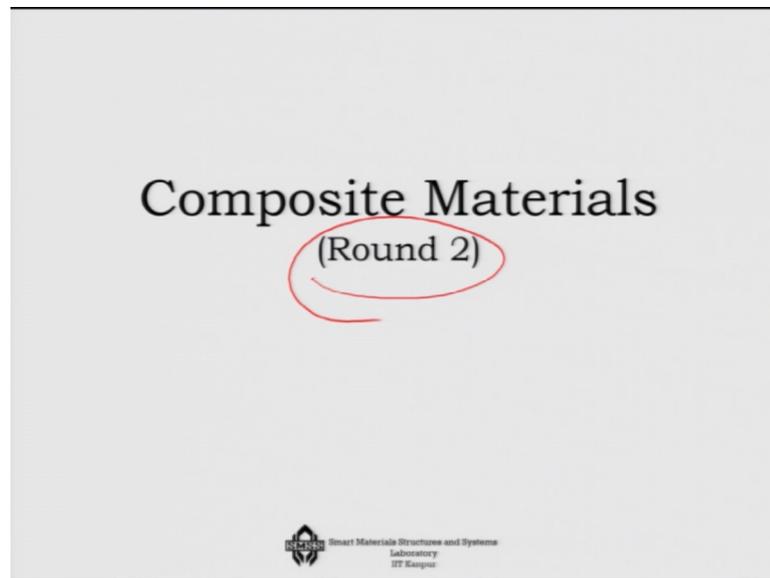


**Smart Materials and Intelligent System Design**  
**Prof. Bishakh Bhattacharya**  
**Department of Mechanical Engineering**  
**Indian Institute of Technology, Kanpur**

**Lecture – 07**

Good morning everybody. So, we are you know having this course on Smart Materials and intelligent System Design, in which we are specifically focusing in this module on composite materials, and this is the round 2 of the Composite Materials

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Whatever overview we have taken yesterday; in the last class, now we will be having the round 2 of it.

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The slide is titled "What we studied in previous lecture?" and contains the following content:

- ✓ Introduction to composites
- ✓ Smart Composites
- ✓ Composite Classification
- ✓ Composite Applications
- ✓ Fibers and their types

Handwritten notes in red ink on the right side of the slide:

- Glass { E, S, C
- Carbon
- Boron
- Polyamid (Kevlar)

Below the handwritten notes, it says: "Fibres/ reinforcements + Matrix".

At the bottom of the slide, there is a logo for "Smart Materials Structures and Systems Laboratory IIT Kanpur".

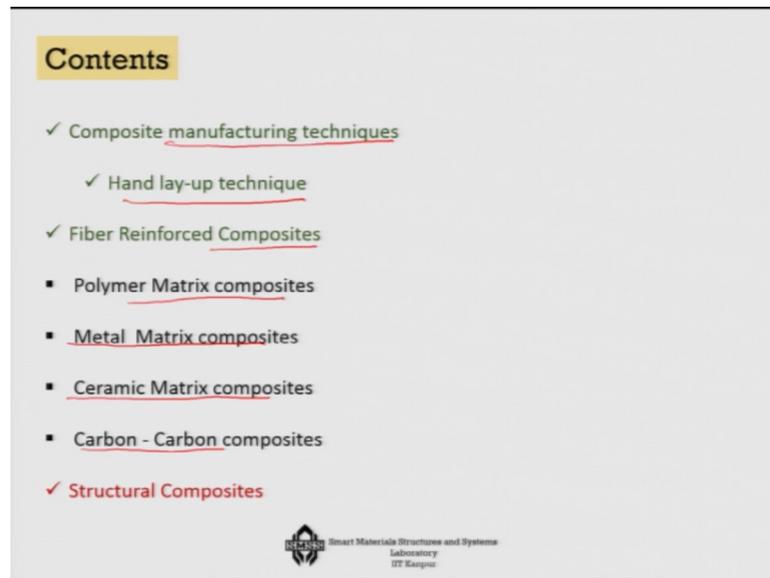
So, here we will talk you know; in the last one just very briefly I had introduced you to composites specifically smart composites, and then composite classifications, composite applications particularly, and also we have talked about various fibers; also although we have not touched all the fibers, but we have touched some of the very important fibers right.

If you remember what were this fibers; Glass fiber always keep in mind which has actually three different types: E fiber and the S fiber and the C fiber. So, this is very important for us to make a composite and then make it a smarter composite. Then also we have talked about carbon fiber and historically I have touched the issue of boron fiber. And, the only other thing that we have talked about are called polyaramides or Kevlars. Polyaramides are commonly known as Kevlar. So, these were the fibers that we have talked about.

Today let us see what we can do with these fibers in order to make a composite. Because as I told you already that in a composite we have to have fibers or some kind of reinforcement; it need not be in the form of a fiber, it can be in the form of chopped fiber even smaller, it can be in the form of viscous, even smaller it can be in the form of particle and even smaller it could be in the form of nanoparticles.

So, fibres are such reinforcements that you will need plus you will need a matrix. In fact, when you will make a smart composite lot of thought process has to go in terms of choosing this matrix also. So, let us see and all these things.

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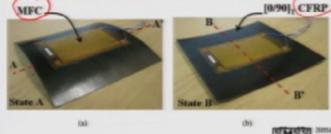


So, what we propose to study now is first of all a very quick overview of composite manufacturing technique with a special emphasis on Hand lay-up technique, there are other two techniques also: resin transfer molding and pultrusion which I will just very briefly mention each one of them. And then we will go to fiber reinforced composites and polymer matrix composites, metal matrix composites, ceramic matrix composites and carbon-carbon composites. And also we will talk a little bit about sandwiches.

So, hopefully once we do these things you will be able to get initiated into the micromechanics of such composites.

