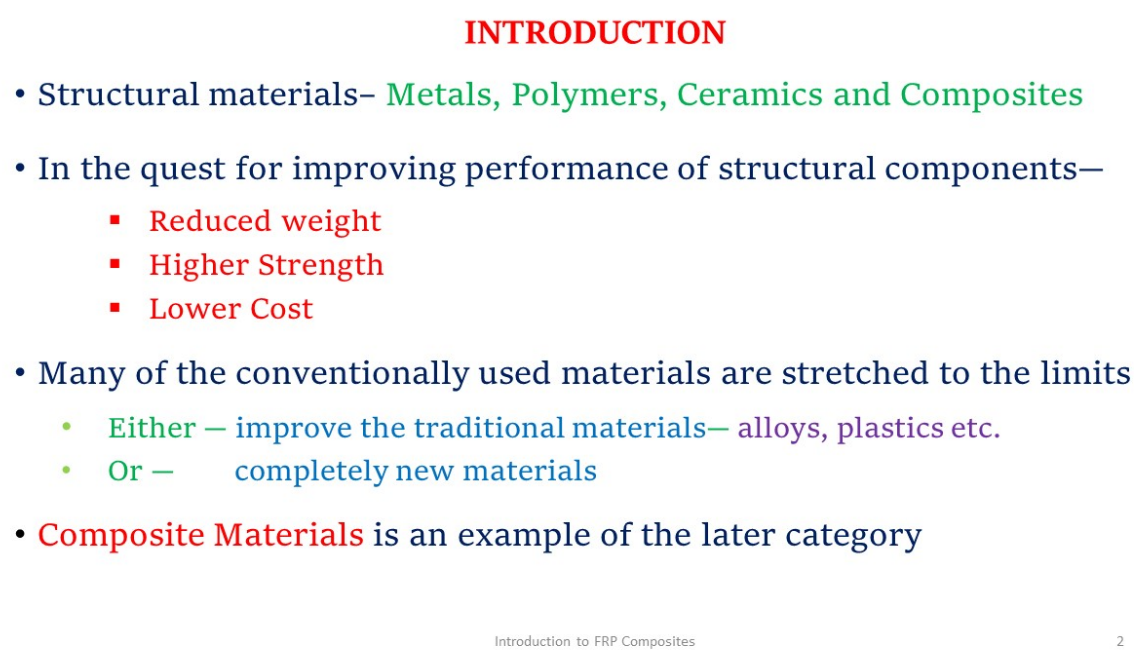
- What is Composites?
- Classifications, types, FRP Composites as structural components
- Important terminologies

Introduction to FRP Composites 1

Basically, the discussions in module one will be as follows. Even though, the course is actually on mechanics of fiber reinforced polymer composite structures, but first we will try to understand what a composite is in general, which is required for further understanding of the fiber reinforced polymer (FRP) composites. Then we will also discuss the classification, types of FRP composites as structural components and then we will try to understand the important terminologies which will be used throughout this course.

So, in the first lecture, mostly we will be discussing in general; what is a composite, what are its uses, its advantages and limitations. In the second lecture of this module, we will discuss different types of composites and FRP composites as well as different terminologies.

(Refer Slide Time: 01:50)

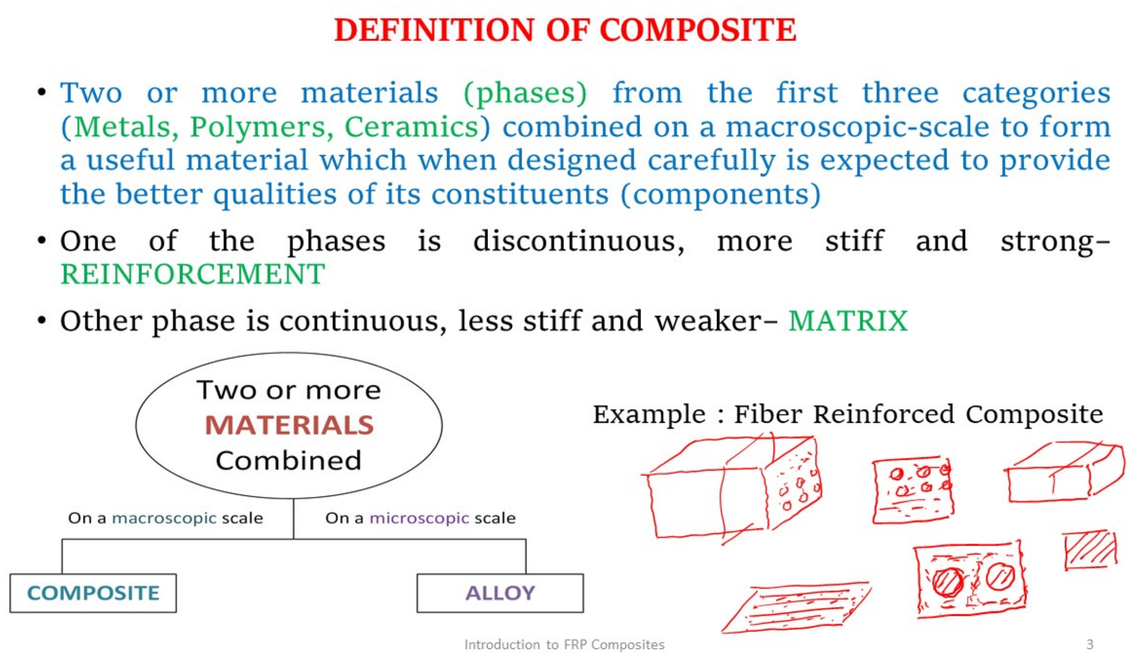


So, to start with, we know that the structural materials basically are classified as - metals, polymers, ceramics and composites. Now, we know that with the advancement of science and technology, the requirements of improved performance also increased. So, there has been quest for improving the performance of structural components also. For example, in many aerospace applications, we like to use materials so that the weight is minimized.

