Carbon Materials and Manufacturing
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Lecture - 42
Carbon/ Metal and Carbon/ Concrete Composites: Manufacture and Properties

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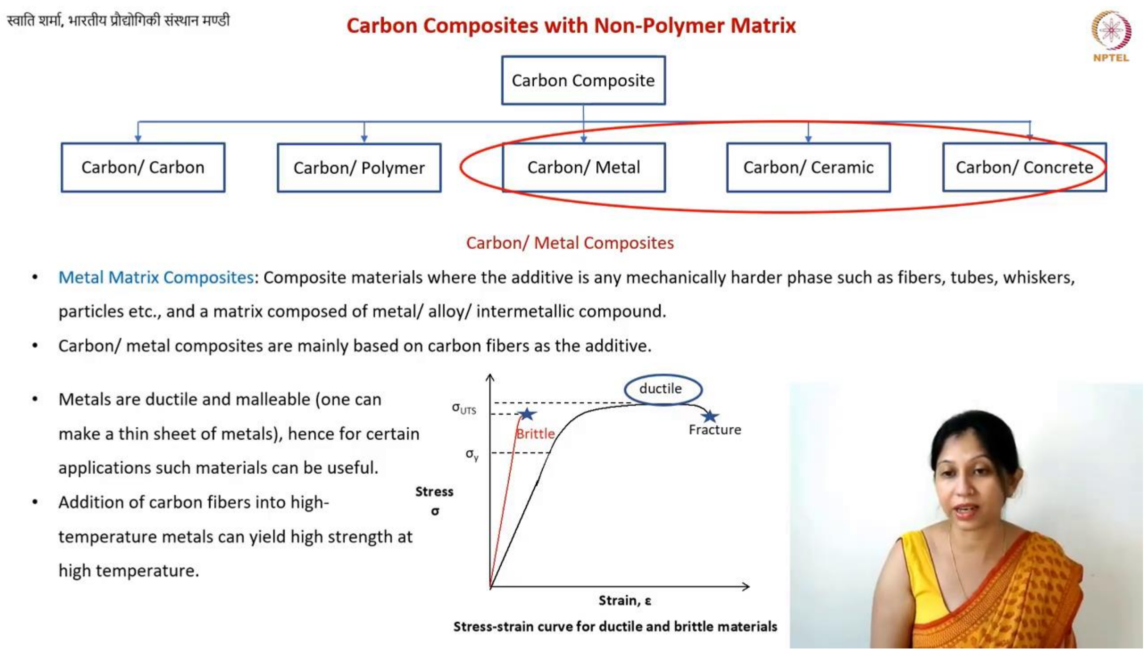

Hello everyone, in this lecture, we are going to learn about some other carbon-based composites. So, we have already learnt about CFRPS, Carbon Fiber Reinforced Plastics. We also know about carbon-carbon composites, but as I had mentioned previously, we also have other materials such as carbon metal, or carbon ceramic composites, or carbon concrete.

Basically, you can keep on changing the matrix, and then you can get newer carbon materials. In all cases, one thing that remains valid is that the interface properties are very important; the interface between your additive phase and your matrix phase.as we keep on changing the nature and the properties of the matrix, then the interface properties also accordingly change.

You need to perform the surface treatment that also accordingly changes. But in any case, that is very important for the strength of your structure. Now, I am not going into the details of the mechanics of all kinds of structures because I may not be an expert in some of these areas, for example, the carbon-reinforced concrete.

However, one thing that we are going to discuss is how to make these materials. So, some manufacturing aspects or some fundamental things about these three types of carbon-based composites. Let us get started with the carbon metal composites.as the name suggests you have a carbon additive which again is mostly carbon fiber, carbon fiber being the most common additive. So, it is carbon fiber mixed inside a metal matrix phase. So, how will that work? What are the things that change? we often mix these carbon fibers into polymer resins, now we are mixing them into metals. So, the manufacturing processes, the preparation processes will definitely change slightly, why?

