Maintenance and Repair of Concrete Structures
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Lecture - 27
Structural Strengthening & Stabilization (Beams and Slabs)

Hi, this is the second lecture in the module on structural strengthening and stabilization. In this, we will focus on beams and slabs.

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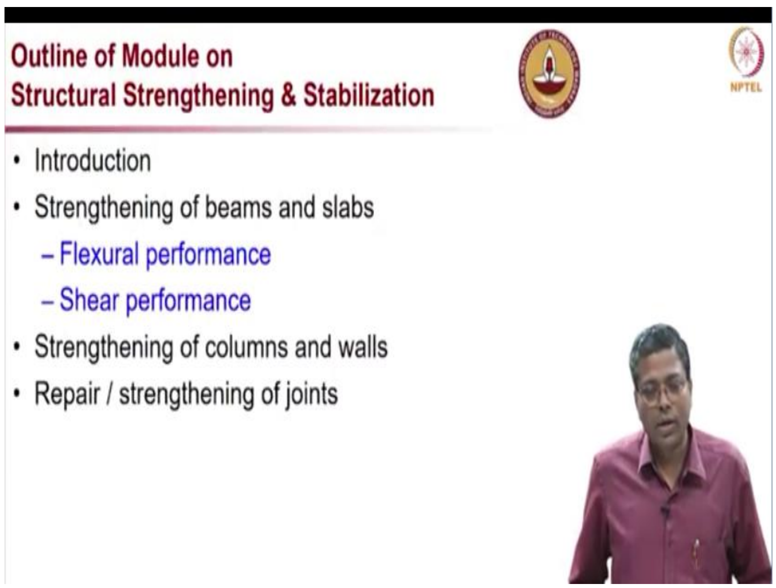

And we will look at methods to enhance both the flexural and shear performance.

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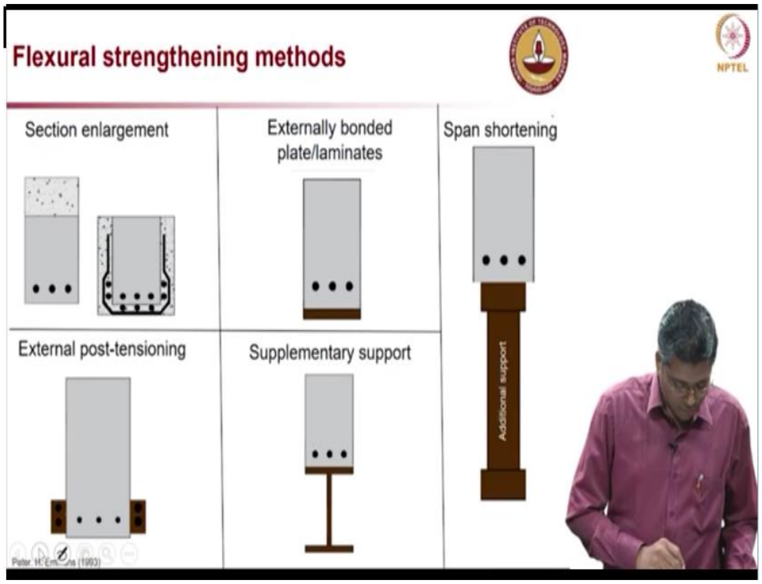

So for first, let us look at how to enhance the flexural performance or flexural strengthening methods. I am showing here five general methodologies. First one is section enlargement that is basically enhancing the cross section of the concrete sometimes with and sometimes without additional reinforcement. Second is externally bonded plates and laminates, then we will talk about external post-tensioning, then also supplementary support systems and finally we will talk about span shortening. So these are the five general methods for flexural strengthening and we will look at one by one.

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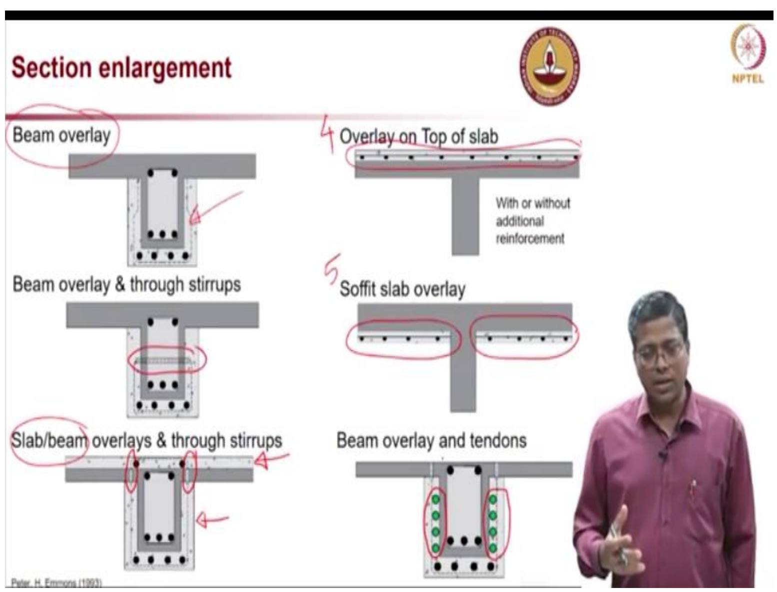

First let us look at section enlargement. I am showing here six different ways by which we can enlarge the section and enhance the flexural resistance. In all these drawings the dark gray region indicates the existing concrete system and the lighter gray towards the outer or peripheral region with typical concrete hatch that indicates the repair material or the new concrete. The area inside on the left is actually not shown as dark region. It is just to show that that is the area inside the stirrup. There is no other significance for that.

Now when you talk about beam overlay, as I mentioned earlier, this is the new concrete which is added and you can also see that there is new primary reinforcement and also new shear reinforcement, the dash line kind of indicates the shear reinforcement. And sometimes like in the first case the shear reinforcement is not drilled into the existing concrete, but if you look in the second case, the shear reinforcement is drilled into the existing concrete, you drill a hole into the concrete, existing concrete and then pass the shear reinforcement through that. Sometimes it is easy if the amount of work is less, but if you are talking about large number of repairs, the process of drilling holes itself might end up in a very big job. So you have to really think whether that is always necessary or is there any other way by which you can still enhance the integrity of the new concrete and the existing substrate and proper load transfer.

Now third one is slab beam overlay, where you have new concrete both on the top of the slab and also around the beam elements. So slab and beam overlay and also you have through stirrups, which is indicated here, you can see that this stirrup is actually going through the flange of the existing concrete system so that from top to bottom all the elements can actually function as one integral unit.

The fourth case is overlay on top of slab, which can actually enhance the compression resistance and thereby enhancing the flexural capacity of the member. And in this case there are two things which I would like to mention, one is with the additional reinforcement and also it is possible to do this without the additional reinforcement, depending on the type of concrete and the material which we use. I will cover that on a later slide.

Then case number five is soffit slab overlay, which is done at the bottom surface of the flange, an additional reinforced concrete provided at the bottom surface of the flange. And also there are strategies by which you can go with beam overlay and the tendons. In here the green circles indicate the new tendons which are added but at the same time they are not external tendons. They are added tendons, but they are tendons are actually inside the new concrete or embedded inside the beam overlay concrete. So, now we will go through, not all six of this, I will show you some examples of each one of these and then we will discuss how they are.

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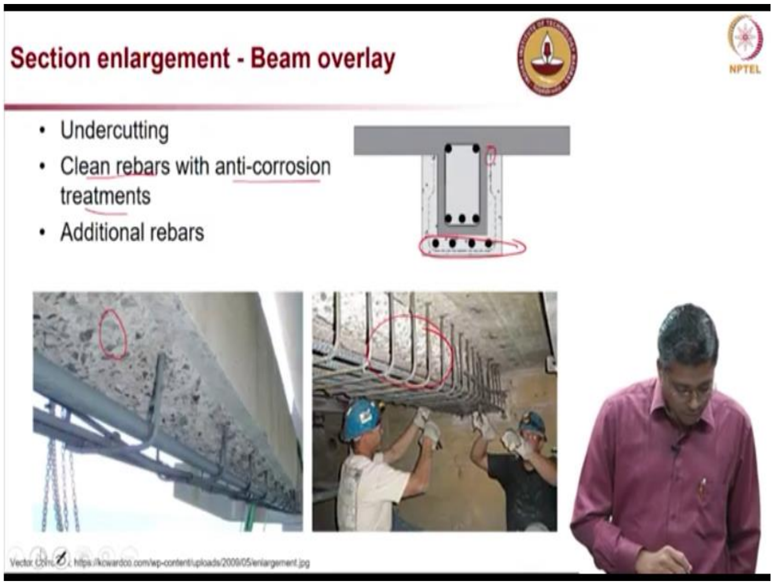

So in beam overlay, as you see on both the pictures at the bottom, undercutting is very important to do. And if we are exposing the existing reinforcement, it may not be the case all the time, but under cutting is very important and at the same time when you put the new reinforcement that reinforcement should be anchored or as you see here, in this case it is going right up to the top flange. I mean, in the picture it is not very clear whether it is going into that, if it is going into the top flange, it is perfect. Now the bar should be clean and also sometimes depending on the exposure condition, you can actually apply anti-corrosion treatment but make sure that those chemicals are not spread or pasted or painted on to the concrete surface, because then that will function like a very weak layer, which will lead to delamination of the new concrete from the existing concrete.