Then, in many load bearing applications, we would like to increase the strength, meaning, we want materials with higher strength. Of course, for all these cases, we always like to minimize the cost. Now, in doing so, what happens is that many of these conventionally used materials are actually stretched to their limits and there is hardly any scope of further improvement. So, how to achieve improved performances? There are two ways viz. either improve the traditional materials or think of a completely new material. Alloys of steels or aluminium are examples of the first approach where different alloying elements are used to steels to improve some of the properties. If this does not work, then the second approach that is a completely new material has to be thought of. This is where the composite materials come up meaning that the composite material is actually is an example of the second approach which comes under the new material.

So, why composite materials had to emerge? In the quest of improving performance of structural components, many of the conventionally used materials are actually stretched to their limits and therefore, the composite materials have come up with an objective of developing some new materials, so that some of the performances could be improved.

(Refer Slide Time: 03:50)



Therefore, with this background, let us first define what exactly a composite material is. Composite material is two or more materials or sometimes called phases which is taken from the first three categories of structural materials (already mentioned the four categories of structural materials) i.e. metal polymers and ceramics and are combined on a macroscopic scale to form a useful new material.

It is important to note that the constituent materials are combined in macroscopic scale to form a useful material, which when designed carefully is expected to provide the better qualities of its constituents. That means, two or more materials are mixed and combined macroscopically with an objective that it will give improved performances which none of the constituent materials could provide alone.

One of these two phases is discontinuous, relatively stiffer and stronger and is termed as **Reinforcement**. The other phase is continuous relatively less stiff and weaker, and is termed as **Matrix**. Which is called reinforcement phase? The one which actually enhances the strength or stiffness when added to another material is the reinforcement and is a discontinuous phase.

If two or more materials combined on a macroscopic scale to have certain desired properties, better than those of the individual constituent components is what a composite material is, then the natural question is whether an alloy is also a composite material? Answer is no. Because even though in alloy also we mix two or more materials, with an objective of getting certain desired properties, but they are actually mixed in microscopic scale and therefore, they are not termed as composite.

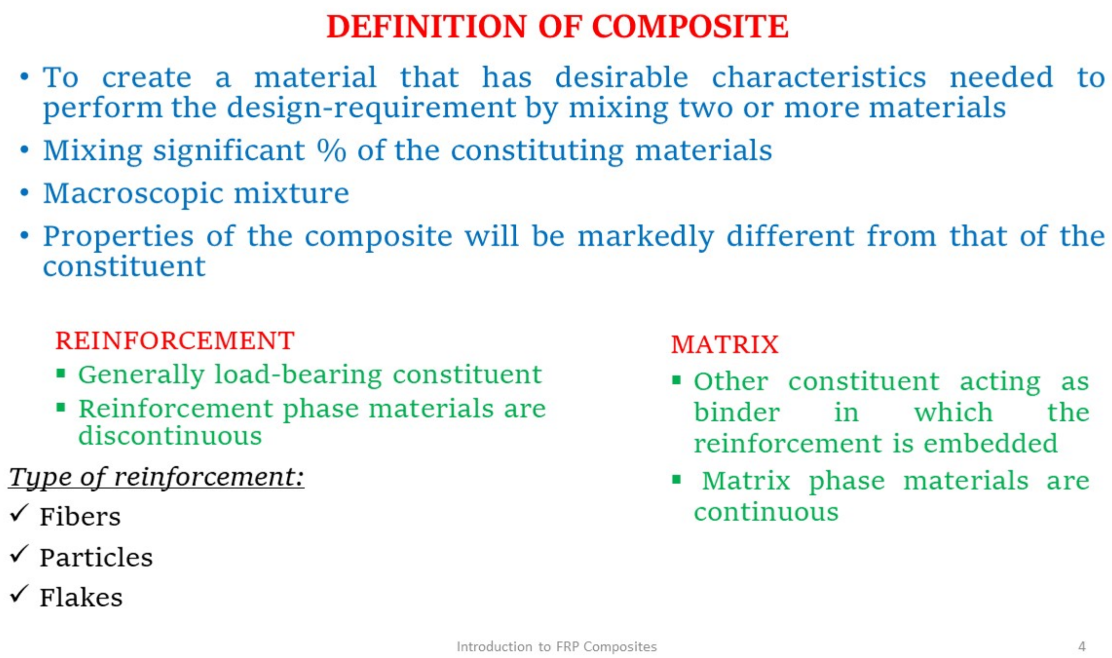
It is important to understand what is macroscopic and what is microscopic? We can understand this with a simple example of an RCC beam, where steel rods are mixed with concrete aggregates. As shown in Figure, if we take a cross section, we can clearly see with naked eye that there are different constituents. We can see the steel rods are distinctly different which are the reinforcement and we can see the aggregates. Of course, the aggregates also are made of more materials like it consists of sand, cement and stones, but for the time being let us assume that there are two constituents one is the reinforcement, which are the rods and other is the aggregates. So, if we take a cross section, with naked eye, we can actually clearly see the two distinct phases. So the rods and the aggregates are combined macroscopically.

