Concrete Engineering and Technology
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Lecture - 30
Using FRP as reinforcement in concrete structures (Part 2 of 2)

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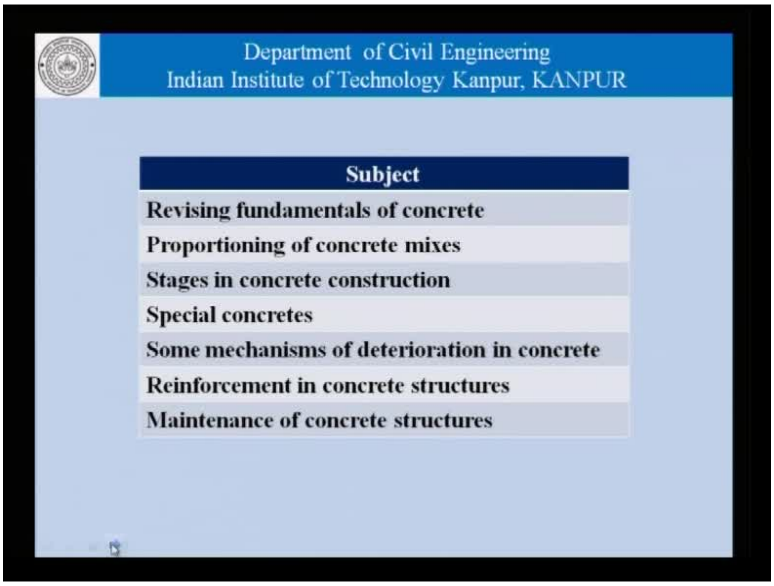

[FL] and welcome back to this lecture on concrete engineering and technology, where we are revising fundamentals of concrete; even proportion of concrete mixes, concrete concentration, special concretes, mechanisms of deterioration in concrete, reinforcement of concrete structures and their maintenance. Basically, the kind of things which all civil engineers do and we are trying to see, how the perspectives have changed in the last couple of years; may be 10 years, 20 years and we want to study or learn a little bit more about the latest developments in this area.

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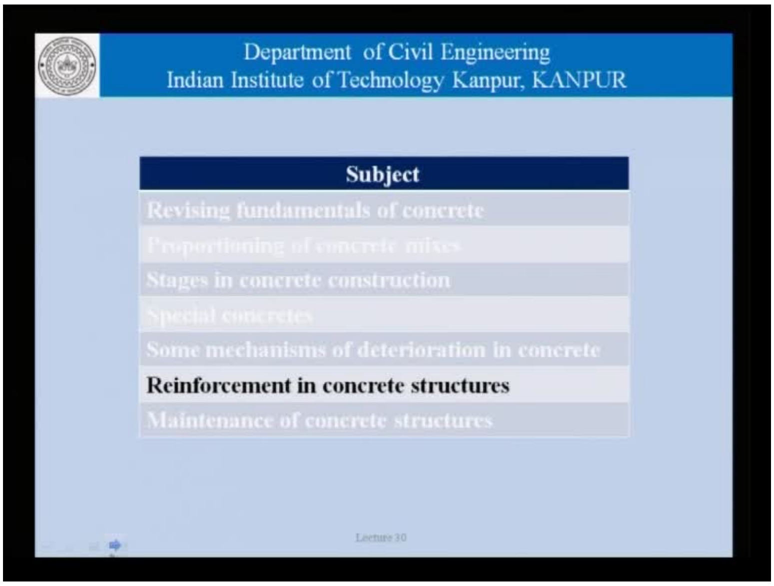

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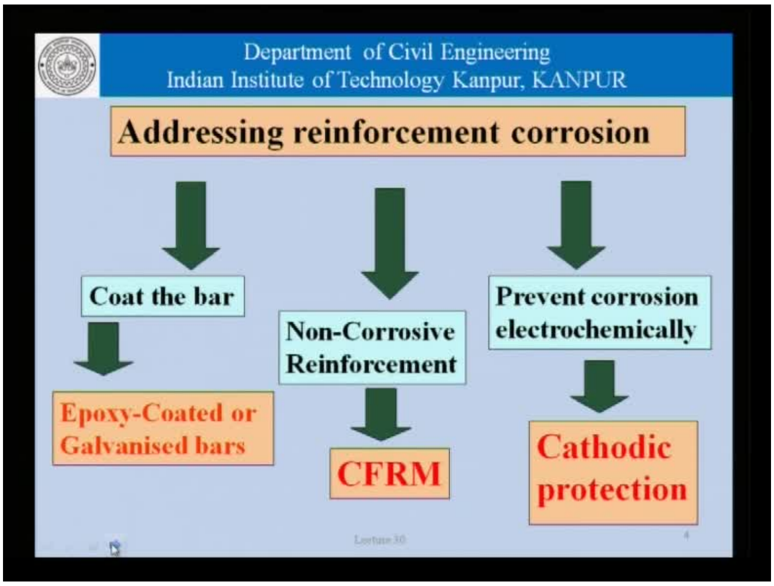

Now, continuing with our discussion on the reinforcement of concrete structures or the reinforcement use therein, we were trying to address the problem of reinforcement corrosion. And, we had said that basically there are three approaches that we can adopt; one is to coat the bar, the other was to use non corrosive reinforcement or to prevent the corrosion electrochemically. As far as coating bar is concerned, epoxy coated bars or galvanized bars was in option as far as non corrosive reinforcement is concerned, using continuous fiber, using CFRM or continuous fiber reinforcement material which has basically long fibers embedded in a matrix; that is the option. And as far as electrochemical prevention is concerned, we could use cathodic protection.

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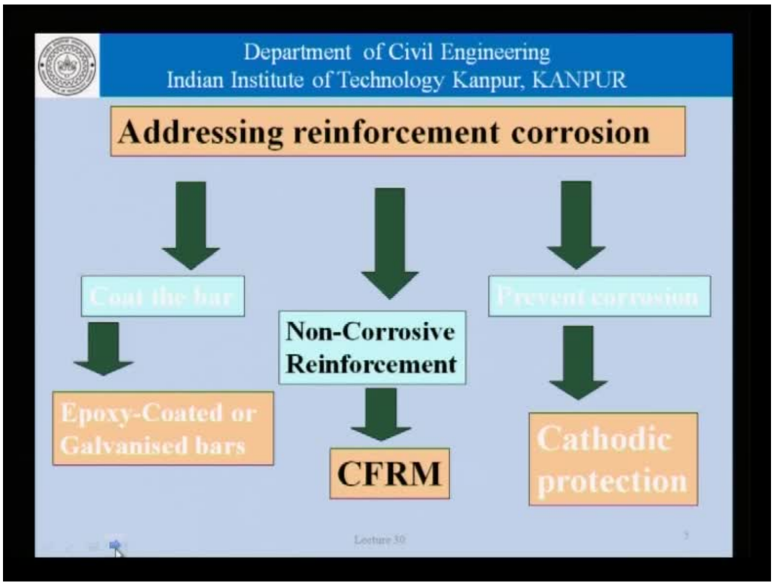

Now, in the last discussion we were trying to address the issue using CFRM. So, we will continue from that point onwards.

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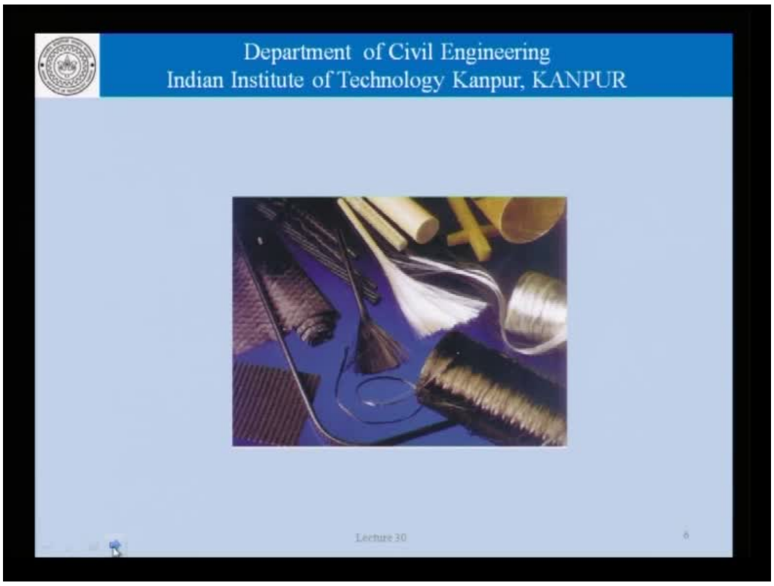

And, these are the pictures that we have seen this is the different fibers; carbon, glass, aramid, in the raw form; that is the fibers themselves which are extremely fine.

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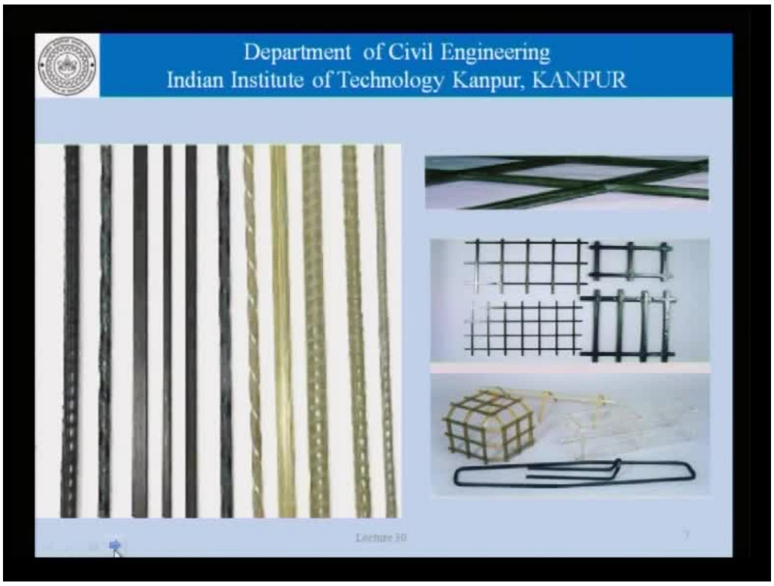

And, then we had seen this picture which is the products from the long fibers. And, we can see that they are in the form of rods, strips, 2 dimensional, 3 dimensional, woven into nets, fabrics and so on and so forth.

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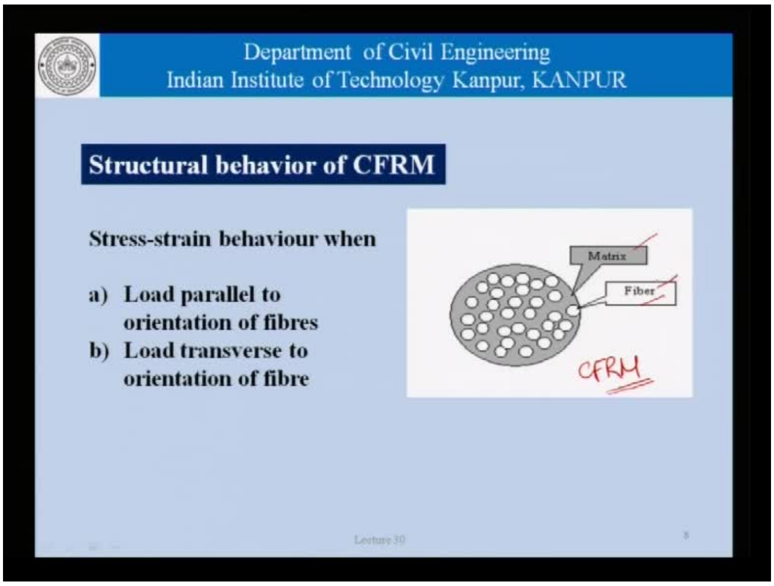

Now, continuing our discussion, let us try to understand a little bit more about the structural behavior. Let us try to understand the structural behaviour of CFRM. We will try to study it using the stress strain curve as the manifestation. We will try to see how the stress strain curve of CFRM goes or behaves; as we use different fibers, as we will use differential equation fiber volumes and so on. We had talked about the fact that a CFRM can be looked upon as fiber embedded in matrix. And the properties of this CFRM could be varied by varying the type of fiber or its content; that is the volume of the fiber in the matrix. And, what we will try to do is to study the stress strain curve of this CFRM in case when the load is parallel to the orientation of the fibers; that is a longitudinal application of load and when the load is transverse to the orientation of fibers and that is a transverse orientation of load.

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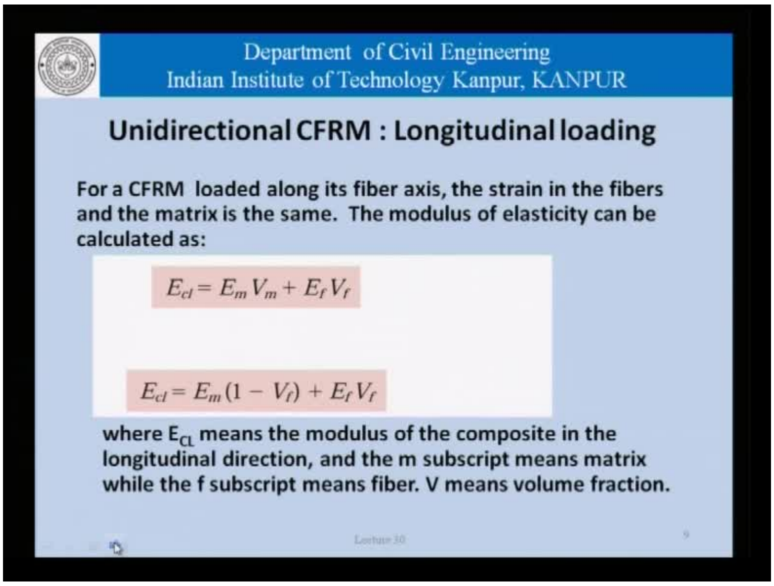

Now, as far as the unidirectional CFRM and that is what we are really bothered about is concerned in the longitudinal loading; for a CFRM loaded along its fiber axis, the strain in the fibers in the matrix is the same.

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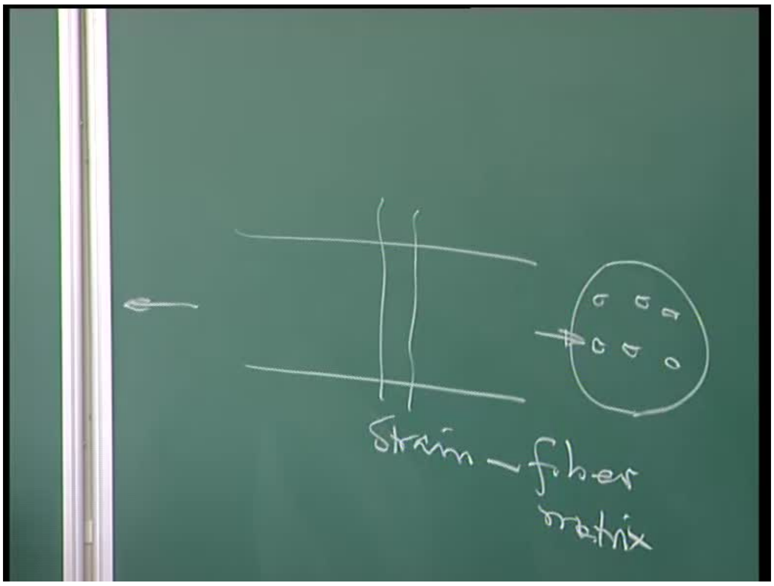

What we are saying is that if we take a CFRM, which is like this, with the lot of fibers and we apply the load in this direction. Then, the strain that we see here, whether it is in the fiber or it is in the matrix; it is the same and that is the value that we have for the composite itself. And under those conditions if we apply simple rules of stress and strain, we will get the equations which are given here.