So on the photograph on the right side, you can see additional rebars which is provided. So what I did is in future slides also, I am going to show you a lot of photographs collected from the internet and other sources and which will kind of help you to really visualize things in addition to the sketches, which we have. Sketches looks very good, very neat and clean, but at the same time it is important to really know, how reality is. So that is why I am putting all these photographs, so that you will remember things much clearer and better.

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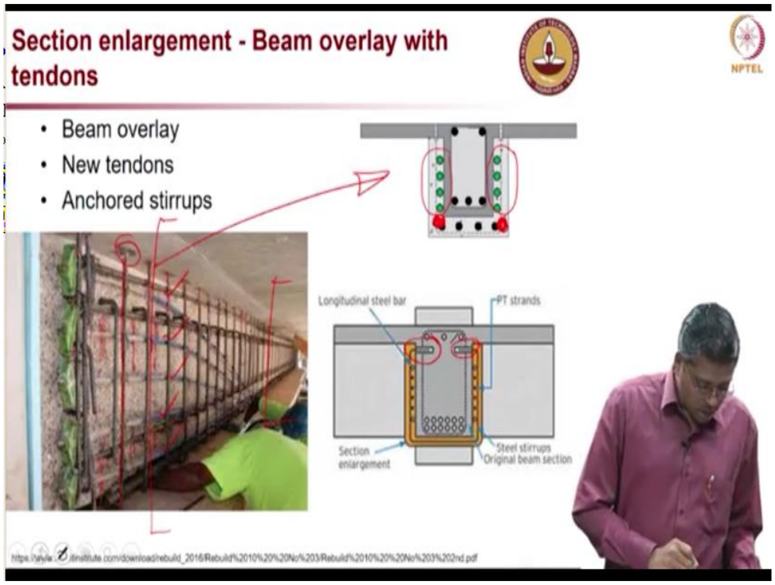

The next thing is beam overlay with tendons. This was the sixth picture in the slide two slides earlier when I showed or different types of section enlargement, this was the bottom right. And you can see here those green circles indicate the tendons and this is a section over here, if I show, not necessarily the section at the mid span. If it is at the mid span, all those green tendons will come kind of here. There will be one here and there will be a couple of them there (Red dotes in the top right sketch). So you can see two sections. In that image you can see 1, 2, 3, 4, and 5 tendons, these tendons typically are provided inside the new concrete or inside the beam overlay and here you can see the additional stirrups, which are actually drilled into the flange, so that you can have very good integrity and a very good load transfer and then the entire section functions as a single unit

In the sketch at the bottom right, these stirrups are not really going into the flange, but they are drilled into the portion of the beam itself. So all those are depending on the case to case basis, which is easier to do looking at the site conditions and practical issues. That is why, it is very important for the structural designer to actually go to the site and then see the reality and then come up with a design which is more feasible and which is easily constructible. So these are also very important, because sometimes we see drawings, but when you go to the site it makes a lot of difficulties to actually implement them or constructability is not really thought by the designer. So structural engineers should really always think about how their designs are going to be implemented. So, good engineers will think about all that. So I request you all to make sure that you know what are the practical difficulties and all that must be thought through before suggesting a particular design to the site.

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Now another way of section enlargement is overlay on top of slab. So as you see on the sketch here, this is the additional material. So you can see that on the photograph, it is a small bridge. You can see that, there are additional reinforcements placed and then new concrete added to enhance the capacity. So some of these pictures are just used to show you real-life scenarios and there may be things which are not relevant for this particular applications or the point which we are talking. But look at the relevant points in all the photographs I am going to show you. So here the photographs are selected, because I can show you the additional reinforcement and at the same time the additional overlay concrete.

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This is an example where there is no reinforcement provided. In other words, these reinforcement is not provided in this particular example, but the concrete is ultra high performance concrete, which has very fine fibers to prevent cracking and they are very thin layer but very strong material so that you do not really need a very thick concrete layer. Because when you provide more and more concrete you are actually adding dead load to the structure, which is not always preferred. So here you have a concrete which has very high strength and good resistance against cracking, etc., and because of those features we are able to design an overlay, which is very thin, but at the same time it helps significantly in enhancing the flexural capacity. So, less material quantity means fewer effects on the dead load.

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I will show a little more detail on the same photograph. This is Chillon viaducts in Switzerland. You can see that here in the bottom right. Now the picture, which I showed in the previous slide is this one (top right). Now you can see the details here. It is actually done using a screed vibrator. You can see that the screed vibrator there, which is the truss structure and then people are pulling and then the concrete is laid in a very fast manner, and you get a nice surface finish also because of the screed vibrator being used. And the height is, you can see that wooden pieces which are kept here which is just about 1 inch height and that is the height of that new newly added concrete overlay. So it is a very thin element and very high strength concrete which helps in increasing the flexural resistance or flexural capacity of the bridge.

The details like why they went for this thing, they had an experience of alkali aggregate reaction, then the structure was about 50 years old, then major upgrade was conducted or the structure was upgraded to ensure that the new seismic resistance standards or whatever the requirements are met, then to make more water resistant or moisture resistant and improve the overall structural properties. So these are all the things which were considered and based on that consideration, ultra high performance concrete was used as overlay and more importantly no additional reinforcement were used. So we can enhance by just adding a very thin layer at the top.

One most important thing when you talk about these thin layers are, how good the bond between, like we said there is no reinforcement. The reinforcements are not there, but the very important thing is how good the bond between, I am drawing this red line along the interface between the existing concrete and the overlay. So that bond between existing concrete and the overlay is very important to consider and it must be very good, otherwise this will not function well, because then when there is a deflection possible, then this new layer will pop out or it will delaminate from the existing concrete. So it is not only the strength of the new overlay material, but also how well it can bond to the existing substrate surface. That is very important, otherwise all these systems will not really work for long term.

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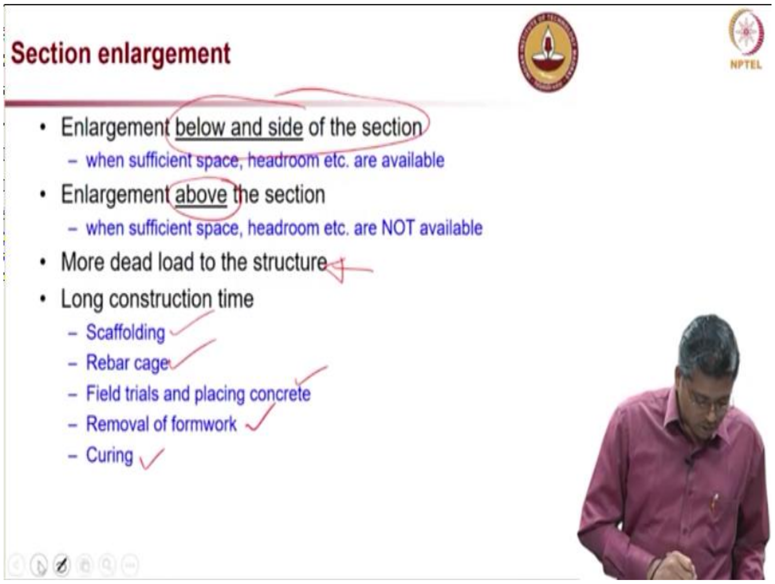

Now where, which type of systems can be used. Enlargement below and side of the section is suitable when we have sufficient space or headroom. If you do not have sufficient space or headroom below, then that is not a feasible option. Second case is when enlargement is done on above the section, that is when you do not really have sufficient space below the section or the section below is not really accessible. For example, if you are talking about a bridge, it is much easier to go over the bridge and do the repair work rather than going below the bridge by make some scaffolding or stay above the water etc. So based on the case to case basis, we can decide which is the easiest way to perform the repair and come out of the work with minimal disturbance.