FIGURE SHOWING RCC and ALLOY (Refer Slide Time 3:50)

On the other hand, suppose if we consider a bar made of alloy steel and take a cross section, we cannot make out with naked eye that it actually consists of more than one material, even though it consists of iron, carbon and other elements like manganese, maybe vanadium, etc. But we cannot make out until or unless we actually put a sample under microscope when we can see the distinct phases differently. Therefore, in an alloy, the constituents are combined microscopically and hence it is not a composite where the constituents need to be combined in the macroscopic scale.

A common example of composite is fiber reinforced composites, extensively used in aerospace applications, where glass or carbon fibers are actually mixed with polymeric matrix and they are used as a structural component as shown in the Figure where, the two distinct phases are the fiber (is the reinforcement) and the polymer (is the matrix). Now, let us see what do we mean by discontinuous and continuous? If we can see in this enlarged view of this figure, and if we look at only two fibers, and rest is matrix. So, these fibers are discontinuous phase because we cannot reach from one fiber to another directly without going through the matrix. But the matrix is continuous as we can reach from any point on the matrix to another point on the matrix without crossing a fiber. Therefore, it is a continuous phase.

(Refer Slide Time: 09:37)



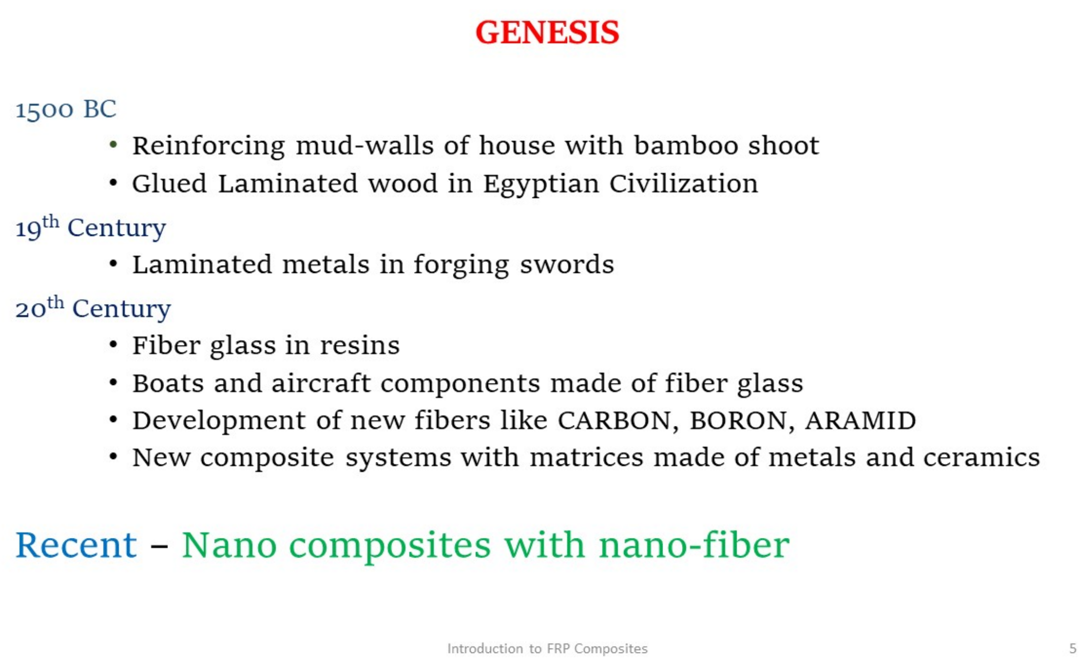
To understand what we mean by achieving desirable characteristics in a composite which is needed to perform the design requirement, for some functional requirements. Suppose, we want a component which should be very strong and at the same time it should be light. Now, we know that the metals are generally denser compared to say polymers. Therefore, weights of metals are much more compared to polymers, but at the same time they are far stronger compared to that of polymer.

Now, could we actually mix, say a strong material maybe in the fiber form with a polymer to obtain a material which is strong at the same time light? So, this is what we mean by mixing or combining two materials macroscopically to obtain certain desirable characteristics.

Another characteristic of a composite material is that the properties of the composite will be markedly different from that of the constituents. Say for example, in a polymer matrix reinforced by say carbon fiber, the Young's modulus of polymer matrix is generally in the range of 3 to 5 GPa, but the Young's modulus of the graphite fiber is of the order of 200 GPa. Therefore, if we mix them at a certain proportion say 40% graphite and 60% polymer then perhaps the Young's modulus of this composite will be around 180 GPa. So, there is a marked difference between the Young's modulus of the polymer and that of the final composite. On the other hand, in an alloy, the addition of carbide in carbide steel, the influence on the Young's modulus insignificant unlike in the case of composite, where there is a marked difference in the properties of the final composite. Then there is a characteristic of significant percentage of the constituents – say in fiber reinforced polymer matrix composites say, there will be 40% fiber and 60% polymer matrix or maybe 30% fiber and 60% polymer matrix. But the percentage of constituents in case of an alloy, say in an alloy steel there is 0.3% carbon, 0.04% of manganese etc. So, the percentage of these elements is insignificant, but on the other hand in a composite there is a significant percentage of the constituent material.