Because the metals have different properties compared to your polymers. Their melting points are different, they have different ductility values, so that is why slight changes in the process will definitely be there. When we say metal matrix; it does not have to be an element, it can also be an alloy, it can even be an intermetallic compound.

So, any metal-based matrix is what we are talking about. In fact, sometimes we have these very high strength or high-performance alloys. And if you further add carbon fiber to it, then you can imagine that the strength increases so many folds. And then those materials can become really whatever is called next generation material.

I mentioned that carbon fiber is the most common additive. Now, the metals are ductile, and then you can also make thin and long sheets out of metal. So, already they are malleable and they are ductile.

Now, we had also learnt about this ductility property before in one of our previous lectures. So, you can see in the stress-strain curve, this is your region before the fracture. After the material stops behaving as an elastic material, and then you have a certain region of strain and then you have the fracture. So, this region is known as ductile behavior.

Now, metals have large enough region of ductility measurable. Also in the case of carbon fibers, occasionally you will see some ductility in the case of turbostratic carbon fibers anyway. This is something we have already covered before. Mostly carbon fibers do not display ductility. So, compared to metals, anyway that is negligible if at all.

This is our matrix phase. And we have carbon fiber as additive. Now, why do we need again? What is the need for carbon matrix composites and why could not we work with carbon composites even if we wanted to work at higher temperatures? Well, here the ductility and the ability to make thin sheets becomes important.

So, if you would like to use the properties of a metal, but at the same time, you want a slightly mechanically stronger material, in that case you can add carbon additives to it. Now, if you do this, then at higher temperatures you will also get better strength from the material.

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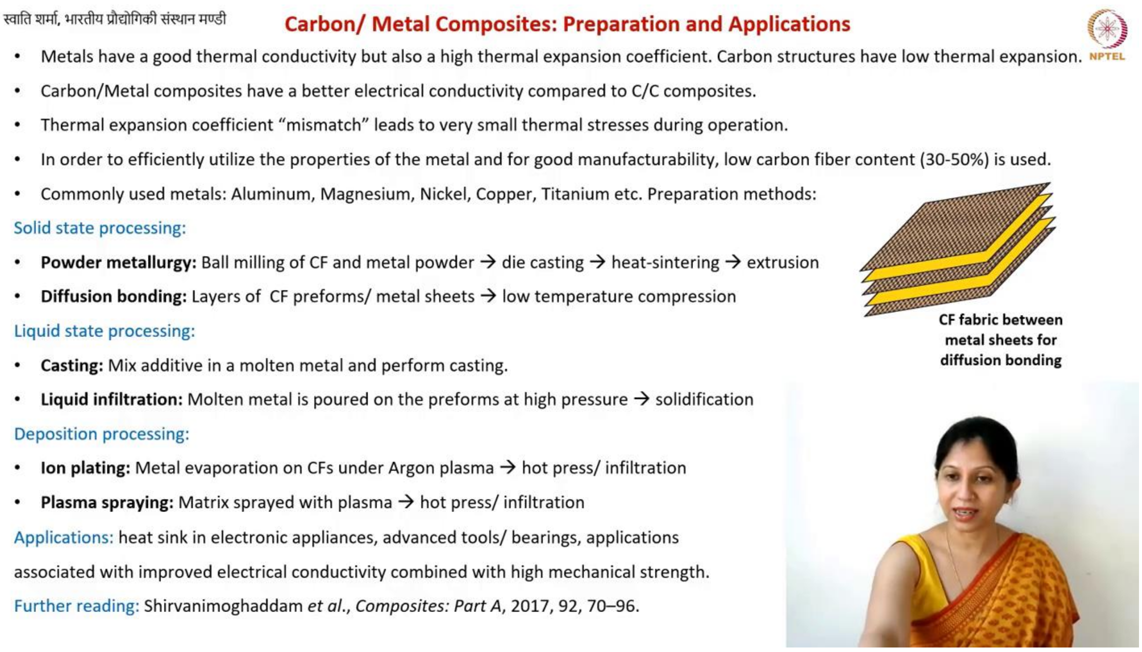

The idea is that metals have very interesting properties. Metals offer a lot of properties that also carbon or ceramics do not. Other than the physical properties or the ductility and malleability, you also have good thermal conductivity and good electrical conductivity.

