**Retrofitting and Rehabilitation of Civil Infrastructure**
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**Indian Institute of Technology Kharagpur**
**Lecture 19**
# Properties of Fibers, Resins and FRP Composite

Hello friends, welcome to the NPTEL online certification course Retrofitting and Rehabilitation of Civil Infrastructure. Today we will discuss module D. The topic for Module D is Fiber Reinforced Polymer Composites and its Characteristics.

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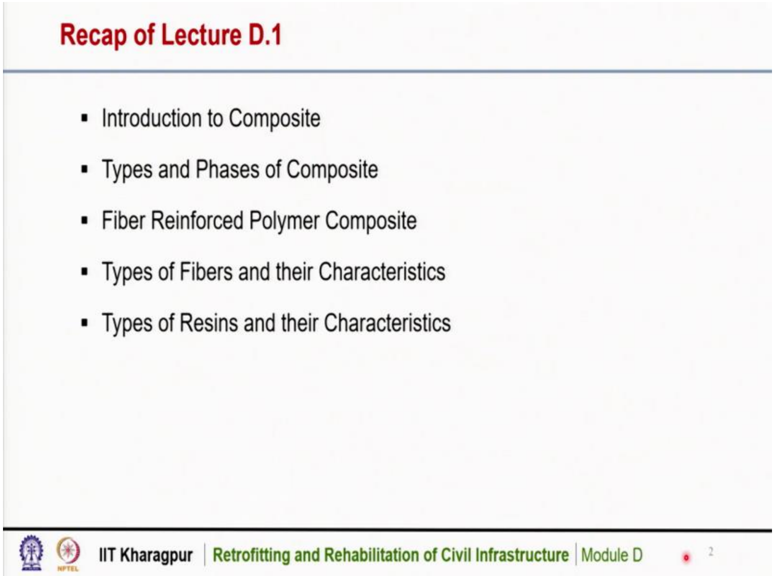


In the previous lecture, we have given an introduction to composites, the types and phases of composites, the two main phases that is the fiber phase and the matrix phase that we have discussed. The concept of fiber reinforced polymer composite has been discussed. And the different types of fibers and resins and their characteristics have been discussed in the previous lecture.

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In today's lecture, we will discuss the properties of fibers and resins, the stress-strain relationships and the properties of FRPC and Stress-Strain relationships. The advantages and limitations of FRPCs will also be discussed and its application in various fields and industries will be discussed in today's lecture.

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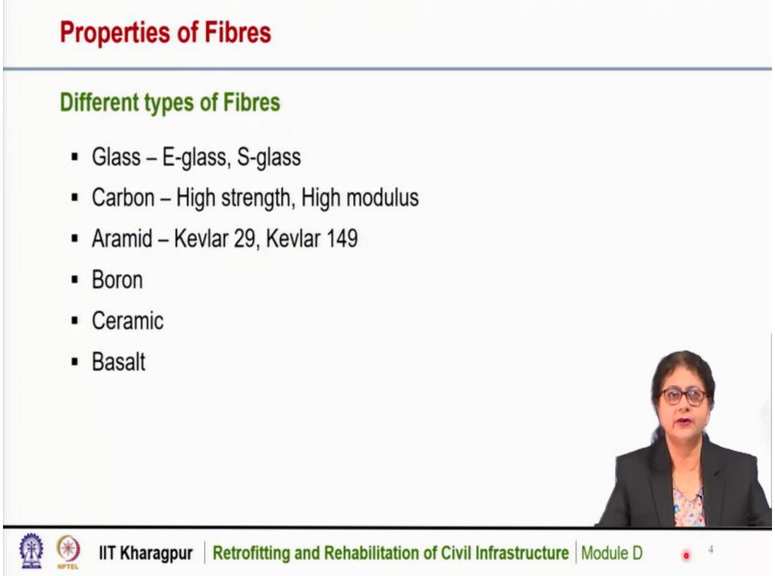


There are different types of fibers that has been mentioned in the previous lecture, glass fibers, carbon fibers, aramid fibers, ceramic fibers, etcetera are there. And they are of different types like E-glass fiber, or S-glass fiber, etcetera. So, they have different properties. And now, we will discuss the properties of the different types of fibers.

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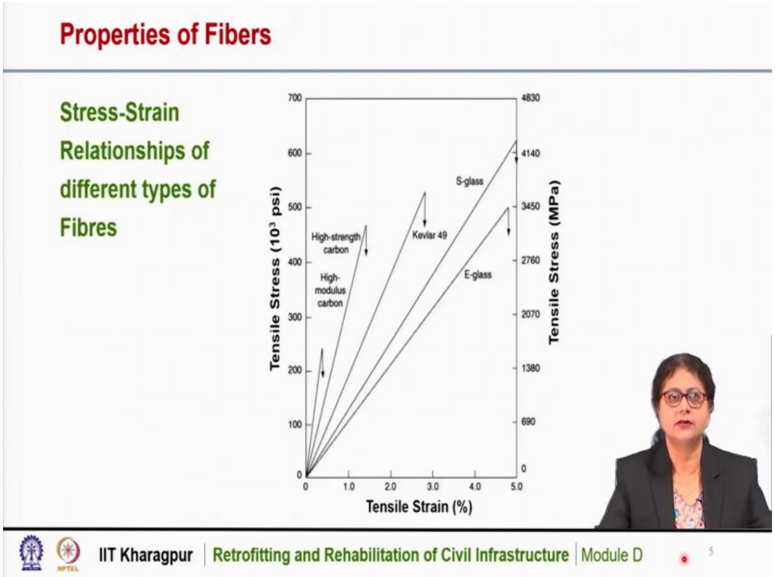


This is the stress-strain relationships of different types of fibers. The tensile stresses are plotted with respect to tensile strain. The variation of stress and strain are plotted for different types of fibers we can see here, the glass fibers, Kevlar fibers, carbon fibers are there. All these fibers have very high tensile strength as we can see here, the tensile strength is high for all types of fibers and the variation is linear.

Glass fibers have significant strain also, glass fibers have significant tensile strain before it fails. As compared to carbon fibers and Kevlar fibers, they have larger strain at failure. Carbon fibers have high strength and high modulus as we can see here the variation of stress-strain of carbon fibers are shown here, the strength is significantly high, but it is strain at failure is low as compared to glass fibers. The relationship for Kevlar fiber is somewhat in between glass fiber and carbon fiber.

