Smart Structures
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Week - 06
Lecture No - 30
Introduction to Fibre Reinforced Composites

In this week and in the next week we will deal with composites.

We will see the behavior of composite plies and composite laminates and we will see how a composite laminate which has piezoelectric patches can be analyzed. Now, before going to that let us have a brief introduction to composites.

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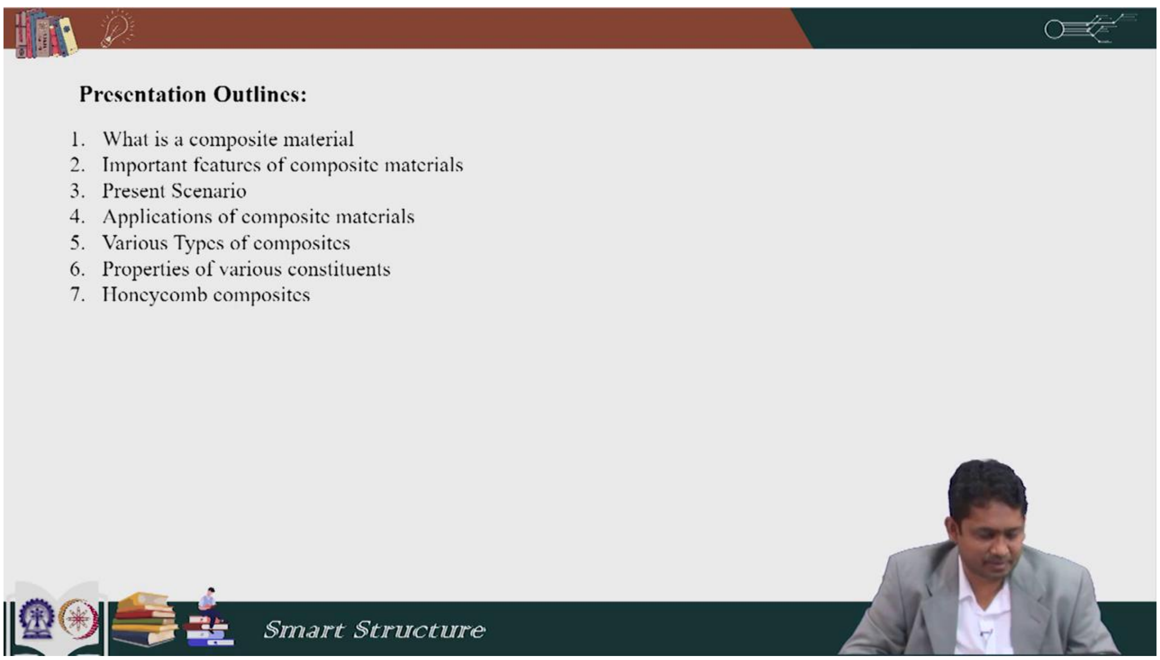

This introductory lecture will contain these topics. At first we will see what a composite is and then we will see important features of composite materials. After that we will see the present scenario of the overall composite market. Then we will talk about applications of composite materials in different fields and then we will see various types of composites. After that we will see properties of various constituents and then we will talk about honeycomb composites.

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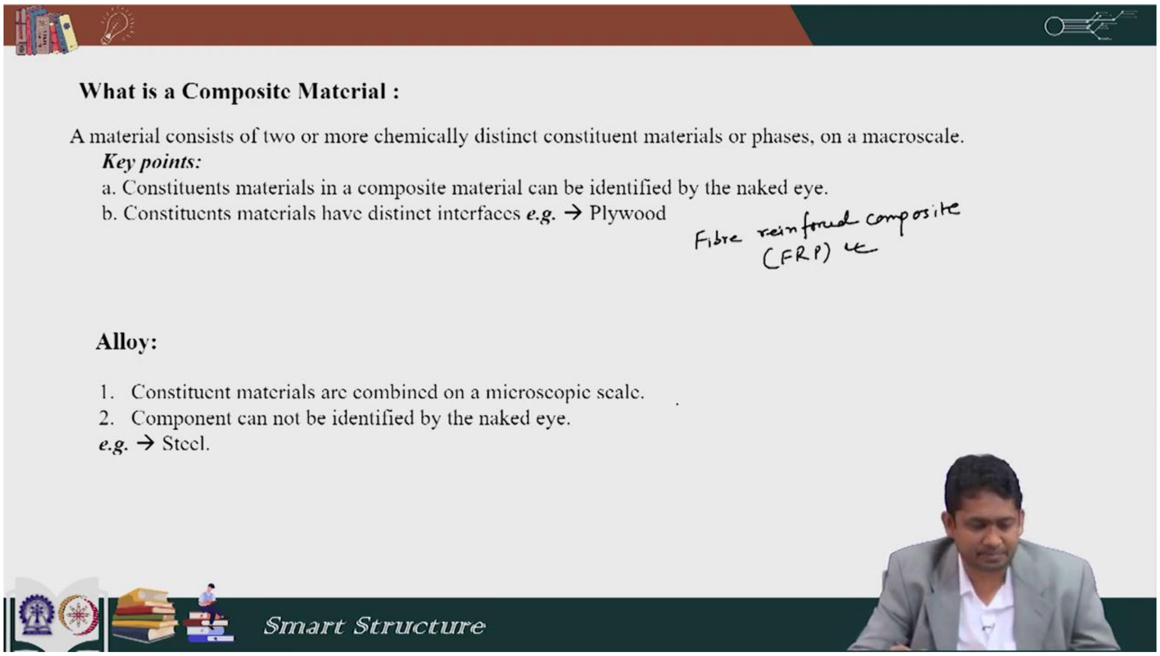

So, a composite is a combination of two or more different materials which are chemically distinct and they do not react. And the kind of composites that we will talk about in this course is composites at macro scale.

So, they are mixed at macro scale. So, the constituents can be identified by the naked eyes if you look at the composite and constituents have distinct interfaces. An example can be a plywood. Now the type of composite that we talk about in this course is called fiber reinforced composite. In short we will call it FRP.

Now there is something called alloys also, but these alloys are micro scale composites. So, that is the main difference between alloys and the kind of composites that we deal with. So, in alloys the component cannot be identified if we see them an example is a steel. So, we will restrict our self to fiber reinforced composites.

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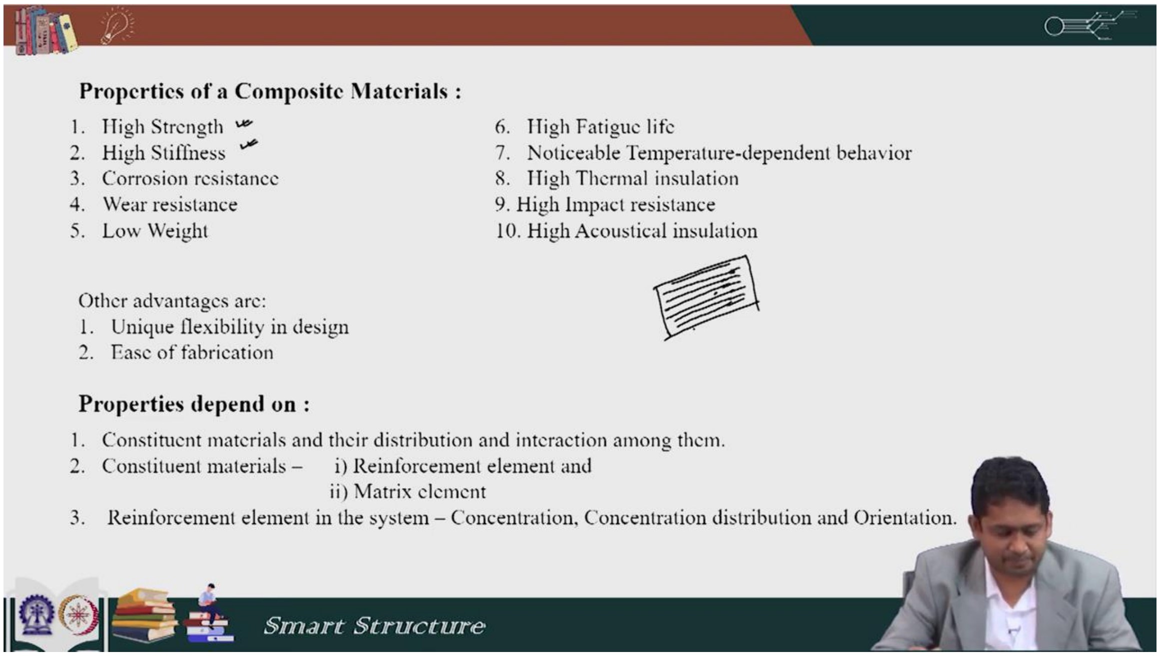

So, here are some important properties of composites. These composites have high strength. They have high stiffness. So, if we take a traditional material like a metal and if we take a composite of the same weight then we generally get high strength and stiffness in the composite. So, the strength to mass ratio or the weight ratio, stiffness to mass ratio or weight ratio is generally higher for composite. And they have good corrosion resistance properties, they have good wear resistance and they are light weight and they have high fatigue life because these composites generally look like this.

We have matrix and fiber laid up. So, if there is a fatigue crack generally its propagation is arrested by this kind of layup. And they have noticeable temperature dependent behavior. They have high thermal insulation, high impact resistance, high acoustic insulation. So, in applications like stealth because it has good acoustic insulation properties composites are widely used.

And these materials give unique design flexibility. That is a very important point. So, if we change the fiber orientations or if we change the orientation sequence in a laminate, you can change the properties a lot. So, we can get different types of properties or different types of unique features by aligning these fibers. So, that is a unique design flexibility which we get from composites and there is ease of fabrication.

So, if you want to get any shape we can prepare the mold accordingly and accordingly we can lay up the composite and make the composite. These properties depend on the constitutive materials and their distribution, their interaction and for our case the constitutive materials reinforcement elements like fiber and matrix elements which is polymer for our case.