If you are talking about an urban bridge, maybe you do not want to go above the bridge and stop the traffic etc. But if it is a rural bridge with very limited traffic, where rerouting or you can use one lane at a time like the photograph shown earlier, they did the work with two lanes, one lane was opened for traffic, but that was a rural case. If you are talking about an urban case, maybe you do not want to stop traffic on the top surface or above the section. So in such case, you may want to go for repair practice below the section, but then again you have to see whether there is traffic below gets affected or not. So, all these have to be thought through before making a choice.

And section enlargement will add more dead load to the structure and how that is going to affect the performance or how that is going to affect the other elements or the foundation, should the foundation also be strengthened, all need to be thought through. So, all these are important.

Now also very important thing is construction time. Typically this section enlargement takes more time compared to other ways of construction. Because most often you will need scaffolding to put the rebar cage, then field trials, then placing concrete and then once the concrete is placed, you have to remove the formwork and then you have to cure. So all these processes takes time as supposed to go and stick something to the existing element. Sometimes money plays a role, sometimes technical things, and sometimes the difficulty to the others. So whichever is the case we have to decide on what type of repair or strengthening technique need to be adopted?

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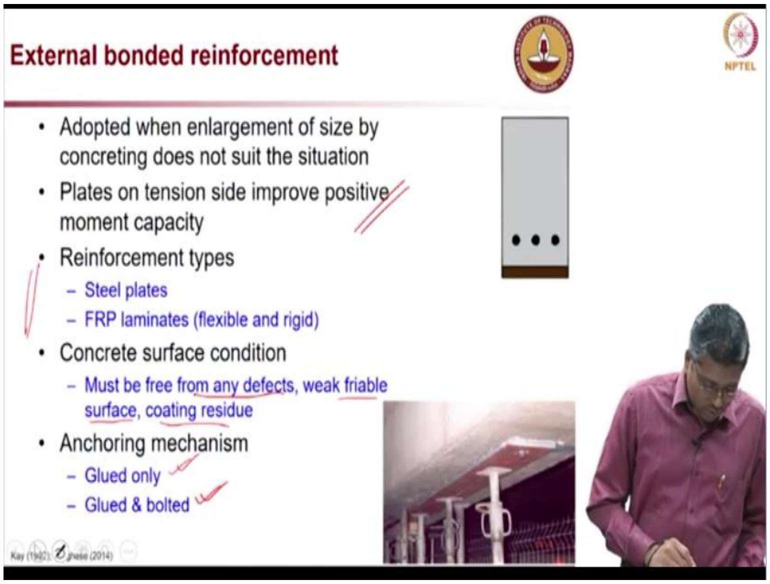

Now externally bonded plates or laminates is the second methodology, which we are going to discuss. And this is adopted when enlargement of size of concrete does not suit. In other words you do not have space or you do not want to enlarge, increase the size or you do not want to increase the dead load. In such cases we can go for this type of bonded reinforcement. And here when I say reinforcement, there are two types in general, steel plates are used sometimes and FRP or CFRP laminates which could be flexible or rigid used sometimes. I mean depending on the case to cases we will, we can use. But these are the materials which are available. And usually these plates or laminates are provided on tension side to improve the positive moment capacity. So whatever it is, it is applied where there is a tension force acting, whether it is above the beam system or below wherever there are tension forces coming that is where we install these types of plates and laminates.

And while installing, it is very important to consider or make sure that there are no freely moving or there is no defects or there is no loose materials on the surface of the concrete. There should be no coating residue, no weak friable surface and also no defects. It is very important, otherwise it will not glue very well and if it does not glue very well to the concrete, then there will not be any integrity between the plates and the existing concrete thus they cannot function well together and they will eventually delaminate.

Now how to anchor or glue these plates to the concrete? Sometimes only glue is used, but most often glue plus bolts or some kind of fasteners is used so that there is a mechanical anchoring also happening. Because if the glue fails, the system should still be there and sometimes because of the bolt system it helps at the time of construction, because the bolted system will hold the plate in place and you can use glue and we can take more time to cure also. So it is more of an application or a practical issue, why bolt and glue are used.

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Now bonded steel plate, let us look at steel plates first and then we will talk about examples of FRP laminates. So steel plates or other shapes can be attached using adhesives. Other shape are, I have also seen angle lines, if you are putting this on the edge of a beam or something, then you go with something like an angle shape, so whatever is the shape of structure. And gluing is easier than drilling plus bolting, but sometimes considering the field conditions, you do not want to hold this plate with hand or something for long period. So it is sometimes better drill hole, bolt it and then inject the glue or epoxy to the space between the plate and the concrete.

Quality of workmanship is very important and critical. How surface is prepared, how the bond strength of the epoxy or the glue to the concrete and plate should be long and thin, that is also something important to think. They should be long and thin to avoid brittle plate debonding. So the plate should not come off. If it is too rigid or too thick then there may be a possibility of debonding from the concrete surface.

Now supplemental anchors to prevent debonding caused by the high local bond stresses, we can provide anchors that is the bolts also they provide additional shear capacity. If you are talking about plate, when there is a lateral movement or a movement along the interface, if you provide these mechanical anchors or the studs into the existing concrete that will also help in increasing the shear resistance or they will not fail due to shear force.

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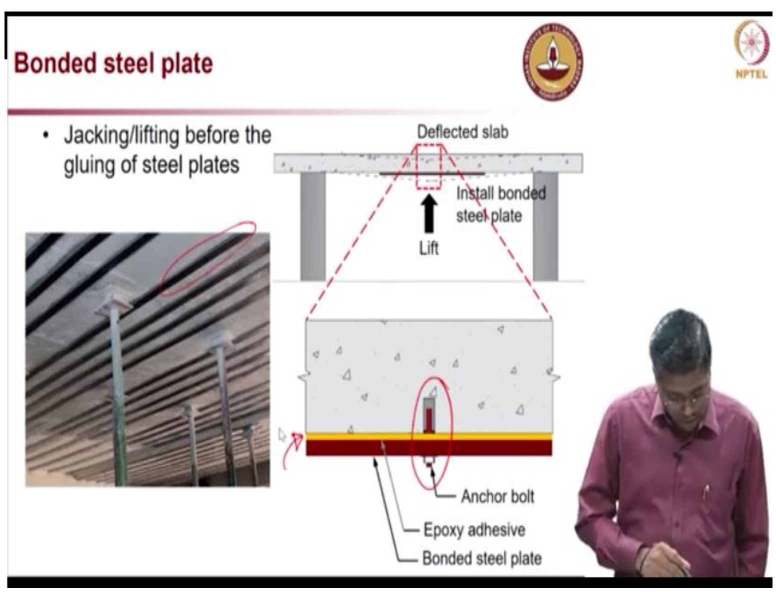

So steel plate, you can see an example here. This picture I showed it is not a steel plate, it is a CFRP laminate here, but I thought this is a good photograph to show you how this process should be. Whenever we are talking about strengthening the first thing to do is, release all the loads acting on that element, if possible. So here you can see on the sketch on the top right, there is a dashed line which is basically showing the deflected shape of the member. So you can see that black dashed line that is a deflected shape. First thing to do a repair or strengthen this is to lift this using a jack or something and then retain that original shape of the slab. Once the original shape is retained, then we stick a plate or this steel plate or a CFRP plate to the bottom surface and glue it there. And let us say the glue takes long time to cure, in such cases we can actually anchor it or bolt it and then inject that into the space in between. So it will take its own time to cure and then you can do other things during that time.

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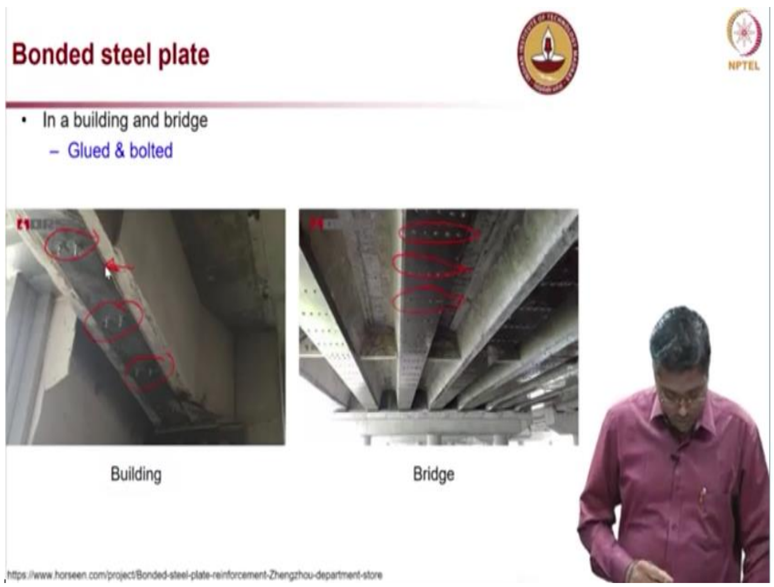

Now in a building, example for a building you can see here there are bolts provided, whatever I just showed in the previous slide. And here also you can see a lot of rivets and which is provided to hold the plate and then facilitate injecting grout into this place. I mean first you will anyway provide some glue there or adhesive but if required we can also go the other way by injecting into the space between the plate and the concrete surface.