Therefore, to summarize, a composite will have actually a reinforcement phase which is generally the load bearing constituents and are discontinuous. On the other hand, the other phase, the matrix actually acts as a binder in which the reinforcements are actually embedded and the matrix phase is continuous. Now, the reinforcement could be of different shapes, though, most of the times we talk about fiber composites, the reinforcement may not be always fiber it could be particles leading to what is known as particulate composite or it could be flake leading to what is called flake composites.

(Refer Slide Time: 14:02)

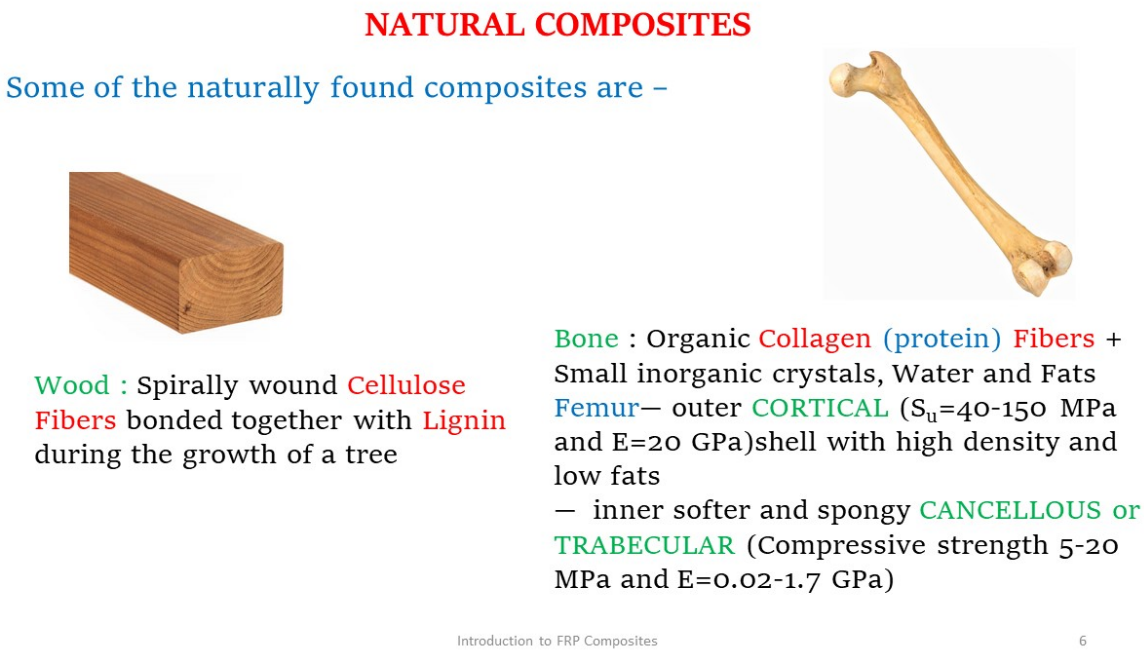


So, having understood the definition of composite materials, let us see the genesis of composite materials. Are composite materials really new? There have been traces of reinforcing mud-walls of house with bamboo shoots in BC. Even now also in some villages, there are huts where the walls are actually made of mud where there are bamboo shoots. Basically, the bamboo shoots are the load bearing members, the reinforcements and the mud actually acts as a binder, the matrix. So these forms of composites were there in BC.

And in the 19^{th} century, there are examples and traces of laminated swords used in war, made of laminated metals by forging. Then in the mid of the 20^{th} century first the fiberglass in resins were used for structural components. Boats and aircraft components were made of fiberglass and then in the latter part of the 20^{th} century actually the development of new and modern fibers like carbon fibers, boron fibers, aramid fibers have come up.

Then new composite systems with matrix made of metal as well as ceramics have been used in the latter part of 20^{th} century leading to what is known as metal matrix composites and ceramic matrix composites. Very recently, there are nano-composites where the nano-fibers are used. Again, the requirement is the nano fibers has been due to some improved performances as nano fibers are much stronger and stiffer compared to the conventional fibers and thus provide much better strength and stiffness to the composites.

(Refer Slide Time: 16:01)



In addition, there have been a number of examples of naturally available composites. A very good example is bone. Animal bone is actually made of organic collagen fibers (protein) and small inorganic crystals, water and fats. So, for example, if we look at the human femur, the outer cortical part is having an ultimate strength between 40 to 150 MPa and with a Young's modulus of 20 GPa. Inside this there is a much softer spongy cancellous or trabecular with a compressive strength of around 5 to 20 MPa and Young's modulus in the range of 0.02 to 1.7 GPa. So, naturally available composites are there. And these designs are of course, with certain objectives.