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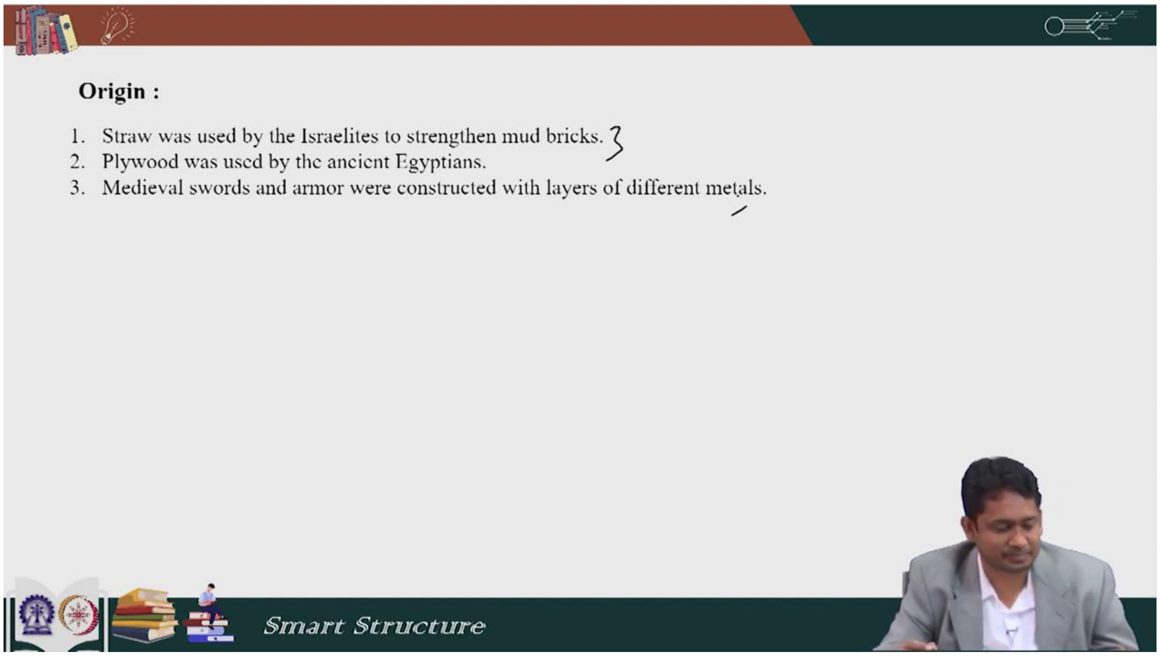

If we try to trace the origin of composite, we can go back to ancient times. In the ancient times, people of Israel used straw to strengthen mud bricks. Plywood was used by ancient Egyptians. So, these are all composites at the basic level and then we have made lot of advancements. Even in the medieval times, swords and armors were constructed with different layers of metals.

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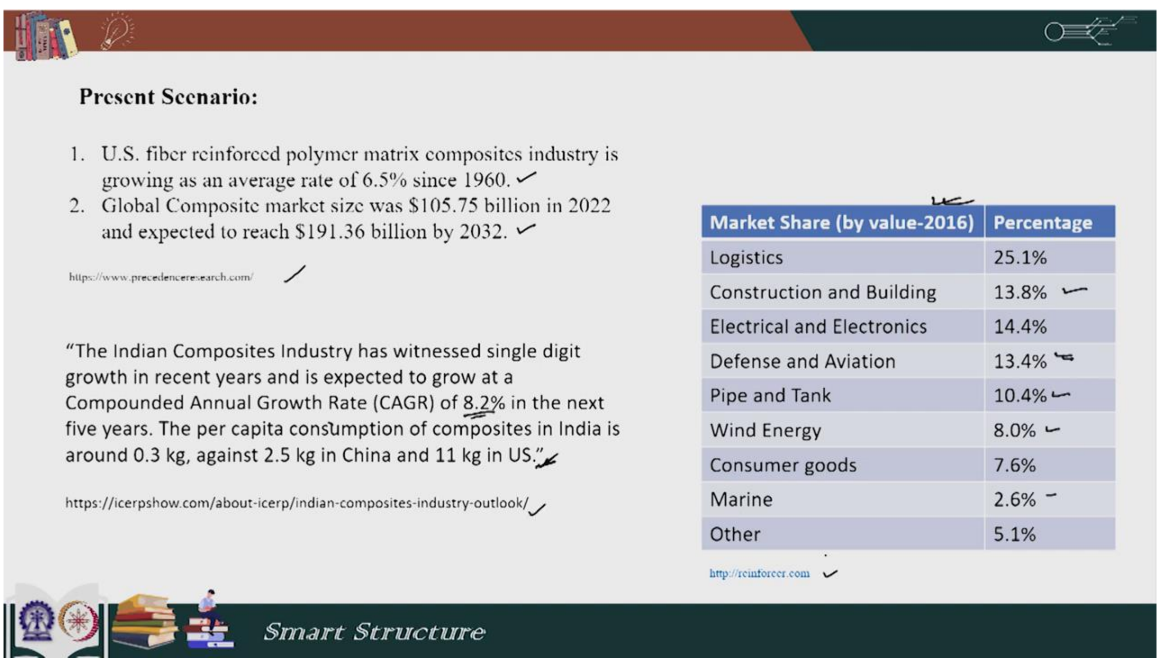

Now here is a brief outlook to the global or Indian market of composites and how it is expanding. In US, FRP composite industry is growing at an average of 6.5 percent since 1960.

If we talk globally the market size was 105.75 billion US dollar in 2022 and it is expected to reach 191.36 billion US dollar by 2032. In India, the Indian composite industry has witnessed single digit growth in recent years and is expected to grow at a compound and annual growth rate of 8.2 percent in the next 5 years.

The per capita consumption of composites in India is around 0.3 kg against 2.5 kg in China and 11 kg in US. So, there is a scope of tremendous development in this field in near future and we can see that by this number. If we look at the distribution into different sectors as per 2016, the logistics sector used around 25.1 percent. Construction and building have around 13.8 percent share. Electrical and electronics has around 14.4 percent share, defense and aviation around 13.4 percent, pipe tank things like that around 10.4 percent, wind energy around 8 percent, consumer goods around 7.6 percent, marine field around 2.7 percent and other sectors around 5.1 percent. So, these all statistics are taken from various resources. So, they are referred here. You can go and look into it in more details.

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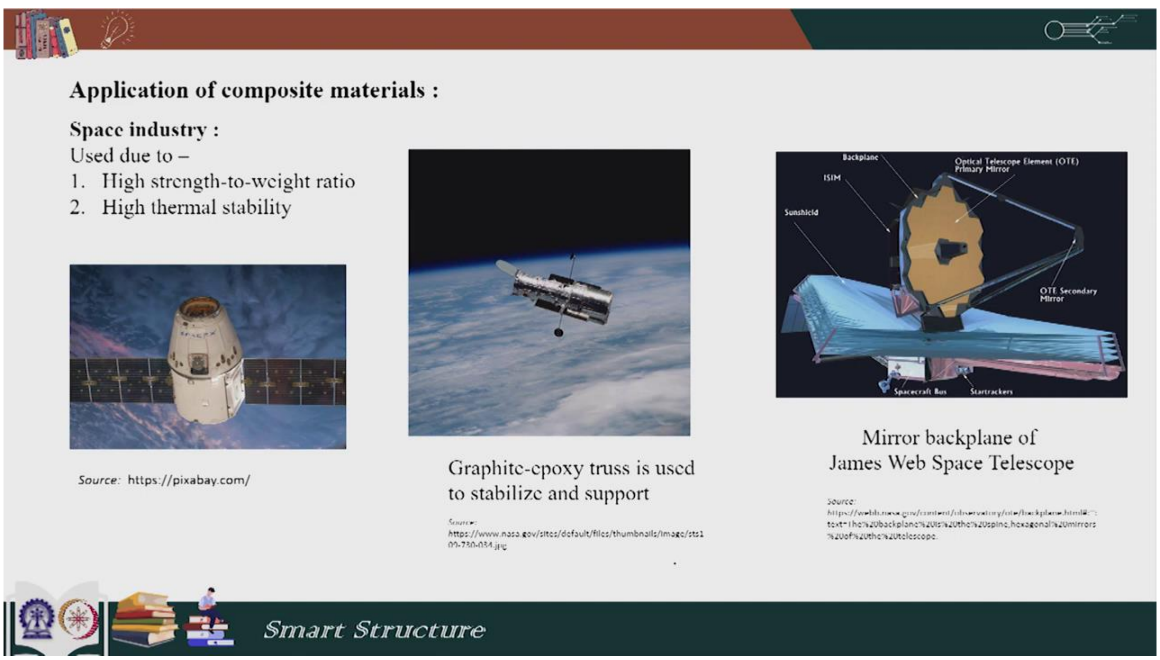

Now let us talk about applications in various fields. Space industry uses composites a lot due to high strength to weight ratio and high thermal stability. We can see a solar panel here and in these panels, composite finds a lot of application. Here we can see Hubble space telescope. Graphite epoxy truss is used to stabilize and support the structure. Similar thing can be seen in mirror back plane of JWS telescope.