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### Composite Manufacturing Techniques

Hand Lay-Up	Resin Transfer Molding	Pultrusion
<p><b>Mold Preparation</b> - A mold of the part to be made is created and a <u>release film</u> is applied to the <u>mold's surface</u>.</p> <p><b>Gel Coating</b> - a specially formulated resin layer which will become the outer surface of the laminate when it is complete.</p> <p><b>Hand Lay-Up</b> - Fiberglass is applied, pre-measured resin and catalyst (hardener) are then thoroughly mixed together.</p> <p><b>Finishing</b> - The composite is allowed to <u>completely harden</u> and any machining or assembly can be performed.</p>	<p>Resin transfer molding (RTM) is a process used to manufacture composite components. Fibers (e.g. glass, carbon, Kevlar, etc.) are placed <u>dry in a mold</u> with the desired orientation. The resin is then <u>pumped in</u> to impregnate the fibers. This hardens to form a composite material.</p> <p>This process has three advantages in that it is inexpensive, stiffness can be provided in <u>all three directions</u>, and any shape can be constructed.</p>	<p>Automated Process for Continuous Manufacturing of Constant Cross-section Profiles. Profiles have high strength and thickness in the length direction.</p>
		<p>Video demonstration for Hand Lay-Up technique</p> 

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So, very quickly we will talk about the composite manufacturing techniques. Now there are many once again, but for the sake of this course we have made some very very brief you know and most important techniques that are used. So, accordingly I have chosen of hand lay-up, because most of the times this is the most popular one where we make the composite and we add the smart materials in that making process itself. One technique which is coming up is actually resin transfer molding, where we are adding the smart fibers in this case. And in order to know what is the curing process going on when a composite is getting harden

And pultrusion we will know, because it is very important, but so far pultrusion has not been added with the smart materials. Now if we first look into the hand lay-up technique mold preparation is a one of the very important part of a hand lay-up technique. So, you have to first prepare a mold, the over which you have to wrap basically the composite material. And then you have to make sure that the composite comes out beautifully.

So, you have to have a release film on the applied on the over the mold surface so that the it comes out beautifully. And there is we also put a gel coating which is a specifically formulated resin layer which becomes the outer surface of the laminate you do not want the fibers to actually come out, so we put a resin layer. So that is the second layer, it will also give a nice glossy finish to the composite. And then we apply the fiberglass.

And in terms of the fibers premeasured the resin and some catalyst, because this resins on its own if you want them to get harden and it will take a lot of time. So, in order to reduce the time and we increase the network densities of these thermoset polymers we use a catalyst or a hardener along with mix them all together. So, it is ready then you apply them over that fiberglass system and then you allow it to get harden with sometimes raised temperature, and also raised pressure. So, what we call an autoclave machine we actually used in order to do it ok. And this is the process which I referred to as the curing process.

Now, in the last class I have shown you this macro fiber composites right MFCs. As you can see that this is a aerofoil here over which what has been done and this is made of carbon fiber reinforced plastics. And there is a description of it 0 90 T. What is this? We will learn gradually, but it has different directions of plies at least that we can you know understand from here. And these two directions plies we apply all these release film gel coatings and then apply the resin. And finally, we put the MFCs outside. We can either surface bonds the macro fiber composite or we can you know also in another way of doing is we can embed the macro fiber composite inside the system.

Let us look at a very brief video in which I demonstrate you the hand lay-up technique.

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So, this was prepared by the Remmi Team in Finland. And, you will just very briefly see here that how they are making the composite laminates in this you know the process that I told you the application of resin films.

So, this one that you can see here this is actually carbon fiber. So, you see they are cutting the carbon fiber of the desired shape. Many times this carbon fiber comes with its own resin and we call it prepregs. So now you see, they are just smoothing the surface applying the release film, so that is getting done so that the composite would come out beautifully and then it is already resin coated. So, now what they are doing is that they are doing the hand lay-up of the ply. So, they are cutting in you can have as many number of layers as you wish ok.

At this stage also you can actually insert the smart you know actuators, but if you do. So, you must actually have you know the electrical leads there. Now there are applying a vacuum forming here as you can see; I told you that pressure is needed now you can have positive or a negative pressure in this case they are applying vacuum here so that the role of the pressure is that the resin will get very nicely uniformly wetted everywhere.

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So, that it is not that there is a resin pockets somewhere more resin somewhere less resin and here they are using the epoxy resin as you can see from the side.

So, epoxy resin is getting applied slowly, you can see that that vacuum that has been made nicely the resin is you know going everywhere it is spreading all around. And sometimes they also keep a additional bleeding pocket so that no extra resin remains there. And now you see that they are just opening it up the whole system and that is where you have the disc.

Incidentally these type of discs are actually used in automobile brake discs and things like that. So, sports car have a good demand of this type of carbon fiber reinforced discs.

The second one in terms of composite manufacturing is actually resin transfer molding. And in this resin transfer molding process what we do is that we first make the pre form of the fiber and then resin are placed this whole thing in a you know dry condition in a mold and then you pump the resin to impregnate the fibers. So, you can as this is the way you know you can actually make quick prototypes etcetera. The only thing here is that the fibers there are in all the direction. So, here you can actually artificially create anisotropy ok. So, here you can create anisotropy, but that means by changing the fiber angle etcetera,, but here there is generally you know you cannot create an isotropy. So, this is I would rather say homogeneous and isotropic that is you know. So, some applications need this kind of a thing where you need to provide you know fibers along all the directions, because possible sources of loading can be from all the directions.

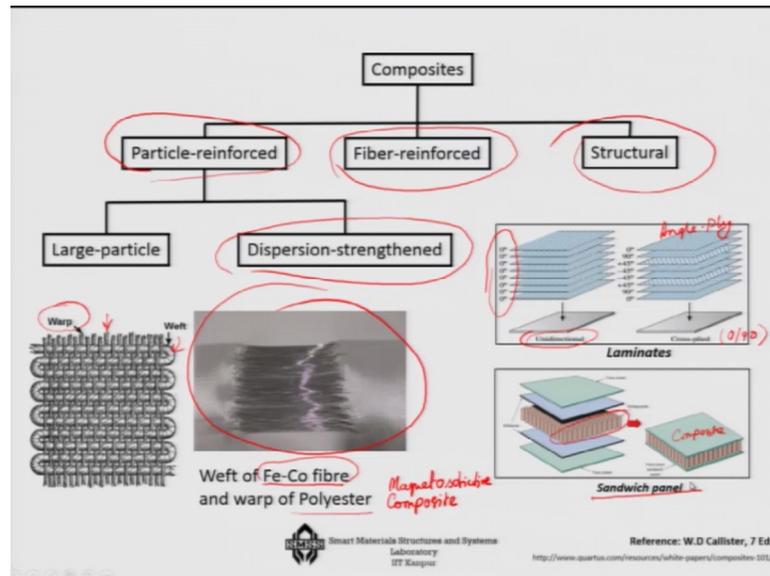
Now how the smart materials is coming into picture? Well, this is one such you know think that is very recent work is getting done in which you can see optical fiber leads you can see here right. All these optical fibers we will call them as OF hence forth. This optical fibers they insert it so that whenever this resin impregnation is happening the optical fiber can actually give you the exact condition. Sometimes they also use other conductive wires to do that the exact condition of waiting how much percentage is getting weight etcetera or not.