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One more example of this injection is the same what I just discussed. This is a very old example, you can see here these are all the bolts, which are holding the steel plate and then this person is actually filling the gap between the concrete and the steel plate and then allowing that material to take its own time to cure. Once it is cured, then you can remove the support system. This is the support system, you can see here. So once it is cured and then glue can take the load, the adhesive starts functioning, then you can remove temporary support systems.

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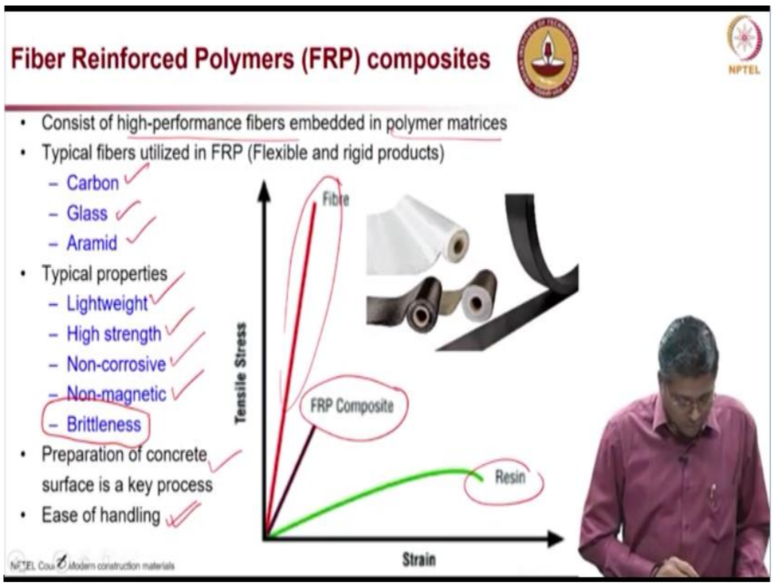

Now let us talk about fiber reinforced polymer composite. It consists of high-performance fibers, very strong and very stiff fibers embedded in polymer matrices. So you can see the stress-strain graph of fiber which indicates high strength and stiffness which is embedded in a resin, which may not have very high stiffness. So the composite have a behavior which is in between. So this FRP composite behavior is what is important to consider and these comes as a flexible roll material, which you can roll over and at the same time thick stiff plates or rigid plates are also available. So comes in three major fibers which are used are carbon fiber, glass fiber and aramid fibers. The key properties which making us use these materials are they are light in weight, so it is not really adding any dead load to the structure. High strength, then they do not usually corrode or in other words it is nonmetallic material, so they do not have the typical metallic corrosion, then non-magnetic, so you do not need to worry about electrical short-circuit etc.

Only one problem is they are brittle in nature. So the designer should think about the failure mode of the structural system or provide redundant systems, so that the structure does not fail in a very brittle manner. So multiple laminates may be provided, so that the structure does not fail in a brittle manner, even though individual laminates might fail, the structure will still fail in more of a ductile mode.

Now preparation of concrete surface is a key process, otherwise they will not glue very well, I already told about it. Very positive thing is they are very easy to handle as compared to other procedures. And it can be done in very fast way, I have heard projects where the entire work is done in a couple of days; that is all, it is very fast. And if you do the preparatory work earlier, then just installation is very fast.

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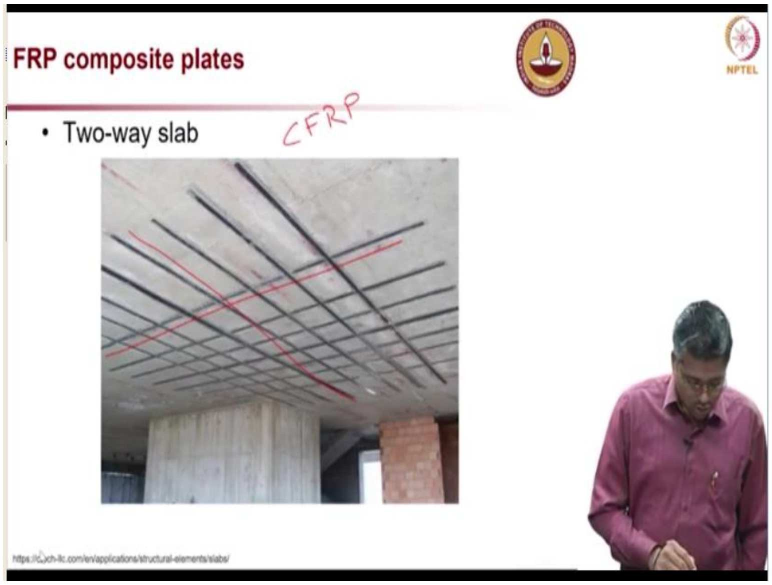

This is an example showing a two-way slab where you have these plates going and these are CFRP or carbon fiber reinforced plates. In a building structure, you can see they are going in both directions for two-way slab.

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I am showing all these examples just to make you more realizing the field structures, how they look and all that, rather than just drawings. Now bridges with minimal headroom, so you can see, this is a culvert actually. You can see that only very small headroom available here and it was very easy to install something like this rather than going for an increased thickness or more concrete at the bottom with additional reinforcement etc.

So beam overlay at the bottom will be very difficult to practice and getting a quality product at the end is more challenging. And one thing is this is passive strengthening with CFRP plates and you can see here that they are not prestressed or anything. It is just glued and it is not even going till the end, because it is mainly to resist the flexural properties. So you can see here it goes up to here and this glued to the concrete surface.

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Now other typical application of this kind of plates is prestressed, which is an active system. Again you can see this girder here which is prestressed, you can see the marking of how the concrete surface was cleaned, you can see that in a bushing wheels marking on that. So cleaning is very important, otherwise they will not work very well. They are cleaned and then glue or whatever the adhesive is applied and then the carbon fiber reinforced polymer is placed and then it is prestressed.

So first you create an anchoring region with the metal system, then attach this CFRP laminate to that and then from the other end pull it or you prestress the whole laminate, you can see the jack here, which is basically pulling or prestressing the laminate. This will result in an active strengthening. In other words, as soon as the work is over immediately the CFRP laminate start taking the stress or start sharing the stress.

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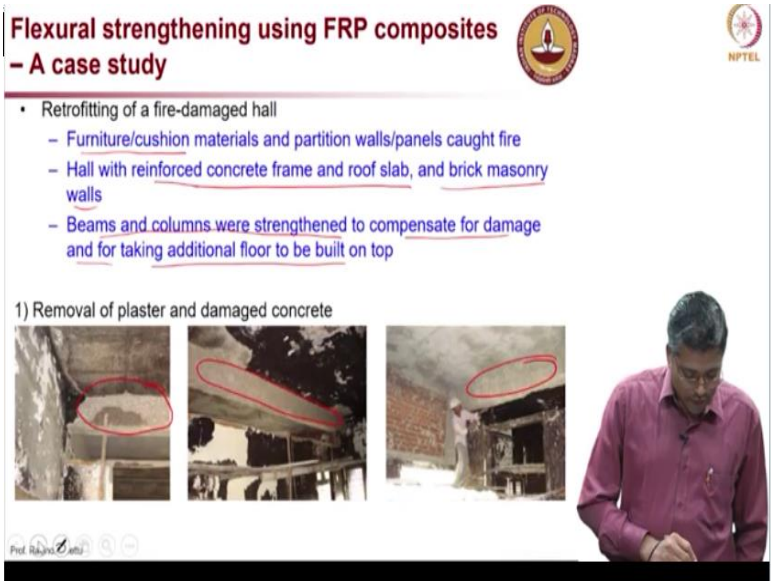

Now I am going to show a case study where this FRP laminates were used. This was actually a building, which had fire incident and basically like a lot of furniture, cushion materials, partition walls, panels, etc. were actually functioning like the fuel for the fire and it lasted for a couple of hours. And then the hall with RC concrete frame, roof slab and brick masonry walls; they were all attacked by the fire.