So, again there is another example of naturally available composite is wood. If we look at the cross section of a tree, we can see the spirally wound cellulose fibers bonded together with lignin matrix. This is formed during the growth of the tree and provides directional strength and stiffness of the wood. So, even though the idea of composite material has been new, maybe it has started from 20th century, but the composite materials have been there since much longer with traces even in BC and there has been naturally available composites also.

(Refer Slide Time: 17:56)

PROPERTIES TO BE IMPROVED

Some of the material properties particularly for load bearing member

- *Strength*
- *Stiffness*
- *Corrosion Resistance*
- *Wear Resistance*
- *Temperature Resistance*
- *Fatigue life*
- *Thermal Properties and so on...*

* It is neither possible nor it is required to improve all the properties in a single composite

Now, in the definition we discussed that two or more materials are actually combined macroscopically in order to have certain improved qualities or properties. Now, what are those improved properties?

From the structural point of view, for load bearing members many a times we want the strength to be very high i.e. the component to be stronger, maybe it has to withstand a very high load.

Then we want this to be stiffer, so that we may need to improve the stiffness.

Then depending upon if a particular component is actually in a corrosive environment, the material must have adequate corrosive resistance.

Then in case of components which are even in intimate contact say for gear teeth, wear resistance of the material is also important.

Then there are high temperature applications, where we want the material to be having a very high resistance to temperature.

Many structural components are actually subjected to fluctuating load and stress and therefore, it is important that their fatigue life is improved.

Similarly, there may be desired thermal properties like - coefficient thermal expansion, thermal conductivity.

Therefore, there are many such properties which need to be improved, but make sure that it is not possible to improve all the properties in a single composite and more importantly neither it is required. For a particular application, we may need one or two or three properties which need to be enhanced and accordingly we decide what should be the design of the composite material. For some other applications we may decide for certain specific mean properties we may go for design of a different composite material.

(Refer Slide Time: 19:39)

STRENGTH AND STIFFNESS OF TYPICAL REINFORCEMENTS

- Reinforcements are stronger materials
- Why we need matrix ?
  - * Brittleness
  - * Catastrophic failure
  - * Strength in bulk form is much less due to
    - ✓ Presence of flaws
    - ✓ Size effect

	ρ (kg/m³)	E (GPa)	σ_u (MPa)	E/ρ	σ_u/ρ
Graphite Fiber	1800	230	2067	0.1278	1.148
Steel	7800	206	648	0.026	0.08
UD GR/E	1600	181	1500	0.1131	0.937
Al	2600	69	276	0.026	0.101

Introduction to FRP Composites 8

Now, let us discuss some of the typical reinforcements. As we have already discussed that there are different types of reinforcements, it could be fibers, it could be particles etc. For example, in Table (in Slide) we have shown the density, Young's modulus and ultimate strength of graphite fibers, steel, graphite fiber reinforced polymer matrix composite and aluminium.

As we have already discussed, the reinforcements are far stronger and stiffer compared the matrix. For example, in this table if we could see that the graphite fiber has a Young's modulus of 230 GPa more or less of the same order compared to steel which has a Young's modulus of order of 200 GPa. While the Young's modulus of the graphite fiber and steel is almost same, but if we look at the strength, ultimate tensile strength of graphite fiber is almost three times that of the steel. As shown in the table, the strength of graphite fiber is 2000 MPa, whereas, that of a typical steel is

640 MPa. So, it is 3 times stronger. Similarly, the table also shows the properties for aluminium and unidirectional graphite/epoxy (where graphite fibers are actually mixed with polymer matrix to give graphite/epoxy).

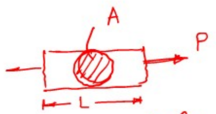
So, when a certain percentage the graphite fibers are mixed with epoxy (polymer) leading to graphite/epoxy, that also gives rise to a Young's modulus of 180 GPa which is comparable to that of steel, but the strength of graphite/epoxy is 1500 MPa which is almost 2.5 times that of steel. Therefore, even graphite/epoxy is still much stronger. Now, the natural question comes if the reinforcement, like the graphite fiber in this case is so strong and stiff, why it has to be in fiber form and mixed with matrix? Why not use this material in the bulk form? The reason is most of these reinforcements in bulk form is not that strong, and mostly they are brittle. Say, if we take glass fiber, it has a certain ultimate strength, but if we take a glass panel, the strength of the glass panel will be much lower compared to that of glass fiber.

The reason why these materials in the bulk form are much weaker is due to the presence of inherent flaws. Presence of flaws actually reduces the strength (Griffith's theory). So, the material in its bulk form will have more chances of having flaws in it. Second thing is that in its fiber form, because the fiber dimensions is of the order of microns, even if there are flaws, the size of the flaw will be much less compared to the flaws in the in the bulk form, which is called size effect. As shown in the figure, as the flaw size increases, the strength decreases. So, this is why these fibers which are very strong and stiff are actually mixed with matrix to form a composite with improved strength and stiffness. Fibers are very thin and slender and alone cannot make a structural component and they are mixed with the matrix to make the composites.