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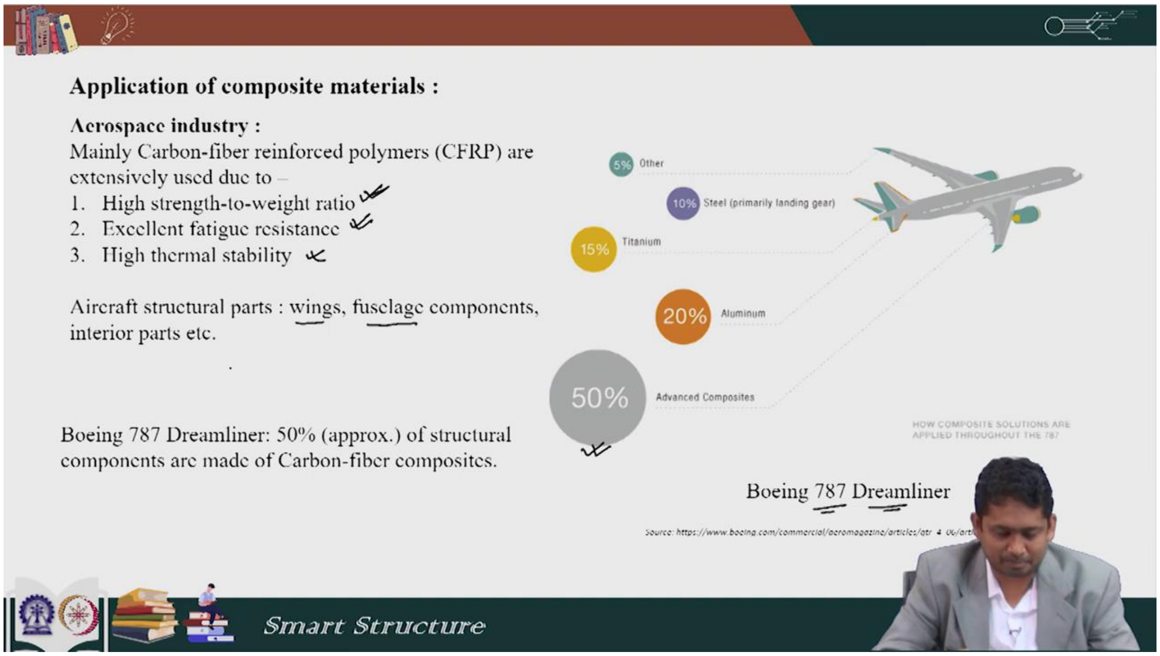

In aviation industry, composites are used. A composite structure finds a lot of applications. So, again the advantageous features that generally makes this material useful for this field are high strength to weight ratio, excellent fatigue resistance which is very important and high thermal stability. So, if we look at aircraft for example, it is a Boeing 787 rim liner aircraft we can see that ah there is around 50 percent of the entire constituents is advanced composites and there is 20 percent aluminum, 15 percent titanium, 10 percent steel and others around 5 percent. So, various aircraft parts like wings, fuselage components, interior parts use composites.

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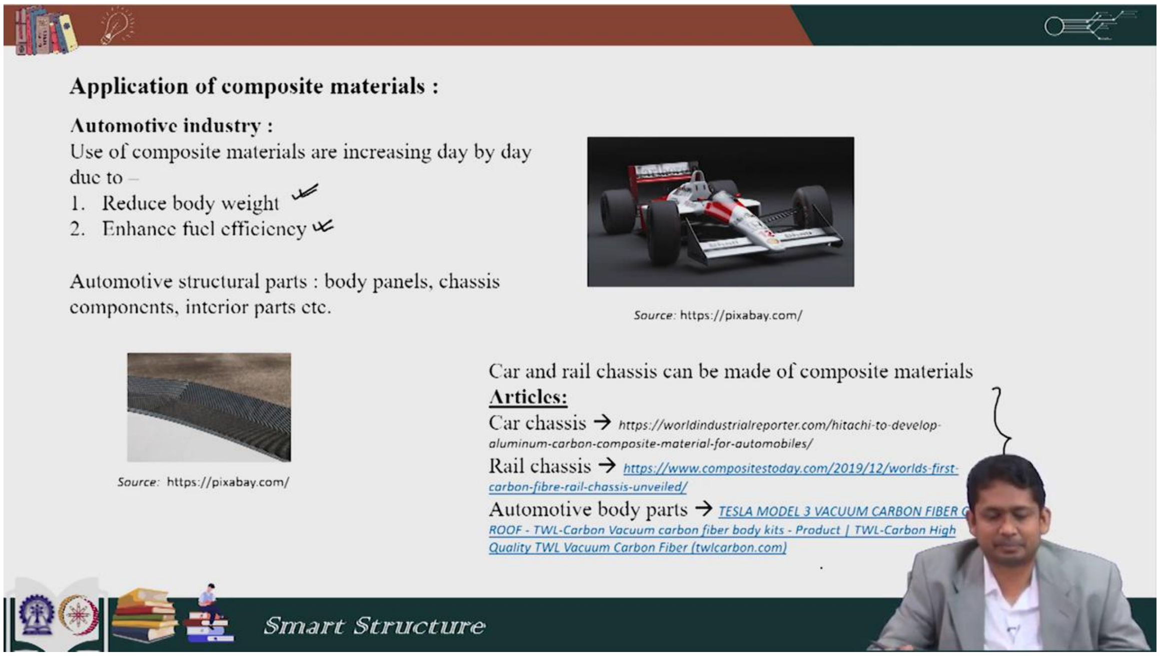

In automotive industry, its use is rapidly growing. We get reduced body weight through composites because it has high strength or stiffness to weight ratio and accordingly we get enhanced fuel efficiency also.

And also if we talk about high speed cars, its impact resistance is also very useful. So, various automobile parts like body panels, chassis components, interior parts have composites. So, these articles show a good overview of the use of composite in this industry.

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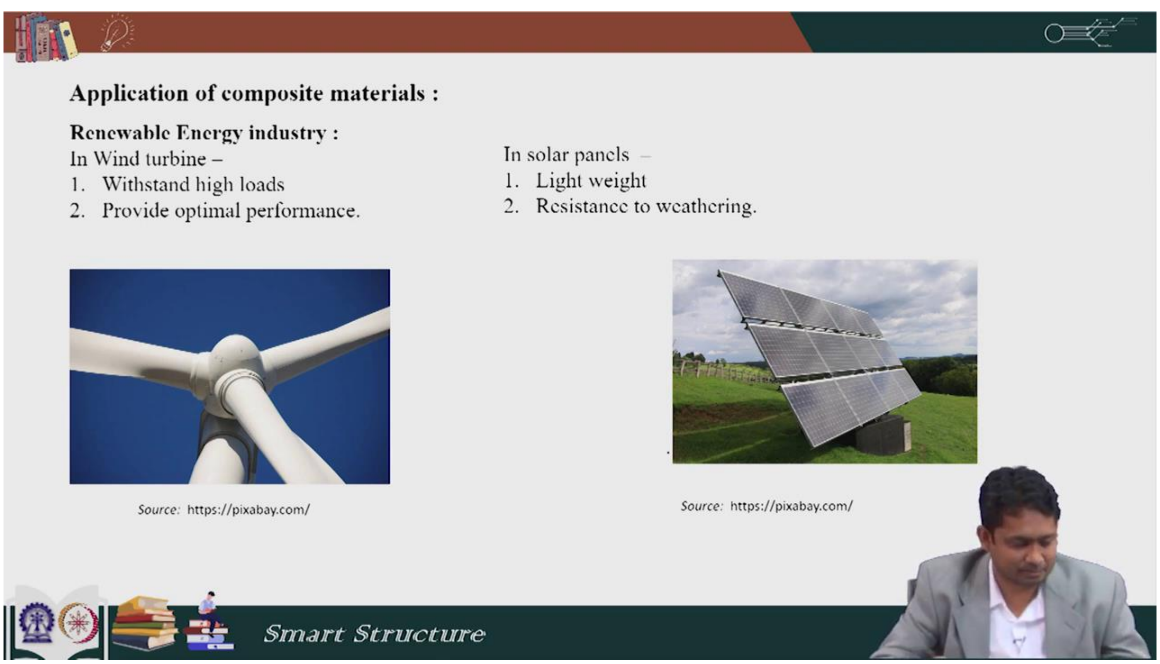

If we go to the renewable energy sector, wind turbine blades are made of composite because it can withstand high loads and provide optical performance accordingly. So, the modern day wind turbines are becoming larger and larger even there are wind turbines of radius around 90 meter or so.

So, a material which does not increase the weight too much and give good performance is very important and in wind turbine, its pitch control is very important for getting better performance and also reduce the aero elastic instabilities. So, composite materials are quite helpful for those cases. In solar panel also composite is used to be due to its light weight and resistance to weathering.

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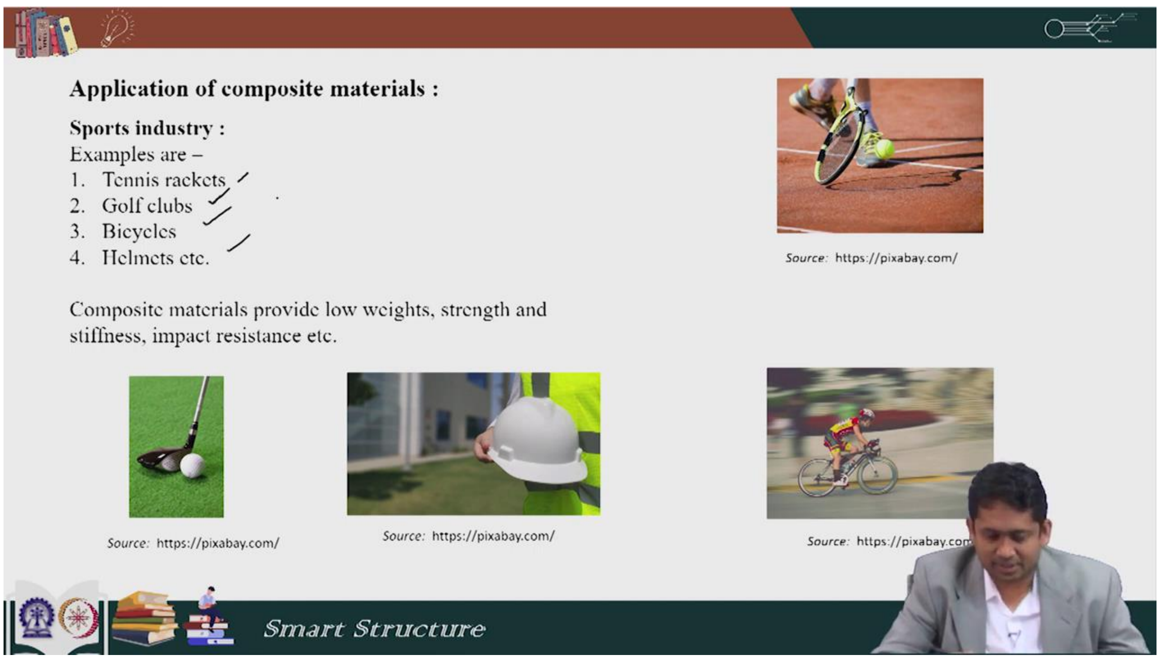

We can see the various applications here in the sports industry. Examples can include tennis racket, the equipments in golf, bicycles, and helmets and so on. So, composite materials provide low weight strength and stiffness impact resistance and that is why these are used a lot.