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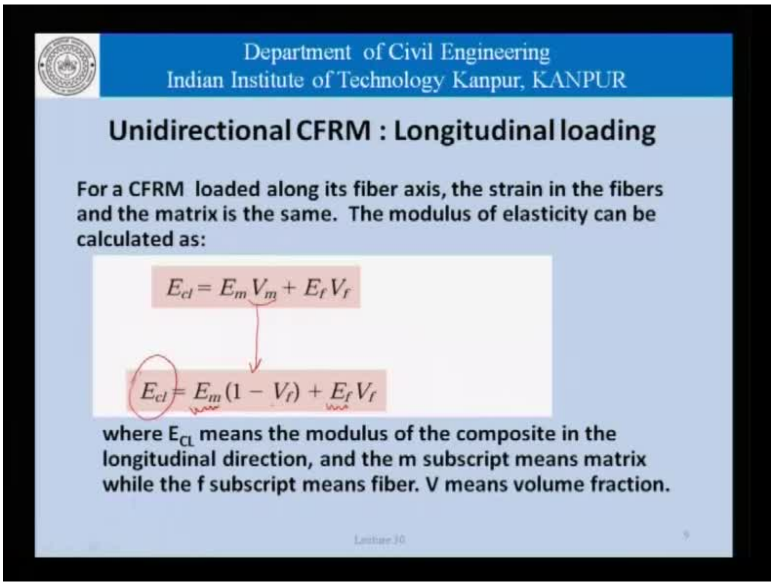

That is E c l will be equal to E m times V m plus E f times V f; which can be written as, because the volume of the matrix is nothing but 1 minus v volume fraction of the fiber as

1 minus V f plus E f times V f. So, different modifications or different adaptations of this equation can be used depending on what we are really trying to determine. Here, E c l is the modulus of the composite in the longitudinal direction and the m and f are the subscripts which are used for the matrix and the fiber. So, naturally we can see that the property as far as the composite is concerned in the longitudinal direction is a function of the properties of the fiber and the matrix. That is the E of the matrix and E of the fiber and the volume fraction of the matrix and the fiber.

So, if we want a certain E; we can get it by varying the E m or the E f or by varying the V f. So, this is something which we must keep at the back of our mind, when we are trying to study applications of CFRM as far as civil engineering or concrete concentration is concerned.

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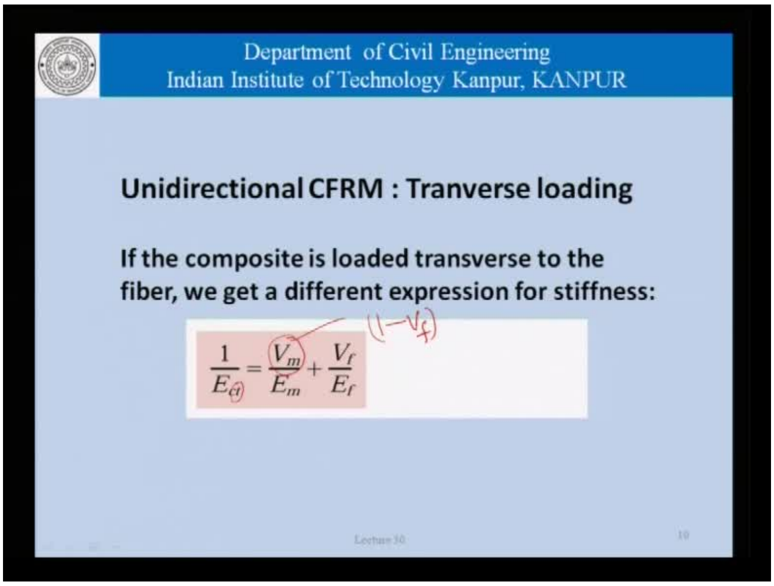

Similarly, if the load was applied in the transverse direction that is in a direction perpendicular with the orientation of fibers we are not doing the derivation here. But the E transverse; so, this t here is transverse. So, the E transverse of the composite can be written in terms of V m upon E m plus V f upon E f and we can write V m as 1 minus V f like we had done in the previous case.

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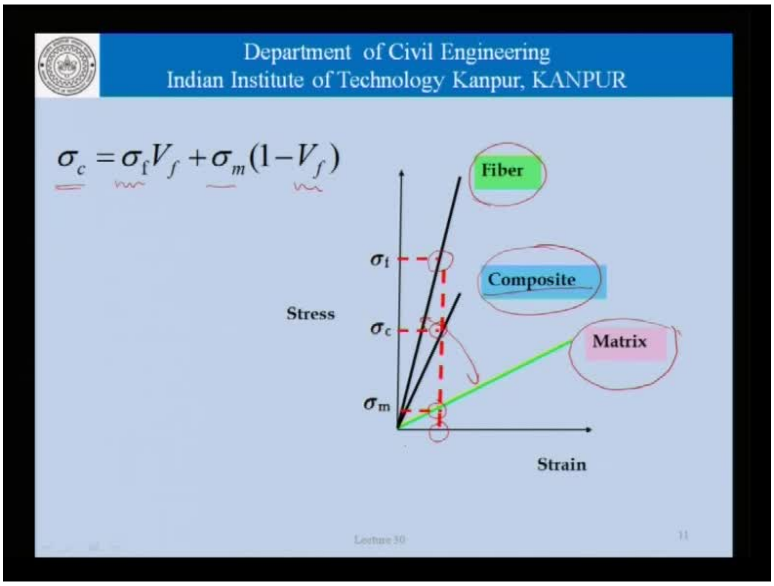

Now, if we translate that into a stress strain curve; this is what we get. The sigma c, which is the stress carried by the composite can be written as sigma f times V f plus sigma m times 1 minus V f; which means, that the total stress that is carried by the composite is equal to some fraction, that is composite some fraction of the stress carried by the composite is carried by the fibers, which is equal to sigma f times the volume of the fraction or the volume fraction of the fibers plus some fraction carried by the matrix which is sigma m times 1 minus V f.

Graphically, if this is the stress strain curve of the matrix material alone and this is the stress strain curve of the fiber alone; then, depending on the volume fraction that we have, we will get the stress strain curve of the composite to be somewhere in between. And, where it lies between these two lines would depend on the volume fraction. And, therefore, this, this and this are critical points; as far as we are concerned for a given strain value.

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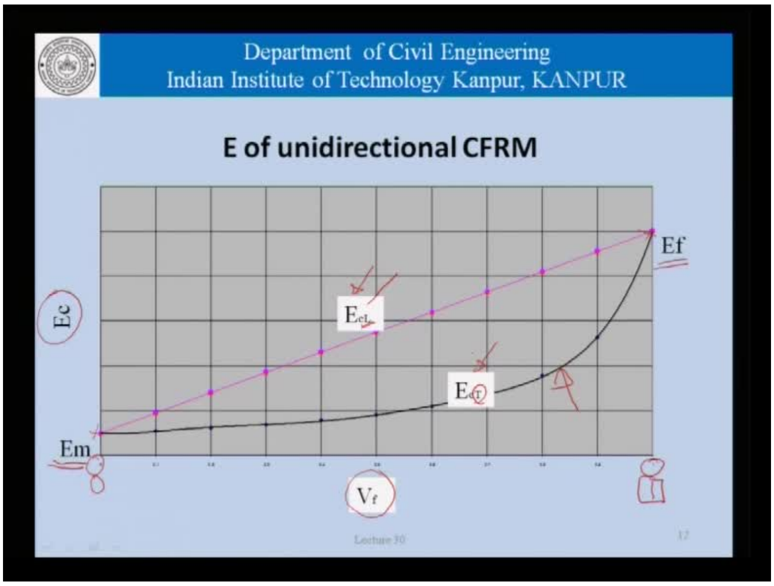

Now, if you translate our understanding of the stress strain behaviour of the composite to a graph which says or which shows us the variation of the E of the composite versus the volume fraction of the fibers. If this varies from 0 to 1; as far as the composite is concerned in the longitudinal direction the variation is linear, as we have seen. Whereas, in the transpose direction, it is not linear and it follows this graph. So, we must keep in mind that the modulus of velocity as far as the composite is concerned is related to both the modulus of velocity of the matrix and the modulus of velocity of the fiber and is determined by the volume fraction. And, also whether the fiber is loaded in the longitudinal direction or it is loaded in the transverse direction. Obviously, in a situation where we are talking of bidirectional or multi-directional fibers, where the fibers are where the fibers are oriented in both directions or in random directions, we have to have this understanding at the back of our mind; when we formulate the derivations for those cases.

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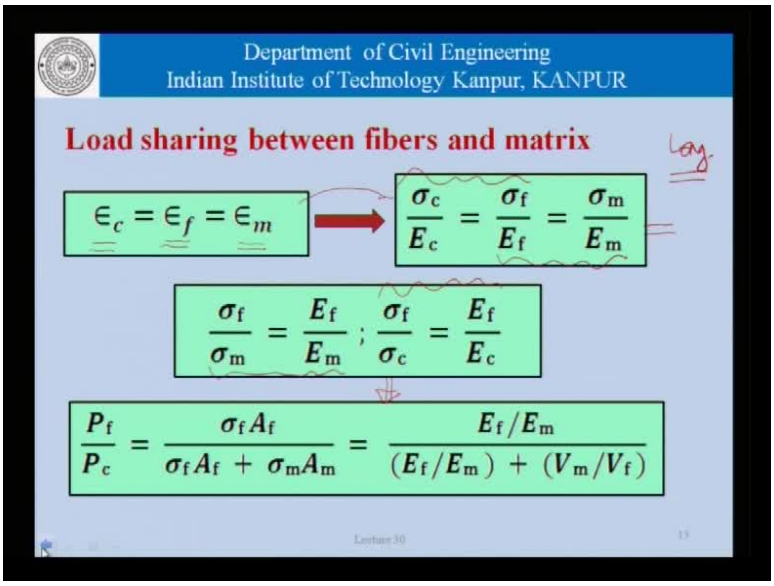

When it comes to load sharing between the fibers and the matrix, there is the formulation that I have shown to you for the longitudinal loading; that is the loading, which is along the direction of fibers. So, we can see that the strain in the composite has been taken to be the same for the fiber and the matrix. And if this is the condition then we can write it as shown here in this box. That is sigma c by E c is equal to sigma f by E f is equal to sigma m by E m. Now, if we take these first two terms or if we take these two terms, then we get this equations here. And, if we take these two things here, we get these two here and we can derive the kind of equations which are given at the bottom.

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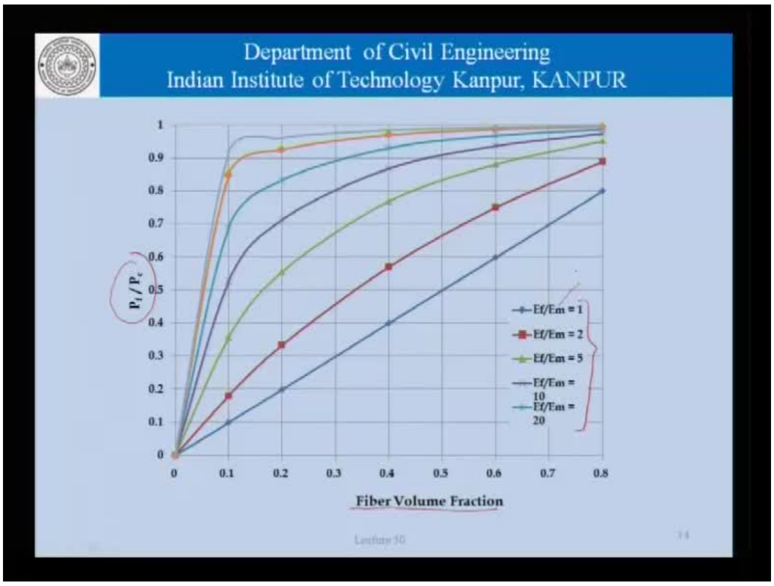

Once, we clearly understand what these equations carry, we can simply carryout a simulation or just put the numbers. And we will find that the percentage of load carried by the fibers, as far as the total carried by the composite is concerned; depending on the volume fraction and the ratio of the E of the fiber and the E of the matrix could be something like this. So, depending on how stiff the fiber is compared to the matrix, the load carried by the fiber will be different. And as the fiber becomes stiffer, it carries more load; that is something which we must carry home from this picture.

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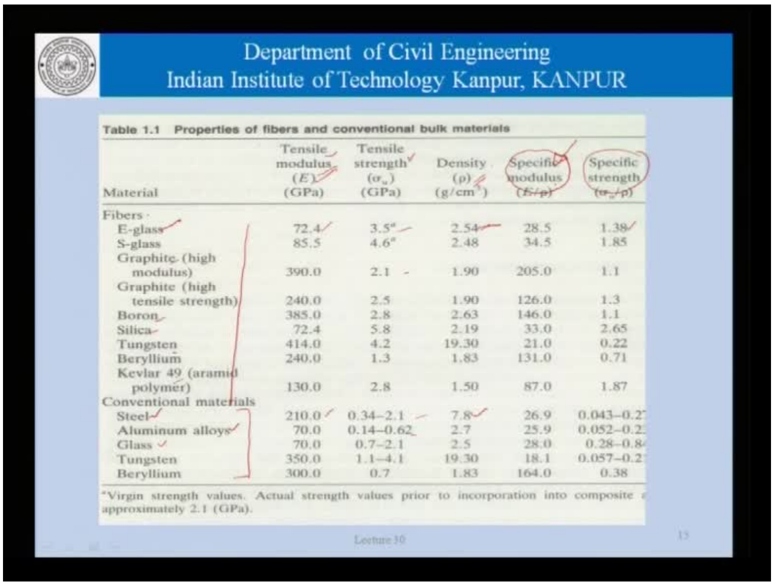

Table 1.1 Properties of fibers and conventional bulk materials

Material	Tensile modulus (E) (GPa)	Tensile strength (σ_u) (GPa)	Density (ρ) (g/cm^3)	Specific modulus (E/ρ)	Specific strength (σ_u/ρ)
Fibers					
E-glass	72.4	3.5[a]	2.54	28.5	1.38
S-glass	85.5	4.6[a]	2.48	34.5	1.85
Graphite (high modulus)	390.0	2.1	1.90	205.0	1.1
Graphite (high tensile strength)	240.0	2.5	1.90	126.0	1.3
Boron	385.0	2.8	2.63	146.0	1.1
Silica	72.4	5.8	2.19	33.0	2.65
Tungsten	414.0	4.2	19.30	21.0	0.22
Beryllium	240.0	1.3	1.83	131.0	0.71
Kevlar 49 (aramid polymer)	130.0	2.8	1.50	87.0	1.87
Conventional materials					
Steel	210.0	0.34–2.1	7.8	26.9	0.043–0.2
Aluminum alloys	70.0	0.14–0.62	2.7	25.9	0.052–0.2
Glass	70.0	0.7–2.1	2.5	28.0	0.28–0.8
Tungsten	350.0	1.1–4.1	19.30	18.1	0.057–0.2
Beryllium	300.0	0.7	1.83	164.0	0.38

[a] Virgin strength values. Actual strength values prior to incorporation into composite approximately 2.1 (GPa).