(Refer Slide Time: 23:37)

SPECIFIC STRENGTH AND SPECIFIC STIFFNESS

- Higher value of specific modulus (E/ρ) and specific strength (σ_u/ρ)– desirable in applications where weight reduction is important
- Higher the values of specific modulus, lower will be the weight for same stiffness– extremely important for transportation applications



$$\delta = \frac{PL}{AE}$$

$$\Rightarrow \delta = \frac{PL^2}{(A \cdot L) \cdot E} = \frac{P \cdot L^2}{V \cdot E} = \frac{PL^2}{\frac{m}{\rho} \cdot E}$$

$$\Rightarrow \delta = \frac{P \cdot L^2}{m \cdot \left(\frac{E}{\rho}\right)} \Rightarrow m = \frac{PL^2}{\delta \left(\frac{E}{\rho}\right)}$$

	ρ (kg/m³)	E (GPa)	σ_u (MPa)	E/ρ	σ_u/ρ
Graphite Fiber	1800	230	2067	0.1278	1.148
Steel	7800	206	648	0.026	0.08
UD GR/E	1600	181	1500	0.1131	0.937
Al	2600	69	276	0.026	0.101

Introduction to FRP Composites 9

Now, another important thing to be noticed from this table is that even though the Young's modulus of the graphite/epoxy composites (graphite fibers mixed with polymer matrix) is comparable to that of the steel, but then the density of graphite fiber is actually almost one fourth that of steel.

The density of the graphite/epoxy composites i.e. the polymer matrix composite with graphite fibers is also much less as could be seen from the Table (in Slide), it is almost 1/4.6 that of the steel. This leads to the definition of what is known as specific modulus, $\frac{E}{\rho}$ which is the ratio of Young's modulus and the density. So, what we could see is that even though the Young's modulus of the steel and this composite is almost comparable, but the specific modulus of the graphite/epoxy is almost, you know, 5 times more than of the steel.

Similarly, if we compare the strength, the specific strength $\frac{\sigma_u}{\rho}$ is defined as the ratio of the strength and the density. The strength of this composite is anyway almost 2.5 times that of steel and when it comes to specific strength it is almost 10 times that of the steel. Now, what does this specific modulus and specific strength signify? It translates to the fact that, in comparing two materials, higher the values of specific modulus, lower will be the weight for the same stiffness.

That means, suppose we have two components, one is made of steel and other is made of graphite/epoxy and we want to have the same stiffness in both of them. Then the weight of the component made from graphite epoxy will be almost five times less than that of the steel. We can take an example here to explain this.

Referring to the Figure (in Slide 9, slide time 23:27)

Suppose

A bar subjected to axial load P, the length of the bar is L, say the area of cross section is A;

We know , the deflection under axial load is, $\delta = \dfrac{PL}{AE}$

So, we can write this as $\delta = \dfrac{PL^2}{(A.L).E} = \dfrac{PL^2}{V.E}$

If m is the mass and ρ is the density of the material of the bar, $V = \dfrac{m}{\rho}$

Therefore, we can write, $\delta = \dfrac{PL^2}{m.\left(\dfrac{E}{\rho}\right)}$; $\dfrac{E}{\rho}$ is specific modulus

$$\Rightarrow m = \frac{PL^2}{\delta.\left(\dfrac{E}{\rho}\right)}$$

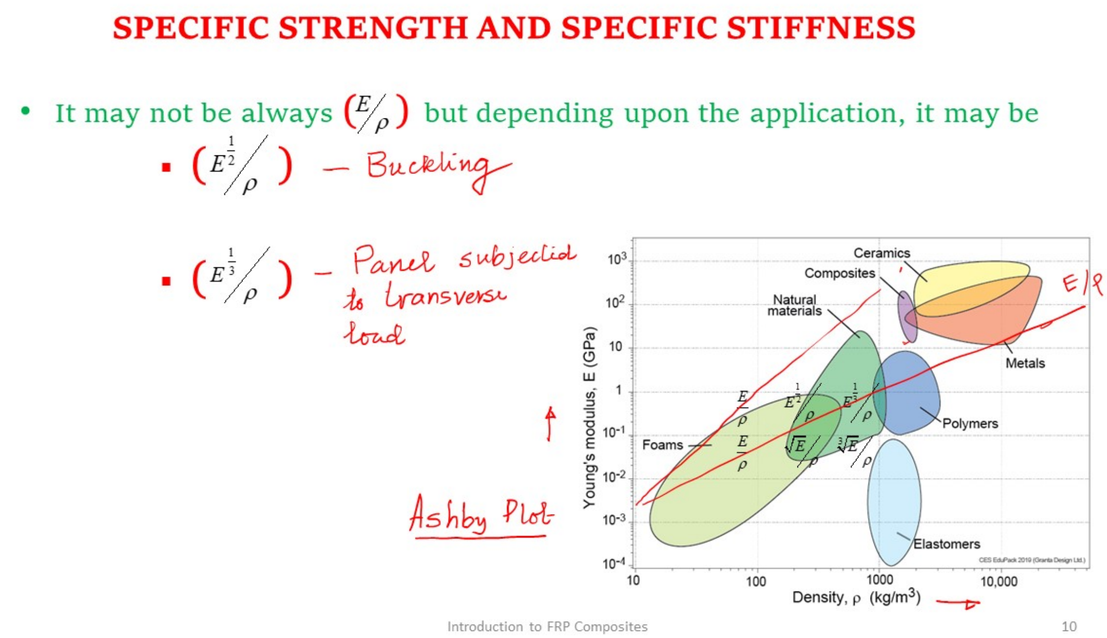
Therefore, between two materials, if $\dfrac{E}{\rho}$ in one material is twice that of the other then the required mass will be half for the same stiffness and for the same deflection. Therefore, more is the value of $\dfrac{E}{\rho}$, less is the weight. It has a tremendous implication especially in the transport sector.