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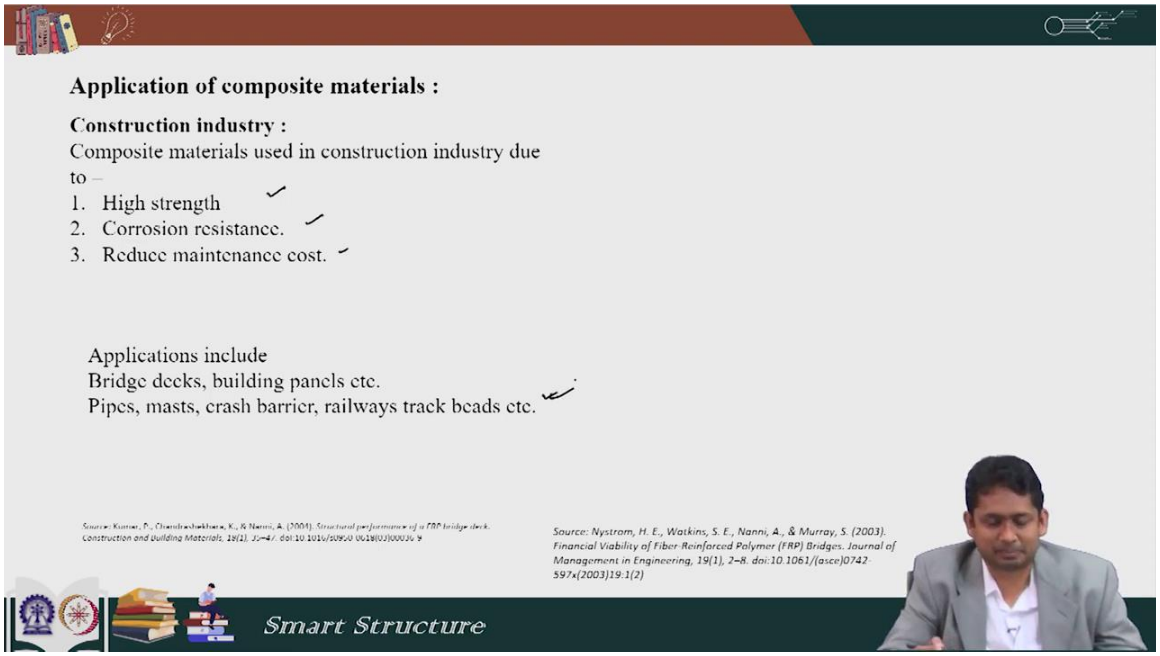

In construction industry, composite is finding rapidly growing application due to its high strength, corrosion resistance and reduced maintenance cost. Now applications can include bridge decks, building panels and so on. Pipes, masts, crash barrier, railway track beads etc have use of composites as well.

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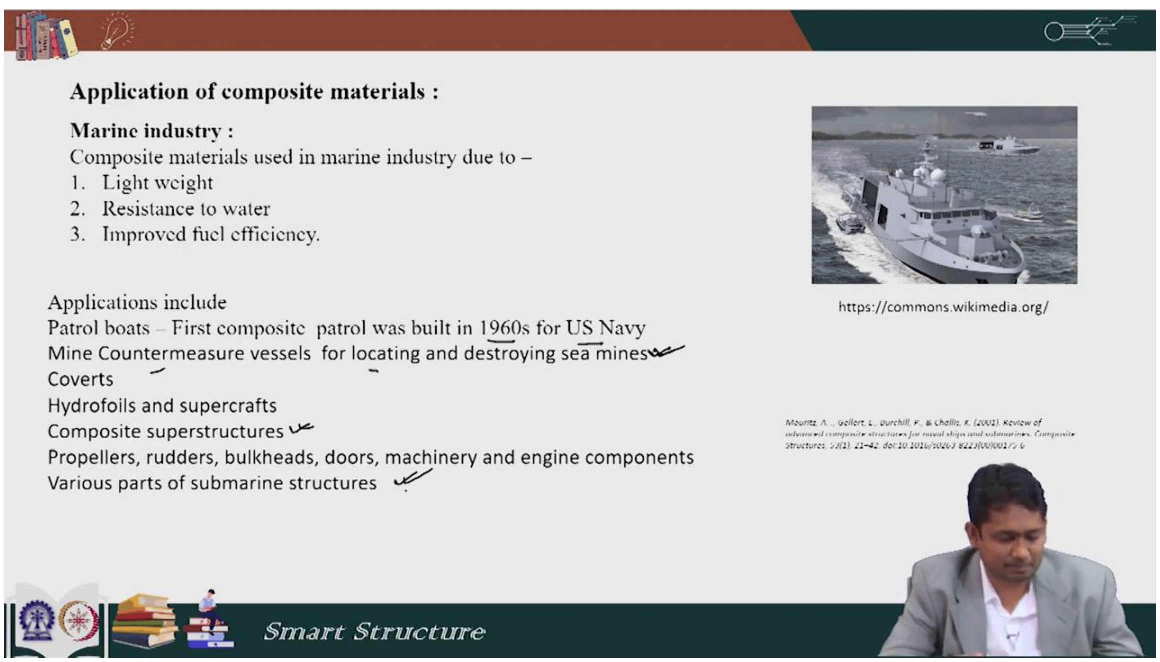

Now, let us talk about marine industry. So, we saw that composites have good corrosion resistance. So, that is quite important for marine field. So, that is why composite is used and apart from that, its light weight make it fuel efficient. So, there are various applications in petrol boats, composites are used. The first composite petrol boat was built in 1960s for US navy and then mine counter measure vessels are used for locating and destroying sea mines.

Now, in this kind of applications we need non magnetic materials so that they cannot be detected. So, previously it used to be made by woods, but because we do not want to destroy nature and we do not want to use too much of wood, so, composite comes into picture here and there are several mine counter measure vessels which have been constructed by composites and are being constructed. Coverts, hydrofoil and supercrafts, composite superstructures, super super structure of a ship are generally made of composites. So, again there are growing applications of composite there and propellers, rudders, bulkheads, doors, machinery and engine components various parts of submarine structures also have composites.

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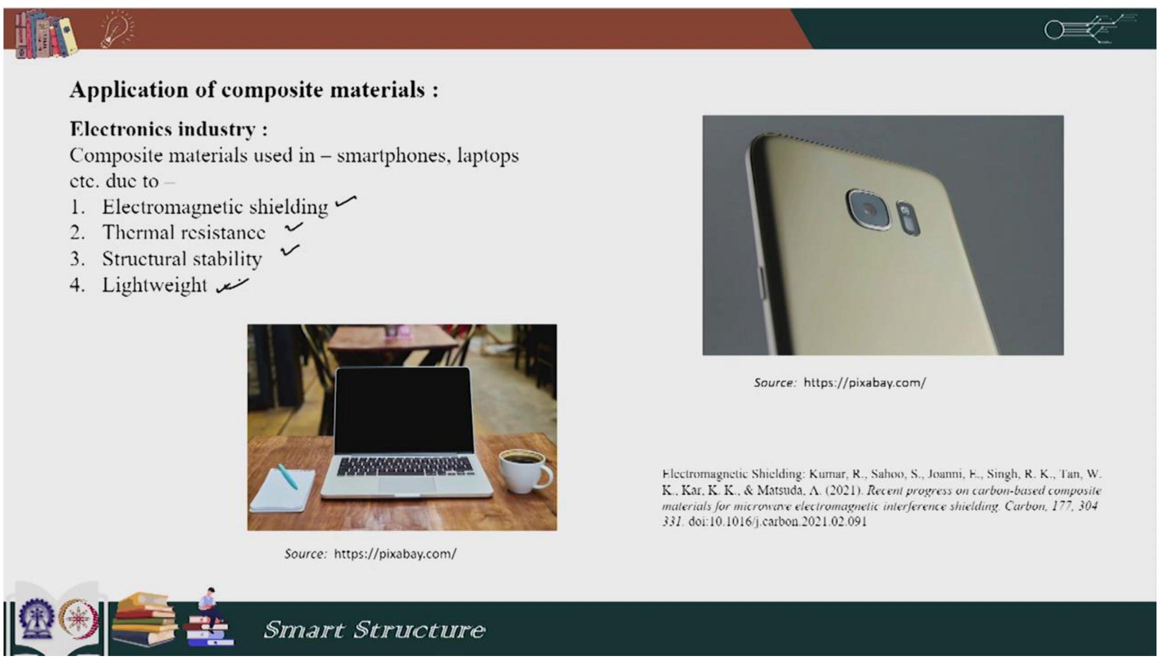

If we look at the day to day equipments like electronic equipments, composite is also being useful there. So, smart phones, laptops are examples. The properties that are useful here are electromagnetic shielding, thermal resistance, structural stability and of course, its light weight.