Now, this table here is just a data sheet which tells you that depending on the type of the fiber which is glass or graphite or boron or silica tungsten and Kevlar, how good is the tensile modulus, the tensile strength, density, how do they change. So, we cannot go into the details of these numbers. But what we have to see is how do these numbers compare with conventional materials; such as steel or aluminum or glass. So, if we see for steel for example, the density is 7.8 and the modulus of velocity is 210 GPa. Now, compare to these two if we look at E glass; the density is just 2.54 and the modulus of velocity is 72.

So, this fiber is approximately one-third as far as density is concerned and is also about one-third as far as the modulus of velocity is concerned; when we compare the performance of E glass with steel. Steel being the conventional reinforcement and E glass being a non corrosive alternative, which we are considering for application in structures; where corrosion could be a severe problem.

Another way of looking at some of this information is to talk in terms of a specific modulus or a specific strength. Now, specific modulus and specific strength is these modulus values divided by the density. So, we try to say that what is the specific strength; that means, for every k g of material that we use in the structure what is the strength that we get. So, if we look at those values we find that the fibers are performing much better because the tensile strengths are much higher. If we look at steel for example, it is 3.5 versus 0.34; for graphite it is 2.1 versus 0.14 and so on, the specific strengths are much higher and so is the specific modulus.

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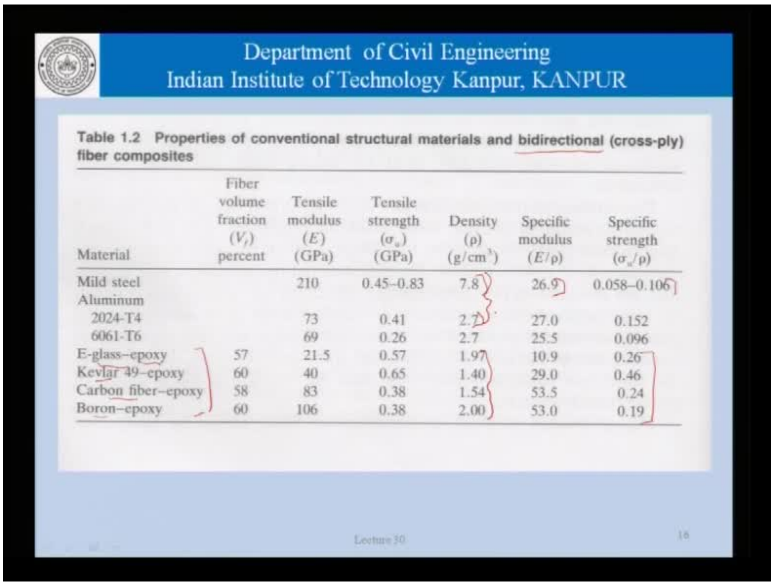

Table 1.2 Properties of conventional structural materials and bidirectional (cross-ply) fiber composites

Material	Fiber volume fraction (V_f) percent	Tensile modulus (E) (GPa)	Tensile strength (σ_u) (GPa)	Density (ρ) (g/cm^3)	Specific modulus (E/ρ)	Specific strength (σ_u/ρ)
Mild steel		210	0.45–0.83	7.8	26.9	0.058–0.106
Aluminum						
2024-T4		73	0.41	2.7	27.0	0.152
6061-T6		69	0.26	2.7	25.5	0.096
E-glass–epoxy	57	21.5	0.57	1.97	10.9	0.26
Kevlar 49–epoxy	60	40	0.65	1.40	29.0	0.46
Carbon fiber–epoxy	58	83	0.38	1.54	53.5	0.24
Boron–epoxy	60	106	0.38	2.00	53.0	0.19

Continuing from the discussion of bulk materials, which was that kind of data which were shown in the last table; we have properties of structural materials and bidirectional fibers. If we look at the similar numbers here, we can draw our own conclusions that if whether we use glass with epoxy Kevlar with epoxy, carbon fiber with epoxy or boron with epoxy. Because we must understand that epoxy is also very important component of the composite and contributes to its structural performance in terms of load carrying capacity; in terms of the modulus velocity and so on. And, we get these numbers here for the fiber composite as compare to these numbers here which is for steel and aluminum here. So, we have these are the numbers for fibers and these are the numbers for conventional materials such as steel and aluminum. Except that of course, aluminum is not very much used as far as reinforcement is concerned and we are really bothered about steel versus fiber comparisons most of the time.

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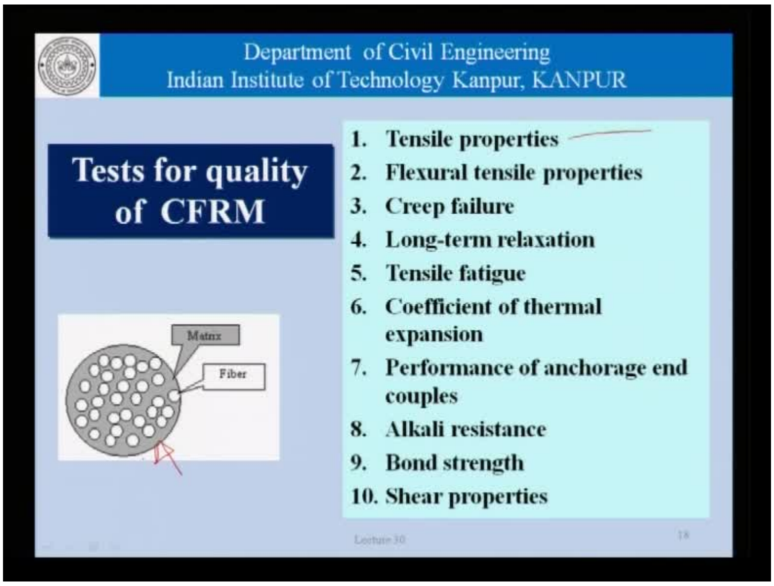

Now, let us try to study or look at the tests for quality of CFRM. It is not only the tensile properties that we are bothered about, we also need to look at flexural tensile properties, fresh tensile fatigue properties, creep, long term relaxation, coefficient thermal expansion, performance in anchorage in couples, alkali resistance, bond resistance and shear properties and so on. If we really want to apply a CFRM such as this as far as reinforcement in concrete structures is concerned. For that we need to look at once again on the basic behaviour of reinforce concrete.

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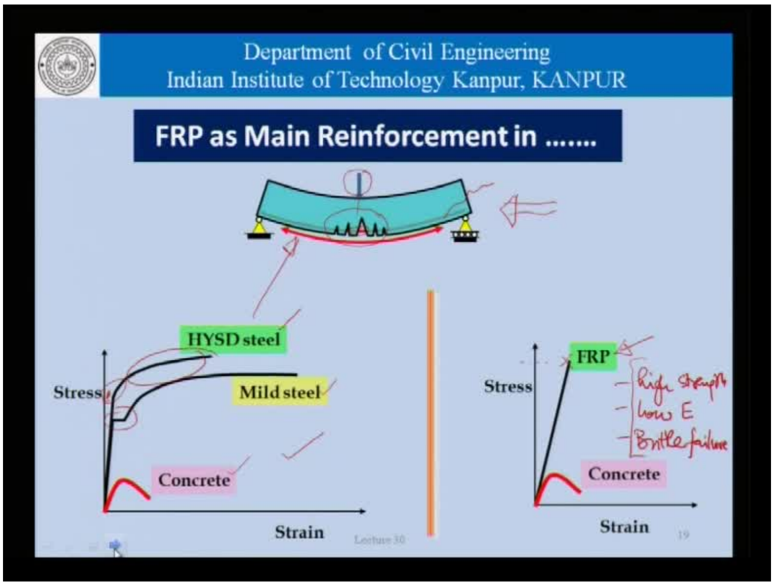

Now, this picture here shows a very simple being which is loaded in the center, simply supported being loaded at the center which deforms like this. And, this here is the reinforcement because concrete is weak in tension. And, unless we have this reinforcement here, these cracks are likely to run through and destroy the beam. So, once we have this reinforcement, the cracks do not run through and these materials go in tension. And, that is what the basic behaviour of reinforced concrete is all about. So, as far as we are concerned, we understand this behaviour pretty clearly. We understand this stress strain behaviour of concrete, we understand this stress strain behaviour of mild steel and high steel and high yield stress deform bars.

So, as far as civil engineers are concerned, we are familiar with this graph. We know how concrete behaves as far as stress strain is concerned; we know how mild steel behaves with this Plato and along yield region in the strain which allows the mild steel to deform. And, how the HYSD bars behave where there is no well-defined yield point; but there still we have a reasonable amount of deformation, after the first yielding that occurs here. Now, we understand this as far as this reinforce concrete beam is concerned or challenge now is to translate this understanding when we are using FRP materials or FRP as a reinforcing material. This material is characterized by a higher strength here as far as the failure stress is concerned but a lower E. So, it is characterized by high strength, it is characterized by a low E and it is characterized by brittle failure. That is it does not have this region of large deformations being possible.

So, with this understanding we have to apply FRP as far as a reinforcing material in concrete construction is concerned. Now, before we apply FRP's in concrete construction we must now understand what are different tests that need to be carried out in terms of fatigue, in terms of creep, relaxation and so on bond; and then try to study the applications in concrete.

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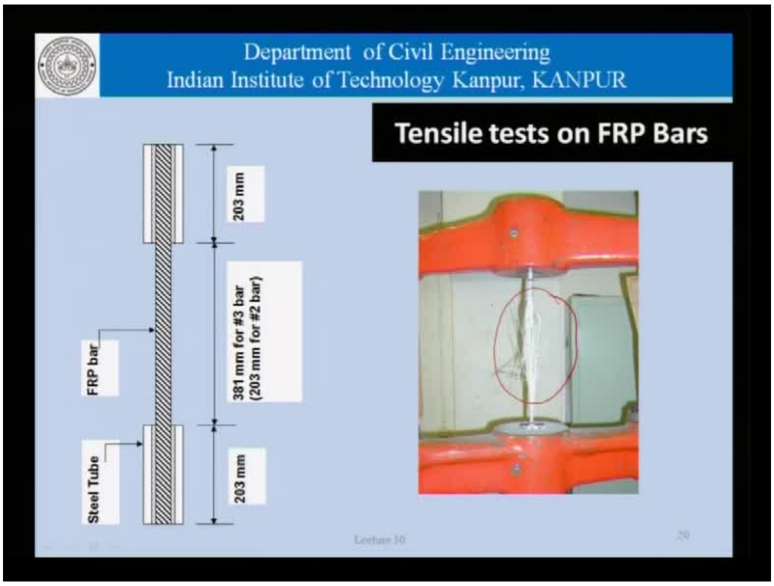

This picture here shows the tensile tests on FRP bars. So, if we look at the tensile test, this is how the FRP bar fails. So, it is a very brittle failure, destructive in nature and does not give us any time as far as the netting is concerned. So, there is absolutely no large deformation region.

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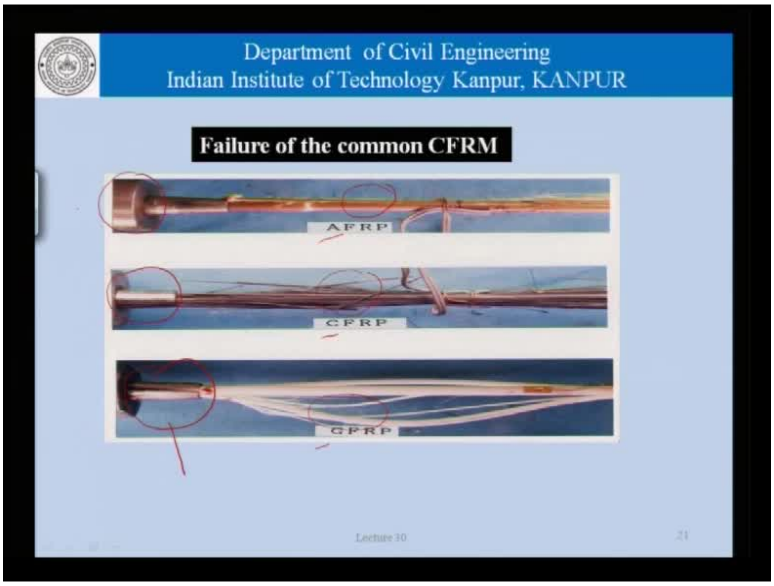

Another thing, which we will see later on in the next slide perhaps. This slide here shows the failure of the common CFRM; the aramid fibers, the carbon fibers, the glass fibers and in all cases we see that there is a fair amount of delamination’s that has occurred, fibers have become separated from the matrix, the matrix has completely collapsed and so on. One thing I would like to point out when testing CFRM is the role of these anchors at the end of the specimens.

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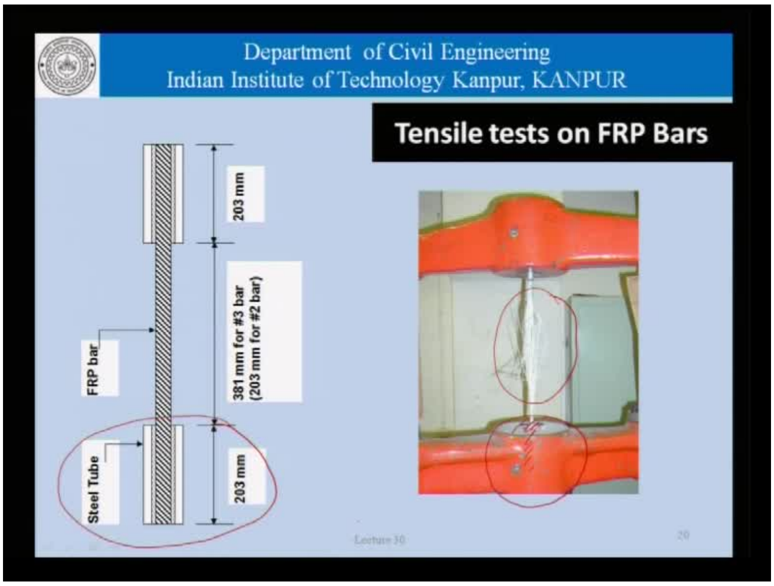

This part here; the region that goes into the machine where the FRP sample is held and the load is applied.