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## Properties of Fibers

### Approximate Properties of different types of Fibers

| Fibre | | Typical diameter (μm) | Specific gravity | Tensile modulus (GPa) | Tensile strength (GPa) | Ultimate elongation (%) | Coefficient of thermal expansion ($10^{-6}$/ºC) |
|---|---|---|---|---|---|---|---|
| Glass | E-glass | 10 | 2.54 | 72.4 | 3.45 | 4.8 | 5.0 |
| | S-glass | 10 | 2.49 | 86.9 | 4.30 | 5.7 | 2.9 |
| Aramid | Kevlar 49 | 11.9 | 1.45 | 131 | 3.62 | 2.8 | -2.2 |
| | Kevlar 149 | 11.9 | 1.47 | 179 | 3.45 | 1.9 | |
| Carbon | T-300 | 7 | 1.76 | 231 | 3.65 | 1.4 | -0.55 |
| | | 8 | 1.80 | 395 | 2.48 | 0.7 | |
| | | 10 | 2.15 | 758 | 2.45 | 0.32 | |
| Boron | | - | 0.93 | 400 | 3.4 | - | - |

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These are the approximate properties of different types of fibers, glass fibers, aramid fibers, carbon fibers and boron fibers have been shown here. The typical diameter varies from 7 to 12 microns and the specific gravities are also shown. The tensile modulus, the maximum tensile strength, the ultimate elongation and the coefficient of thermal expansion of different types of fibers are given here.

These are the approximate properties; it depends on the volume of fiber. Glass fibers have comparatively higher specific gravity as compared to Kevlar fiber and carbon fibers. Carbon fibers are lighter than the glass fibers. The tensile modulus of carbon fibers is higher as compared to other types of fibers and also the tensile strength. However, the ultimate elongation or the strains are higher for glass fibers as we can also see in the diagram and this is advantageous for glass fibers.

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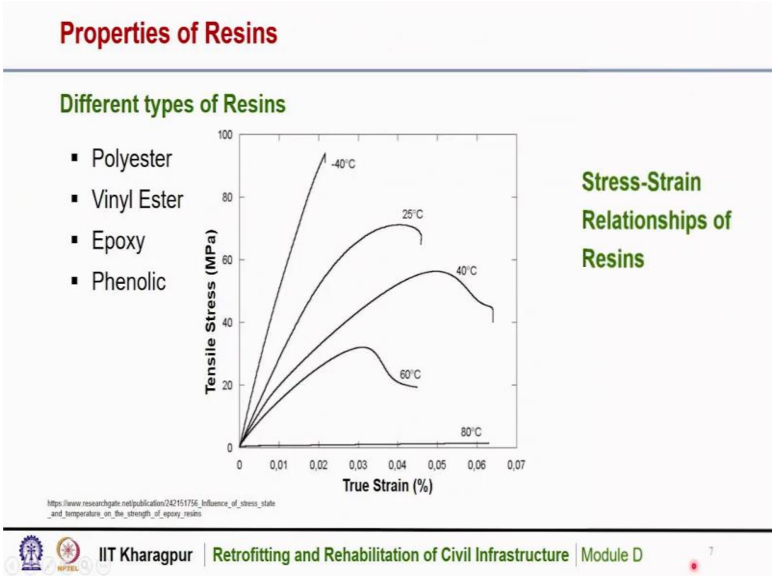


There are different types of thermoset resins as we have mentioned in the previous lecture. Polyester resin, vinyl ester resin, epoxy resin and phenolic resins are the types of resins. These are the stress-strain relationships of resins. The resins are very much susceptible to temperature. The strength depends significantly on temperature, as we can see here, if the temperature increases the strength of resin decreases significantly. It has high strain before it fails.

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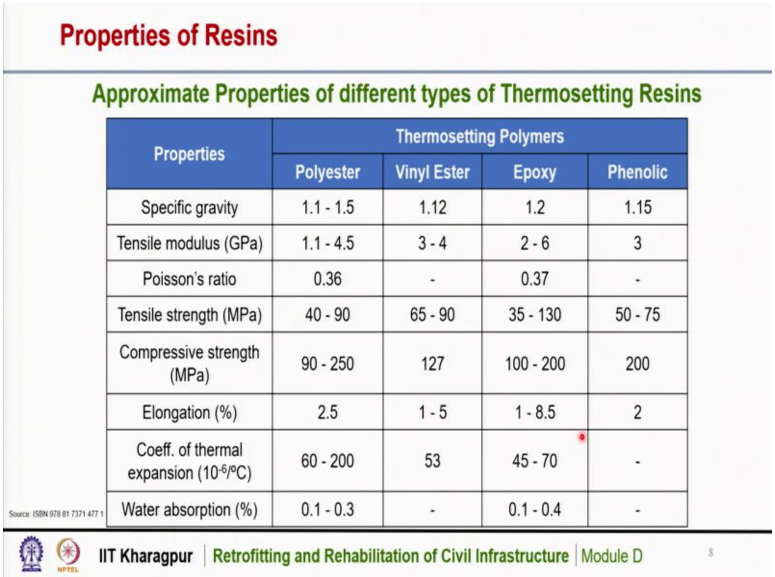
Properties of Resins

Approximate Properties of different types of Thermosetting Resins

| Properties | Thermosetting Polymers | | | |
|---|---|---|---|---|
| | Polyester | Vinyl Ester | Epoxy | Phenolic |
| Specific gravity | 1.1 - 1.5 | 1.12 | 1.2 | 1.15 |
| Tensile modulus (GPa) | 1.1 - 4.5 | 3 - 4 | 2 - 6 | 3 |
| Poisson's ratio | 0.36 | - | 0.37 | - |
| Tensile strength (MPa) | 40 - 90 | 65 - 90 | 35 - 130 | 50 - 75 |
| Compressive strength (MPa) | 90 - 250 | 127 | 100 - 200 | 200 |
| Elongation (%) | 2.5 | 1 - 5 | 1 - 8.5 | 2 |
| Coeff. of thermal expansion ($10^{-6}/^oC$) | 60 - 200 | 53 | 45 - 70 | - |
| Water absorption (%) | 0.1 - 0.3 | - | 0.1 - 0.4 | - |

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These are the approximate properties of different types of thermosetting resins. The specific gravity, tensile modulus, tensile strength, elongation, etcetera are given here for different types of thermosetting polymers. The polyester resin, vinyl ester resin, epoxy resin and phenolic resins are given here. So, as we can see here the tensile modulus and the tensile strength are much lower as compared to the fiber strength.

The elongation is however, significantly high as we can see here. So, it elongates before its failure. The coefficient of thermal expansion for all types of resins are significantly high that shows its susceptibility to temperature.