For example, say in the case of an aircraft. Typically, the mass of say a big aircraft like Airbus 320 is around 40,000 kg. Suppose in an aircraft by some means, by changing the materials, if we can reduce the mass by 10% ie. reduce the weight by 10%. It is not that easy, but as an example, suppose the mass is 40,000 kg and by choosing some lighter materials, if we could reduce the mass by 10% or 4000kg. That means, this 4000 is the gain in the payload in the sense that, since we could reduce the mass by 4000 kg, we can actually add 4000 kg more in the aircraft. So, it has a tremendous economic implication as fuel savings.

The same is true for launching the satellites in rocket. If the payload could be increased, that leads to a direct savings in the economy of the whole program. So, this is what exactly the implication of higher specific modulus is. Therefore, a comparison is made with the specific modulus not with the modulus in case of composites. The higher the specific modulus of the material, the lighter will be the component.

Similarly, for same strength, the higher the specific strength, lighter will be the component.

(Refer Slide Time: 29:40)



Now, it may not be always $\frac{E}{\rho}$. We have taken the example of an axial loading and here it is $\frac{E}{\rho}$;

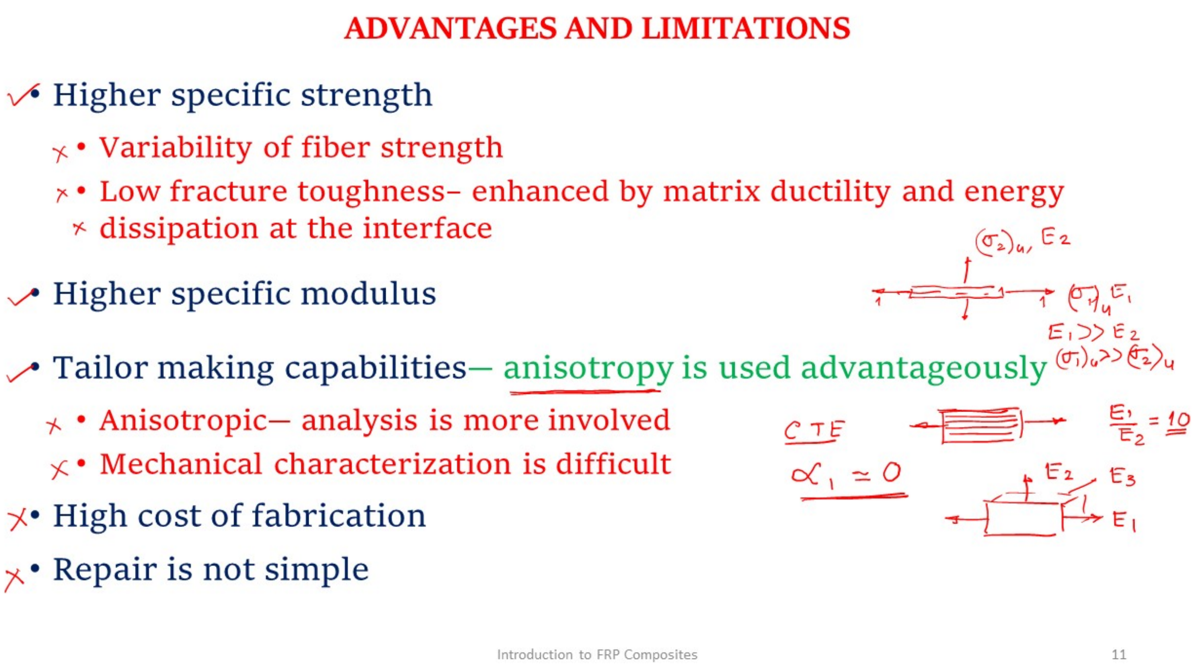
But, for example, in case of buckling, it is actually $\frac{\sqrt{E}}{\rho}$ because in buckling, it is a critical buckling load; which actually decides that what is the limiting condition and from there we could show that if $\frac{E^{1/2}}{\rho}$ is maximum that will lead to minimizing the mass.

Similarly, if we consider a panel subjected to transverse load, it is actually $\frac{\sqrt[3]{E}}{\rho}$, which decides that for the same deflection the mass will be minimum if $\frac{\sqrt[3]{E}}{\rho}$ is maximum.

Referring to the Ashby plot (we know this from our Machine Design course at UG) as shown in the figure, horizontal axis is density and the vertical axis is Young's modulus and we could see different types of materials right from very low density and very low strength to high density high strength.

We could see from this figure that as far as the strength goes, composites are almost in the same place with metals, but the density is much lower in the scale. Similarly, the ceramics and the polymer is in between. This plot is very useful in selecting materials depending upon the stiffness requirements. From constant $\frac{E}{\rho}$ line or constant $\frac{\sqrt{E}}{\rho}$ line or say constant $\frac{\sqrt[3]{E}}{\rho}$ line we could decide what material to be selected based on the functional requirement. Now having understood the definition of composite, let us discuss the advantages and limitations also.