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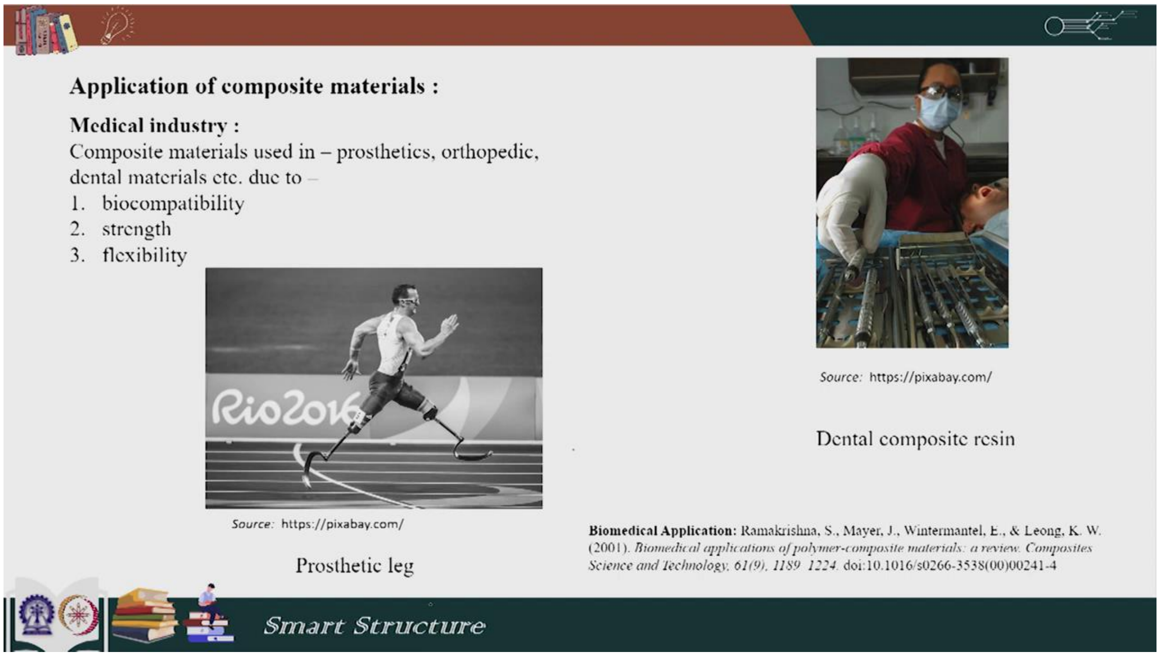

In the medical field, composites are used for prosthetics, orthopedic uses have there. In dental also, dental materials are composites. So, here it is used because of its biocompatibility, strength and flexibility. We can see a prosthetic leg here.

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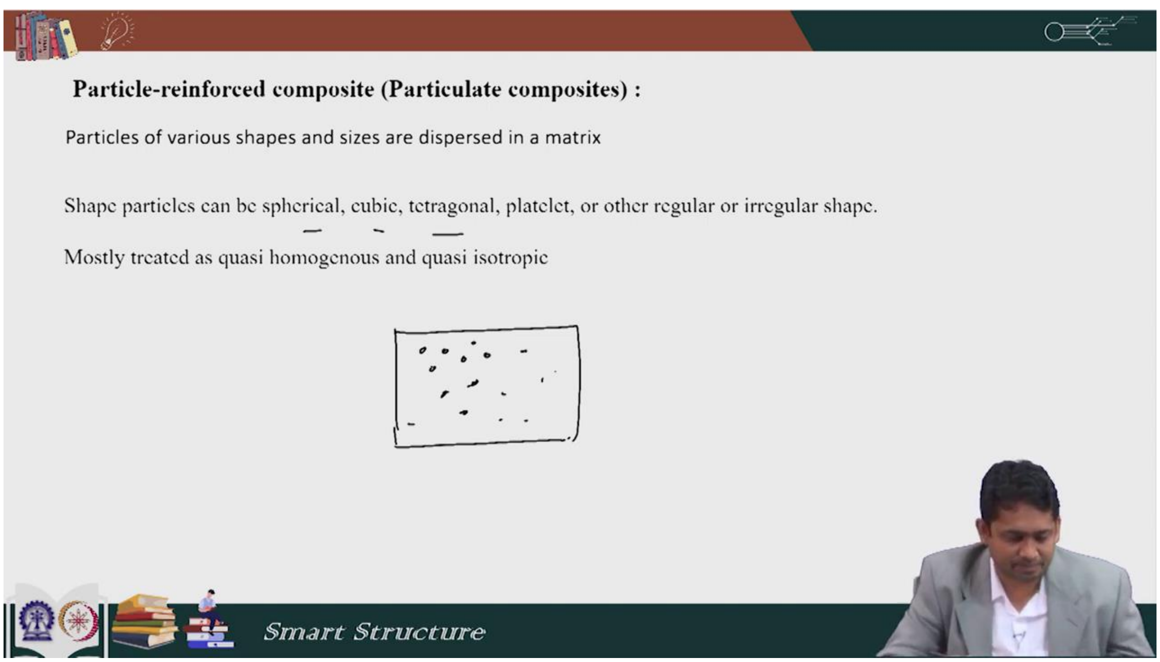

Now we will see various types of fiber reinforced composites. So, there is something called particulate composites. So, in particulate composites, particles of various shapes and sizes are dispersed in a matrix. So, if we see a composite like this, so, in the matrix, there are particles of various shape and size and because they are randomly placed and oriented, it can be treated as quasi homogeneous and quasi isotropic. Now these particles can be spherical cubic tetragonal or different kind of shape.

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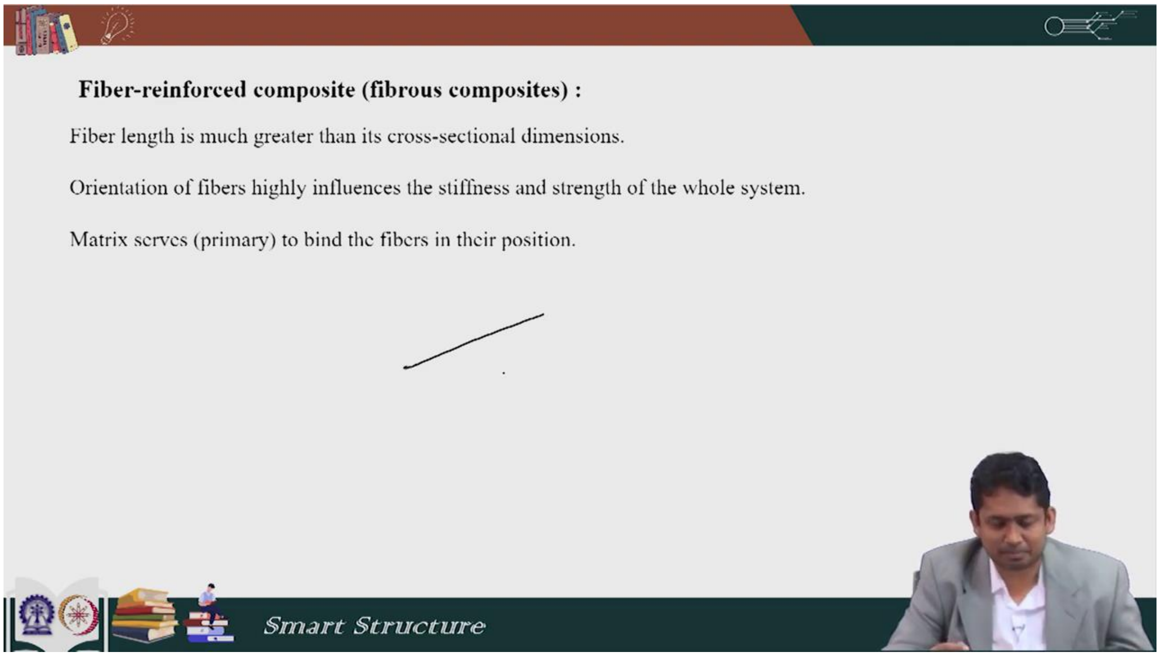

Now comes fiber reinforced composites. So, as the name suggest we have fibers that are placed in matrix. Here the fiber length is much greater than the cross sectional dimension. So, they are long fibers. Now orientation of the fibers here highly influences the stiffness and strength of the whole system and matrix are polymer matrix. They hold the fibers.

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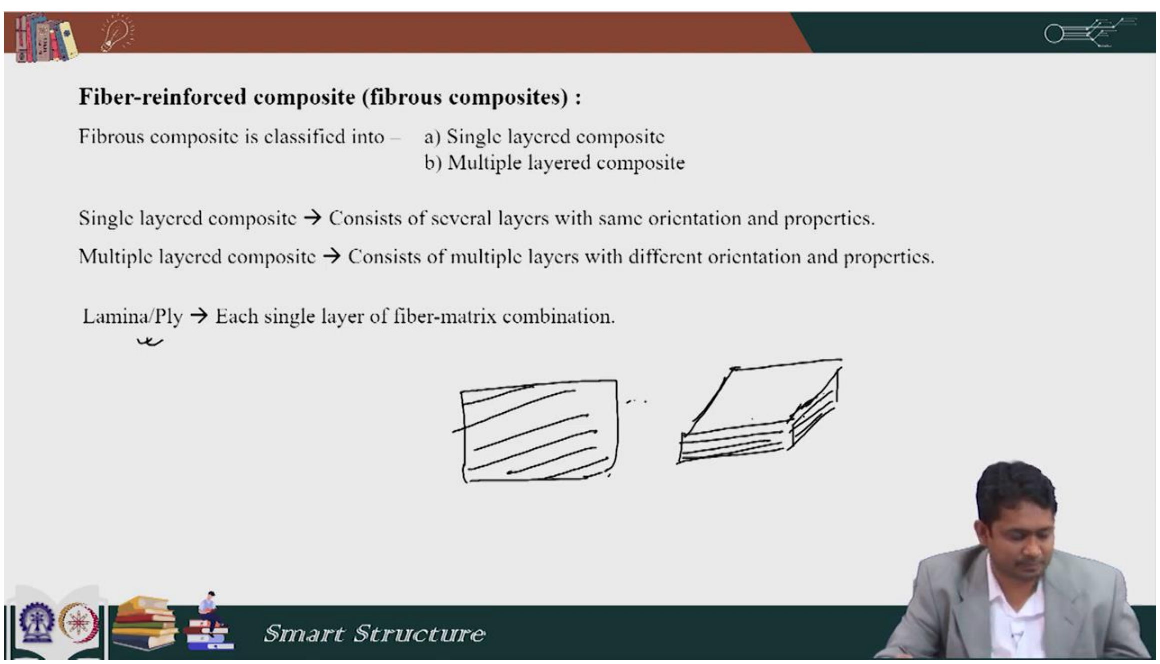

Now this fiber reinforced composites can be single layered or multi layered. So, there can be just one layer with some fiber orientation or there can be many of those which are stacked one over another. So, something like this where there are many layers which are one over another. Now each layer is called a lamina or ply. Now these multiple layers can have different ply orientation and they can have different constituents also.