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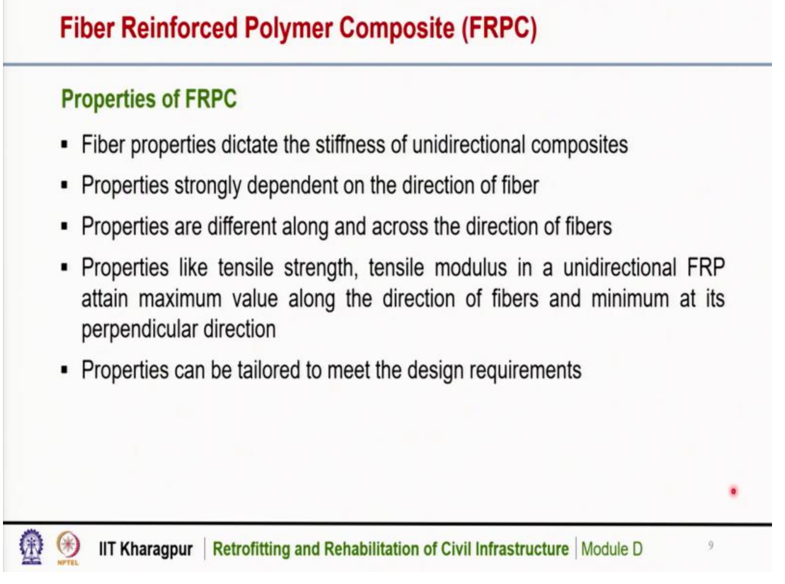


Now, the properties of fiber reinforced polymer composite depend significantly on the properties of its ingredients, it is mainly the fiber that dictates the stiffness of the unidirectional composites. The properties of FRPCs depends strongly on the direction of the fiber, also on the amount of the fiber. The properties are different along and across the direction of the fibers.

So, the properties of fiber reinforced polymer composite depend significantly on the amount of fiber, the orientation of the fiber and also on the type of fiber. The properties like tensile strength, tensile modulus in a unidirectional FRP attain maximum value along the direction of the fibers and minimum at its perpendicular direction.

The advantage of composite material is that we can tailor the properties as per our requirements. So, this is an important consideration for FRP composites, and that gives its wide application in various industries.

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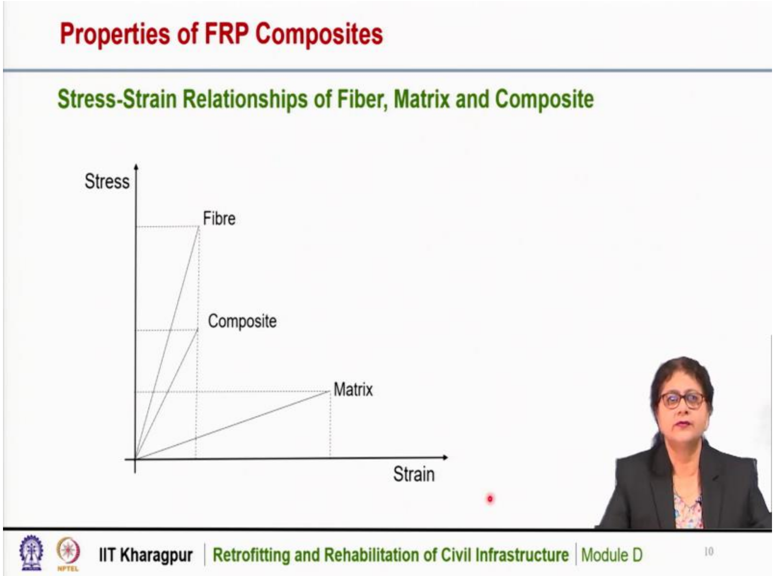


This is the schematic diagram of stress-strain relationship of fiber matrix and composite. As we can see here, that the fiber has the maximum strength and the highest stiffness. The matrix has much lower strength as compared to fibers. However, its elongation before failure is higher. Composite properties are in between fiber and matrix. So, the properties of composite depend significantly on the properties of the fibers.

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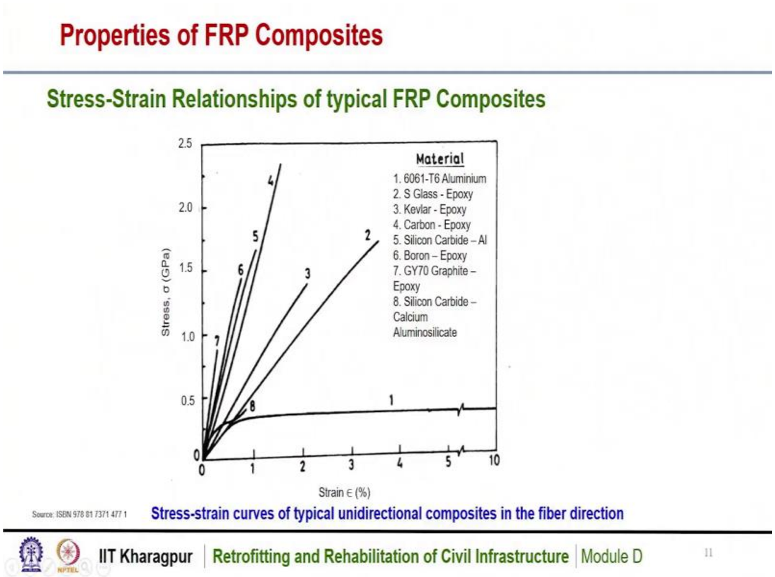


This is the stress-strain relationships of typical FRP composites, there are different types of composites as shown here in this diagram, and also the stress-strain relationship of one alloy that is aluminium alloy T6 aluminium 6061, is plotted and also the stress-strain relationship of different FRP composites are also plotted.

So, the composites that are used here S-glass epoxy, Kevlar epoxy, carbon epoxy, silicon carbide aluminium composite, boron epoxy composite, graphite epoxy composite, silicon carbide and calcium alumina silicate composite. So, these are the different types of composites. As we can see here, the strength of composite is significantly high as compared to the aluminium alloy.

The carbon fibers, you can see here this is the carbon fiber composite, carbon fiber epoxy composite has the highest strength and this graphite fiber has the highest stiffness. This is the graphite fiber has the highest stiffness. So, the properties of composite depend significantly on the type of fiber and its amount. The properties are superior in general as compared to the normal alloys.