(Refer Slide Time: 32:09)



We have already discussed some of the advantages like higher specific strength. Why it has higher specific strength? Because the reinforcements are far stronger. But because they are stronger, the variability in strength is much more compared to the conventional materials. So, the overall strength variability is more and is a disadvantage.

The fibers actually behave like brittle materials and therefore they have low fracture toughness. But when it is mixed with matrix, like - polymer matrix, the ductility of the matrix actually, enhances the fracture toughness sometimes by dissipation of energy.

Higher specific modulus compared to conventional materials leading to weight savings in the applications where weight minimization is important.

Besides all these, there is an important advantage of composites in the form of tailor making capabilities. That means we can actually tailor make the properties as per our requirements.

The fibers are actually anisotropic (direction dependent properties), that means the properties are actually direction dependent. For a typical fiber, the longitudinal (that means along its axis) strength and stiffness are far higher compared to those in the transverse direction. That is referring to the figure (Slide 11, Slide Time 32:09), $E_1 > E_2$.

Strength in direction 1 is also greater than strength in direction 2 i.e. $(\sigma_1)_u > (\sigma_2)_u$. This is anisotropy and this is used advantageously. Suppose we want a component which is supposed to take only axial load. Therefore, we will choose a fiber reinforced polymer composite, where the fibers are in the direction of the load and it can serve. But we do not require suppose the stiffness or strength in the other direction so high. Suppose we want our desired E_1 / E_2 is say is equal to 10. So, we can actually tailor make that by choosing the reinforcement and the matrix and the relative proportion. Another example of tailor making may be related to an important aspect is in space applications where some components may actually experience a temperature range between -90°C to 150°C. In that range of temperature, depending upon the coefficient of thermal expansion, there will be shape distortion and the dimensional stability will not be there. But with composites it is possible to choose the reinforcement and the matrix in such a way that the coefficient of thermal expansion in a particular direction may be made almost 0 and thereby actually reducing the dimensional instability.

These are advantages of anisotropy. But anisotropy also has limitations. The analysis in anisotropic materials is more involved compared to that in isotropic materials. Like, the analysis of a component made of steel is much simpler compared to the analysis of a composite which is made of anisotropic fibers and isotopic matrix.

Then mechanical characterization is difficult. For example, if we want to characterize a material say steel, we prepare a sample, load it in universal testing machine, and from one single test we can find out, the Young's modulus and the Poisson’s ratio and the rigidity modulus as a function of Young’s modulus and Poisson’s ratio.

But it is not that straight forward in the case of composites because it is anisotropic. That means in case of a component made of composites, Young’s modulus, Poisson’s ratio etc need to be found out in different directions. In addition, presence of inherent coupling (between different stresses like shear and normal) in anisotropic materials makes it further difficult for the mechanical characterization.

Then, components made from composites have high cost of fabrications. The manufacturing method is entirely different compared to that in conventional metallic materials and the cost of manufacturing is higher. But with mass production it is coming down.

Repair is not that simple, like in case of conventional metallic materials we can do welding. If there is a flaw it may not be that straight forward to repair a component made of such composite materials.

(Refer Slide Time: 37:59)

APPLICATIONS

- Aerospace–
  Wings, Fuselage, Radome, Antennae, Helicopter blades, Landing gears, Seats, Floors, Internal panels, Fuel tank, Nose cone,...
- Automobiles–
  Body panels, Bumpers, Leaf springs,...
- Boats
- Chemical– Pipes, Tanks, Pressure vessels,...
- Sports– Racquets, Diving boards, Helmets ,...

Introduction to FRP Composites 12

Why we are actually studying this course, what is the importance of this course. There are huge applications of composite materials, especially the fiber reinforced polymer composite materials.

Applications:

Aerospace: If we look at aerospace structures - wings, fuselage, Radome, antennae, helicopter and so on, so many components are actually made of composite materials and therefore, there are a huge weight saving in these aerospace structures.

Automobiles - body panels, bumpers, leaf springs there are many such components. Boats are also made of fiber glass.
In chemical industries - pipes, tanks, pressure vessels.
In sports - racquets, diving boards, helmets you know then hockey sticks many components of the sports equipment are actually made of composite materials.
(Refer Slide Time: 38:52)

SUMMARY

- Composites— Consists of two or more materials
  - Reinforcement and Matrix phase
  - Markedly improved properties compared to the constituents
  - Naturally available composites— Wood, Bone etc.
  - Some synthetic composites were in use for more than 1000 years
  - Major development in man made composites last 50/60 years
  - Extensively used especially in aerospace and automobile applications

In this lecture, we understood what is a composite material? It consists of two or more materials actually mixed in macroscopic scale with an objective of achieving improved properties or desirable properties, markedly improved compared to that of the constituents.
Even though the composite materials have been there for maybe for last six or seven decades but the traces have been there since long time. Even there are naturally available composites like wood, bone etc. Synthetic composites were there in use for more than thousand years, there have been traces in earlier civilizations. However, the major development of composites has come in last 50-

60 years and these are extensively used for aerospace and automobile applications. Nowadays, of course there are even daily use materials also made of composites.

We also understood what the need for such composites is. So, in the next lecture, we will discuss the detailed classification of composites and fiber reinforced composites in particular and important terminologies.