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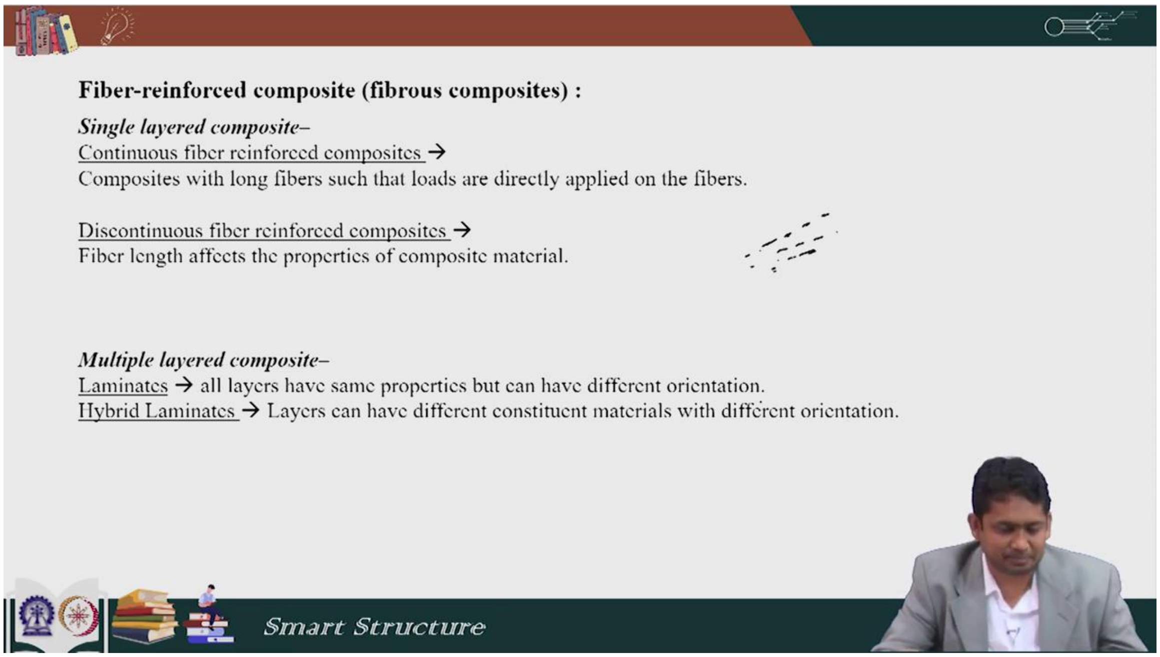

Single layered composites can have continuous fiber reinforced composites or they can have discontinuous fiber reinforcement also. So, when it is discontinuous so, there are fibers of different small lengths. Now this fiber length affects the property of the composites. In multiple layered so, there can be hybrid laminate. So, in hybrid laminate the property of the constituents can be different as we go layer by layer and at the same time the orientation of the fiber can also be different. Whereas, if it is not hybrid just the material properties are same the constitutional properties are same layer by layer, but the orientation can be different.

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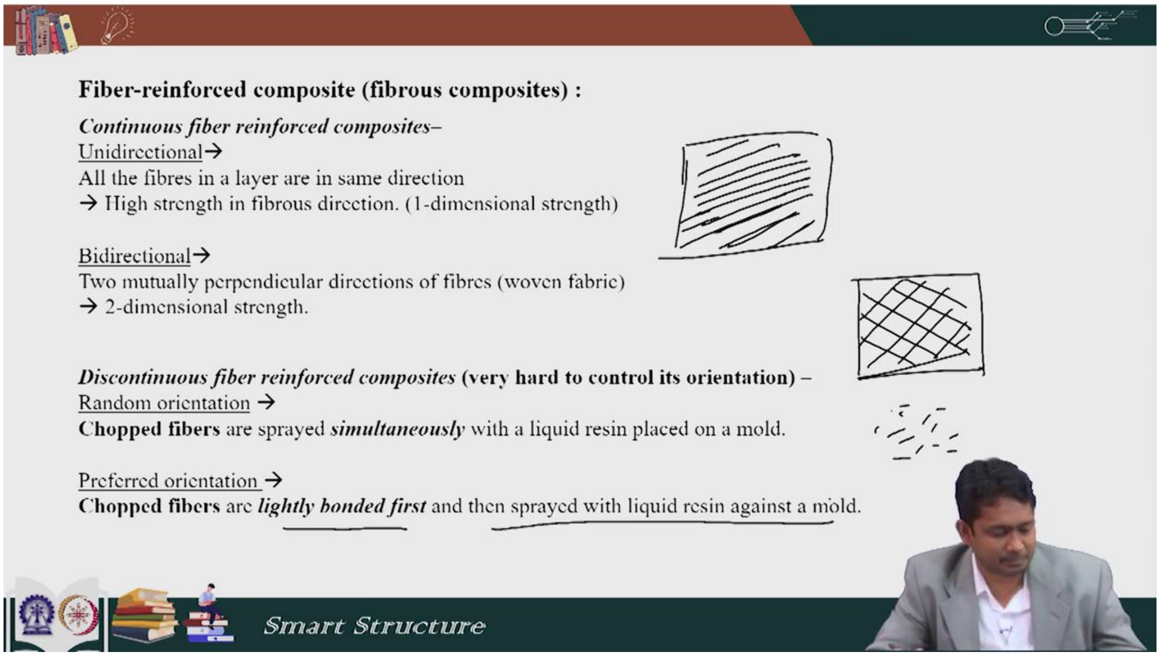

Continuous fiber reinforced composites can be unidirectional. So, if we lay the composites just in one direction so, if our one ply looks like this, it is called a unidirectional composite and there can be bidirectional where there are plies which intersect each other and they are laid in different directions. Again in bidirectional there are woven or braided we will talk about it. When it comes to discontinuous fiber reinforced composite, there can be random orientation or there can be preferred orientation also. Random means the various short fibers are randomly oriented and if we want to have some preference in the direction then generally what is done is this chopped fibers are tightly bonded first and then spread with liquid resin against a mold.

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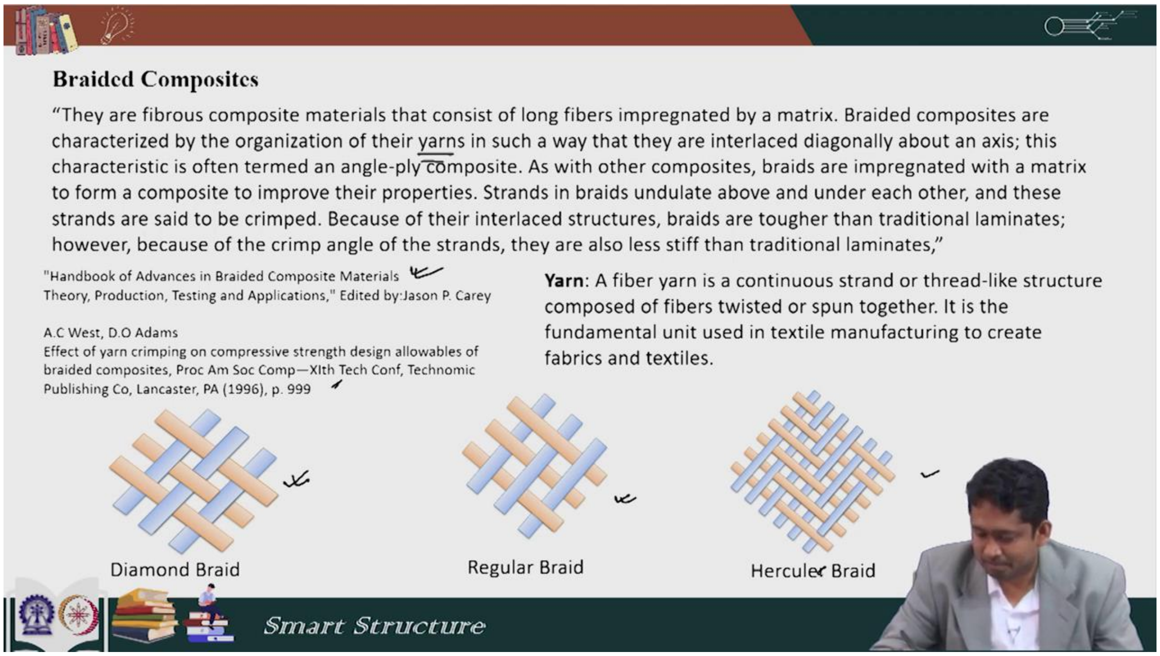

Now in bidirectional composite there can be braided composites. So, braided composites are fibrous composites that consist of long fibers impregnated by a matrix. Braided composites are characterized by the organization of their yarns in such a way that they are interlaced diagonally about an axis. These characteristics is often termed an angle ply composite.

As with other composites, braids are impregnated with a matrix to form a composite to improve their properties. Strands in braids undulate above and under each other and these strands are said to be crimped. Because of their interlaced structure, braids are tougher than traditional laminates; however, because of the crimp angle of the strands, they are also less stiff than traditional laminates. So, a more description about the braided composites can be found in this handbook and in various papers also.

Now here we talked about one term which is yarn. A fiber yarn is a discontinuous strand or thread like structure composed of fibers twisted or spun together. Now it is a fundamental unit which is used in textile manufacturing to create fabrics and textile. Now there can be different types of braids. Here we can see some 2D braids. It is a Diamond braid. It is a Regular braid and it is a Hercules braid.