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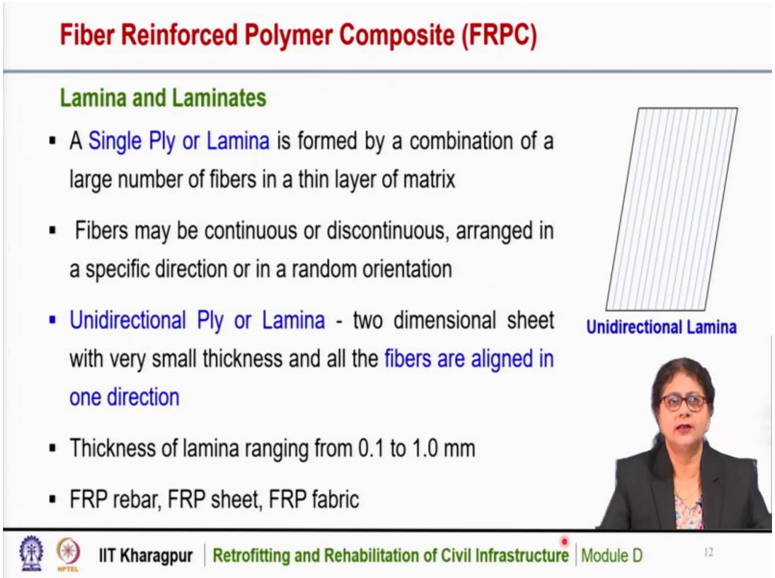


Now, we will discuss the lamina and laminates. For discussing the properties of FRP composites, it is important to understand the lamina and the laminate. A single ply or lamina is formed by a combination of a large number of fibers in a thin layer of matrix. So, a lamina is a single ply that is formed by the combination of a large number of fibers and they are placed in a thin layer of matrix, it is like a sheet, a two-dimensional sheet.

Fibers in the lamina may be continuous or discontinuous, they may be arranged in a specific direction or in a random orientation. A unidirectional ply or unidirectional lamina is such that it has fibers aligned in one direction only. So, the unidirectional lamina is a two-dimensional sheet with very small thickness and all the fibers are aligned in one direction.

So, this is a schematic diagram of a unidirectional lamina and these are the fibers and they are aligned in one direction only. The thickness of the lamina is very small ranging from 0.1 to 1 millimetre. FRP sheet or FRP fabric or even FRP rebar can be considered as a lamina, FRP lamina.

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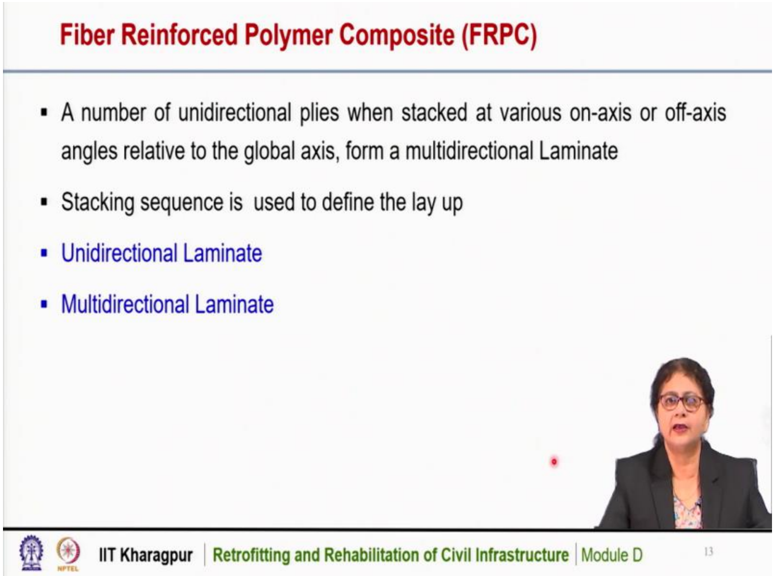


Now, when a number of unidirectional plies are stacked at various on-axes or off-axis angles relative to the global axis that forms a multi-directional laminate, so a laminate consists of a number of lamina and those laminas have fibers and they may be of different direction. Each lamina are stacked in sequence and the stacking sequence governs the properties of the laminate. Based on the direction of the fibers, the laminate can be of unidirectional or multi-directional.

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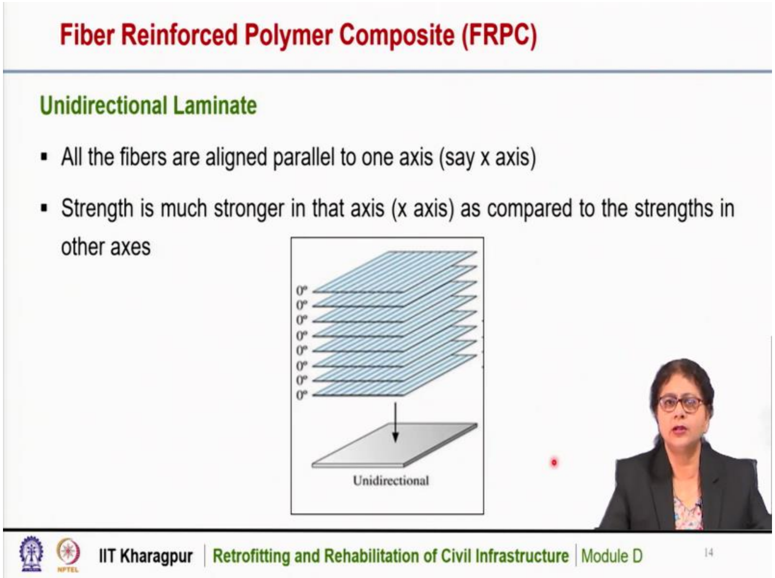


In unidirectional laminate, all the fibers are aligned parallel to one axis, say x axis. And the strength is much stronger in that axis as compared to the strength in other axes. So, here you can see that, this is a schematic diagram of a unidirectional laminate, this is the unidirectional laminate which is consisting of so many lamina, unidirectional laminates and in each of these laminate the fibers are oriented along the length of the laminate.

So, they are arranged at 0 degree as you can see, the fibers are oriented at an angle of 0 degree along the length of the laminate and all laminas are similar. So, this forms the unidirectional laminate and in unidirectional laminate, the strength along the axis where the fibers are oriented is much stronger as compared to the other directions.