Now, that is about resin transfer molding. There is another automated process which is called pultrusion and in this particular process what they have is that they actually have the fibers which gets pulled. So, pultrusion is actually pull plus extrusion that is what we will call as pultrusion. So, in this pultrusion process what they do is that they continuously pull the fibers and there is a resin pocket in which these fibers are getting dipped and then they are pulled again. So, as a result you know you are getting

composites in the form of plate actually ok; unidirectional composite plates. And later on you can arrange them for various forms of laminates etcetera.

So, that is about a very brief introduction to the composite manufacturing technique.

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Now if we proceed further let us talk about the different types of composites that you can produce a through this ways in terms of architecture. You can have reinforcements as particle reinforcements which can be used in resin transfer molding or such processes. You can have fiber reinforced, and that I have shown you just now you can have structural composites ok

Now, in terms of the fiber reinforced there is one very good example this is used in magnetostrictive composites. So, magnetostrictive material it is used both in terms of fiber reinforced as well as in terms of particle reinforced composite. Now in the fiber reinforced composite what they do is that; they actually make Fe-Co of fibers. And they make pattern in which I have already told you about different architectures particular unidirectional ones. In this case it is a bidirectional one in which in the fiber you know architecture you have a warp part which are the straight parts as you can see that is the warp. And there is this weft part now this warp part is made of polyester and the weft part is actually made of iron cobalt fiber. So, you get something like that.



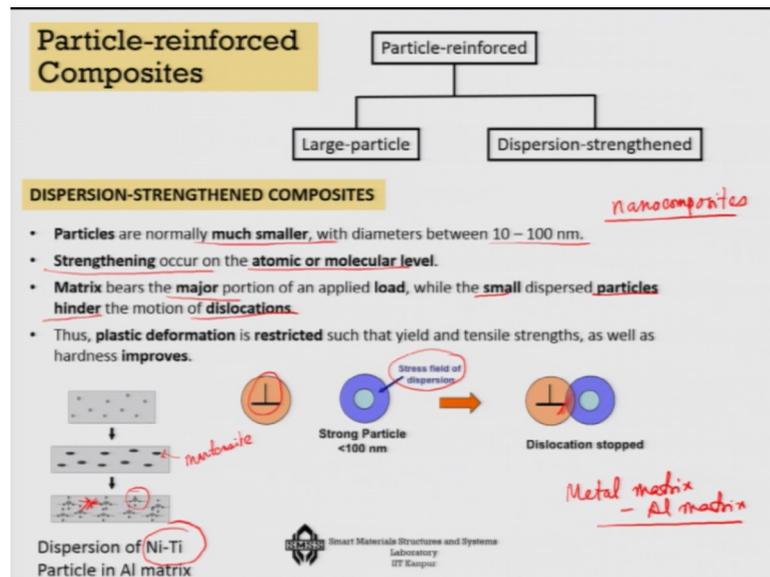
Now, Terfenol-D is actually used for this dispersion these large particle based reinforcements. For example, Terfenol D which is a magnetostrictive material you already know it is actually mixed with epoxy resin, and the particulate phase is harder stiffer and this is what that impart the magnetostrictive behavior. So, these reinforcing particles will restrain the movement of the matrix phase in the vicinity of each particle. So, that is the hardness is coming into picture. And the matrix role is to transfer the fraction of applied load to the particles.

So, it is a Terfenol-D particle which works like a big boss, it actually takes the load, it also deforms itself and matrix has to be the follower; its role will be that all the particles are getting equal share of the loading. So, in a micro scale you can see that you know how these particles are getting you know; so this are the particle as you can see this are Terfenol-D particles this white parts and all along what you have is the resin.

If the particles behave the way wires behave then you get further you know anisotropy further strengthening extra, but to do that you have to align the particles. How do we align such particles? While one way to do is that while manufacturing you keep magnets so that the particles will align themselves along these lines; as you can see that all particles are aligning themselves along these lines and a sort of particle chain is getting created inside epoxy. As a result you get you know a sort of a directionality designs which helps in a lot of way; that means, you can then have a control over the nature of deflection of the system

So, that is about Terfenol-D in a large particle case. Let us look into another example of dispersion strengthening.

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Now, in case of dispersional strengthening particles are normally much much smaller, something like in the nanometer level. In fact, that is what is used for making something which is called nanocomposites. So, nanocomposite what is nano in it. The nano part that is in it is nothing, but this nanoparticles of you know various passive material or active material, if the active material is Terfenol-D can be also made in nanoparticles and the one that we are particularly would like to discuss is nickel titanium nanoparticles. Now of course, in this case the strengthening occurs at the atomic or molecular and as usual matrix bear in the one point one small difference is here with respect to the large particle one.

In the large political ones epoxies role was just so that the load is to make sure that the load is uniformly distributed, but in this case matrix can bear the major portion of the load. So, what kind of matrix can do it? Polymeric matrix generally cannot do it well yes the metal matrix can do it ok. So, these metal matrix are like you know aluminum matrix in this particular case, they can do it beautifully.

So, metal matrix and inside that you have this small dispersed nanoparticles which will hinder the motion of the dislocations. Because you know most of the times the strength of the metal gets degraded, because of the presence of dislocations in the metallic crystals.

So, that dislocations movement side these or between the grains if that can be stopped or restricted then you know you can get a much higher strength. So, that is what you know is done here. So, you can see that there is a dispersion, as there is a dislocation here and you can see this stress field of the dispersion, and you have a strong particle here; that strong particle is actually affecting these you know movement of the dispersion it is blocking the movement of the dispersion.

It can also generate its own you know state of stress around so that you can completely you know make it much more tougher etcetera. So, you can see here that nickel titanium particles are inside and in a deformed state so this will be possibly in the low temperature marten site state. Now you hit it up ok; that means, you go to say higher temperature. Immediately these fellows will try to expand and they cannot because they are inside a matrix so they are going to develop sort of you know a state of stress depending on how they are expanding or trying to expand that is actually a generating compressive stress.