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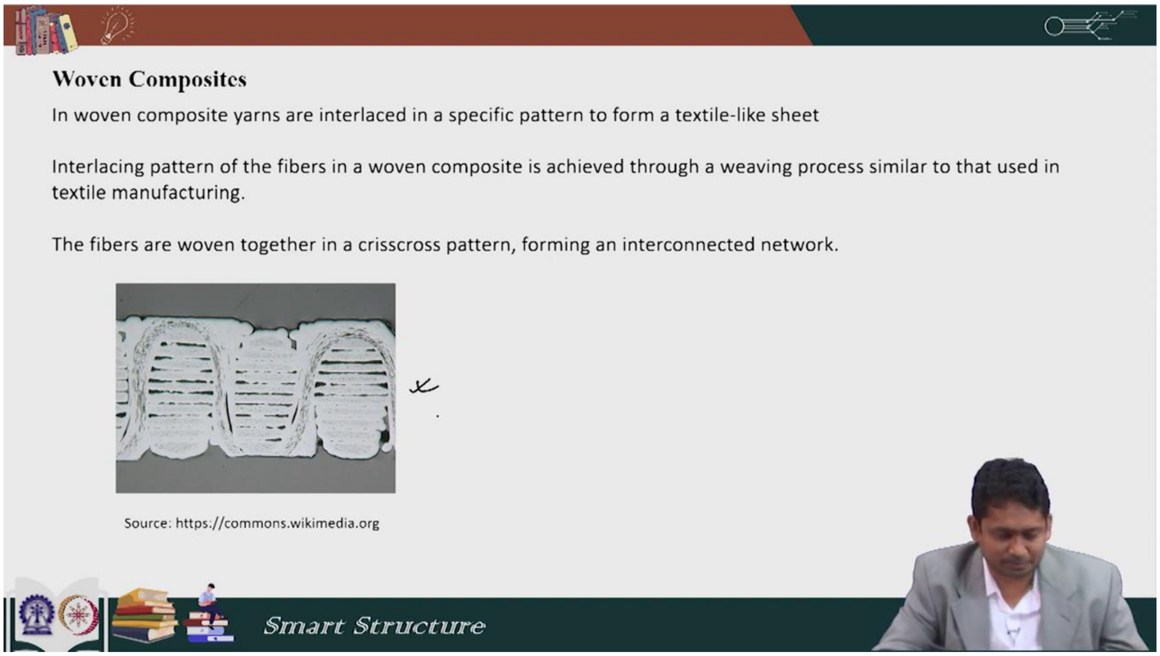

Similarly there can be woven composite. So, in woven composite, yarns are interlaced in a specific pattern to form a textile like sheet. Now interlacing pattern of fibers in a woven composite is achieved through a weaving process similar to that used in textile manufacturing. Again there can be 2D or 3D weaving. Now here we can see a cross sectional view of a woven composite.

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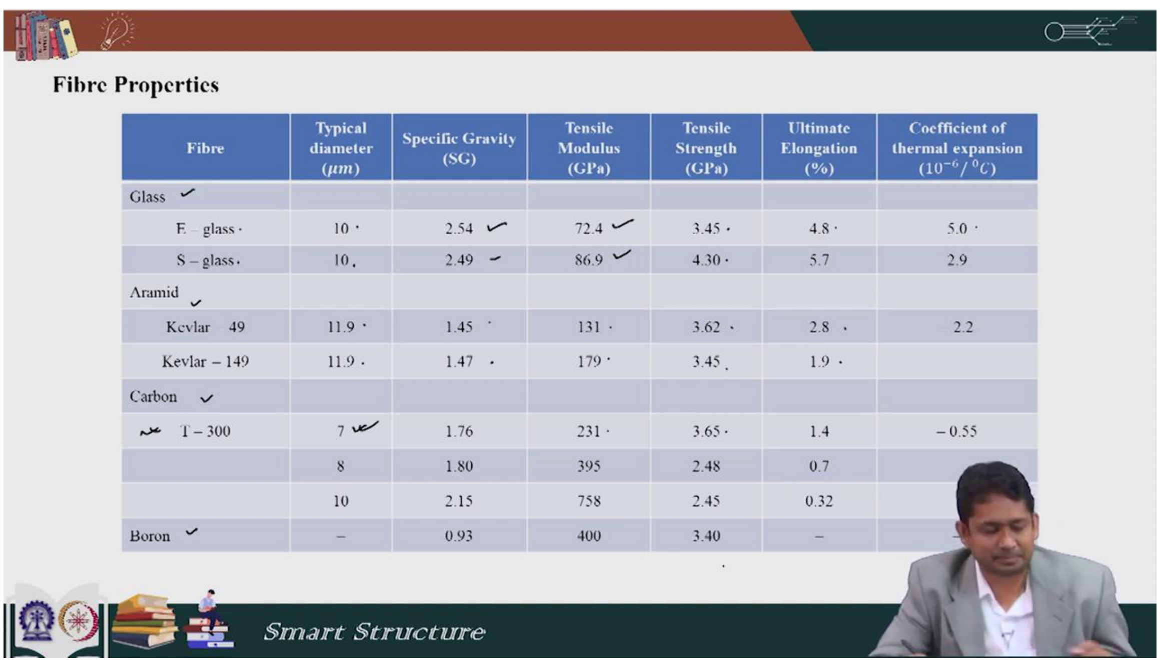

Fibre	Typical diameter (μm)	Specific Gravity (SG)	Tensile Modulus (GPa)	Tensile Strength (GPa)	Ultimate Elongation (%)	Coefficient of thermal expansion ($10^{-6}/{}^{0}C$)
Glass						
E – glass	10	2.54	72.4	3.45	4.8	5.0
S – glass	10	2.49	86.9	4.30	5.7	2.9
Aramid						
Kevlar – 49	11.9	1.45	131	3.62	2.8	– 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	3.40	–	

Now in this course, we will stick our self to unidirectional composites. So, we will consider composite where there can be many plies, but each ply has just one direction of composite orientation. Now let us look into the fiber different constituent properties. The fiber that we generally used in fiber reinforced composites are glass fiber, aramid fiber, carbon fiber and boron fiber.

Again in glass fiber, there can be E glass fiber and S glass fiber. E glass fiber costs less and these are the different properties. So, these are the typical diameters of fiber. Here, specific gravity is given. A tensile modulus around 70 to 80 GPa, tensile strength is around 3 to 4 GPa, ultimate elongation in strain is around 4 to 5 percent and coefficient of thermal expansion varies from 5 to 2 into 10 to the power minus 6 by per degree centigrade.

Kevlar fiber properties again the typical diameter is somewhat same, specific gravity is little less, tensile modulus is higher than the glass fiber, tensile strength is somewhat same, ultimate elongation is less than the glass fibers. And if you talk about carbon fiber, carbon fiber is much costlier than glass fiber, however they have much better properties. So, in aerospace applications carbon fibers are very widely used even in formula car also. So, depending on the applications fibers are chosen depending on how much strength we need, how much accuracy we need and what is our budget.

So, accordingly fiber has to be chosen. If we talk about carbon fiber, the diameter is less than the glass or Kevlar fiber. Its specific gravity is comparable with the aramid and carbon fiber's tensile modulus is much higher than the glass fiber. And then we have the tensile strength which is comparable. Ultimate elongation is much less and boron fiber have this properties. Specific gravity is much less, its tensile modulus is much higher, tensile strength is somewhat comparable.

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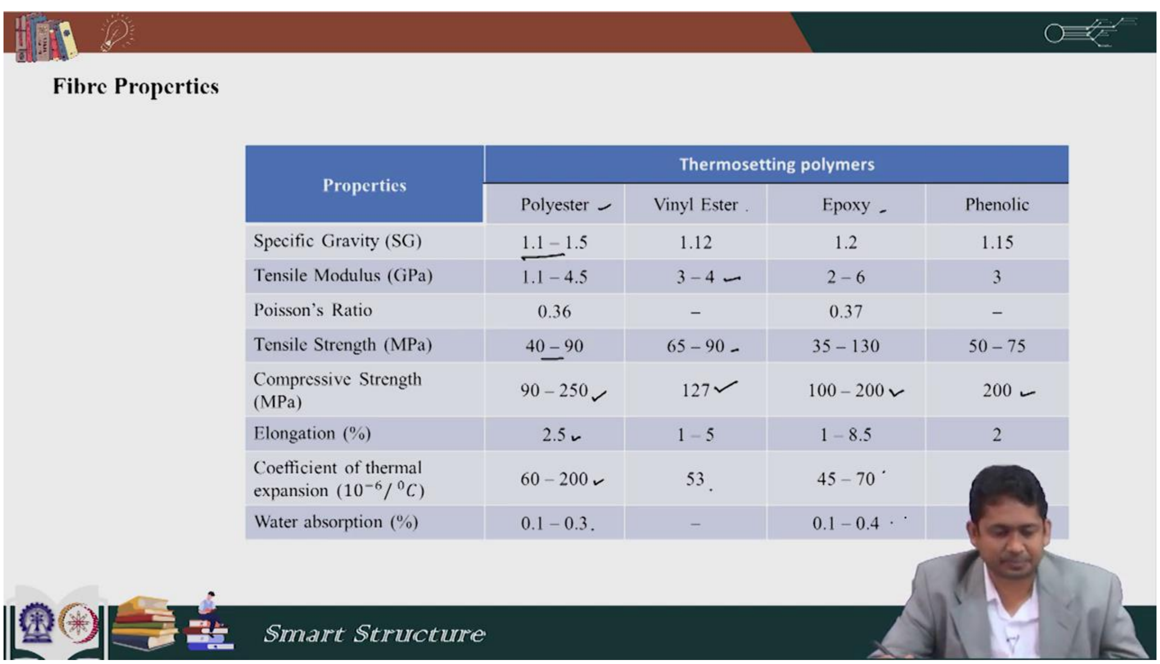

Properties	Thermosetting polymers			
	Polyester	Vinyl Ester	Epoxy	Phenolic
Specific Gravity (SG)	1.1 – 1.5	1.12	1.2	1.15
Tensile Modulus (GPa)	1.1 – 4.5	3 – 4	2 – 6	3
Poisson's Ratio	0.36	–	0.37	–
Tensile Strength (MPa)	40 – 90	65 – 90	35 – 130	50 – 75
Compressive Strength (MPa)	90 – 250	127	100 – 200	200
Elongation (%)	2.5	1 – 5	1 – 8.5	2
Coefficient of thermal expansion ($10^{-6}/{}^0C$)	60 – 200	53	45 – 70	[illegible]
Water absorption (%)	0.1 – 0.3	–	0.1 – 0.4	[illegible]

Now comes polymers. So, when we talk about this polymers, polymers means the matrix material. So, the matrix is generally a polymer which we call resin and this resin is mixed with a hardener and then it is cured and it forms a matrix. Now this polymers resins can be thermosetting or thermoplastic. Now thermosetting polymers once it is cured and it is hardened if we heat it we cannot melt it. Now thermosetting polymers example include polyester, vinyl ester, epoxy, phenolic.