And then beams and columns were strengthened to compensate for damage and for taking additional floor to be built on top. So this incident was used for enhancing the capacity so that we can build one more floor above. So you can see in the picture, first thing which was done was removal of the plaster and the concrete which got damaged, as you see here all the plaster and concrete everything is removed. Not much damage was observed on the brickwork anyways, but concrete really had a lot of problems. So here also all the plastering material and the damaged concrete was removed.

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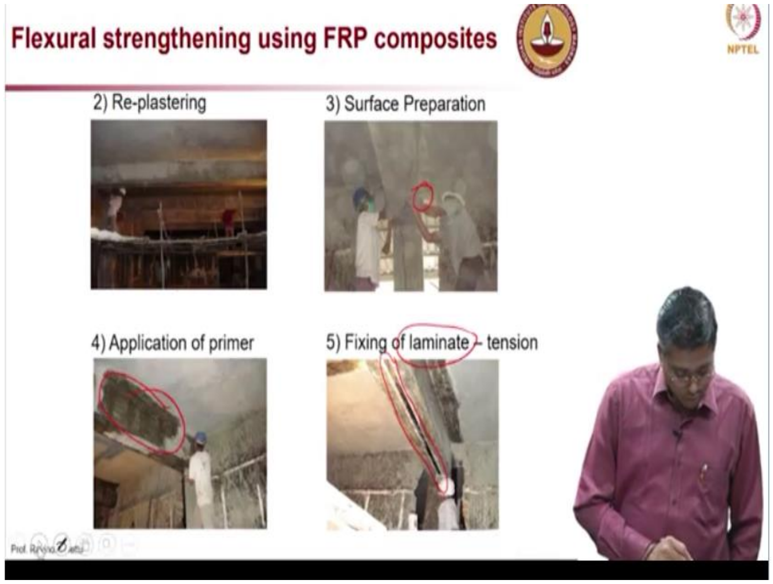

And then new plastering material was applied or re-plastered and then cleaned, the surface of the plastered surface was cleaned so that the chemicals or the primer and then can be glued well. So after the surface preparation, you can see a person cleaning it here, then to the cleaned surface this primer was applied and then the laminate. The stiff plate was glued to the bottom where the tension forces are acting, bottom most fiber.

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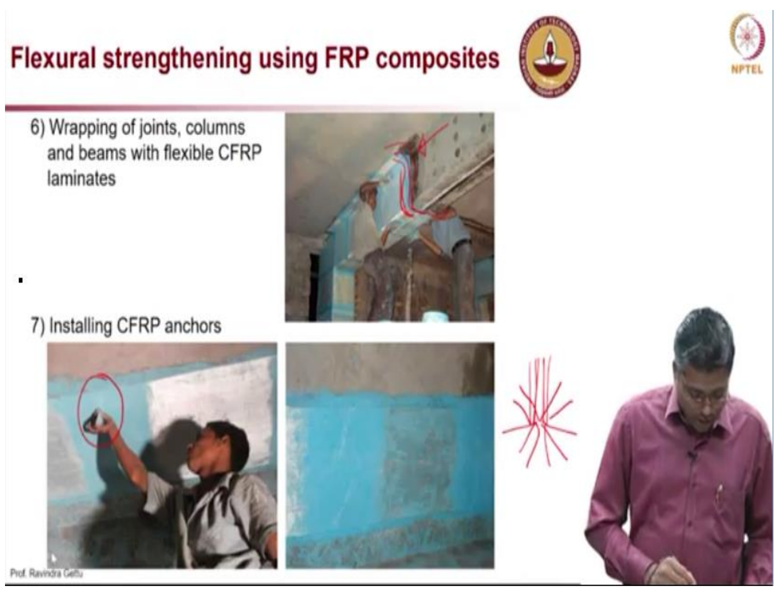

And then after that for better confinement the flexible sheets were also glued to the surface. So the flexible CFRP sheets were also glued to the surface, you can see here this is the primer and then you can this blue color, it is again the glue and this is the laminate. After that for preventing the delamination of the sheets from the concrete surface, they were anchored to the substrate concrete. And how it was done was, I am going to draw that here. So, as I draw here, first the fibers were inserted into a hole which is drilled into the concrete with sufficient glue and once it was held in place the remaining fiber which is protruding out what kept like a star shape or spread like this, you can see here also, look very closely and here also you can see how the anchoring was done. So I am going to delete these markings so that you can see what I was just telling. So just opens up and then again that was glued so that you have a really a nonmetallic nail over there or a very good anchor.

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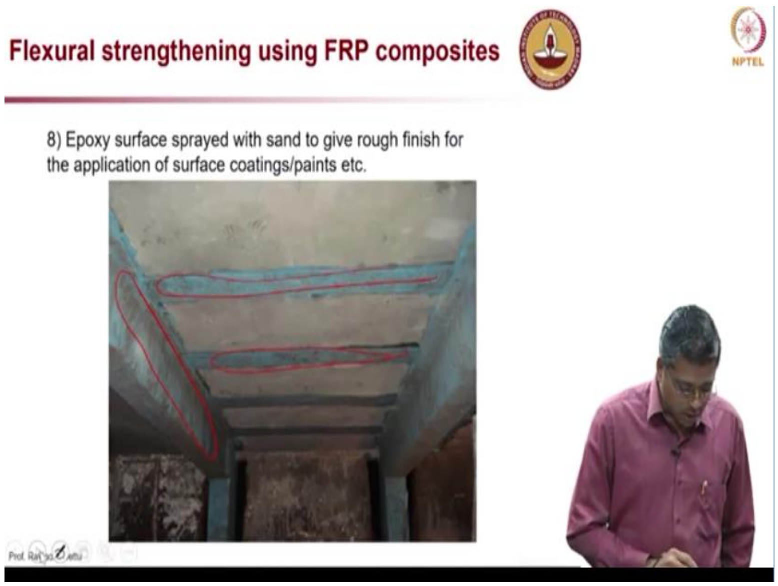

And then after that, before the chemical was dried, to have additional paintings and other coatings, you need a rough surface. For that purpose, sand was sprayed on the epoxy surface. So you can see here to get a rough surface finish, sand was sprayed so that other additional paintings, etc., can stick well or bond well to this surface. So that was the work, recent work on CFRP or strengthening using CFRP.

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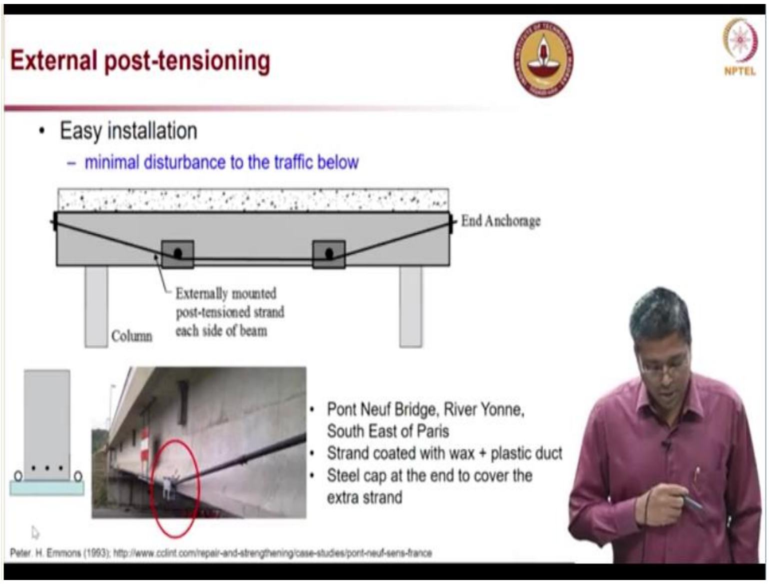

Now next way by which flexure strengthening is done is external post-tensioning. I am going to show some examples on this too. You can see here an anchorage; a tendon is placed like this, these are the deviator blocks and this black line indicates the additional tendon. Photograph at the bottom very clearly shows the tendon here and it goes like this and goes up on the other end of the bridge and this is the deviator point there.