So that, compressive stress imagine that if you have a crack here. So, because this fellow is trying to expand so there is a compressive stress from both the sides which will not allow the crack to expand. So thus, dispersion of nickel titanium particle in aluminum matrix is a good example of dispersion strengthening.

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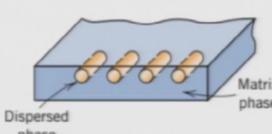
### Fiber-reinforced Composites

#### The Fiber Phase

**Role of fibers in composites includes:**

- To enhance stiffness and strength
- To initiate shape change ~~✗~~
- To provide crack-bridging
- To enhance thermal resistance



Dispersed phase

Matrix phase

On the basis of diameter and character, fiber phase can be grouped into

- **Whiskers** : They are very thin single crystals that have extremely large l/d ratio but has the form of fiber.
  - ✓ Flaw free and thus extremely high strength – but expensive. *damping <math>< \mu\text{m}</math>*
  - ✓ Include graphite, zirconia, and PMN-PT, etc.
- **Fibers** : A material that has at least l/d ratio equal to 10 : 1 *- ✓ Either polycrystalline or amorphous.
  - ✓ Generally polymer and ceramics*
- **Wires** : Relatively large diameters *- ✓ Typical materials include Ni-Ti wires*



Reference: W.D Callister, 7 Ed.

Now, we will come to fiber reinforced composites ok. This is the most popular one out of all the smart composites. So, here what will be the role of fibers? Well, in like just like

traditional composites they will definitely enhance stiffness and strength in comparison to the matrix. They will initiate shape change in the whole system; I must have shown you the macro fiber composites so that is a one example of a fiber reinforced composite. They will also help in terms of crack bridging; we will discuss it we will talk about cell filling. They enhance thermal resistances and some other you know properties also you can improve through them.

Now, this fiber can be of three different forms if it is small very small  $l$  by  $d$  ratio you know wise so then we call it as viscous ok. So, this viscous are actually flaw free so that way they are having high strength, but they are expensive there is graphite as viscous, zirconia as viscous, PMN-PT as viscous and they are generally used for damping; structural damping these are very good also for strength improvement etcetera.

Now, if it has  $l$  by  $d$  ratio at least equal to 10 is to 1 then if the more the better then it will become the fibers. And they are can be polycrystalline like piezoceramic fibers or they can be amorphous like you know if we develop the glassy fibers of things like that. And generally they are made of polymers or ceramics right; like polycrystalline fiber is a ceramic one the active fiber composites they have they use the piezoceramic fibers also sometimes you can use the polymers.

And, a about the other feriation that is wires they are relatively of large diameter. The diameter that we are talking in this case it is about micron meter range, in this case the diameter can be less than micron meter range, and in this case the diameters are greater than the micron meter range. And these are relatively large typically nickel titanium wire for example, is used in terms of wires in the fiber reinforced composite.

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**Fiber-reinforced Composites**

**The Matrix Phase**

Role of matrix in composites includes

- Binding fibers together
- Protect the individual fibers from damage by external environment.
- Act as a medium to transmit and distribute externally applied stress to fibers.
- Serves as a barrier to crack propagation
- Serves as a conductive/permeable medium

It should be noted that :

- ✓ The matrix material should be ductile.
- ✓ Elastic modulus of the fiber should be much higher than that of the matrix.
- ✓ There should be adequate bonding between matrix and fibers.

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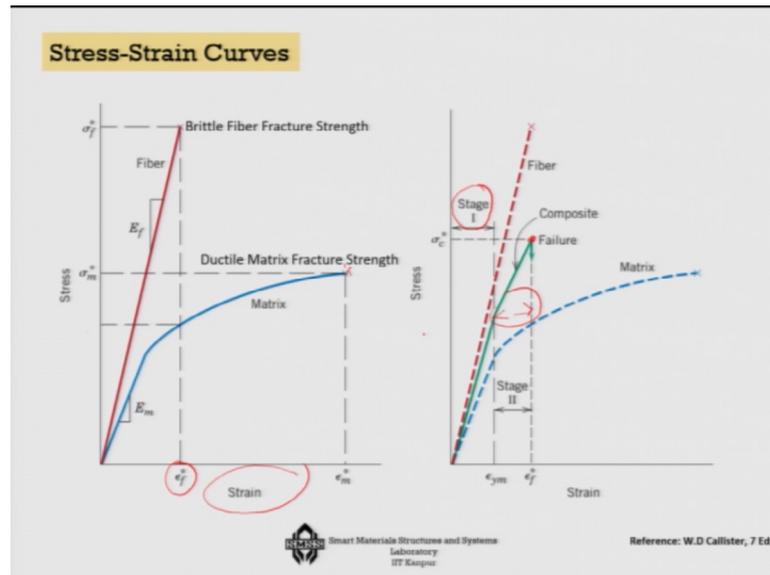
Now, what is the role of matrix in the fiber reinforced composites? A, is that it binds the fibers together; that is very important otherwise the fibers will work individually that will not help us. It will protect the individual fibers from damage by external environment. As I told you that glass and ceramic fibers often get damaged in the handling; so the matrix protects that.

It act as a medium to transmit and distribute externally applied stress to fibers. So, this also I told you that matrix takes the load first and make sure that none of the fiber remains idle they get you know equally loaded. And they also serve as a barrier to crack propagation; if the crack start they are the first barrier and then it goes to the fibers. Sometimes, it serves as conductive or permeable medium; this is very important when we will be making smart composites. I told you that is nickel titanium wire reinforced composites if you try to make then in that case you would see that this nickel titanium wire is to be heated.

Now, by applying heat through direct electrical leads that is something difficult sometimes difficult to do. So, what we do is that we use a conductive matrix and we heat up that conductive matrix very easily and then through that the nickel titanium wires are actuated. So, that is how we know that could be another additional role for smart composites the matrix of a smart composite.

So, the matrix in general should be ductile, elastic modulus of the fibers in general are much higher, and there should be adequate bonding between matrix and fibers. This is an area of active research that how can you enhance adequate bonding. In fact, if you can generate fibers which can do this you know those kinds of fibers are of very high demand.

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Now, we just very briefly look at the stress strain curves. So matrix being ductile: as you can see that it takes a large amount of strain before it actually fails here. And fibers being brittle you can see that it takes only epsilon f times much less strain for failure, so naturally we expect the composite to be somewhere in between as you can see that it shows some amount of you know plastic strain before it goes to failure.