Their specific gravities are more or less same. If we talk about tensile modulus, we get more tensile modulus through vinyl ester. Poisons ratio is again somewhat comparable. Tensile strength again we can see for polyester 40 to 90 mega Pascal, vinyl ester 65 to 90 mega Pascal and epoxy 35 to 130 mega Pascal, phenolic around 50 to 75 mega Pascal. Compressive strength in mega Pascal it is 90 to 250, for polyester 127, for vinyl ester 100 to 200 for epoxy, 200 for phenolic, elongation 2.5 percent maximum elongation, vinyl ester 1 to 5 percent, epoxy around 1 to 8.5 percent, phenolic 2 percent. Coefficient of thermal expansion 60 to 200 into 10 to the power minus 6 per degree centigrade for vinyl ester and epoxy around 53 or 40 to 70 in the same unit. If you look at the water absorption properties, polyester absorbs water 0.1 to 0.3 percent, epoxy 0.1 to 0.4 percent.

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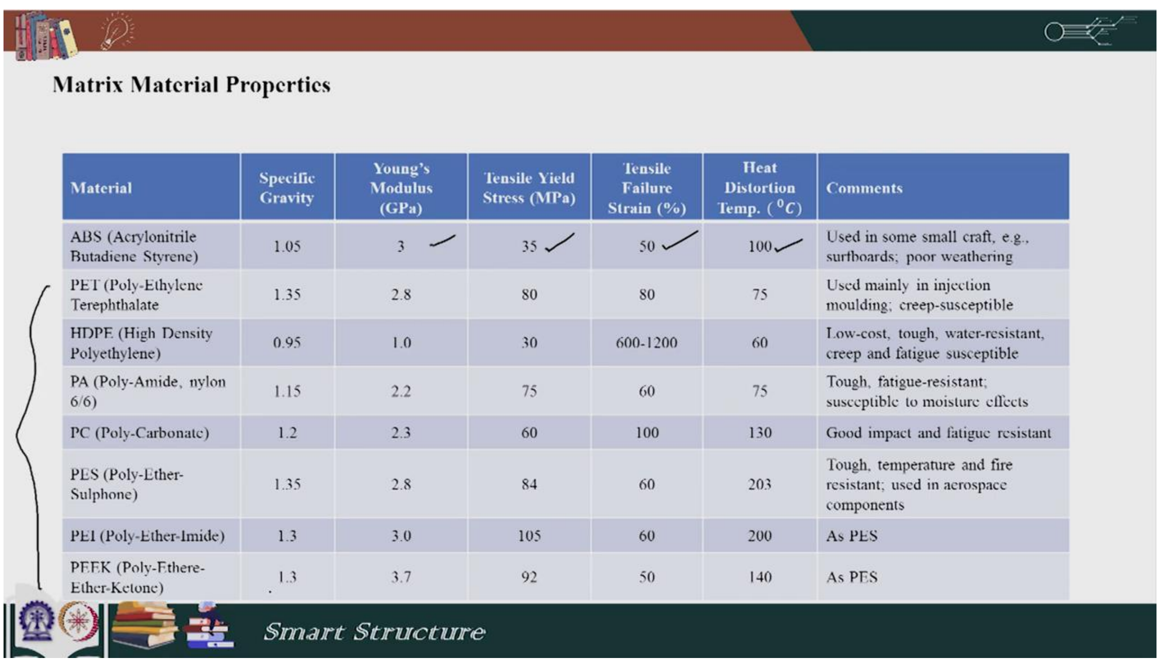

Material	Specific Gravity	Young's Modulus (GPa)	Tensile Yield Stress (MPa)	Tensile Failure Strain (%)	Heat Distortion Temp. (^0C)	Comments
ABS (Acrylonitrile Butadiene Styrene)	1.05	3	35	50	100	Used in some small craft, e.g., surfboards; poor weathering
PET (Poly-Ethylene Terephthalate	1.35	2.8	80	80	75	Used mainly in injection moulding; creep-susceptible
HDPE (High Density Polyethylene)	0.95	1.0	30	600-1200	60	Low-cost, tough, water-resistant, creep and fatigue susceptible
PA (Poly-Amide, nylon 6/6)	1.15	2.2	75	60	75	Tough, fatigue-resistant; susceptible to moisture effects
PC (Poly-Carbonate)	1.2	2.3	60	100	130	Good impact and fatigue resistant
PES (Poly-Ether-Sulphone)	1.35	2.8	84	60	203	Tough, temperature and fire resistant; used in aerospace components
PEI (Poly-Ether-Imide)	1.3	3.0	105	60	200	As PES
PEEK (Poly-Ethere-Ether-Ketone)	1.3	3.7	92	50	140	As PES

Then comes the matrix which is thermoplastic. So, here after curing we can heat it and melt it. Now there are different types of this polymers. ABS used in small craft for example, surfboard, but they have a poor weathering. Specific gravity 1 to 1.05, Young modulus 3 giga Pascal, tensile yield stress is 35 mega Pascal, tensile failure strength 50 percent, heat distortion temperature in centigrade is 100. Similarly there are various types of this polymer resins and we can see their comparisons.

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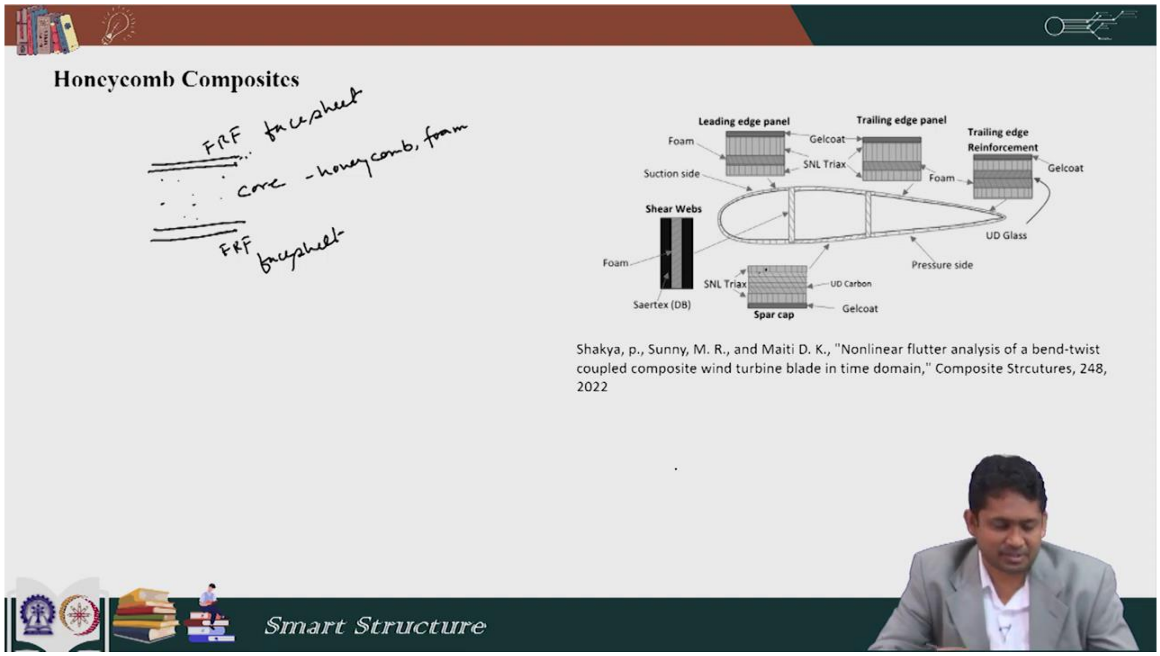

Now, let us spend some time in talking about the honeycomb composites. In honeycomb composite, there are two phase sheets, the phase sheets can be a fiber reinforced composite laminate and at the core there is some core material.

So, we can see a FRP at the phase. So, they are called phase sheet. Now again, phase sheet always does not need to be FRP. It can be a metal also and the core can be honeycomb may be of aluminum, there can be foam, there can be cellular core and so on. Now, we get tremendous advantage by using honeycombs. We get much more strength and stiffness with less weight. So, here we can see that these fibers reinforced plastics they have high Young modulus.

So, they are placed at the two extremes. So, that takes care of the bending and this deep core takes care of the shear. So, accordingly we can go for better light weight and high strength design with honeycomb composites. Now for example, here we are showing one airfoil section of a wind turbine blade. So, we can see that at different places there are foam cores and various laminates are used and at the surface there is a gel coat for better finish and better protection.

So, again these laminates have different names like SNL, Triax, Sertex. So, mostly unidirectional laminates are there. So, this gives an overview of how this composites are placed and the foams are placed and the protective materials are placed to make a real life airfoil composite structure. So, with this brief introduction I would end this lecture here. Now we will gradually move on to analysis. So, as we said in this course we will restrict our self to unidirectional composite.

So, in the next lecture we will start looking into the properties of a unidirectional ply. So, we have the properties of each individual constituents here. So, for example, in a glass fiber reinforced composite, we can have the properties of glass fiber and the matrix material, the matrix material can be epoxy or polyester and so on. Similarly, in a carbon fiber composites, we can have the properties of carbon fiber and the matrix material and from those constituents we will see the properties of a lamina or ply. So, we will do some kind of homogenization, so that instead of having to deal with the individual properties, we will deal with the equivalent property of a composite and that will start defining from the next lecture and then we will gradually move on to the properties of a laminate and its analysis.

So, with this let us end the lecture here.

Thank you.