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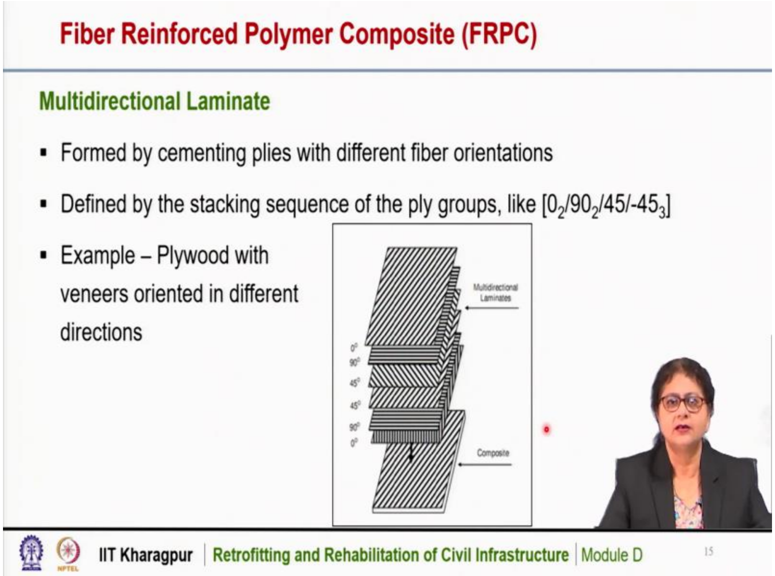


In case of multi-directional laminate, the fibers in each lamina may be of different orientation. It is formed by a number of laminas and those laminas are placed or stacked with each other and it is defined by the stacking sequence of the ply groups. So, here you can see that this is a multi-directional laminate, this is the multi directional laminate, which is consisting of different unidirectional laminas.

And in each of these unidirectional lamina, the fibers are oriented at different angles. So, here we can see that at the bottom most lamina the fibers are oriented at 0 degree. Next to that, the fibers are oriented at 90 degrees. Next to that, it is oriented at 45 degree. The next one is also at 45 degree but a reverse angle, like this. So, the stacking sequence can be represented like this 0 degree, there may be 2 or 90 degree there may be 2 like that plus 45, minus 45 like that.

So, example of multi-directional laminate is plywood with veneers oriented in different directions. So, this type of multi-directional laminate has strength in other axis as well not that only in one direction, but other direction also the strength is significant. As per the requirement we can place the unidirectional laminas in the laminate.

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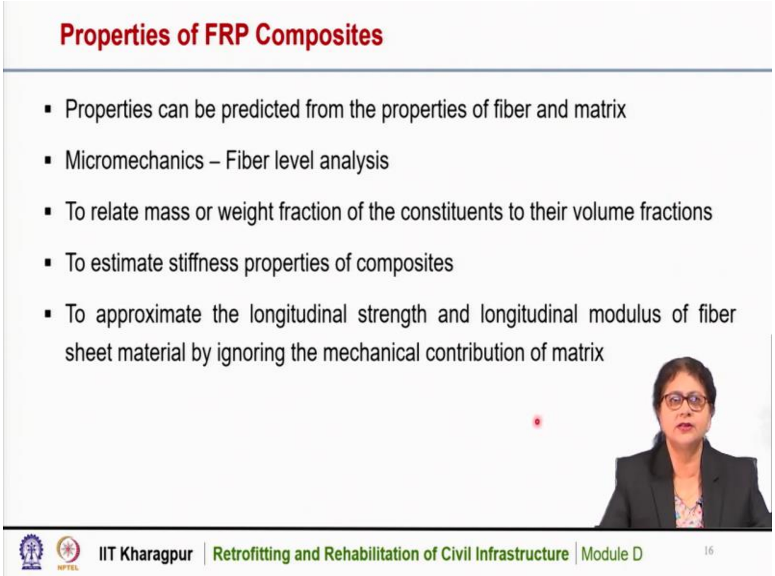


Now, in case of FRP composites, the properties are predicted from the properties of the fiber and the matrix. The properties can be estimated from the fiber level or from the lamina level or from the laminate level or from the full section level. When it is done with fiber level analysis, it is termed as micromechanics that we will discuss in subsequent lectures. In fiber level analysis, it is aim to relate the mass or weight fraction of the constituents to their volume fractions.

That is done to estimate the stiffness properties of the composite, because we can estimate the stiffness properties of the composite, the elastic modulus in different directions that can be estimated by knowing the fiber volume fraction and their weight fractions, to approximate the longitudinal strength and longitudinal modulus of fiber sheet material by ignoring the mechanical contribution of matrix. So, this is done to determine the properties of FRP composites.

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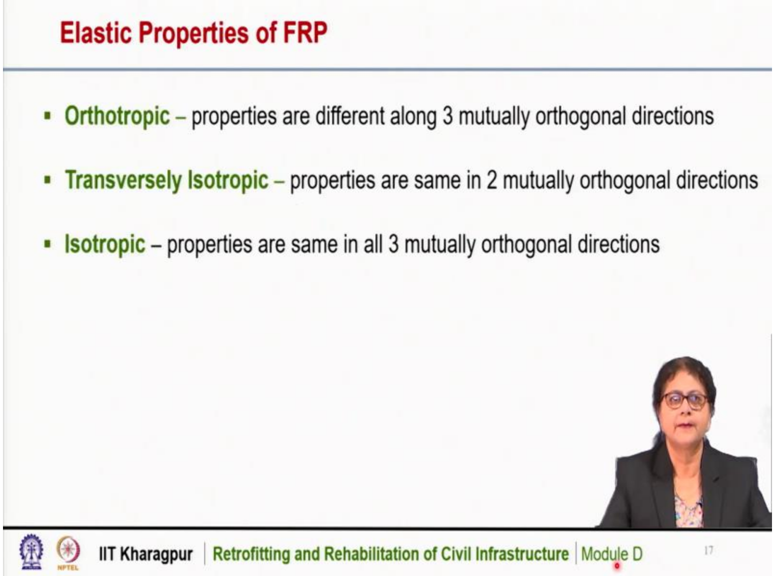


Now, to understand the properties of FRP composite, we have mentioned that fibers play a significant role in determining the properties of FRP. The fibers may be oriented in different directions and based on its orientation, the properties are different. Now, the composite materials are not similar as the normal conventional materials like concrete or steel, where we have properties uniform and same in all directions.

So, in case of metals, they are mostly isotropic materials, where the properties are same in all three mutually orthogonal directions. However, in case of composites, it depends on the orientation of the fibers. And based on the orientation of the fibers, it may be orthotropic or transversely isotropic material.

In case of orthotropic, the properties are different along 3 mutually orthogonal directions. And in case of transversely isotropic the properties are same in 2 mutually orthogonal directions. So, in composite depending on the orientation of the fibers, the FRP composite may be orthotropic or transversely isotropic.