Generally, we consider when the fibers fail in the composite we consider that to be the failure point. So, a composite will have 2 stage: a stage 1 that is the elastic stage and a stage 2 where the plastic region will be coming into picture. So, that is the composites stress strain behavior.

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**Polymer-Matrix Composites (PMC)**

Matrix – Polymer resin — *Epoxy*  
Fibers – reinforcing medium

A) **Glass Fiber-Reinforced Polymer (GFRP) Composites**

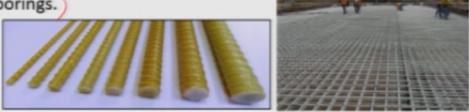
Matrix – Plastic (most often epoxy, polyester resin)  
Reinforcement – Glass fiber/E-glass (Diameter = 3-20  $\mu\text{m}$ ) + MFC/AFC/OE

- ✓ Typically 55% SiO<sub>2</sub>, 16% CaO, 15% Al<sub>2</sub>O<sub>3</sub>, 10% B<sub>2</sub>O<sub>3</sub>, 4% MgO.
- ✓ Easily drawn into high-strength fibers from the molten state.

**Limitation** – Service temperature up to 200°C (above which polymer/matrix starts deteriorating).

**APPLICATIONS**

Automotive and marine bodies, plastic pipes, storage containers, and industrial floorings.



*GFRP rebar used for making pedestrian bridges*

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Now, in terms of polymeric matrix composites we have matrix as polymer resins like epoxy and we have you know fibers as I told you. So, suppose I use glass fiber; E-glass fiber diameter between 3 to 20 micron meter. And I can use also some additional fibers, like macro fiber or active fiber or optical fiber we can do that ok. So, that is what is the fiber part and the matrix part is something like epoxy or polyester resin.

Now this is used mostly in building up automotive marine bodies and different types of storage you know containers industrial floorings. Industrial flooring active glass fiber composite is very much used for noise suppression.

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**Polymer-Matrix Composites (PMC)**

**B) Carbon Fiber-Reinforced Polymer (CFRP) Composites**

Matrix – Polymer resin  
Fibers – Carbon fiber (reinforcement)/Graphene/SMA

- Carbon is a high-performance fiber material because
  - ✓ **Highest specific modulus** ( $E/\rho$ ) and **specific strength** of all reinforcing fiber materials and **retain same at elevated temperature.**
  - ✓ At room temp. **not affected** by moisture or a wide variety of solvents, acids, and bases.
- Fiber diameters normally range between 4 - 10  $\mu\text{m}$ .

**Applications**



**Lamborghini Aventador LP700-4**  
CFRP - Wheels, frame, seats



**Boeing 787 Dreamliner** – nearly 50% frame of CFRP

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The other group I have shown you that is the carbon fiber reinforced group in which the matrix remains the polymer and fiber is the carbon fiber system. So here, because of the carbon fiber you get highest specific modulus specific strength is can work in the elevated temperature. And that is why it is used mostly in all these types of you know sports cars or racing cars advanced automobiles and also in advanced aircrafts like this, Boeing Dreamliner. So, that is what is the carbon fiber reinforced.

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**Polymer-Matrix Composites (PMC)**

**C) Aramid Fiber-Reinforced Polymer (AFRP) Composites**

- **Trade name** of most common Aramid fiber – **Kevlar™** and **Nomex™**
- **Chemically**, this group of materials is known as **poly(paraphenylene terephthalamide)**.
- Known for its toughness, impact resistance, and resistance to creep and fatigue failure.
  - ❖ Strong covalent bond axially, weak hydrogen bond transversely.
  - ❖ Negative Coefficient of expansion due to kinks
  - ❖ UV sensitive – degrades

**Applications**

- Ballistic products (bullet proof vests and armor)
- Sporting goods
- Ropes
- Missile cases
- Replacement for asbestos in automotive brake and clutch linings, and gaskets.



**Bullet proof Vest**

Smart Materials Structures and Systems Laboratory IIT Kanpur Reference: W.D Callister, 7 Ed. [www.kevlarp.dupont.com](http://www.kevlarp.dupont.com)

One aramid fiber reinforced composites are generally used for making bullet proof jackets as you can see. So, they are good in terms of shock absorption. And that is why you know they are used in these cases. And here also we have actually different types of smart fibers we insert inside in terms of making what we today call intelligent textiles which takes care of not only you know that what is the kind of you know curing process etcetera, but also what is the state of stress whether there is a fracture already need then you cannot use the bullet proof jacket for the second time of use etcetera.

So, in all these cases you would need the aramid fiber you know reinforced composite along with some intelligent fibers in it.

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Comparison				
(Fibre volume fraction = 0.6), Epoxy matrix				
Material	Tensile Modulus (GPa)		Tensile Strength (MPa)	
	Longitudinal	Transverse	Longitudinal	Transverse
GFRP (2100 kg/m <sup>3</sup> )	<u>45</u>	<u>12</u>	<u>1020</u>	40
Aramid (Kevlar-49) (1440 kg/m <sup>3</sup> )	<u>76</u>	5.5	<u>1380</u>	30
CFRP (1600 kg/m <sup>3</sup> )	<u>230</u>	10	<u>1240</u>	40

Now, there is a brief comparison. If you go for GFRP your tensile modulus is about 45, your transverse modulus is 12, longitudinal strength is 1020 MPa, but if you look at a Kevlar it has a higher modulus it has higher tensile strength. If you look at CFRP you have even higher thinks the tensile modulus and you have even higher tensile strength in the system. So, that is a brief comparison between the 2 system.

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**Metal-Matrix Composites (MMC)**

**Matrix** – Ductile Metal (usually alloys of aluminum, magnesium, titanium, and copper)  
**Fibre** - Carbon, Silicon Carbide, Boron, Aluminum oxide, Ni-Ti, Fe-Co

Advantage over PMC includes:

- ✓ Higher operating temperatures.
- ✓ Non-flammability.
- ✓ Greater resistance to degradation by organic fluids.