In all these applications when we talk about composites we focus on mechanical properties of the material. We have been ignoring the electrical properties because mostly we are talking about structures with high strength, but we are often ignoring the electrical properties.

Thermal properties are also important. But in the case of metals thermal and electrical properties are often utilized for making a lot of devices. But what happens is that your metal will have high thermal conductivity, but it will also have a high thermal expansion coefficient.

What is that mean that? When you heat the material, it will expands that is something that can be undesired when you want to make structures that need to function at very high temperatures. Because when you say certain material or certain structure is good for high-temperature applications, what you basically mean that it does not deform at higher temperatures, or it can withstand thermal shocks; that is unfortunately not the case with metals or most of the metals.

Of course, we do make these high-performance alloys and superalloys. But in general if you want to ensure that your metal does not expand so much at higher temperatures, then you can add these carbon fiber-like materials, carbon materials.

Because we know very well that our carbon materials have a low thermal expansion coefficient, and they are very good at withstanding the thermal shock. And that is why now you can have the property of the metal good thermal conductivity, but low thermal expansion coefficient. So, this is why we need these kinds of materials.

So, there is what is known as the mismatch of thermal expansion coefficients and that basically makes your material withstand a lot of thermal stresses. And these kinds of structures are also used for making heat sink for various electronic devices.

Now we need to figure out how much carbon fiber should be added. So, that in the case of CFRPs, it is typically 60 percent. But in the case of metal matrix composites, it is slightly lower. Because often you want to utilize the properties of your metal efficiently, you do not want to reduce the thermal conductivity of your overall structure or electrical conductivity.

So, the goal here is to strengthen the metal, utilize the properties of the metal rather than that of the carbon fiber. Carbon fiber here would be here to typically provide a low thermal expansion and also mechanical strength to the structure at higher temperatures. So, that is why you will use something like 30 to 50 percent carbon fiber.

So, there are various metal matrix metals that have been used as matrix materials, for example, aluminium and magnesium. You can also find various metals in the literature. Now, how do we perform the processing, that is important for us. Now, think about the manufacturing techniques that you can use with metals.

There are so many of them. In fact, we are rather limited when we work with carbon or when we work with ceramics. But when we are working with metals, then a lot of traditional manufacturing techniques can be used. So, if we carefully use the content of carbon fiber, so we do not make it with a high concentration that we lose the properties of the metal.

And again you will have to think about what kind of composites it is going to be? Is it going to be a short fiber composite, or is it going to be a laminate? The answer is both, we can make both types of composites again using a metal matrix, but the manufacturability slightly differs. So, I have divided it into three types. So, there is solid-state processing, liquid-state; where your metal is liquid, and then there are some deposition techniques as well. So, let us talk about them.

The first one is solid-state processing. Now, we talk about powder metallurgy. So, powder metallurgy is again a good old-fashioned manufacturing process. I had also provided you with a reference in the previous lecture, where you can learn about basic manufacturing techniques in case you are not from that background.

What you do is, you take carbon fibers, in this particular case chopped fibers or short fibers. They can be vapour grown or they can be spun and then chopped. You take these fibers. And then you perform simple standard ball milling. You mix metal powder and you mix your carbon fiber, and then you perform ball milling, of course, you will need to optimize ball milling parameters.

But, well this is how you mix the two phases and then you can perform simple powder metallurgical techniques such as die casting. So, you can pack this entire mixture inside a die, and then perform the heat treatments for sintering. If you want to go to higher temperatures, that would depend on your metal. If you want to go to very high temperatures then you have to accordingly choose the material of your die. You can even choose the graphite die; typically steel die would work.