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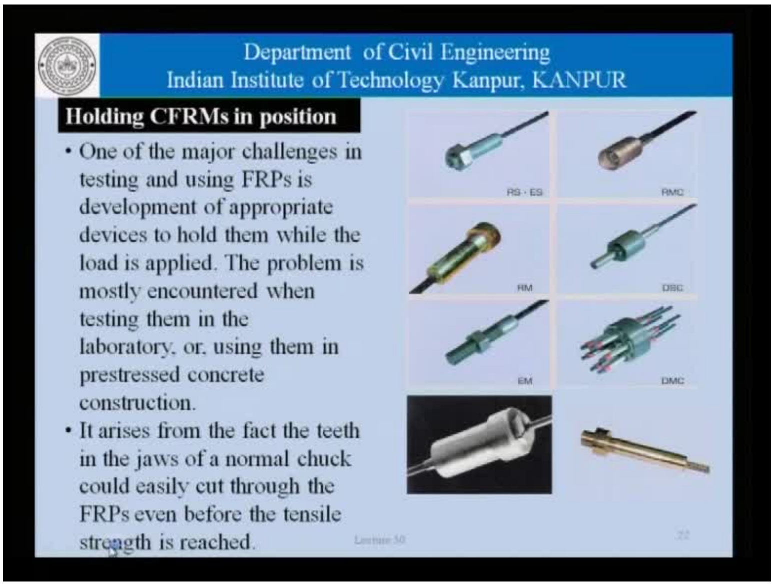

One of the major challenges in testing and using FRP's is the development of appropriate devices to hold them in position while the load is applied. The problem is mostly encountered when the testing is carried out in the laboratory or when they are used in pre-stress concrete construction. You know that in post tension pre-stress concrete the fibers or the reinforcing tendon is to be held in position over a long period of time, using a device which will anchor the tendon. And, this is more or less similar to the device that holds the tendon in position or specimen in position, when it is tested in the laboratory. The problem arises from the fact that the teeth in the jaws of a normal chuck could easily cut through the FRP's even before the tensile strength is reached.

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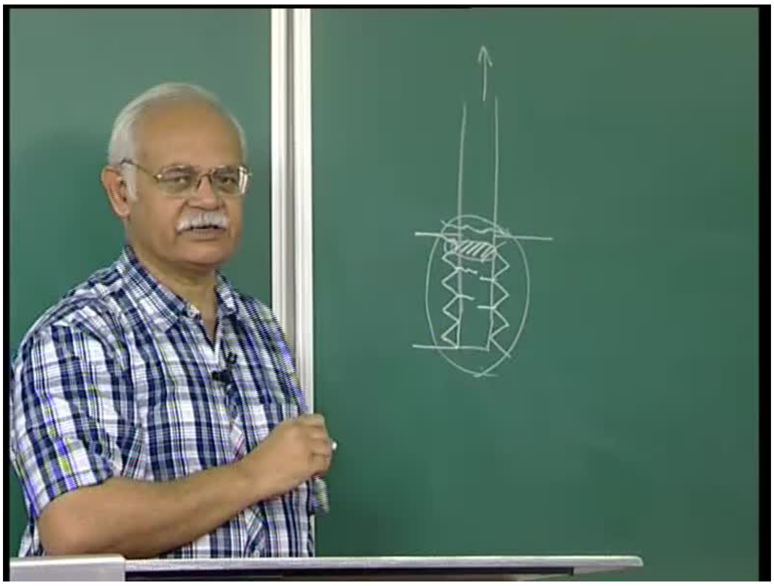

An FRP rod, when it is held inside the chuck and we want that only this portion should be pulled or the load should be applied. How do we hold this in position? One of the ways to do it is to have some kind of teeth, which will grip the specimen. Now, if this material here, which is the FRP is soft, compare to whatever material we are using here for the chuck; it is lightly that as the load levels will increase this material will cut through the FRP's. And, the failure will occur at the chuck itself or within the chuck and this is a major challenge as far as testing of FRP's is concerned.

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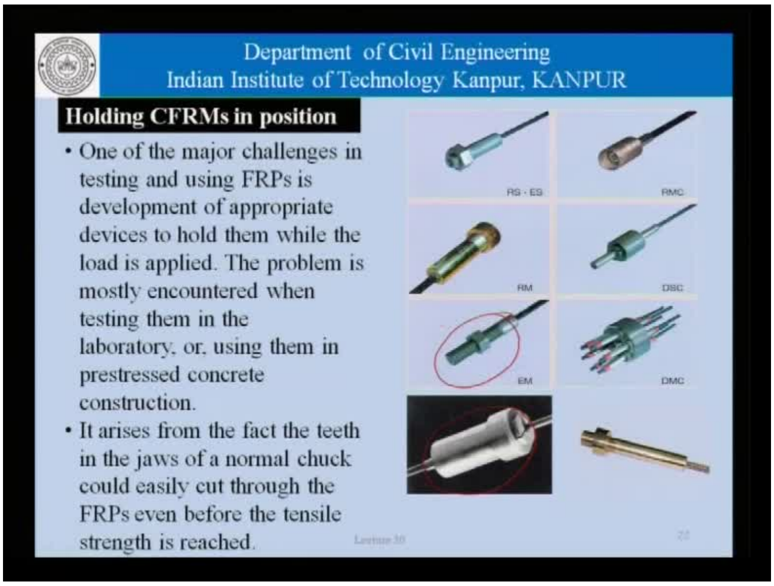

So, designing these devices or these anchorages is a technological challenge as far as FRP's are concerned, their use in the field in the post stationed, pre-stress construction is concerned.

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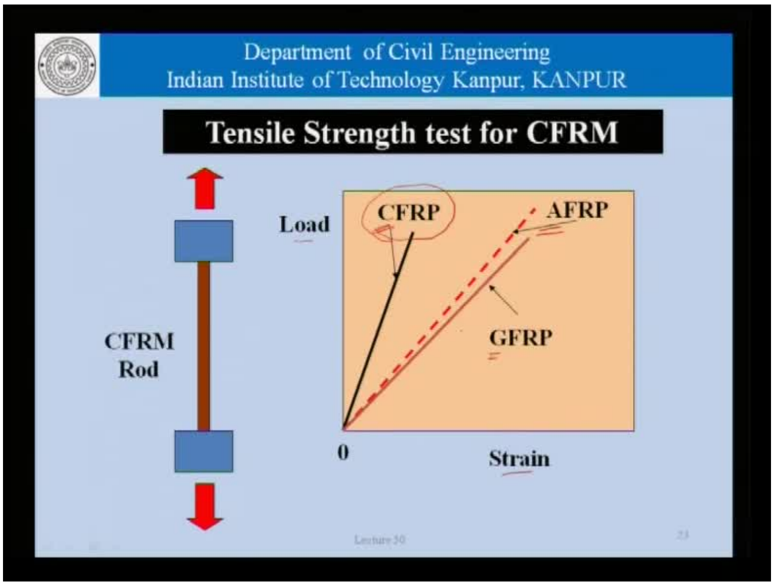

Now, if you look at the tensile strength stress of CFRM the way it is shown, if we take the stress strain curve, the load strain curve; then, depending on whether the material is aramid or glass or carbon, the stress strain curves are quite different. Carbon fibers are comparatively stiffer; you will recall from the last discussion that we did have high modulus of elasticity carbon fibers and intermediate modulus of elasticity carbon fibers. And, that is what makes the carbon fiber reinforced plastics stiffer than glass or aramid which have more or less the same behaviour.

We must remember that the stress strain behaviour or the load deformation behaviour of the carbon reinforced plastic rod or the aramid fiber reinforced plastic rod would be different than this. Because this actual stress strain behaviour also depends on the volume fraction of the fiber. And, the epoxy or the matrix in combination with which that particular fiber volume has being used.

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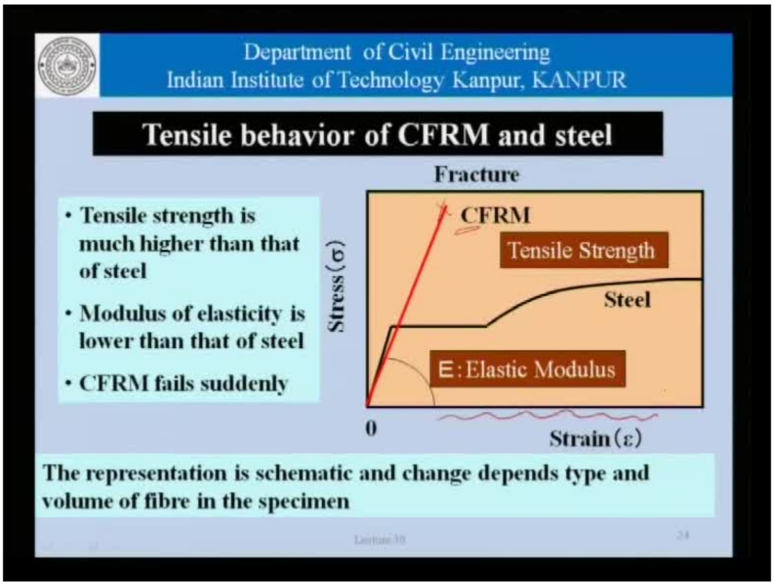

Now, comparing it once again as far as steel is concerned, then what it looks like. For carbon, the modulus of velocity is about one-third that of steel and the biggest difference is that we have a large fracture load but we do not have any capacity in terms of deformations is concerned. The deformation is brittle; it does not allow us any warning, there are no large deformations possible and that is something, which we must be keep in mind when we are designing structures using CFRM.

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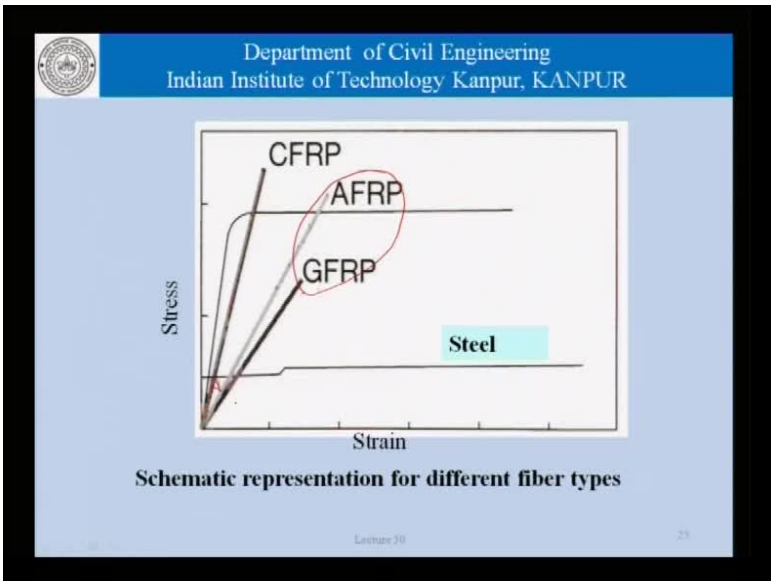

And, once again this is a comparison of the carbon and aramid glass compare to steel and we can see that as far as aramid glass is concerned, they are again softer than carbon. And, therefore, as far as steel is concerned they become even more soft.

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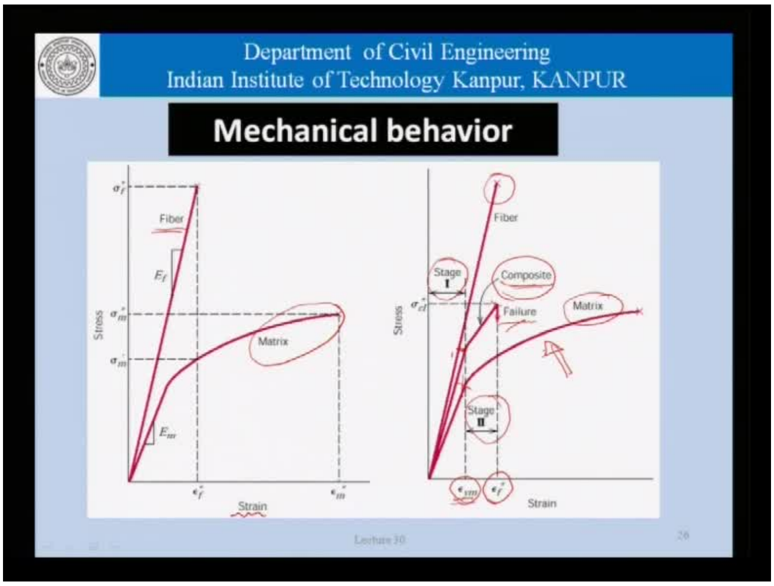

Once again if we plot the mechanical behaviour of in terms of stress and strain of the fibers, we can divide the stress strain behaviour of the composite into two stages. Stage 1 and stage 2, which are separated by this value here which is nothing but the value at which the matrix becomes non-linear. So, long as the matrix is linear and the fiber is linear, then the behaviour of the composite is also linear determined by the equation that we have already derived. When the matrix becomes non-linear, the behaviour of the composite also becomes non-linear or at least it changes its slope and it fails at the value which is governed by the failure value of the fiber.

So, we can see that even though the matrix itself has some capacity to sustain load in terms of higher stress; the fibers do not have that capacity. And, therefore, the behaviour of the composite as far as the stress strain is concerned till failure to a certain point in time; it is linear governed by the matrix. And, once the matrix cracks, it is governed by the, the failure is governed by the failure strain of the fibers.

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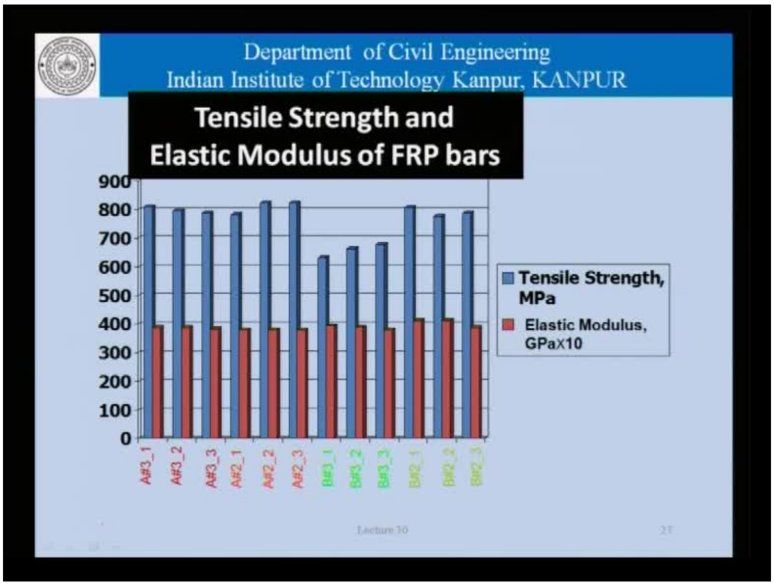

So, with this understanding; so, this is a very important understanding as far as the stress strain behaviour of fiber composites is concerned. This picture is just some data for tensile strength and modulus of elasticity of FRP bars. And, I am skipping this because the data itself is not really important because it depends on the volume of the fibers that are used matrix that is used and so on.