**Demerit:** MMCs are costlier than PMCs

**Properties of Several Metal-Matrix Composites Reinforced with Continuous and Aligned Fibers**

Fiber	Matrix	Fiber Content (vol%)	Density (g/cm <sup>3</sup> )	Longitudinal Tensile Modulus (GPa)	Longitudinal Tensile Strength (MPa)
Carbon	6061 Al	41	2.44	320	620
Boron	6061 Al	48	—	207	1515
SiC	6061 Al	50	2.93	230	1480
Alumina	380.0 Al	24	—	120	340
Carbon	AZ31 Mg	38	1.83	300	510
Borsic	Ti	45	3.68	220	1270

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Reference: W.D Callister, 7 Ed.

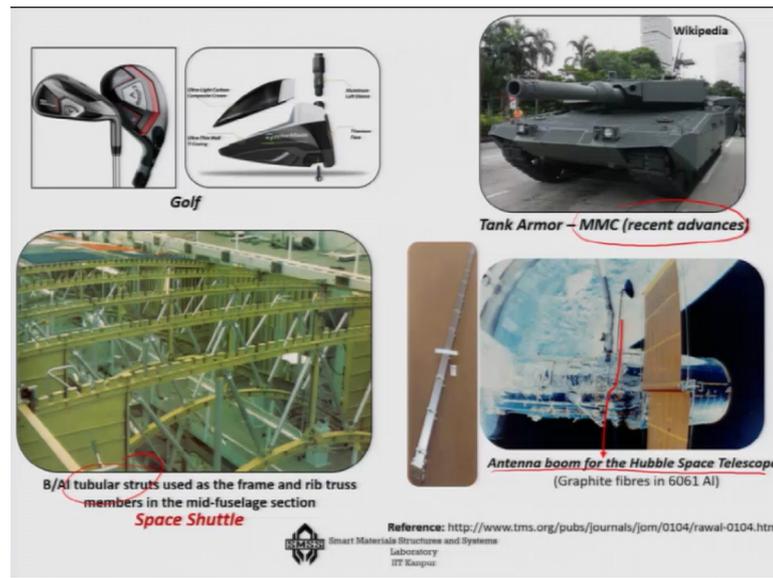
And then we will talk about metal matrix composite. We have talked about polymer matrix composite, another matrix that we can use is metal matrix composite. Now once again matrix should be ductile. So, we use ductile metals like aluminum is very popular also magnesium, titanium, and copper are used as matrix. As fiber you need to you know in this case is not the ductility, is not the just the strain, but you also need to improve sometimes the hardness of the system, fracture toughness, etcetera. So, we put fibers as carbon fiber silicon carbide boron aluminum oxide and the last 2 are smart materials; nickel titanium or ferrous cobalt system.

So, you see the intention here is that to improve the property of the basic matrix like let us say aluminum ok. So, to improve you know you can give some additional hardness to the system, you can also improve it is strength of the whole system. And in addition to that you can use it for structural controlling structural deformation and things like that. So, that is what is the MMC. Advantage is that you have a higher operating temperature, it is non flammable, and you have a greater resistance to degradation by organic fluid.

For many you know applications in space types applications this is actually quite good. And I have given here just for your you know comparison sake of several metal matrix composites which are reinforced with continuous and aligned you know fibers like carbon fibers etcetera. One important thing you have to see here is that the fiber content cannot be too high, sometimes it is quite low in fact here this the only case where it is

little high ok. And the density that you are achieving is not very low, because in comparison to polymer composite. On the other hand you can see here that the strength that you are getting can be actually very high. Some of the cases like borons silicon carbide borosilicate extra. So, that is what is the metal matrix composites.

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Where we can use it well golf balls sports applications one of the fantastic application is metal matrix composite: Tank Armors made of metal matrix composites, space shuttles or other tubular struts metal matrix composite, antenna boom of the Hubble Space Telescope is made of metal matrix composite; so, quite a few high end applications.

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**Ceramic-Matrix Composites (CMC)**

- Ceramics are **highly brittle** in nature. Thus, **low fracture toughness**.
- In general the fracture toughness of
  - ✓ Ceramics :  $1 - 5 \text{ MPa } \sqrt{\text{m}}$
  - ✓ Metal alloys :  $20 - 90 \text{ MPa } \sqrt{\text{m}}$
- By using CMC, fracture toughness can be increased to lie in the range  $6 - 20 \text{ MPa } \sqrt{\text{m}}$ .
- Crack initiation normally occurs within **matrix phase**, whereas **crack propagation** is hindered by the **particles, fibers, or whiskers**.
- Exhibit **improved** high-temperature **creep behavior** and **resistance to thermal shock**.



Cermet inserts





Brake disc of Ferrari Race Car  
(Carbon fiber-reinforced in SiC matrix)

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Reference:  
[www.ceramec.com](http://www.ceramec.com)  
<http://global.kyocera.com/news/2008/1202.html>

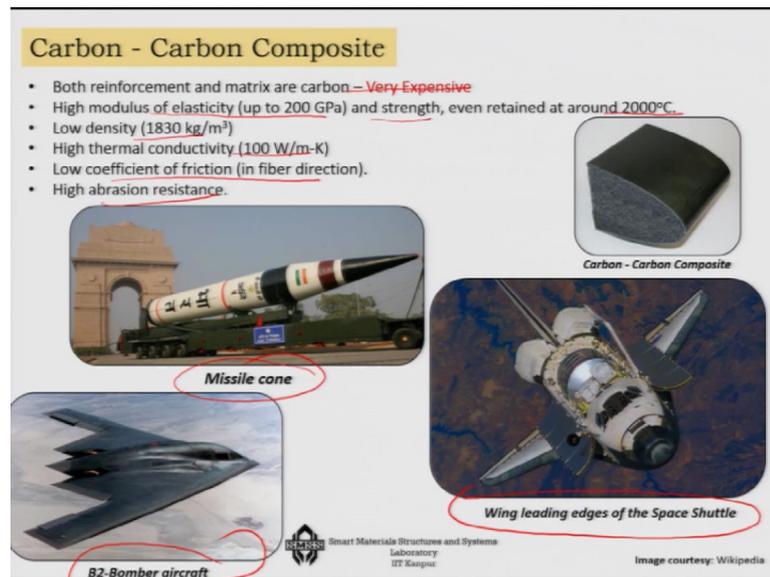
Now we talk about ceramic matrix composites. Ceramics as matrix they are highly brittle in nature. So, definitely they are going to have low fracture toughness. In general for example, the fracture toughness of ceramics is 1 to 5 MPa root meter and for metal alloys 20 to 90 MPa root meter. So, if I mix you know metallic fibers in ceramics then I am going to increase the fracture toughness of the ceramics. And that means, you know the crack initiation which will normally occur in this case in the matrix space. So, that will be hindered by the particles, fibers or whiskers. I have already shown you how dispersion strengthening can happen by using actually these parts you know nickel titanium particles.