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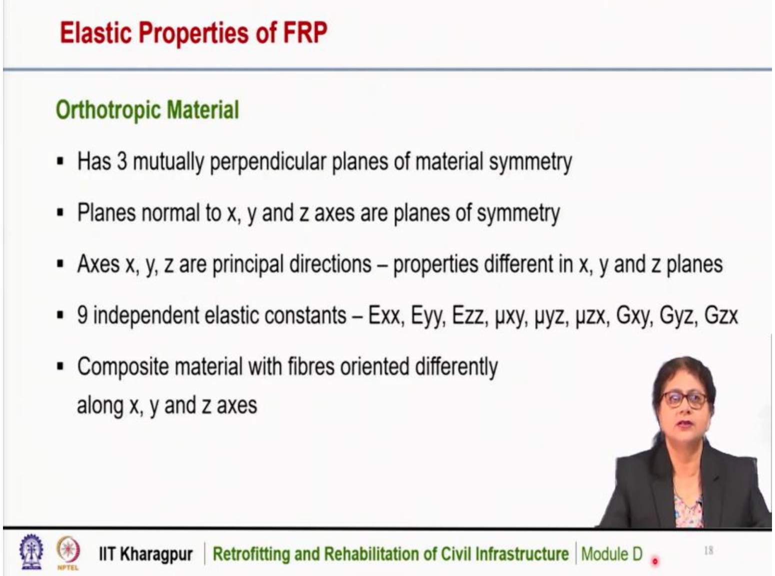


In orthotropic material, it has three mutually perpendicular planes of material symmetry. The planes are normal to x, y, and z axes and are the planes of symmetry. The axis x, y, z are the principal directions and thus the properties are different in x, y, and z planes. So, in case of orthotropic material, the three orthogonal planes say x, y, and z they are the planes of symmetry and they are the principal directions.

So, properties are different in these three orthogonal planes. The orthotropic material has 9 independent elastic constants. So, in each plane the properties are different, we have different elastic modulus, we have different Poisson's ratio and shear modulus. So, an orthotropic material has 9 independent elastic constant $E_{xx}$, $E_{yy}$, $E_{zz}$, E is the elastic modulus and x y and z subscripts denote the planes.

Similarly, we have three Poisson's ratio $\mu_{xy}$, $\mu_{yz}$, $\mu_{zx}$, and three shear modulus. The composite materials with fibers oriented differently along x, y, and z axes behave as an orthotropic material.

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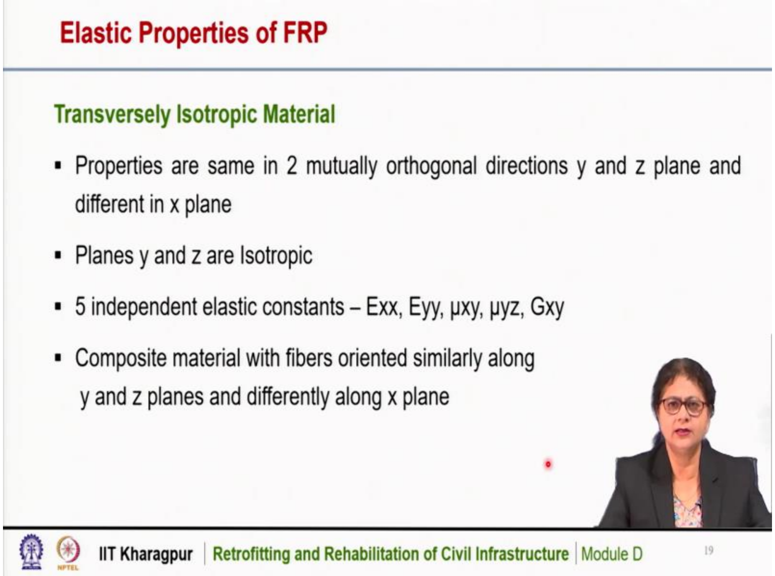


In case of transversely isotropic material, the properties are same in 2 mutually orthogonal directions say y and z plane and different in x plane. So, in case of an orthotropic material, the properties are different in three different planes, three different orthogonal planes. Here it is simplified to transversely isotropic material, but the properties are same in 2 orthogonal directions, but different in one direction.

So, planes y and z are considered as isotropic because they are similar. So, we have 5 independent elastic constants because the two planes y and z are similar. So, we have from 9 elastic constants we have 5 independent elastic constants. Other constants are there, but they are dependent.

So, we have 5 independent elastic constants $E_{xx}$, $E_{yy}$, $\mu_{xy}$, $\mu_{yz}$, and $G_{xy}$ , that is the elastic constant the poisons ratio and the shear modulus. The composite material with fibers oriented similarly, along y and z planes and differently along x plane behaves as an transversely isotropic material.

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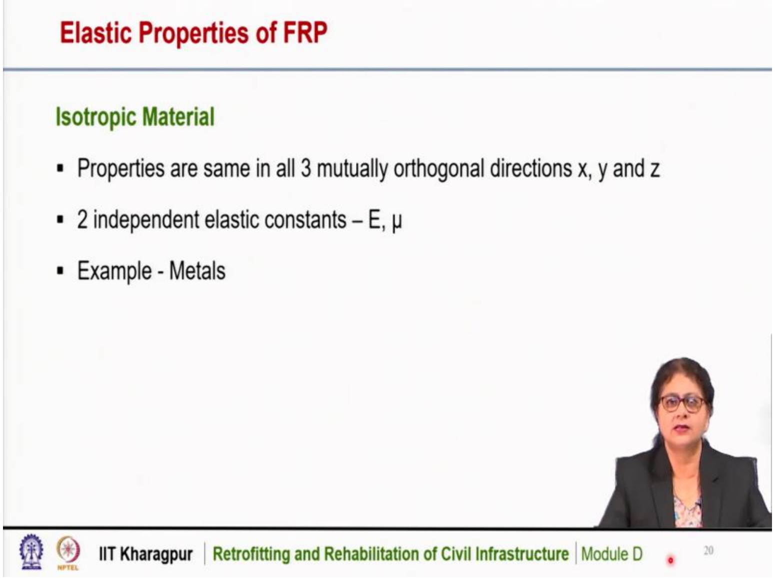


In case of isotropic material, the properties are same in all three mutually orthogonal directions x, y, and z. So, we have 2 independent elastic constants for isotropic material, which is the elastic modulus and the poisons ratio, and they are the same in all 3 mutually orthogonal directions. Generally, all metals are isotropic in nature and composites are generally either orthotropic or transversely isotropic material.