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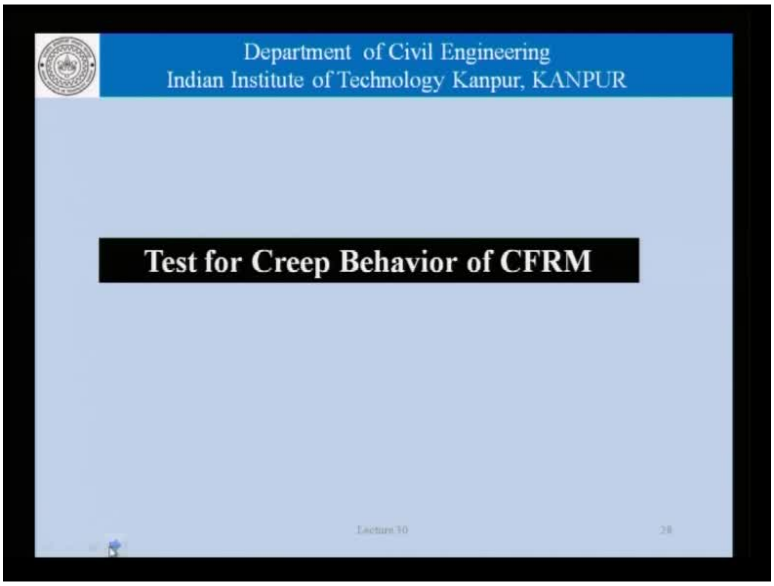

And, now let us try to look at some other tests which are relevant form the point of view of using CFRM as a reinforcing material in reinforced concrete or pre-stress concrete. One of them is creep; now, what is creep? Creep is the change in strain at a constant load.

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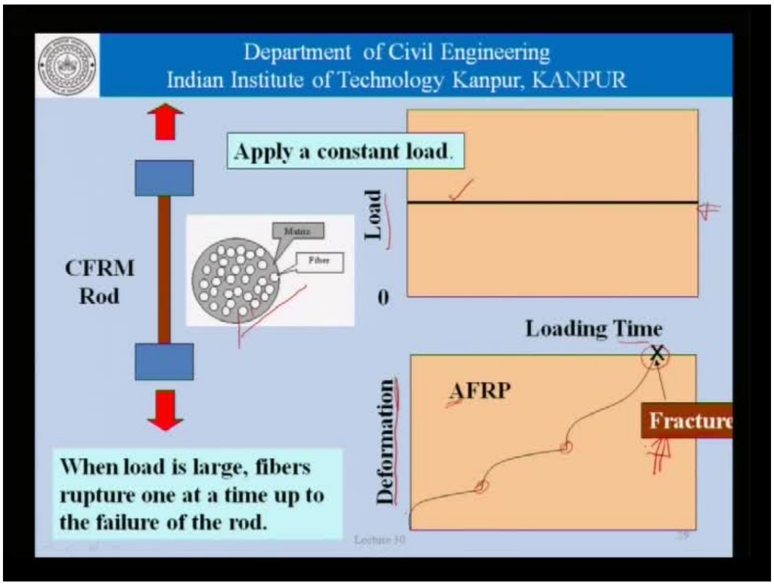

This picture shows the representation of a creep test using CFRM rods. What is done is that a CFRM rod is held in position at a constant load; that is the load is held constant over a period of time. Now, depending on the load level, there will be a certain amount of deformation; that is initially present in the CFRM and that is the elastic deformation. As the load is sustained over the long period of time, successive fibers will one by one snap; that is they will fail. And, as the fibers fail the other fibers will carry that load, because the load is not being changed over time.

Now, what happens as a result of that is that the deformation over a period of time changes; as I shown here in the case of aramid fibers. And, as one fiber phase after the other, the deformations suddenly change. And, as more and more fibers continue to fail, there is a point where the deformation is reaching a level where the entire rod has basically failed. So, this is what is the basic creep behaviour that is observed; when we come to the CFRM. Because these fibers are independent units, so the behaviour is quite different from that of steel; where we have basically a bulk material under sustained load. Then, we have the concept of relaxation.

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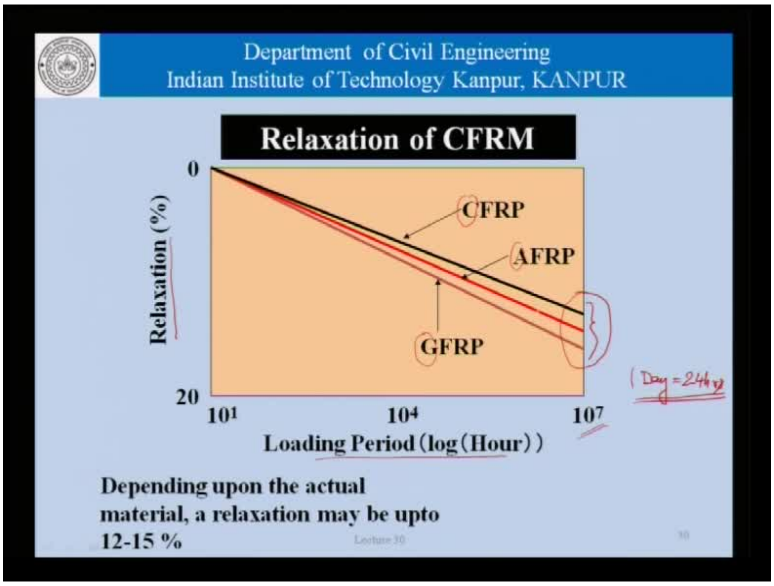

Now, relaxation is the change in stress at a constant strain. And, now depending upon the actual material we may find that there is up to 15 percent of relaxation. And, that relaxation again is represented as the change in stress values at a constant strain and is monitored over a long period of time. And, we can see that carbon, aramid and glass; all show certain amount of relaxation as far as changes in the stress values is concerned over a long period of time. Of course, 10 to the power of 7 is a very long time, considering that one day is just 24 hours. So, we know that in order to be able to carry out this test for so many days, it is not easy. And, therefore, experimental data is very very hard to come by as far as CFRM or any material is concerned.

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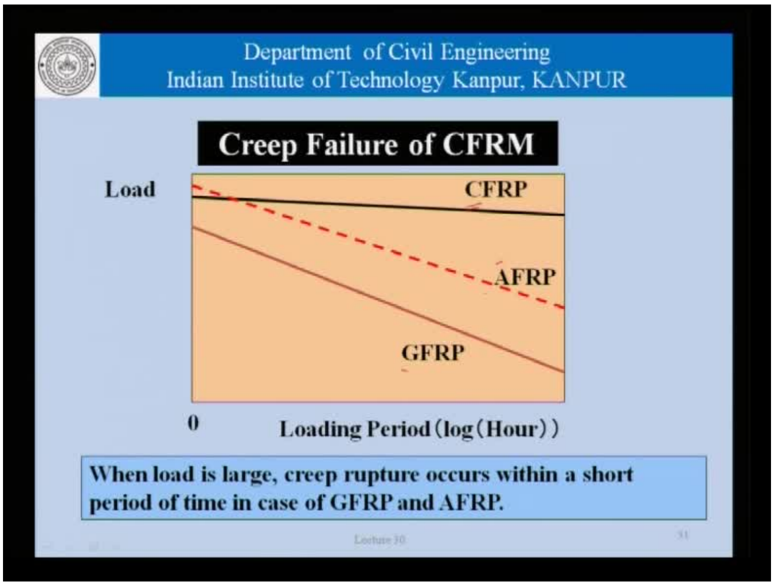

This is the representation of creep failure of CFRM depending on whether material used for carbon fibers or aramid or glass. So, we can see that the behaviour of carbon fibers is much better than aramid or glass; which shows that all these fibers do not behave in exactly the same way, as far as performance at higher load levels is concerned over a period of time.

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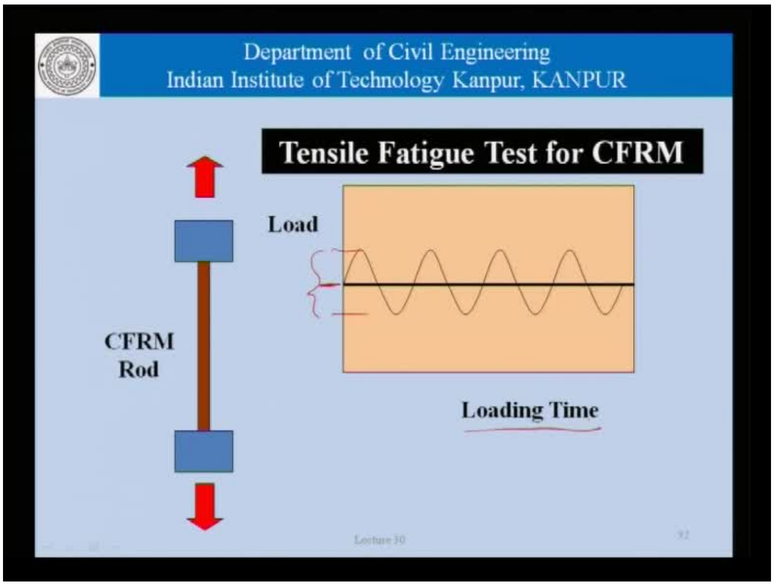

Now, coming to tensile fatigue; tensile fatigue means the load is varied of course, the way it is shown here, it is sinusoidal; it need not be sinusoidal at a certain mean load level in ensuring that all this region, from here to here is still tensile. So, the material is not being unloaded completely and within a certain band, the material is being tested as the load is being varied over a period of time. And, the variation could be in terms of the mean load being applied in relation to the failure load or the amplitude of the load being varied or the frequency of the variation and so on.

So, in a nutshell the load is time dependent; as against the, as against creep when the load is held constant. So, in tensile fatigue the load is always in the tensile region, the material is always in tension; except that the level of tension varies depending on the amplitude and the frequency of the load application. And, this load is applied over a long period of time there is a loading cycle and we apply cycles of load.

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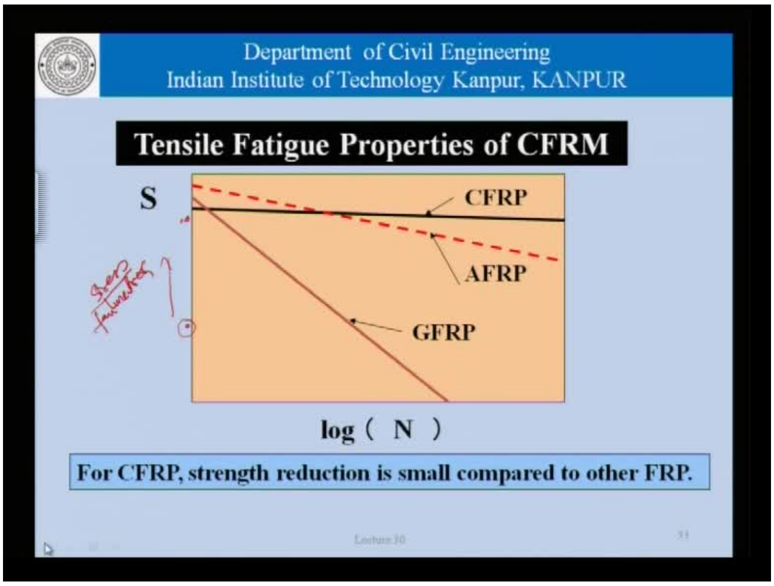

Now, this is represented traditionally in the form of an S N curve which really shows that the number of cycles to failure at a certain stress level. So, this level here on the y axis is the applied stress to the failure stress. So, if we are going higher up in this picture here, we are moving in a manner where the applied load level is closer to the failure stress. Whereas, the stress here is lower than the failure stress.

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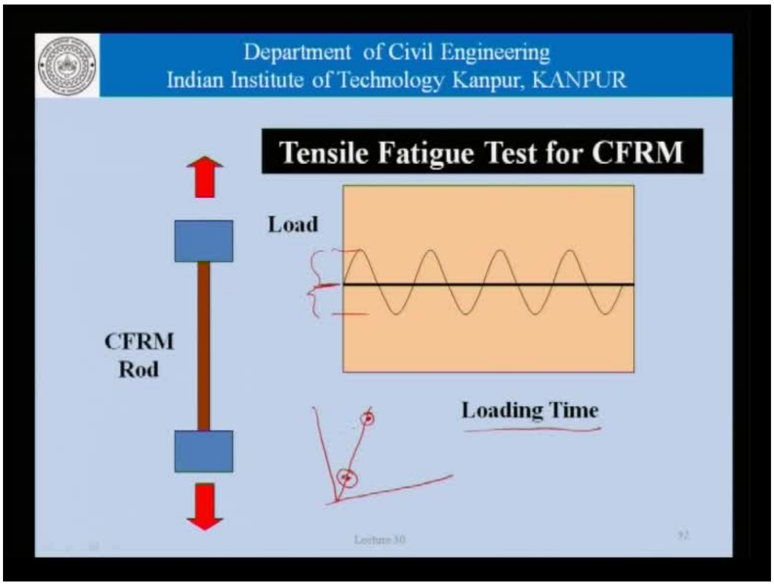

Basically, this level here how high or how low is this level compare to the failure level. If this is the stress strain curve of the material and the applied load is being varied at this point versus the applied load is varying at this point; this here is at a lower stress level and this is at a higher less stress level.

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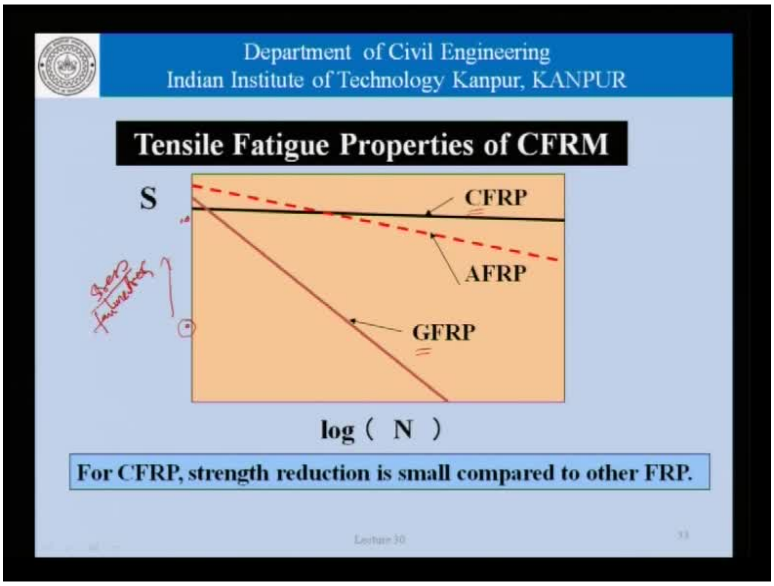

And, that is what is represented by these two points here along the y axis and naturally if the stress levels are lower and naturally if this stress levels are lower, the number of cycles to failure or higher. And, if the stress levels are higher, the number of cycles to failure is low. And, if we study this S N curve for the different fibers, we find that the glass fibers are most vulnerable as far as fatigue loading is concerned. Comparatively, the carbon fibers show much better performance.