Now you perform the heat sintering. And then with that mixture, you can even perform extrusion and high-temperature extrusion again depending upon the properties of your metal. Again our carbon fibers will not be affected, no matter what temperature do you use. So, carbon fibers are stable. So, then your manufacturing technique will mainly depend upon the matrix material rather than the fiber.

What else we can do, something is known as diffusion bonding. So, I just told you that we can also use laminates. How do we do that? We can buy these carbon fiber preforms. So, preform is basically a woven carbon fiber mat. Of course, it will also contain some resin for lubrication but not so much.

You may have to perform certain surface treatment or sizing if you want to mix it into a metal matrix. here I have shown it in this picture, then what you can do is you can have metal sheets thin sheets, foils of metal.

Then one carbon preform and then another foil. So, sandwich structure looks like this. And now what you can do? Afterward, you can heat it slightly, but not too very high temperatures. You can heat it and compress it. So, basically what you want? You want the metal to diffuse through the carbon fiber sheets or your fabric.

Now, why low temperature? Because well you can also perform this at high temperatures, but this process is typically used when you do not want to go to very high temperatures. So, you rather use pressure than temperature, that is why this is known as low-temperature compression.

But anyway, if you want, you can use higher temperatures, however, you need to slowly heat the entire structure. Because you want the metal to melt and slowly diffuse through your structure. So, this is another way of making laminate types of metal matrix composites. So, metal matrix composite by the way is a more general term.

You can also have other additives, not just carbon then this is a more general term. But when we talk about carbon-metal composites, then we typically call them Carbon Metal Composites, but I have not used the term CMC because that may be a little bit confusing. There may be Ceramic Metal Composites, they are also called CMC. So, let us just stick with carbon metal composites.

Coming to the second type, liquid state processing. The most common liquid state process of manufacturing process for metals is casting. So, you melt a metal. You have a cast which is made of a refractory material such as sand. And also for more sophisticated molds, you can even use graphite. So, you have this mold, you fill the metal, it solidifies, then you perform the finishing operations. This is very common.

Now, you have these chopped fibers mixed inside your metal. And since the volume of these fibers is relatively low, in this particular case you need to ensure that you do not go to very high volumes. But if you take this mixture and then you melt the overall mixture, which will melt at the melting point of the metal, then you can perform casting.

You can pour it inside something and then you can solidify your metal. However, there are certain challenges here. So, carbon fibers are much lighter in terms of weight. They are much lighter compared to metal. So, there is a high probability that they will float. So, you may need to stir. So, there is something known as stir casting. So, slightly stir casting or squeeze casting. You need to make sure that your fibers are uniformly distributed inside your metal matrix when you are performing the casting. What else? Liquid infiltration. So, this is something similar to the diffusion bonding that we learned, but the only difference is that now your metal is liquid, you are not using the solid sheets or foils of the metal.

So, what you do is you pour your molten metal on top of the preform and you allow it to diffuse and solidify it. Now, this can be done at high pressures. Remember that you need to ensure that your metal does not immediately solidify. You may need to control its solidification, therefore, you can play with the pressure parameters a little bit. Again your molten metal now diffuses through the carbon fiber.

The advantage that carbon fiber offers as compared to any other additive is that there is no sort of expansion because of the heat, or there is no adverse effect on the structure of fiber because of the heat. In fact, we know that when we perform heat treatment, carbon fibers always become better and better. So, we do not need to worry about the effect of high temperature on the fiber itself.

Now, coming to the third one, as the name suggests that we are depositing something. What are we depositing? If you remember from the carbon-carbon composite class, there we talked about pyrolytic carbon deposition on top of the carbon fibers from gaseous hydrocarbons.in this particular case, something very similar happening. Here you do not have the carbon being deposited, but the metal being deposited on top of your carbon fibers.

This can be done using evaporation techniques. You evaporate a metal at lower pressures or higher temperatures. So, these kinds of techniques like evaporation and sputtering techniques are actually rather common in the case of microfabrication. These kinds of techniques often enhanced with plasma, supported with plasma, at least a little bit of impregnation of the ions. So, this is why it is known as ion plating.