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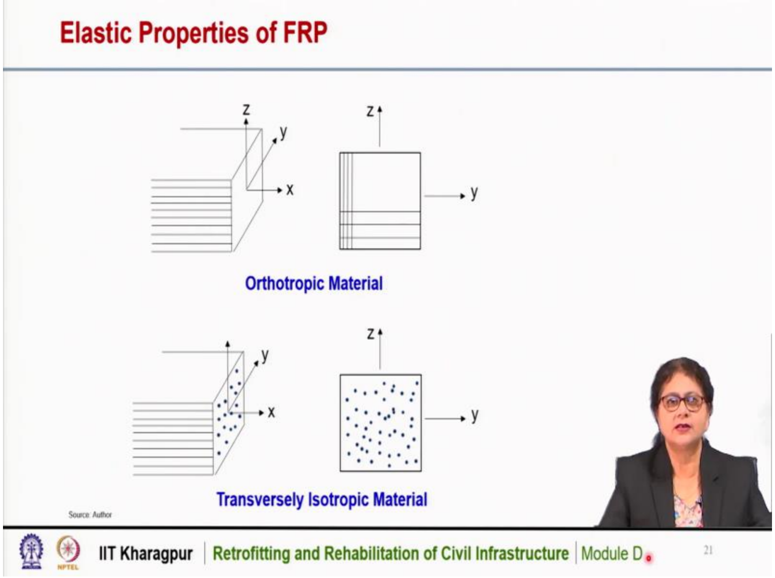


These are the schematic diagrams of orthotropic material and transversely isotropic material. We can see here this is a orthotropic material and these are the fibers, these lines represent the fibers in the x direction, in y direction also there are fibers, but they are different and in z direction also, they may be different.

So, the properties are different in three orthogonal planes x, y and z whereas, in case of transversely isotropic material the planes y and z are similar and it is different from the x plane. So, here we can see that the fibers are oriented along the x direction, whereas, in y and z it is the same. So, this is the cross section of the y-z plane and it is similar. So, this is transversely isotropic material whereas, this is the orthotropic material.

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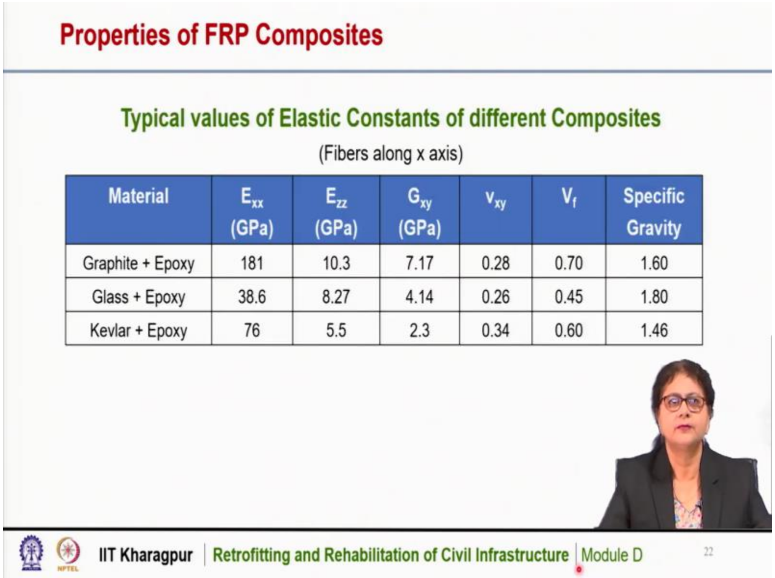


| Material | $E_{xx}$ (GPa) | $E_{zz}$ (GPa) | $G_{xy}$ (GPa) | $\nu_{xy}$ | $V_f$ | Specific Gravity |
|---|---|---|---|---|---|---|
| Graphite + Epoxy | 181 | 10.3 | 7.17 | 0.28 | 0.70 | 1.60 |
| Glass + Epoxy | 38.6 | 8.27 | 4.14 | 0.26 | 0.45 | 1.80 |
| Kevlar + Epoxy | 76 | 5.5 | 2.3 | 0.34 | 0.60 | 1.46 |

Now, these are the typical values of elastic constants of different composites. The elastic modulus values along the direction of the fiber and perpendicular to the direction of the fibers are given, also the Poisson's ratio and the shear modulus values are given. The specific gravities have been given and also the volume fraction.

It is important to mention the volume fraction of each composite and this gives us the volume percentage of the fibers. This is the graphite epoxy composite. Next is the glass epoxy composite and other is the Kevlar epoxy composite. As we can see from this table, the elastic modulus of graphite epoxy is significantly high and the elastic modulus in the other plane is quite low as we can see it is 10.3 whereas, $E_{xx}$ is 181 GPa.

So, there is much difference in the elastic properties on the two different planes. The elastic modulus of the graphite epoxy is much higher as compared to the elastic modulus of Kevlar composite and glass composite. So, we can see here that these values are much lower as compared to the carbon fiber composite.

The volume fractions of course, play a significant role in estimating the elastic modulus values. The specific gravities are also shown and we can see that glass epoxy has the highest specific gravity as compared to the graphite epoxy composite and Kevlar epoxy composite.

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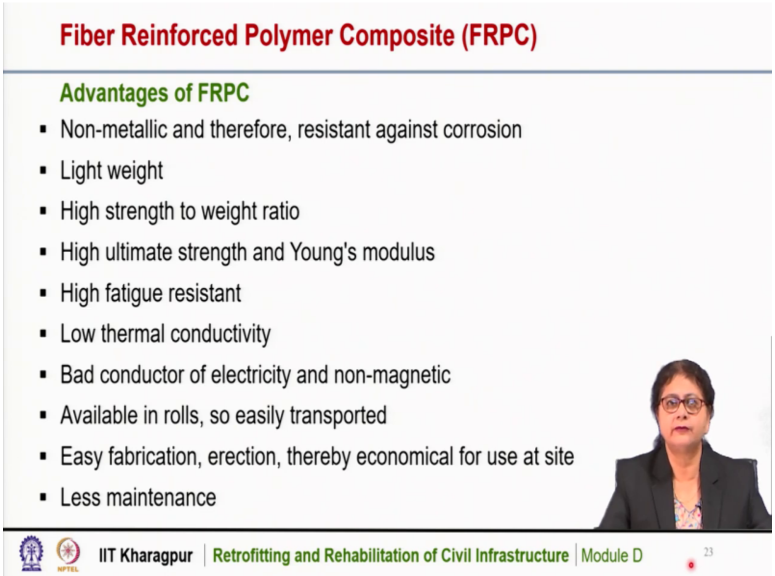


So, we have discussed the properties of different types of fibers, different types of resins and also the properties of fiber reinforced polymer composites. The properties of fiber reinforced polymer composite depends significantly on the properties of fibers and its orientation and also its volume content. Now, fiber reinforced polymer composites has several advantages and that is why it is used in various industries in recent years.