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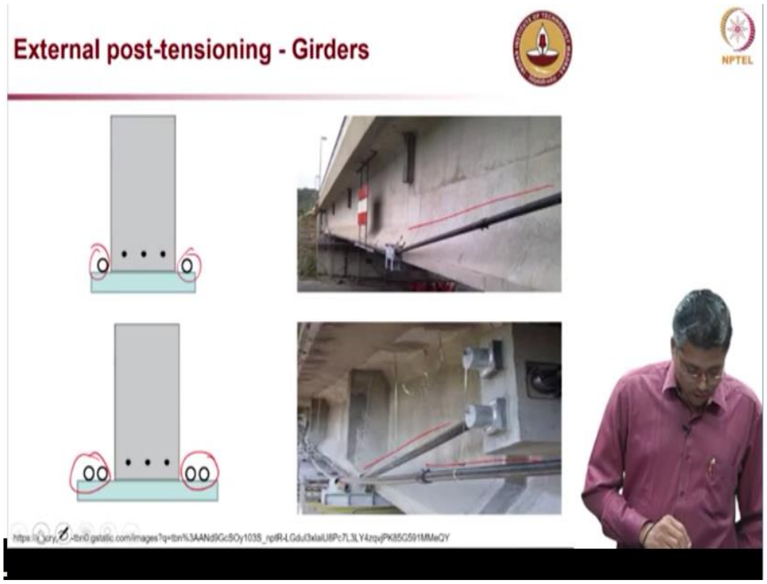

Now the same picture, I am reproducing here, so that you can compare one thing, here on the top picture, you see one tendon, at the bottom you can see two tendons, mainly to take care of the change in the bending moment as it reaches the near support. So where you do not want too much bending moment, you change the direction in which the tendon goes, so that you can have an adjustment on the bending moment, whatever the pre-stress is required provide only that at that cross section or post-tensioning is required. So corresponding to that I am showing here two tendons and in this case, there is only one tendon. But these are all case to case basis, how you want to do it.

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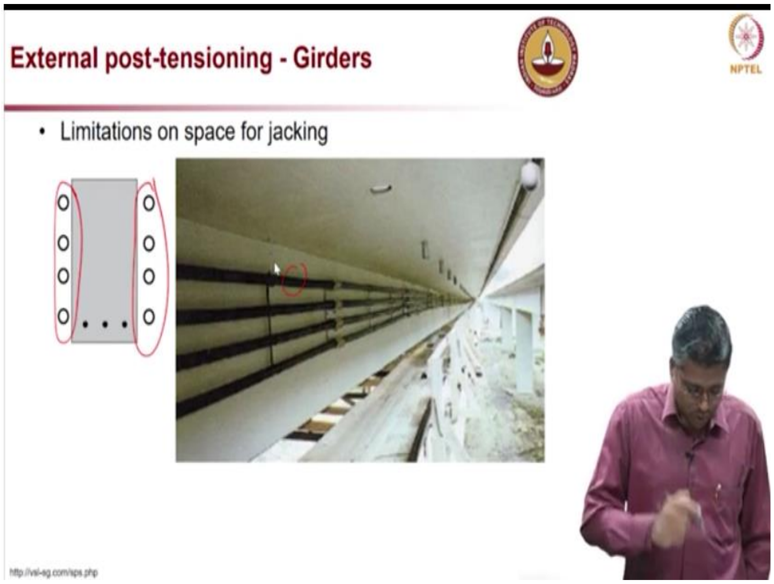

Now this is a case where there are four external tendons provided. You can see four tendons here indicated by these circles and similar tendons are on the other side of the girder also. So, this is just one more example. One thing to note here is, in these types of structures, you have to also think about how you will apply the tension. So the anchorage zone, do you have enough space for placing the jack, if you do not have space, how do we actually do the stressing operation, whether we do the stressing operation from the end or we can use some couplers and stress not at the ends, but somewhere else along the tendon. For example, if you do not have a space for jacking, then we can also design a proper coupler system and have it somewhere along the tendon and then tighten there like a turnbuckle or something similar to that. Those things are discussed later in two lectures down the line on repair of prestressed concrete, but similar things can be done in this repair also. So availability of space for placing the jack is also important to think about.

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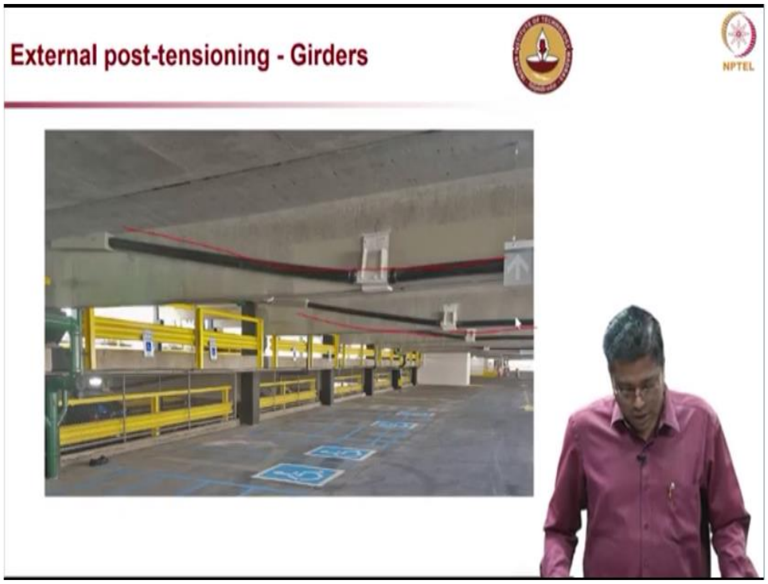

This is another example. I am just trying to show you more and more photographs, so that we can think in different ways on how these systems can be actually implemented not just knowing the theory using a nicely looking sketch. So this you can see many structures have been repaired or strengthened by using all these technologies.

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This is another one, where you can see a straight tendon is provided. There is no deviator block or anything, but this goes up to that point only, it is not really reaching the end of the girder and a straight tendon is provided. So it all depends. This is the way in case you have a very long tendon, how to connect them. So you can see a very nice system there, where you can actually increase the stress or decrease the stress as you want. Because when you talk about multiple tendons like this as you see in this bridge, the load which you apply on one might actually have an impact on the other tendon. So you may have to come back and check that each tendon is actually taking sufficient stress or in other words, when you apply prestress or post-tension to one of the tendon, the already existing tendon might lose some of the stress. So we have to think about all that. That is why these kind of flexible systems are essential.

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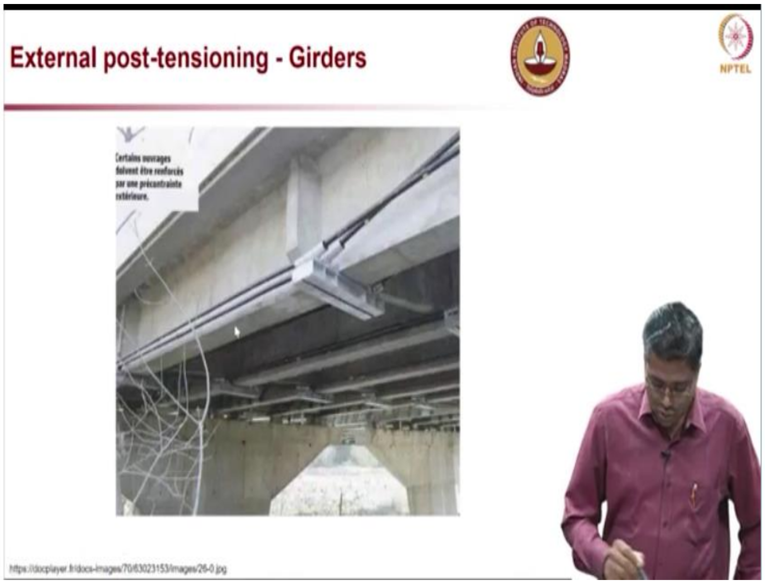

This is another example showing two tendons.