So, you are doing plating but you want a very good adhesion, not impregnation in the same way that you do doping or anything that is not your goal. You just want surface plating, but at the same time, you wanted to ensure that the region is very good, and you have nice atomic layers of metals on top of your fibers. And this is what is known as ion plating. You will typically use argon plasma or any inert gas plasma for that matter.

Now you have the metal deposited on top of your carbon fibers. Now, you would like to further process it. So, you can do hot pressing. You give it a certain shape let us say you wanted to make a hollow cylinder out of this. So, you can take one carbon fabric, then you can perform the ion plating.

And now you can give it a certain shape. Or if you just want to use the sheet, then you can perform hot pressing. And if you want to give a shape also, you may need to use the heat a little bit because to make the metal softer, only then you can work.

This is also certain type of infiltration because this hot pressing will ensure that your metal now diffuses through or infiltrates through all your carbon fiber strands. What else? Something again very similar using plasma. You can spray the metal on top of your carbon structures, and again you can perform hot pressing or infiltration.

This was all about how to we make metal-based carbon composites or metal matrix composites. Applications; as I have already mentioned, you can make heat sink because the property that you require from the heat sink; you require good thermal conductivity, but low thermal expansion. So, any application that can utilize this property, we can use these materials for that.

We can also make advanced tools or bearings. Again, this is the same property that we are using, low thermal expansion, but good thermal conductivity. You can make advanced tools and also improve the tribological properties of your material by adding carbon fiber to it.

We also have other various applications that are related to electrical conductivity. So, you can do further search. There are various applications where these kinds of materials are being used. Here is one article for further reading. However, you can also find many more articles.

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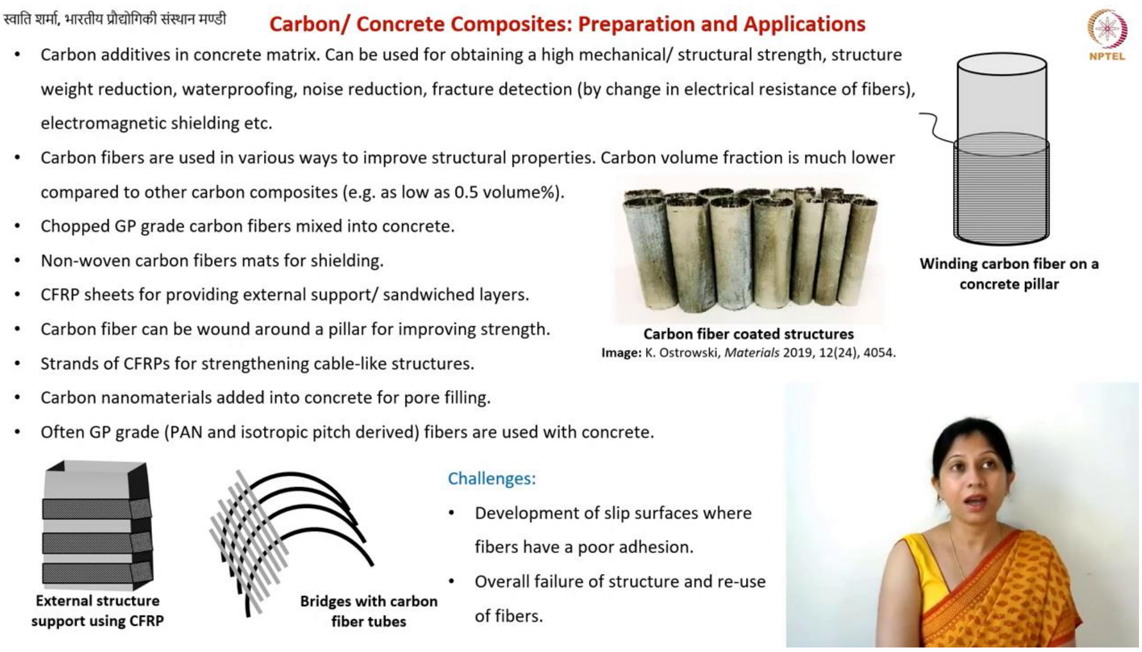

Yet another very interesting material is carbon-reinforced concrete or carbon concrete composite. in this particular case, we are also using not just carbon fibers, but other types of carbon materials.in most of the composites, we were always using fibers.