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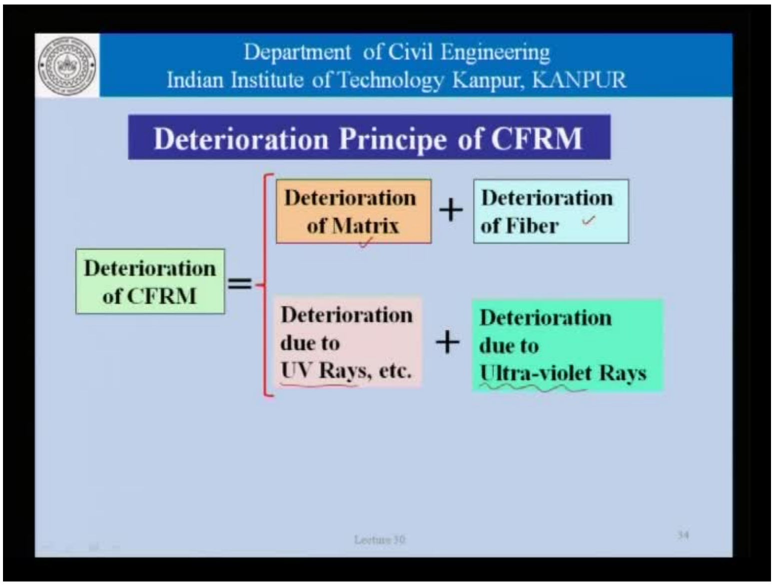

Now, coming to the deterioration of fibers or deterioration of the CFRM. This really consists of the deterioration of the matrix or the deterioration of the fiber, looking at another way; what is the mechanism of deterioration? Whether it is ultra-violate rays or we are talking of alkali.

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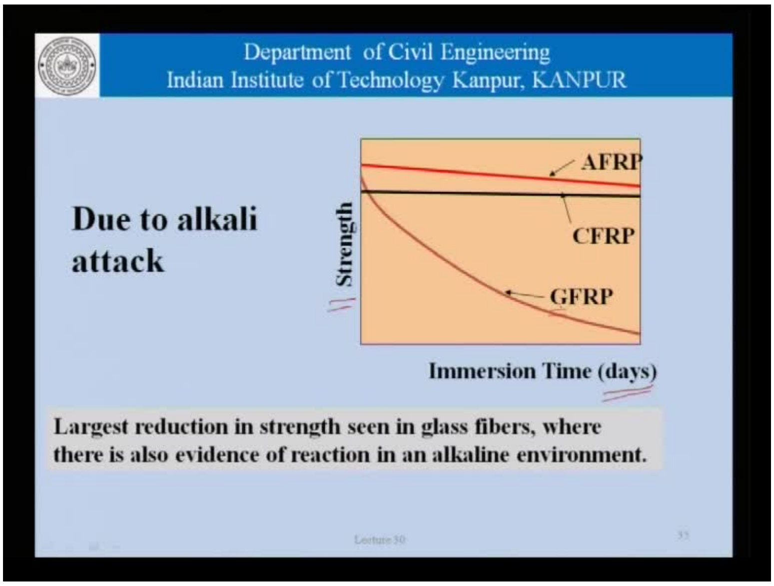

Coming to alkali attack, we see that if we immerse the CFRM in an alkali solution. And, why alkali? Because we are expecting that the concrete is alkaline, we know that the concrete is alkaline. And, the fibers or the CFRM is in contact with the high alkaline solution; that is we talked about last time. And, if we look at the change in strength with immersion time in the p H or a high p H environment; we find that glass is particularly vulnerable as far as its durability in high alkaline environment is concerned.

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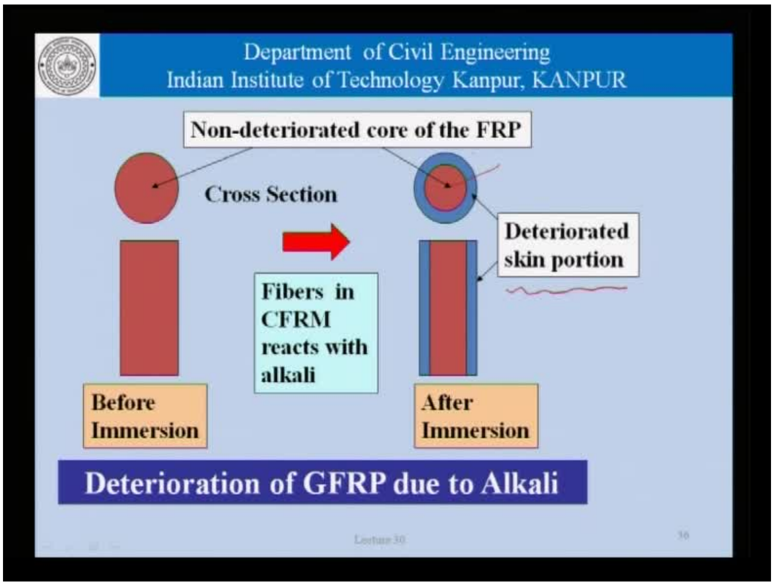

As far as a model is concerned we can look at it the way it shown here, that there is a deteriorated skin portion; that can be identified as far as a glass FRP is concerned. And, only the core remains unreacted or undamaged. One of the ways therefore, to use glass reinforced fiber plastics in concrete construction would be to have a coating on the glass fibers and the CFRM in order to protect them from reaction of alkalis in the environment.

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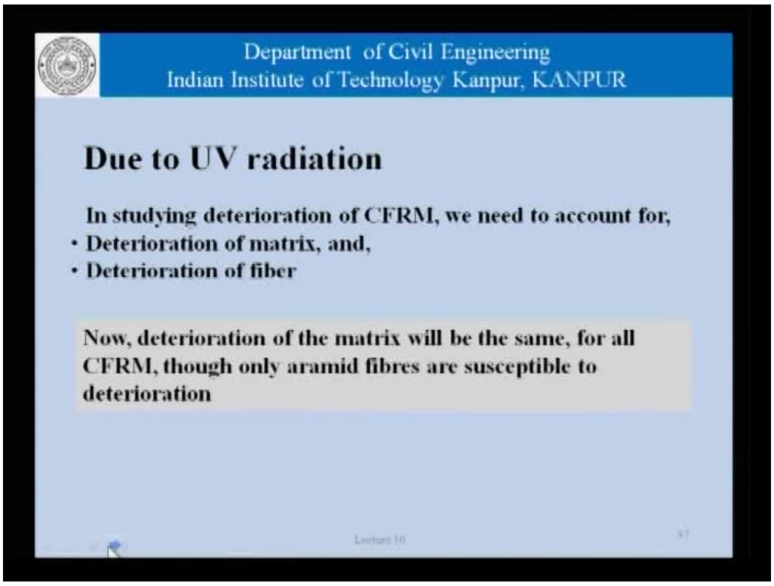

As far as ultraviolet radiation is concerned we have to account for of course, the deterioration in the matrix and the fiber. And, what most experiments of the studies are found that the deterioration in the matrix of course, will be the same. But only for aramid fibers there has been some reported deterioration as far as the change in strength on account of the exposure to ultra violate rays is concerned.

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Now, continue again from the last discussion; let us look at some more field applications of CFRM.

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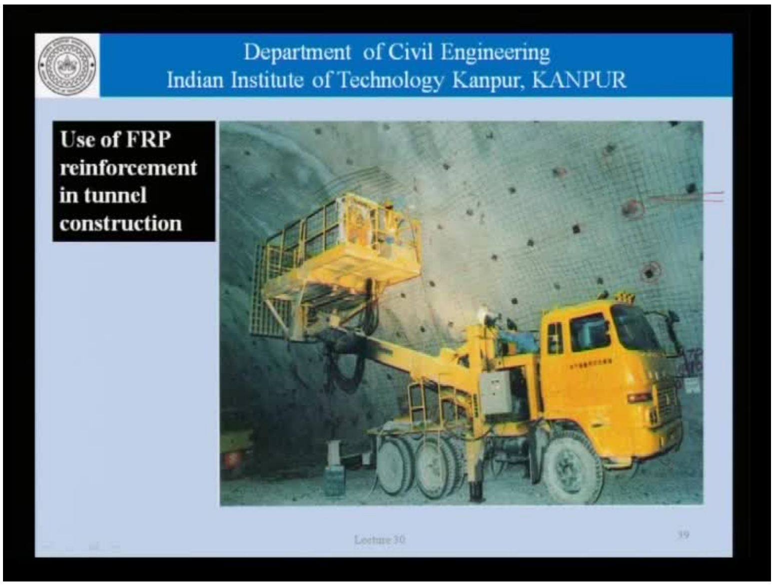

Here we are using CFRM in a tunnel construction. So, we can see that there are there is a net which has been placed using these bolts to hold a lining which is going to be applied on the tunnel.

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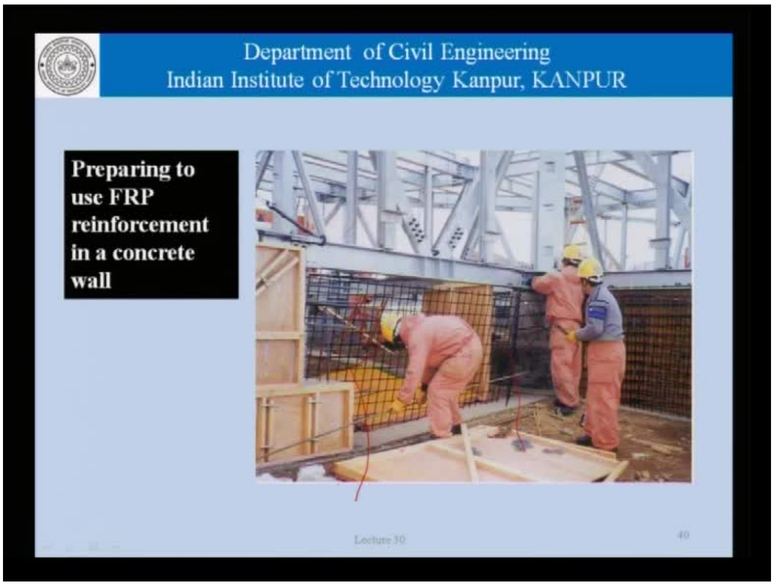

Similarly, here we are looking at FRP reinforcement being placed, which again is a grid as shown here; for the reinforcement in a concrete wall. In this case, we are using FRP as cables.

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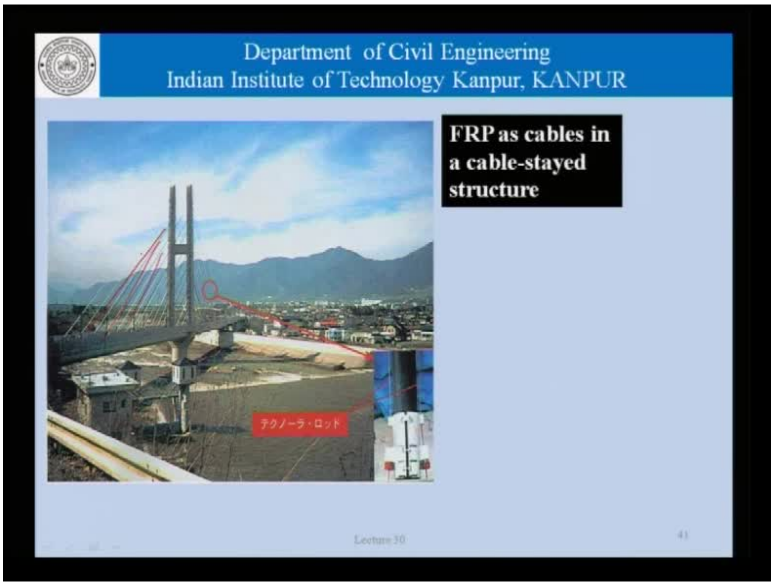

These cables are FRP cables in a cable-stayed bridge.

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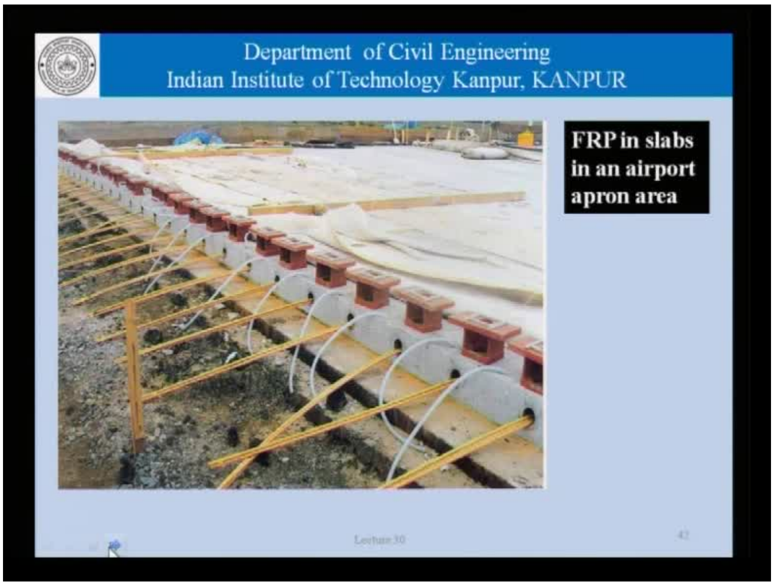

Another example is shown here; where we are trying to use FRP in the reinforcement of slabs, in the airport apron area.

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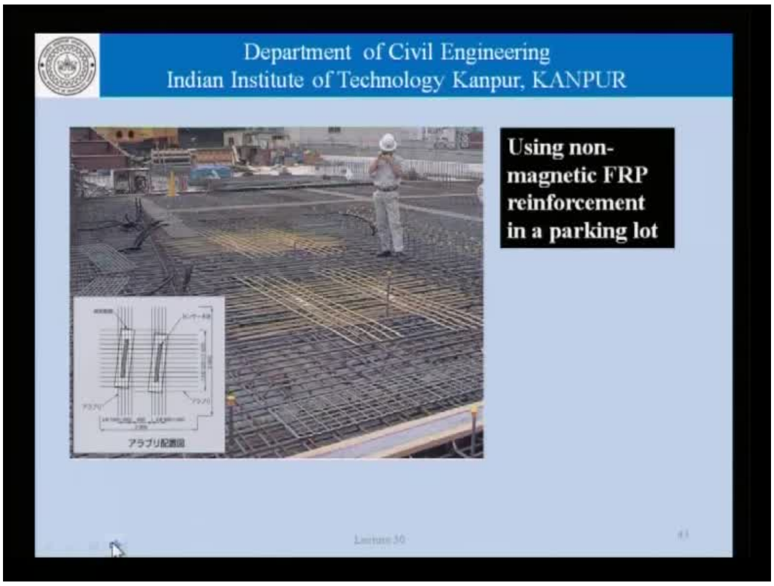

This is another application of FRP where its nonmagnetic properties are being used in a lot. Because there are some devices embedded in the slabs, which will help detect the presence of a car, when it is parked. And, if there is a normal steel reinforcement that may not be possible; and therefore, FRP may be used in at least certain places where those senses are placed.

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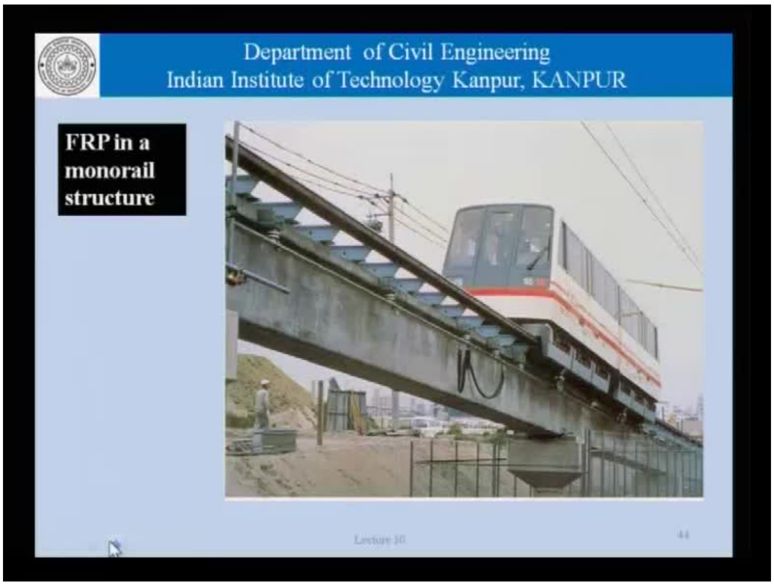

This structure here shows FRP on a monorail structure.