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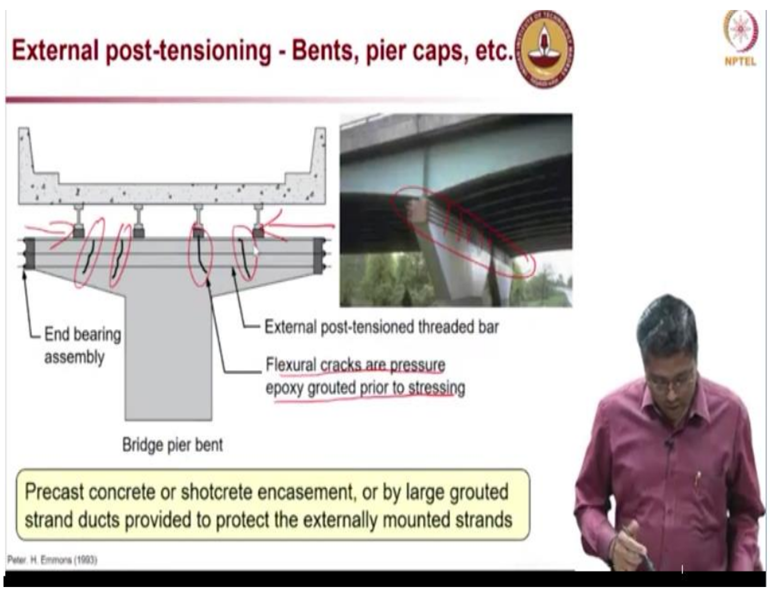

And external post-tensioning is also done on bents, pier caps, etc., not only the girders, but also the elements which are supporting the girders. So here is one bent cap or pier cap, you can see here, which was showing some cracks like this in this direction, vertical cracks as it is shown here, these kinds of cracks. So when we see those kinds of cracks, it is very clear that there is a reduction in the prestress or horizontal prestressing is not adequate. And that is why those vertical cracks are forming. So how to prevent this is first we have to seal or close the crack and then apply a horizontal prestress in this direction (as arrows shown in the sketch). So first you have to fill the cracks with epoxy and then compress the element, so that the problem does not happen again and so flexural cracks are pressure epoxy grouted prior to prestressing. It is not that you first do the prestressing and then fill the crack. No, it is the other way. First you fill the cracks with injecting epoxy into it and so that there is proper load transfer possible or uniform load transfer possible and then you apply the prestressing. So the cracks have to be closed, so that load from one side of the crack is actually going to the or transferred to the other side of the crack. That is very, very important process.

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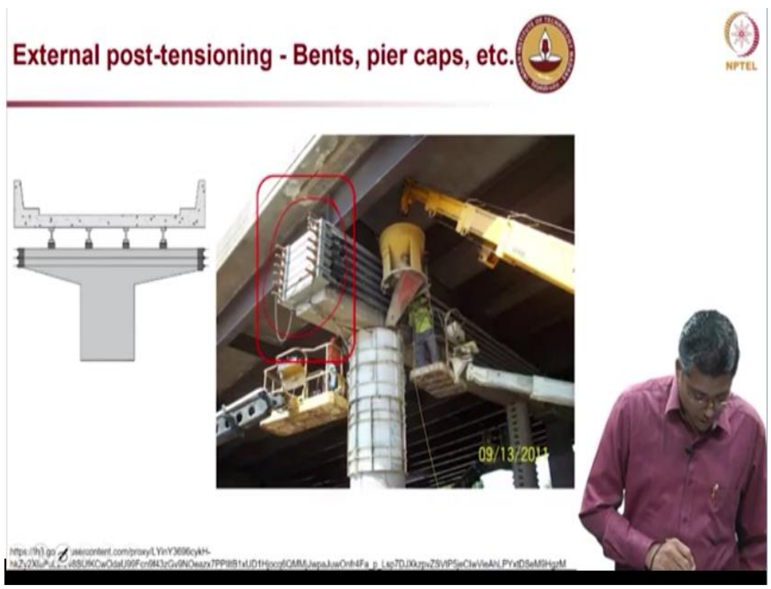

This is another example where similar strengthening is happening. You can see all these. In this case, if you look very closely they are not strands, they are actually high-strength prestressing rebars. Usually you will see both, strands and rebars are used in this, but if it is strands they will be typically monostrands, which are coated with grease or wax and then placed inside a plastic sheathing.

So, protection mechanisms of these repair systems are also equally important or probably more important, so that the system last for as long as possible or as long as we desire. In this photograph, there is a column, section enlargement is also being done, but I am not going to discuss that right now. That is a separate topic.

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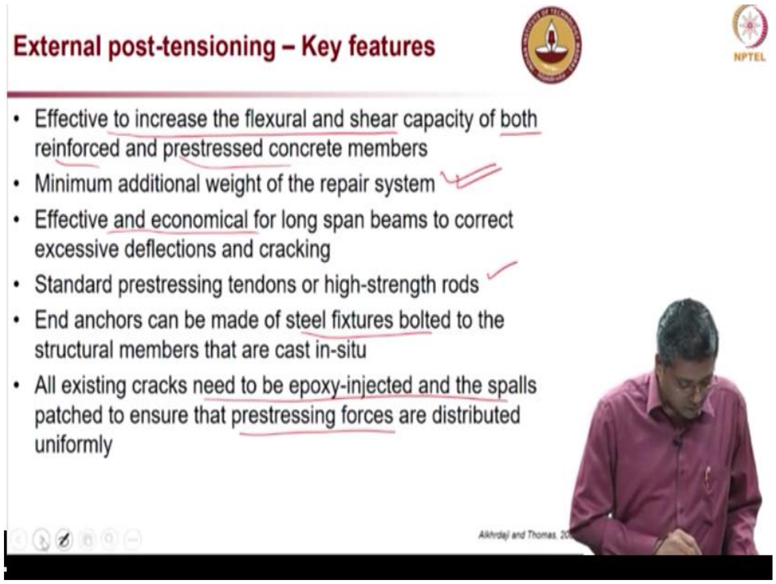

So what are the key features, which we have to think about when we talk about external post-tensioning? If they are very effective to increase the flexural and shear capacity of both reinforced and pre-stressed concrete members, minimal weight is added because essentially they are high strength materials and then effective and economical for long span beams to correct excessive deflections. When the longer the span, then these becomes more economical and more effective and standard prestressing strands or rods can be used. End anchors can be made of steel fixtures bolted to the structural member that are cast in situ like it was shown in the previous two photographs also, there were thick steel plates at the end of the bents. Now all existing cracks need to be epoxy injected first and if there is any spalling or any of those surface repairs also need to be finished or completed before we do the prestressing of the element.

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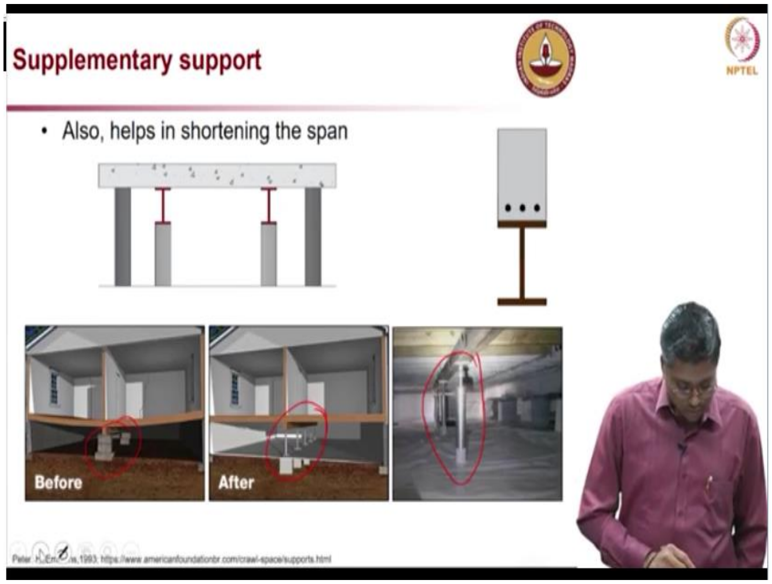

Now next is supplementary support system, where we are talking about structures which might have significant deflection and which need to be strengthened. One example is, look at here in the bottom left two images before and after, you can see there significant deflection and then that deflection can be nullified or the whole system can be jacked up by using some supplementary support systems. You can see here this is an example photograph; it is a jack where the height is actually adjusted.

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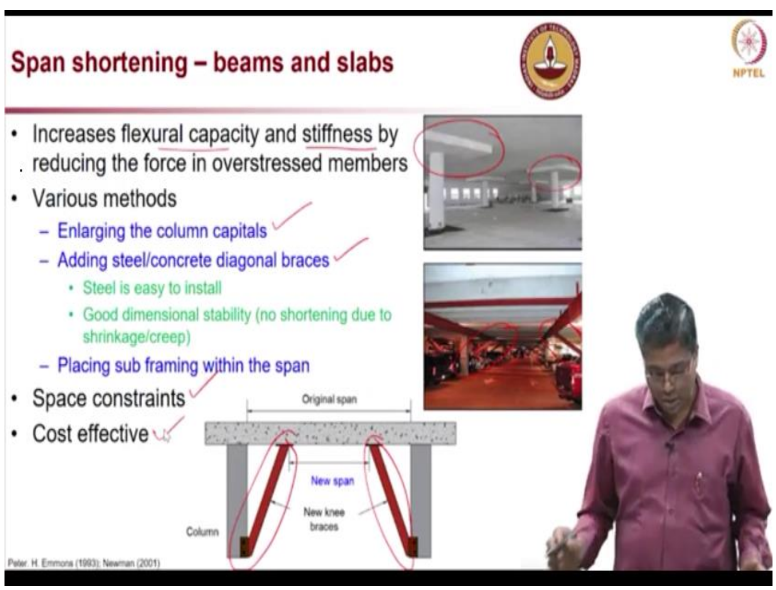

Now span shortening is another widely used practice to enhance the flexural capacity. Not only capacity, it also helps in enhancing the stiffness of the member by reducing the amount of stress coming on the existing members. Then various methods by providing column capitals, as you see here. That is mainly for a slab system where even for beams it works.