For structural engineering applications, what do you want? You want better mechanical strength in your structures. So, fibers should be the first choice. Indeed, fibers are used for reinforcement, however, sometimes you just want to make your concrete stronger. And for that you need filling of the pores of the concrete and that can be done using carbon nanomaterials.

So, in this particular case, we are also using carbon particles, although very small nanoscale particles or graphene or even carbon nanotubes. So, for reinforcement of concrete, you can use carbon nanomaterials. However, fibers still happen to be the first choice for giving the structural strength. We will see how.

First of all, why do we need carbon reinforced concrete? Well, we always need concrete that is stronger. We always need building structures that are stronger. And if they are lighter that is very good for us. If you want to make a roof which is lighter, so for that purpose our carbon materials work very well. They are strong, and they are lightweights. So, that is of course one property of carbon materials that we utilize.

But there are many more things, actually carbon-reinforced concretes have become indeed very popular. There is a lot of work going on. The reason is, you can also use it for many other applications, for example, waterproofing. You know that the carbon materials are always hydrophobic unless we do certain surface treatment. They typically repel water.

Also, if you just fill the pores of the concrete or you can strengthen your material with it, then you have this additional layer of hydrophobic materials. So, you can use it for waterproofing. You can also use it for noise reduction. And some other very interesting applications like fracture detection.

How do you detect fracture? Your carbon materials are electrically conductive. If not very high electrical conductivity at least it will offer some kilo ohm resistance. So, it is reasonable electrical conductivity. Now, when you have a change in the electrical resistivity of your carbon fibers, in that case, you can detect the crack. So, you can use these structures also for detection of cracks.

One more thing is electrical and electromagnetic shielding of the walls or of whatever structure house. Now, you must have heard of these smart buildings and intelligent buildings. Actually, if you add carbon fiber to your concrete that is when it becomes a smart structure.

So, basically you add carbon fiber to anything, and it becomes a smart structure that is why I added carbon fiber in this course. So, it becomes a smart course. The point is that, for all of these smart city, smart housing applications, carbon fibers play a very important role.

How do we make these structures? What are the different types of structures that you can have from carbon fiber? And how many different ways you can use carbon-based materials as reinforcement? First of all how much carbon material should you add? So, unlike CFRPS or other carbon base composites, here you will have much lower volume fractions because your primary material is concrete.

You are using this as an additive for reinforcement. But if you add too much, then your concrete may lose its properties. So, you will even use volume fractions as low as 0.5 percent. We were talking about 50-60 percent, now here we go down to even 0.5 volume percent. So, of course, 0.5 is more of the lower side, you will have 2 percent, 3 percent, 5 percent also, but compared to other carbon-based composites this value is pretty low.

you will mostly use the general-purpose grade carbon fibers because you do not really care much for the very high Young's modulus or very high tensile strength. So, you would rather go for general purpose carbon fibers. So, you can mix them as small chopped pieces or as short fibers inside your concrete, that is number 1. here is one picture. These are some structures where they are coated with carbon fiber. So, this is how they look like.

Now, you can also have non-woven carbon fiber mats. Non-woven is what do you get or after melt spinning or electro spinning also. Spun mats are basically known as non-woven mats. So, where you are not doing any braiding and you are also not preparing the fabric. Non-woven mats have randomly oriented fibers. So, they actually can be used for electrical shielding of the walls.

In fact, there are fewer applications where you use non-woven carbon fiber mats. For mechanical strength, weaving is important because we have these perpendicular woven structures and that is why that sort of distributes the stresses very well. But for electrical shielding, the non-woven carbon fiber mats works better.