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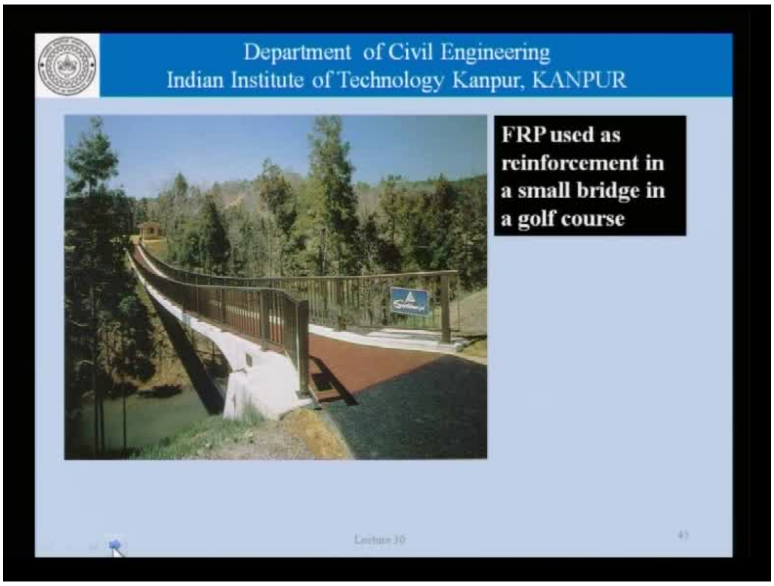

This picture shows the fiber reinforce plastics being used as a reinforcement in a small bridge, in a golf course.

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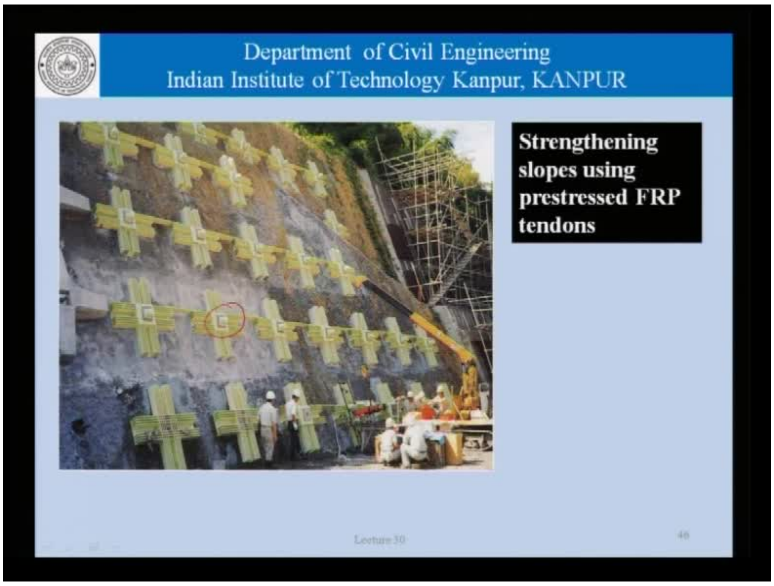

Yet another example of using FRP’s in concrete construction or civil engineering construction is in strengthening slopes using pre-stress FRP tendence as I shown here.

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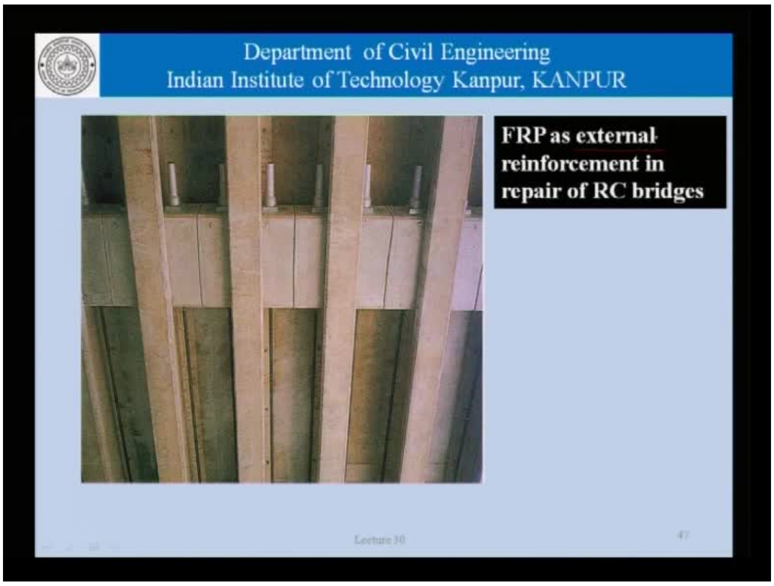

This is another interesting example of using FRP as external reinforcement in the repair of RC bridges or reinforce concrete bridges. Let me explain what external reinforcement in repair work is.

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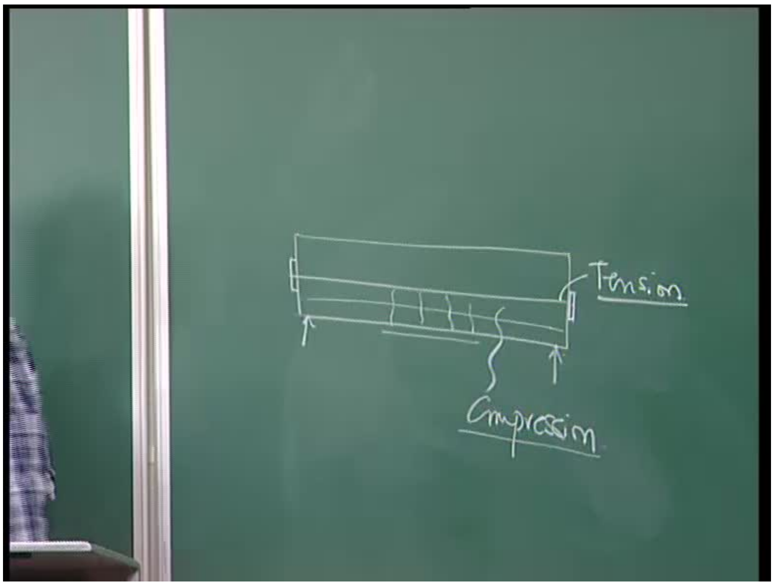

When we have a beam and it deteriorates (No Audio From: 39:17 to 39: 26). If there is a concrete beam with reinforcement which has cracked; one of the ways of repairing this beam with external reinforcement would be to just have something outside this beam and tie the two ends using something like a fiber reinforced plastic rod. And, if we introduce tension, that is we introduced tension in the FRP rod, which is being used external to the beam. Then, what we ensure is that we have, then we ensure compression under concrete. That is we are externally compressing the concrete. And, this helps in closing the cracks, getting rid of additional deflections and so on. So, that is a principle of external reinforcement in repair works of RC bridges. And, given their high strength FRP's are a good candidate for using this condition.

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This picture here is that of FRP as reinforcement and highway construction.

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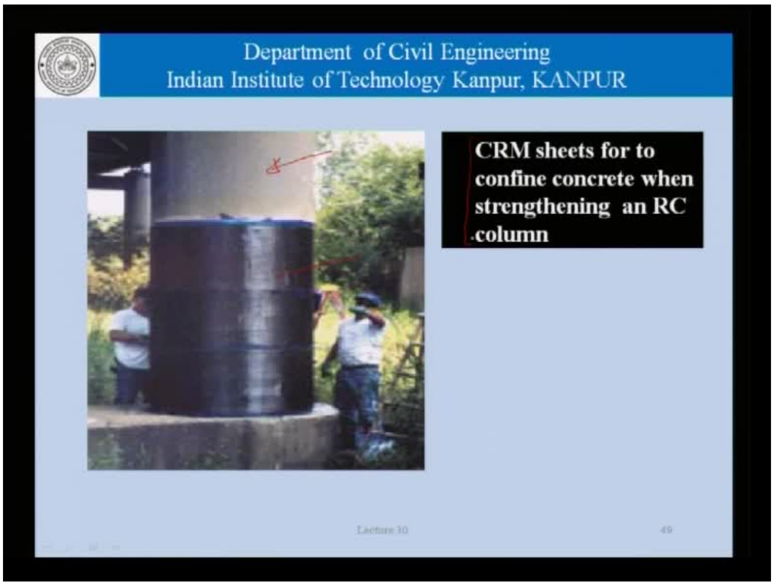

This is another example where CFRM sheets have been used for a strengthening of RC columns. We can see that as far as the concrete here, this is concrete; we can see that the concrete here in the column has now been wrapped using this FRP sheets. Now, how this helps as far as strengthening is concerned is by the following action.

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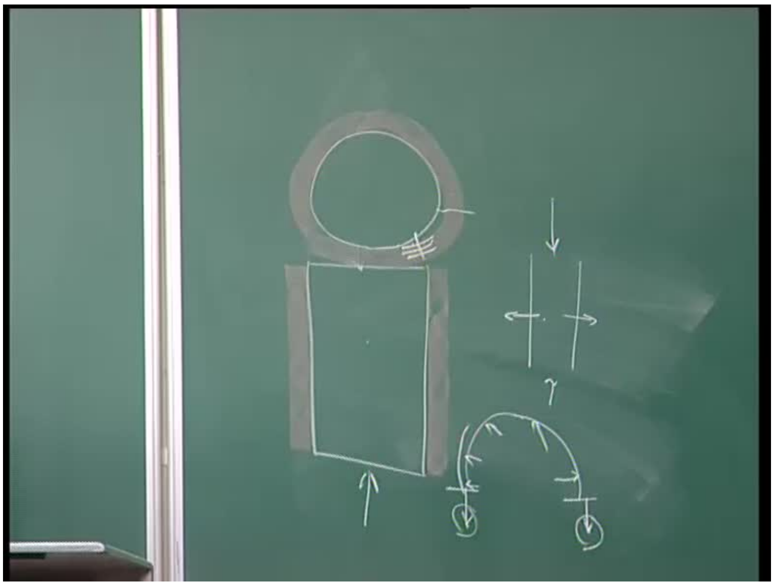

If this is a concrete column which is under the action of compressive loads; what happens with the column is that this concrete when it is under compression would tend to expand. Now, if we are able to wrap this concrete which is something like this in the front view, then this tendency to expand is arrested. Because in order that this concrete be now able to expand, this has to cause failure of this fiber sheets. Effectively, as far as the fiber sheets is concerned, for them they are under the action of radial expansion. And, the sheets themselves depending on how many layers of these sheets is there; all these sheets have to be all these sheets are subjected to tension. And, in order that the concrete fail, it is important that all these sheets fail. So, this is one of the methods where FRP sheets are used in several layers, wrapped around concrete columns to increase the load carrying capacity of the deteriorated reinforced concrete column.

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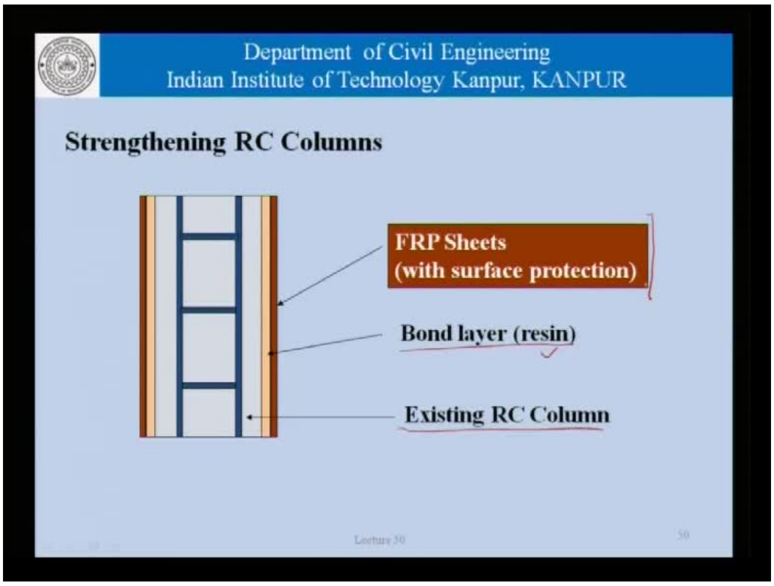

Schematically, the process is shown here; where the existing reinforced concrete column is wrapped using FRP sheets, which are bonded using a resin or a matrix. So, in this case the FRP rod is not manufactured; it is not something like an FRP rod is not manufactured in the plant, but we get a composite made of FRP sheets and the matrix applied at site. Of course, at the end we could apply surface protection as far as matrix is concerned in order to protect the matrix as well as the fibers, from external influences such as water, air and so on.

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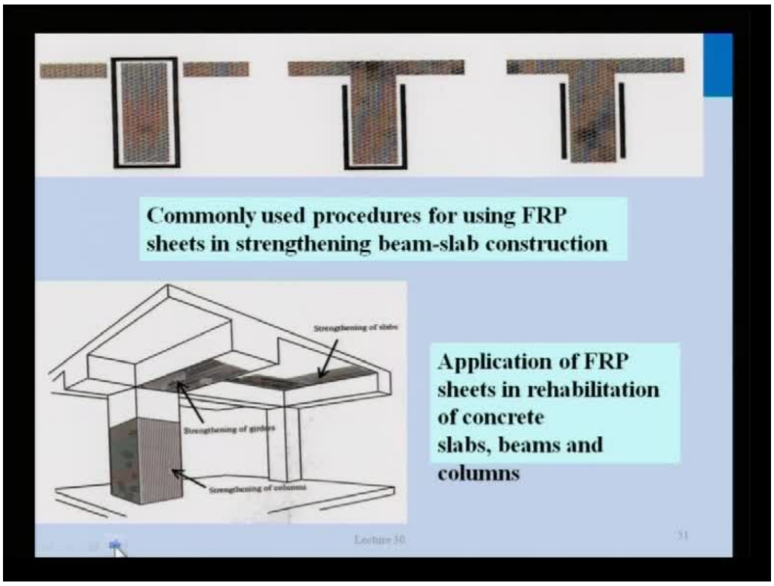

Similarly, we can use FRP sheets for strengthening being slab constructions and depending on what we want, we could use any of the configurations shown here.