So, that can be you know applied in ceramic matrix in order to increase the fracture toughness. So, there are different types of ceramic inserts where we make it of ceramic matrix composites or brake disc of Ferrari race car is of you know ceramic matrix composite.

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### Carbon - Carbon Composite

- Both reinforcement and matrix are carbon – **Very Expensive**
- High modulus of elasticity (up to 200 GPa) and strength, even retained at around 2000°C.
- Low density (1830 kg/m<sup>3</sup>)
- High thermal conductivity (100 W/m-K)
- Low coefficient of friction (in fiber direction).
- High abrasion resistance.



Carbon - Carbon Composite

Missile cone

B2-Bomber aircraft

Wing leading edges of the Space Shuttle

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Image courtesy: Wikipedia

Now finally, we talk about carbon-carbon composite; they are very very expensive, because they are unusually high in terms of modulus of elasticity strain specific modulus of elasticity. Suppose you go to 200 GPa with as light as close to the density of water you can imagine that what is the you know kind of lightness per stiffness we are talking about. And the temperature resist up to 2000 degree centigrade. So, this is some of the fantastic very advanced materials that has been created by this material specialist.

So, low density, high thermal conductivity I told you that that is a good thing that can be used in terms of activating shape memory composites, low coefficient of friction in the fiber direction, high abrasion resistance. There are lot of defense based applications, you know lot of them a space shuttles for example; so carbon-carbon composite is very much used in all this advanced applications.

So, this is where is the general you know polymeric matrix composite.

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### 1. Laminated Composites

- A laminate is constructed by stacking a number of laminae.

**Examples**

- Unidirectional laminate**
  - Fiber orientation angles are the same in all laminae such as  $\theta = 0^\circ$ .
- Angle-ply laminate**
  - Fiber orientation angles in alternate layers are  $/\theta/-\theta/\theta/-\theta/$ , where  $\theta \neq 0^\circ$  or  $90^\circ$ .
- Cross-ply laminate**
  - Fiber orientation angles in alternate layers are  $/0^\circ/90^\circ/0^\circ/90^\circ/$ .
- Symmetric laminate**
  - Identical ply (in material, thickness, and fiber orientation angle) at an equal distance about centerline, i.e.,  $\theta(z) = \theta(-z)$ , where  $z$  is the distance from the mid-plane of the laminate.

1	2	3	4	5	6	7	8
0	+90	-45	-45	+45	+45	+90	0

Code:  $[0/90/45/-45]$

Unidirectional laminate

Angle-ply laminate

Cross-ply Laminate

Symmetric laminate

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Now, I just introduce you to the concept of structural composites. And here, you can have many variations based on the variations of fiber angles, like if it is  $\theta = 0^\circ$  you get unidirectional laminate, if some other angles you get the angle ply laminate, if it is 0 and 90 you get the cross ply laminate. And, there is another thing that is possible that you arrange them in a symmetric manner. Now symmetric manner with respect to what; with respect to the geometric mid plane of the system; like if you look at this that you have eight layers 0 plus 90 plus 45 minus 45 and then again minus 45. So, you have 1 2 3 4 layers here, this is the line of symmetry minus 45 plus 45 plus 90 0 exactly the symmetry. So, you can actually take half of it and put a s to say that this is a symmetric laminated plate.

So, you can you know develop later on we will show that what is the advantage of developing symmetric or asymmetric plates.

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• **Symmetric laminate (contd.)**

- ✓ The bar over 90° indicates that the plane of symmetry passes midway through the thickness of the 90° lamina
 

1	2	3	4	5
[0/+45/90/+45/0]				
Code:				
- ✓ Adjacent +45° and -45° laminas are grouped as ±45°.
 

1	2	3	4	5	6	7
[0/+45/-45/90/-45/+45/0]						
Code:						
- ✓ Four adjacent 0° plies are grouped together as 0<sub>4</sub>.
 

1	2	3	4	5	6	7	8	9	10	11	12	13	14
[0/90/0/0/0/+45/0/45/0/0/0/0/90/0]													
Code:													
- ✓ Two adjacent ±45° plies are grouped as (±45)<sub>2</sub>.
 

1	2	3	4	5	6	7	8	9	10
[0/45/-45/+45/-45/+45/0]									
Code:									

• **Antisymmetric laminate:** Ref. : P. K. Mallick - Fiber-reinforced Composites Materials, Manufacturing, and Design-CRC Press (2008)

- ✓ Ply orientation is antisymmetric about the centerline of the laminate,  $\theta(z) = -\theta(-z)$ .
- Example : /+θ/-θ/+θ/-θ/ is an Antisymmetric laminate while /+θ/-θ/-θ/+θ/ is Symmetric laminate.

• **Quasi-isotropic laminate:** Equal angles between each adjacent lamina.

- ✓ If the total number of laminas is n, the orientation angles of the laminas are at an increments of  $\pi/n$
- ✓ Example: [0/+60/-60], [0/+45/-45/90]

N = 3 (Δθ = 60°)      N = 4 (Δθ = 45°)      N = 6 (Δθ = 30°)

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 Ref: [https://people.iitk.ac.in/courses/20230402/lecture17/17\\_7.htm](https://people.iitk.ac.in/courses/20230402/lecture17/17_7.htm)

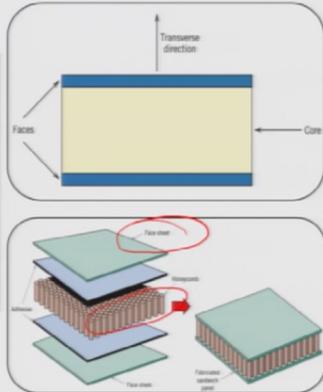
So, this is a symmetric laminate plates for example, 0 45 90 symmetry and then if you have 45 minus 45 generally we group them as plus minus 45 another shortcut that we take. If there are four zeros generally we put them as 0 4 another shortcut we take. If there are 2 of plus minus 45 we tell them as plus minus 45 2, so to quickly refer then. Aand antisymmetric is a peculiar case where it is actually that with respect to the meet plane you actually loose the symmetry of the system. For example, look at this one that with respect to the meet plane here once side is minus another side is plus reverse, whereas, if it is like this then it will be a symmetric laminate. And quasi isotropic laminate where you have equals angles between each adjacent laminar. So, for example, 0 plus 60 minus 60 or this one; so these are all quasi isotropic they are generally isotropic in plane.