The advantages of FRP composite are that it is non-metallic in nature and therefore, resistance against corrosion. So, this is a very good idea advantage for FRP composites and it is particularly useful for the civil infrastructure. In civil infrastructure, we are using the steel reinforcement. And in case of steel reinforcement, the main problem is the corrosion of reinforcement.

So, by using FRP composites, we can reduce this type of problem in our civil infrastructure. So, FRP composite is non-metallic and resistant against corrosion. Another big advantage is that it is lightweight, it is very thin and the specific gravity is significantly low for all composites. So, it has high strength to weight ratio. The strength is significantly high, the ultimate strength, the stiffness or all are significantly high.

And it is lightweight, so it has high strength to weight ratio, it has high fatigue resistance, low thermal conductivity. The composites are bad conductor of electricity and nonmagnetic, so it is advantageous. The composites are available in rolls, so easily transported. So, this is also an advantage over steel because steel is generally very heavy and it is available in particular thickness or in particular shapes.

However, FRP composites are available in rolls and they are very lightweight, so easily transportable. It is easy in fabrication, erection and thereby it is economical for use at site, easily we can use it in the site for our work and for its easy fabrication, erection, properties. And the maintenance is less in case of FRP composites.

So, FRP composites gives us several advantages over conventional materials like steel, it is non-metallic therefore, resistance against corrosion is there, it is lightweight, it has high strength. So, the high strength to weight ratio is another advantage of this type of material. It is available in rolls, so it can be easily transported and erected at site and it has less maintenance.

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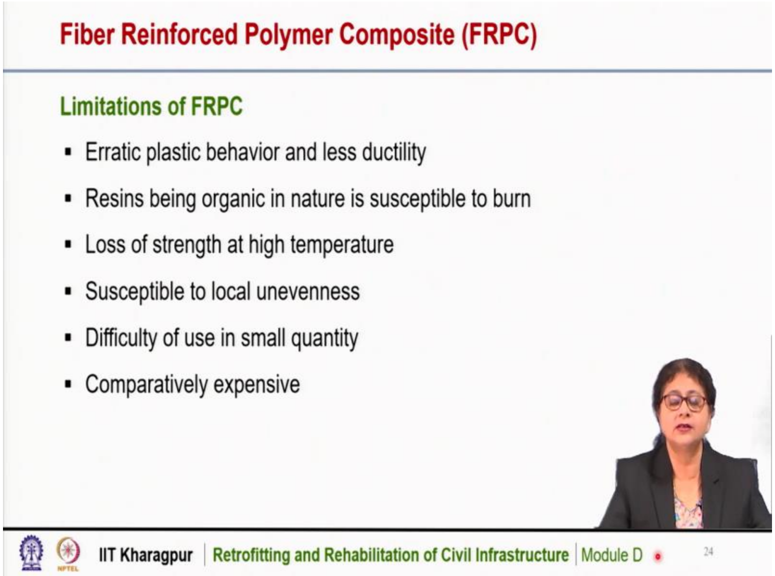


There are several limitations of FRP composites in spite of its several advantages. Though it has several advantages, FRP composites has some limitations as well. There is maybe erratic plastic behaviour of the composite and less ductility. So, less ductility is one limitation of FRP composites. The raisins which are used as a matrix in FRP composite being organic in nature is susceptible to burn.

There may be loss of strength at high temperature. So, it cannot sustain very high temperature. Susceptible to local unevenness, it is available in roles. So, some local unevenness may be there in the material. And it is sometimes difficult to use in small quantities. So, generally the roles are of very large length. So, if I want to use for smaller quantity, then it may be difficult sometimes.

And it is comparatively expensive as compared to conventional materials. So, some of the disadvantage or limitations of FRP can be that it is showing some erratic plastic behaviours with less ductility. And resins being organic in nature, so it may be susceptible to burn. And also, it is susceptible to local unevenness and at high temperature it may lose strength.

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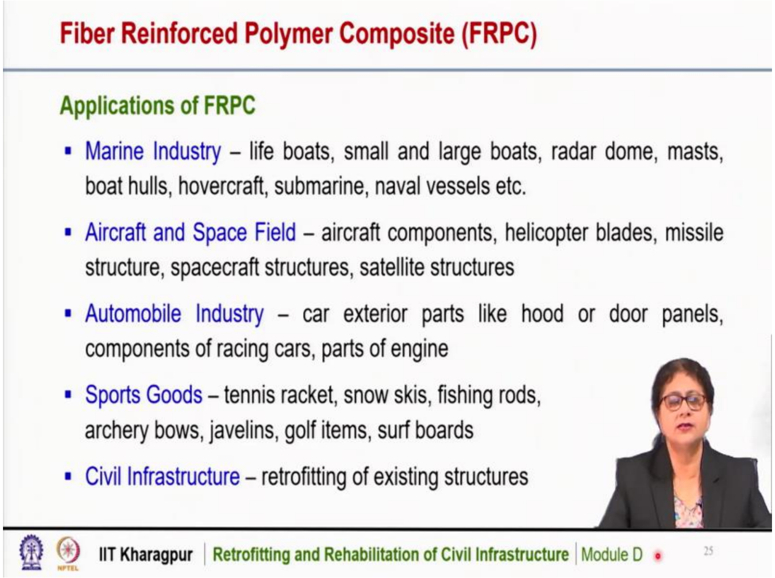


Because of several advantages FRPCs have several applications in various industries. In last two decades FRP is being revolutionary in the field of materials. And in several industries, it is used. In marine industry, there are several marine structures like lifeboats, small and large boats, masts, hovercraft, submarine, naval vessels, etcetera are made using FRP composites. It has a wide application in aircraft and space field.

Several aircraft components, helicopter blades, missile structures, satellite structures and components are made with FRP composites, because of its high strength to weight ratio, because weight is one of the important factor for all aircraft structures. And that is why FRP is used widely in aircraft and space field. It also has application in automobile industry, several exterior parts of cars like foot, door panels, components of racing cars, parts of engines are made by FRP composites.

Several sports goods are now made with several FRP composites, like carbon fiber composites, tennis racket is nowadays made with this light FRP composites carbon fibers, snow skis, fishing rods, golf items, surf boats, javelins, etcetera are made of lightweight carbon fiber composites. And in civil infrastructure also FRP has its application in recent years in particularly in retrofitting of existing structures.

It has also some use in the new construction like FRP rods, bars and FRP pultruded sections, but in retrofitting of existing structures, it has wide application.

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So, to summarize, we have discussed today the properties of fibers and resins and the stress-strain relationships of fibers and resins. We have discussed the properties of FRP composites and the stress-strain relationships, the advantages and limitations of FRP composites have been discussed and the wide applications of FRP composites in different industries has also been discussed in today's class. Thank you.