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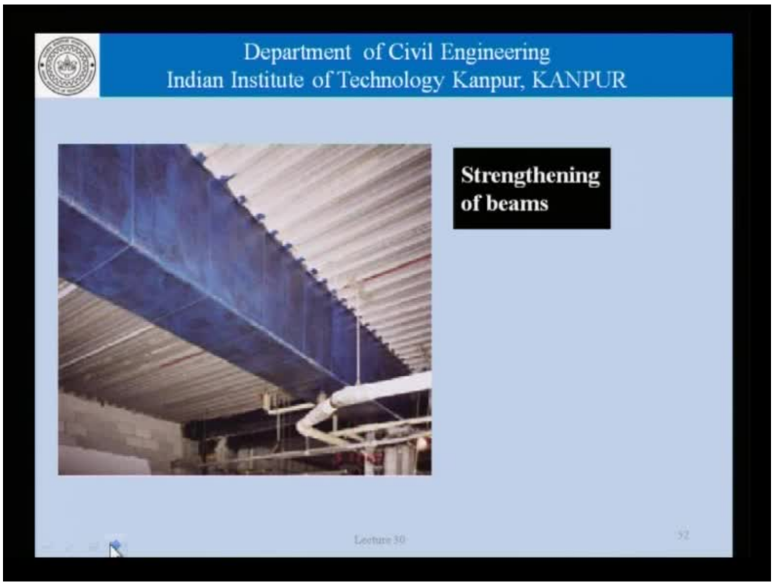

This is a picture of strengthening of beams using FRP sheets and in this cases, well the FRP sheets applied in certain layers or a certain number of layers which have to be designed. And, these layers are held in position using appropriate matrix material. And, these fabrics are they are reinforced, in both directions; it is not unidirectional material in that sense.

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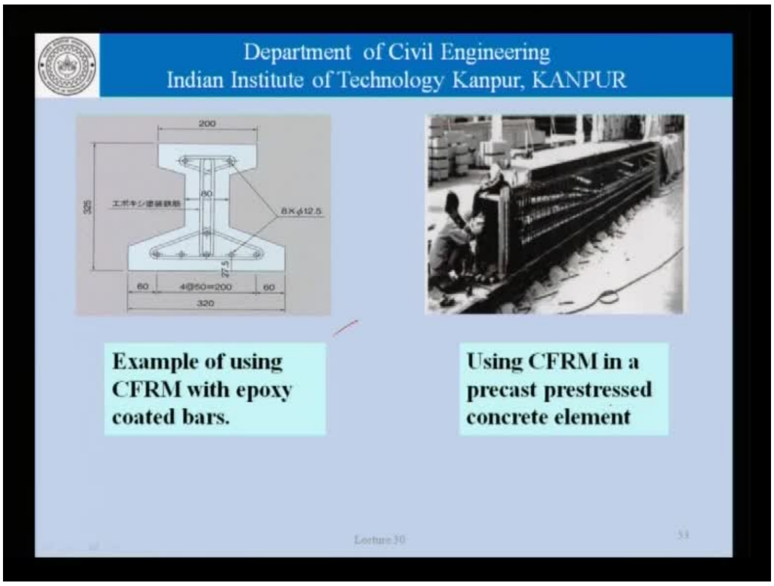

Continuing with the examples, we have CFRM with epoxy coated bars in the case of girders which is shown here. In this case as well as in a pre-stressed, pre-cast concrete element has been shown here.

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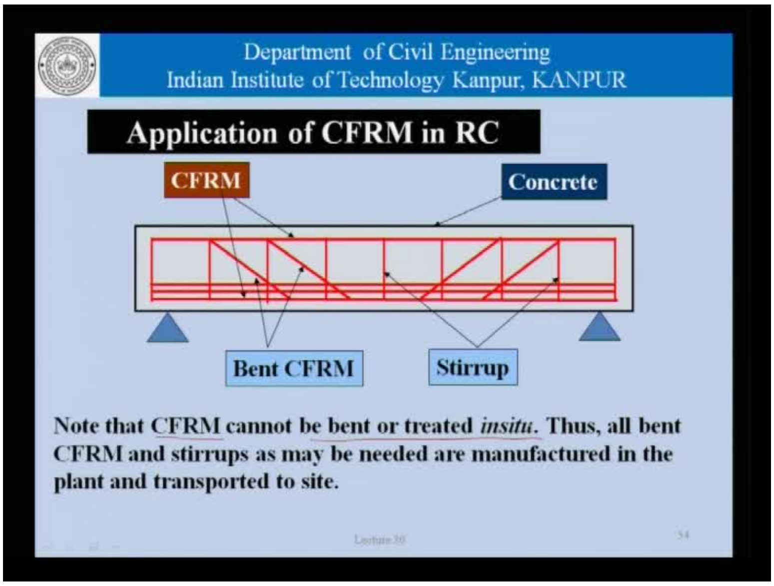

There is no reason that as far as the application of CFRM in reinforced construction is concerned, it should be remembered that these cannot be bend or treated at site. And, therefore, all bent CFRM and the stirrups need to be manufactured in the plant and then brought to site.

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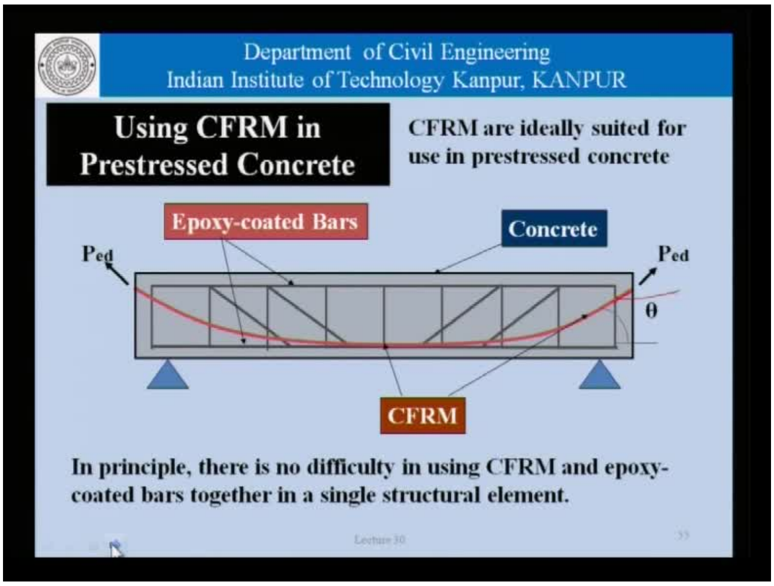

And, there is no reason why CFRM cannot be used with traditional reinforcement or epoxy coated bars and so on in RC members or pre-stress concrete members. And, given their high strength the CFRM or an ideal material for use in pre-stress concrete as I shown here. So, this tendon here which is going to be used for pre-stressing could be a CFRM and the other reinforcement is simple epoxy coated bars or normal bars whatever we want.

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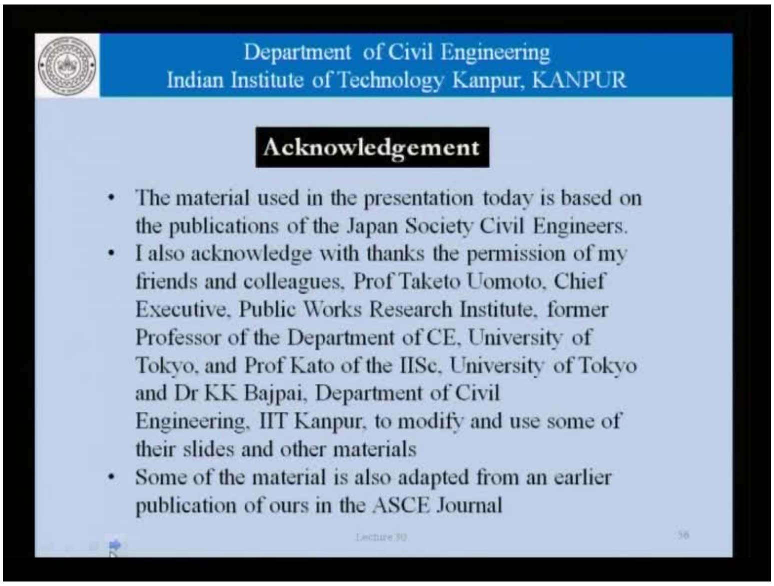

Coming to the close of the discussion today, let me once again acknowledge all the help and the material which I am using from the JSCE and my friends and colleagues professor Uomoto, Kato and Doctor Bajpai of the department civil engineering at IIT Kanpur; who have kindly allowed me to modify and use some of the slides and from the publication in the ASCE.

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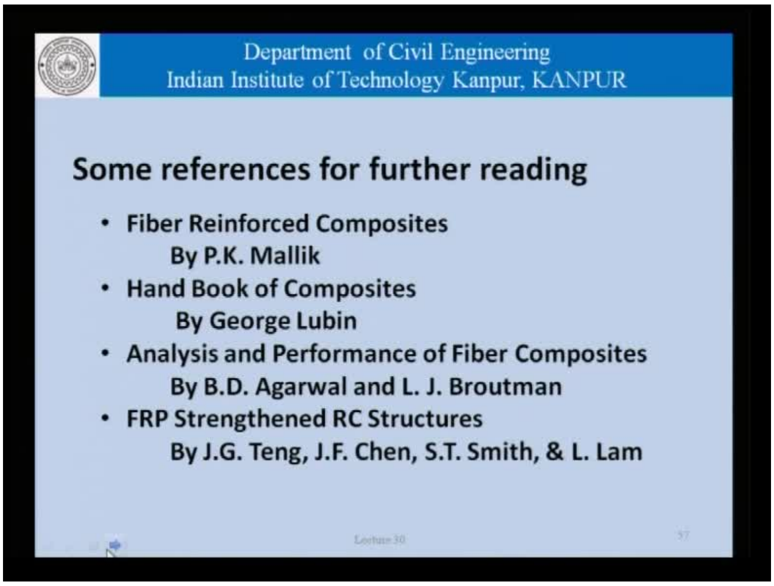

Now, at the end, this is the some of the references that one may use in order to learn more about fiber reinforced plastics and their use in civil engineering.

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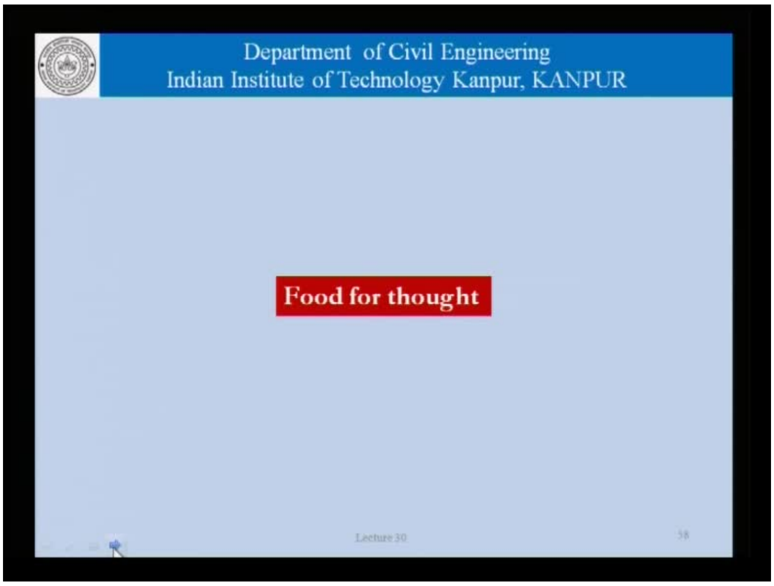

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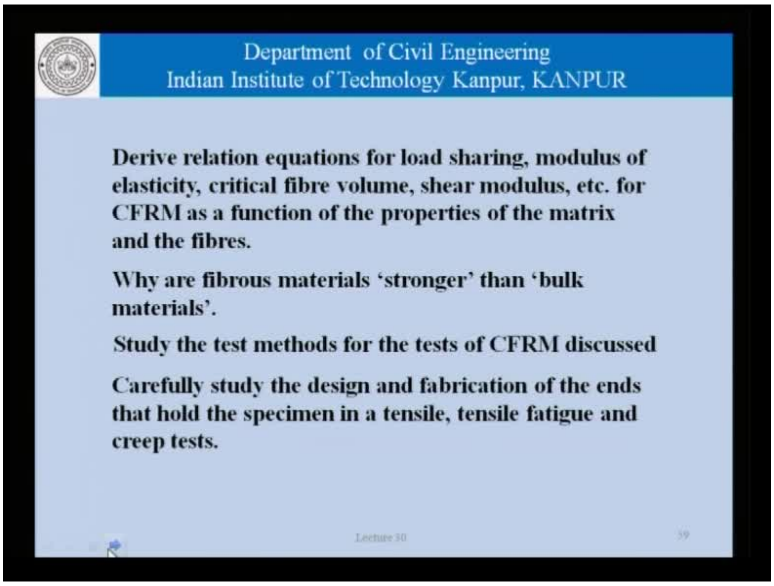

And, before we close some of the things which one could do a little bit more of study and thought. We could derive relation, we could derive equations relating the load sharing, modulus of velocity, critical fiber volumes, shear modulus and so on for CFRM; as a function of the properties of the matrix in the fibers. Some small derivations were shown in the discussion today for longitudinal loading. But a lot more can be derived if we use the same principles and try to understand the shear modulus of a composite material or the behaviour as far as the transverse loading is concerned. We may try to answer the question as to why are fibrous materials stronger than bulk materials? We could study the test methods for the test of CFRM, which has been discussed.

We talked about the creep test, we talked about durability test, we talked about fatigue test and it is important to understand, what exactly is the nature of the test, which need to be carried out. We can study the design and fabrication of the ends or the chucks that hold a specimen in a tensile or a tensile fatigue or a creep test. So that we better understand the kind of discussion that we had as far as the importance of holding this specimen together or holding the specimen in place; while carrying out loads or while applying the loads on the specimen is concerned. This is important because the stress levels are much higher than that of steel. And therefore, it is important that the chucks are designed and fabricated in an appropriate manner.

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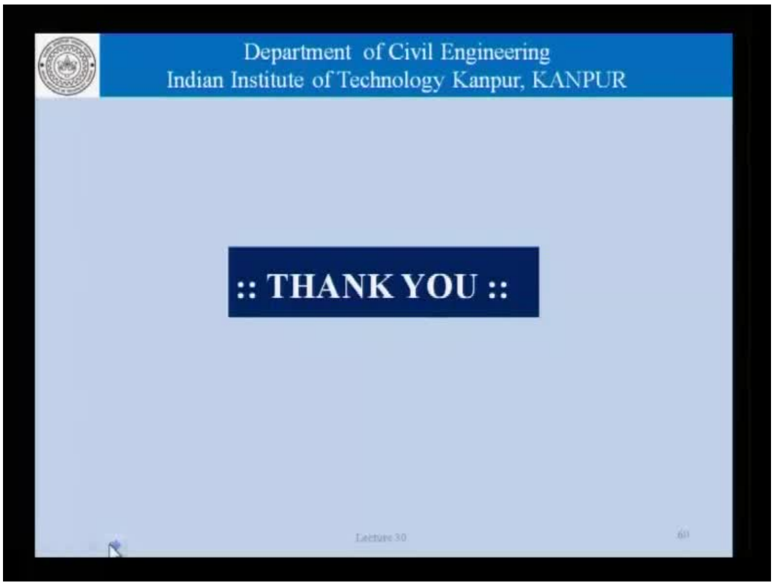

With this, we come to an end for the discussion today.

Thank you.