What you can also do is rather than using the carbon fiber directly, you can use the CFRP preforms. So, we already talked about in the case of metal matrix composites, you can use these performs. And you can also use CFRP sheets or CFRP structures.in this particular case you can use laminates to provide external support to your structure.

here is an image, let us say this is your pillar. And now you want to provide external support. So, you can attach CFRP sheets around it, so that is also one option. What else? Carbon fiber can also be wound. So, basically again, maybe this is clear from the picture here. You have a pillar, and you can wind your carbon fiber around it.

these are not individual carbon fibers, these are going to be the ropes of carbon fibers. These are probably going to be thick ropes. do you remember from our mechanical property testing lecture have carbon fiber mechanical property testing? There you need to have a good tensile strength in these fibers.

Again, modulus may not be so important, rather the ultimate tensile strength is more important. And you will most likely choose PAN derived or isotropic pitch derived carbon in this particular case because you do not really want to go for mesophase pitch because you do not much care for the modulus, tensile strength is more important. And turbostratic nature can also offer a little bit of strain hardening. So, you may want to go for these kinds of fibers.

So, CFRP strands can be used for strengthening cable-like structures. So, actually this kind of cables carbon-reinforced cables have been used for a lot of bridge-making applications because here now we are utilizing their load-bearing ability. Now, we are utilizing mainly their mechanical properties right.

Then you can actually make fancy structures. So, there are some structures have already utilized. There are certain bridges that have already utilized carbon fiber cables or CFRP reinforced concrete cables. There are also several models and all these futuristic buildings that we talk about, all these smart buildings and smart bridges will often have some component of carbon fiber into it because that makes it lighter and stronger.

So, in this particular case, for example, this is just a basic drawing that you can have hollow carbon fiber tubes. And then you can also further perform the reinforcement with other carbon fiber tubes, and that would make your bridge structure very strong as well as light.

What else? This is the one that I had mentioned in the beginning already that you could use carbon nanomaterials that will fill the pores of your concrete and make it stronger. Now, you will typically use PAN derived carbons as I have already explained.

What are the challenges? Of course, the interface properties remain a challenge. So, that is true for all kinds of composites, having the optimum interface properties. What else? The mechanical failure of the structures because you do not have just one type of structure here; you have various different types of carbon concrete composites. You have something with bound wire, and you have also these sheets. Sometimes these CFRP sheets are also used as sandwiched structures not just for the external support, but also as sandwich structures between two different concrete plates.

For each one of them, the mechanical properties are going to be different. So, if you have just your concrete with the carbon nanomaterial, the mechanical property are different compared to what you have when you have a sandwiched CFRP sheet.

For each one of them you need to perform different analysis for understanding their failure behavior. What often happens is there are slip planes, slip surfaces developed when you have even slightly poor adhesion, and that can lead to a catastrophic failure of your entire structure. So, adhesion is important.

Yes, but also you need to understand what will be the distribution of loads on your CFRP or structure your load-bearing structure, or what happens if there is a certain crack in your structure? How much load can the CFRP bear? And where is going to be the slip surface? How is it going to break?

So, optimization of these mechanical performance and deformation is very important in the case of carbon-reinforced concrete. Overall failure of the structure something that you need to understand. One more issue with carbon fibers, again this is with a lot of carbon fiber-based composites is the reuse or recycle of the carbon fiber.

Once the structure fails, then what do you do with the carbon fibers? This is something that you need to think about because carbon fibers can be reused to some extent. But every time you reuse or their properties; their value goes very low because you have brittle carbon fibers.

So, they may end up breaking a lot when you are trying to remove them from their parent structure, and then trying to reuse them. So, then you can have a lot of breakage in the case of carbon fibers. And the microstructure of the carbon fiber is also compromised.

So, you may end up inducing the voids that then can lead to further cracking. So, the recycling of carbon fibers is also one important issue in all. Now we have discussed a number of carbon-based composites, and carbon fibers. And from the next lecture onwards we will be talking about carbon nanomaterials.