So, these are different descriptions of the composite laminates

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## 2. Sandwich Panels

- Consist of two **strong and stiff sheet faces** that are separated by a **core material** or structure.
- Combine relatively high strengths and stiffness with low densities.
- **Outer sheet** - aluminum alloys, fiber-reinforced plastics, titanium, steel, or plywood.
- **Core materials** - Rigid polymeric foams (e.g., phenolics, epoxy, polyurethanes), wood (i.e., balsa wood), and honeycomb (hexagonal cells).



*ACL D Active Constraint Layer Damping*

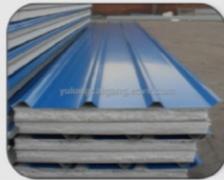


Reference: W.D Callister, 7 Ed.

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Now, the last thing is the sandwich panels. In this case what we have is that a strong and stiff sheet face sheets that we have and then adhesives and the honeycombs. So, honeycombs gives the lightness and also it gives this active seats at for away. So, this is used very much in applications like constraint layer damping ok; C L D we call it or A C L D active constraint layer damping we use this type of a system. In fact, when I will talk about one of the applications of vibration control I will talk about how you can develop anything using S E L D type of systems.

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Steel - Polystyrene Sandwich roof panel

**Sandwich panels**

1. Low water absorption
2. Good anti-corrosion
3. Good thermal insulated capacity



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This is how the applications of this type of systems generally for housings etcetera because it is very light, but sandwiches are now also applied in space applications.

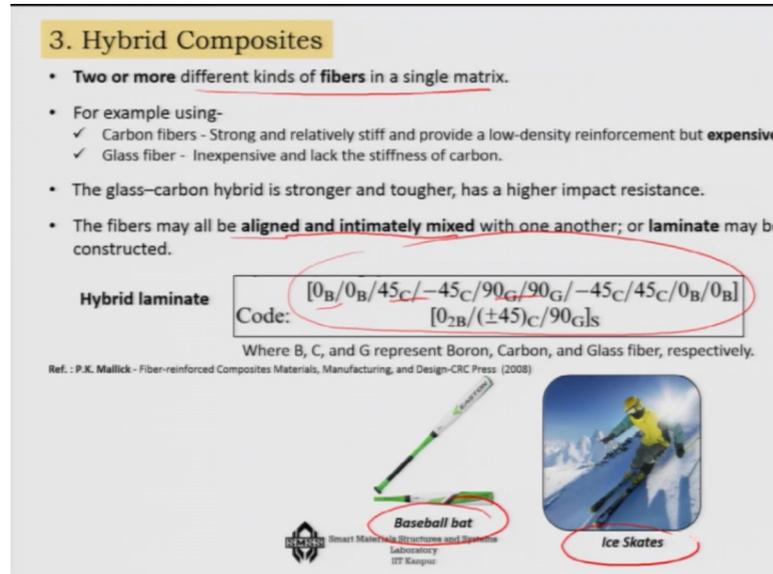
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### 3. Hybrid Composites

- Two or more different kinds of fibers in a single matrix.
- For example using-
  - ✓ Carbon fibers - Strong and relatively stiff and provide a low-density reinforcement but **expensive**
  - ✓ Glass fiber - Inexpensive and lack the stiffness of carbon.
- The glass-carbon hybrid is stronger and tougher, has a higher impact resistance.
- The fibers may all be aligned and intimately mixed with one another; or laminate may be constructed.

Hybrid laminate Code:  $[0_B/0_B/45_C/-45_C/90_G/90_G/-45_C/45_C/0_B/0_B]$   
 $[0_{2B}/(\pm 45)_C/90_G]_s$

Where B, C, and G represent Boron, Carbon, and Glass fiber, respectively.  
Ref.: P.K. Mallick - Fiber-reinforced Composites Materials, Manufacturing, and Design-CRC Press (2008)



Baseball bat

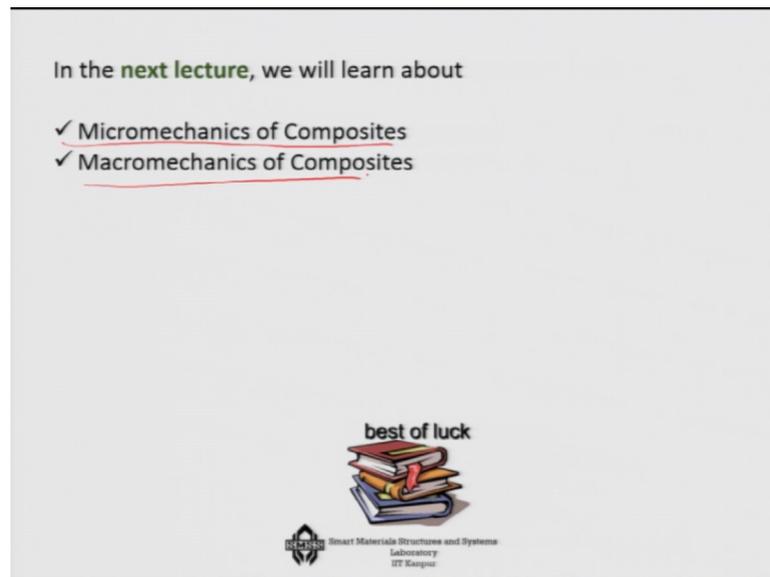
Ice Skates

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One last thing is the hybrid composite. In fact, all the smart composites are by default generally they are hybrid composites, because they have different kinds of fibers in it, they have passive fibers also they have active fibers. So, they become hybrid in nature. So, whenever more than one fiber comes into picture it becomes hybrid ok. And this fibers may all be aligned and intimately mixed with one another that is one of the objective so that they work integrated way. You can see one of the example of a hybrid fiber composite here where you are using boron fiber, carbon fiber, glass fiber all of them together.

So, you know many you know applications are now coming up in which we use the hybrid composite, which is invariably more expensive and it is more difficult to actually fabricate such systems.

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So, this is where we will put an end to this lecture. In the next lecture we will concentrate on the micromechanics of composites and further to the macro mechanics.

Thank you.