But the picture shown is for a slab system, where by providing these capitals the span for the remaining slab is actually slightly reduced. And also you can provide diagonal bracing system or additional columns like this. You can see here this photograph over here, it shows that, how they look like and main problem is when you provide this additional bracing or knee supports the space constrained is a problem and cost-effectiveness is also another thing which we have to look at.

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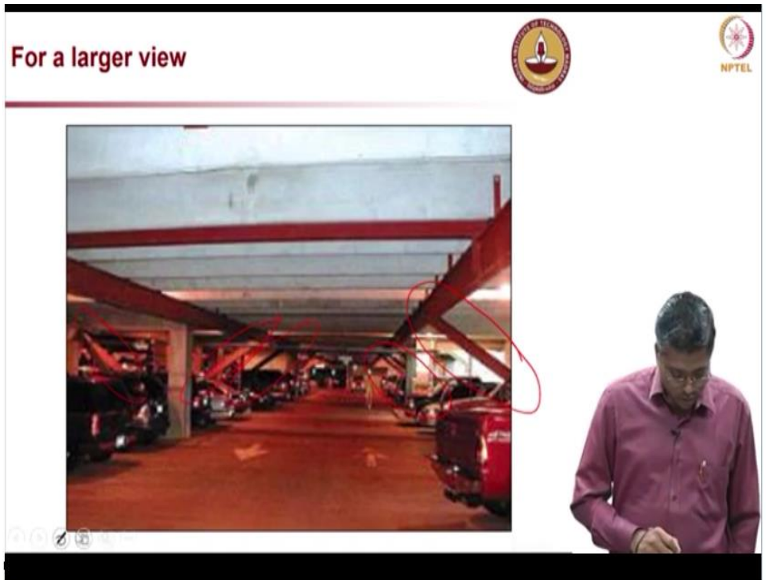

I am showing a zoom out image of this, so that you can see this is the bracing which we are talking about. You can see all these inclined elements; they are all the knee supports, which we are talking. And now when you talk about this, these knee supports, they are actually resting onto the columns which are visible and how the columns take these loads? That is also something needs to be considered and if they also need to be strengthened along with this work that also need to be done.

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This is an example photograph, not a concrete structure here. It is just a bamboo structure, you can see there is an additional support given here. On the picture on the bottom right, you see a deflected bamboo beam. It is essentially a beam and that is supported by providing additional knee bracing and also sometimes this vertical column. So I just thought of showing you this nice image, which I took it in one of the restaurants in Gujarat.

So it is not only concrete structures which have problem, even other structures also have problem and there are these types of techniques, which are not necessarily adaptable or applicable only to concrete. It can be applied everywhere.

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This is a roof slab which is a heavily corroded reinforced concrete system. I actually visited this site and it is almost nothing, it is not really taking any load. I felt that even it is standing because probably by the arch action or something of the concrete itself, the whole concrete is probably under compression and this temporary supports are there. So in such cases, how we can do without really removing everything? We can go for an overlay, but at the same time overlay just to cover up, but at the same time if we can reduce the span that is a feasible way of doing it. If you want to renovate these kinds of structures, you want to also come up with a feasible solution, which does not take much time and does not create much difficulty to the inhabitants.

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So, attaching just simple crossbars like this to that floor will actually finish the job faster. You can attach to the concrete beams available. I am going to go back (previous slide), if you take this beam here, you can actually attach the additional supports like this onto the beam. So essentially what you are doing is, you are shortening the span for that slab. So that might work and then you can provide some minimum reinforcement required and so that it can be really safe. And also if such steel elements are provided, depending on the environment, if it is an indoor environment, I think it is okay, but if it is an exterior environment where you have moisture issues, then you can also probably provide concrete around the steel and then or encase the steel member inside a concrete, which will help in protecting the entire structure.

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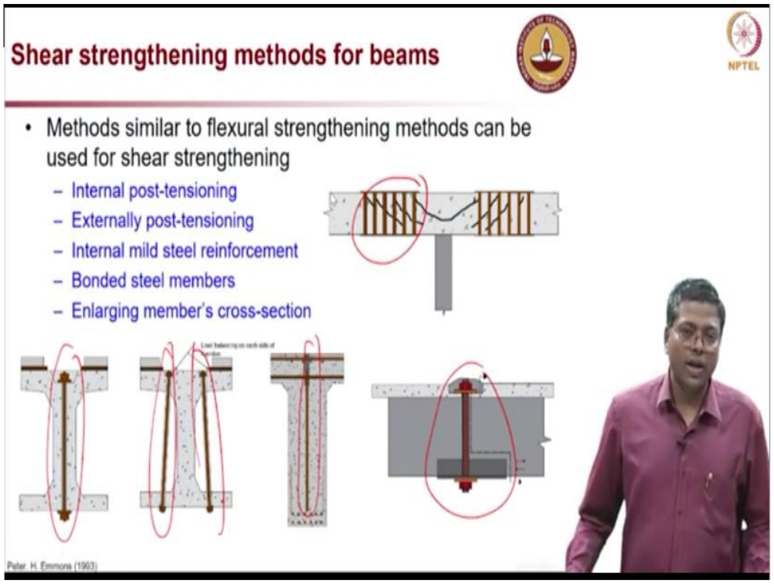

Now shear strengthening is another topic. Until now, we discussed about flexural strengthening, now we have few slides on shear strengthening methods. Typically, most methods which are adopted for flexure strengthening can also be modified and used for shear strengthening. All these methods which we already discussed, first is internal post-tensioning, then external post-tensioning, then internal mild reinforcement, mild steel as a passive reinforcement, then bonded steel members, and then enlarged member cross section or even provide a straps. So all these are the different ways by which flexural strength can be enhanced.

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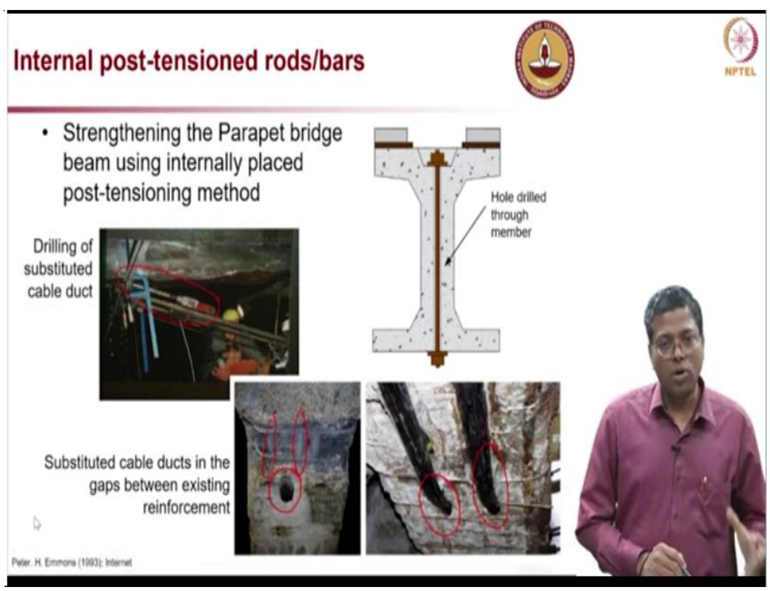

So I am going to show you couple of examples on some of these and then close the lecture. So strengthening the Parapet bridge using internally placed post-tensioning method, this is a case study where you can see here a long drill and that is used to drill a very long hole through the deep girder which is visible and which is in very bad shape. So they drilled this hole without damage. You can see the hole here on the second photograph without really damaging the reinforcement. So they found a space between the reinforcement and then drill through that and then placed the additional cables through that and then post tensioned them or in this example it was cable duct, but you can use either a strand system or a cable system or a high-strength rebar or high-strength rods. So anything can be used depending on the amount of stressing required or the load required etc.

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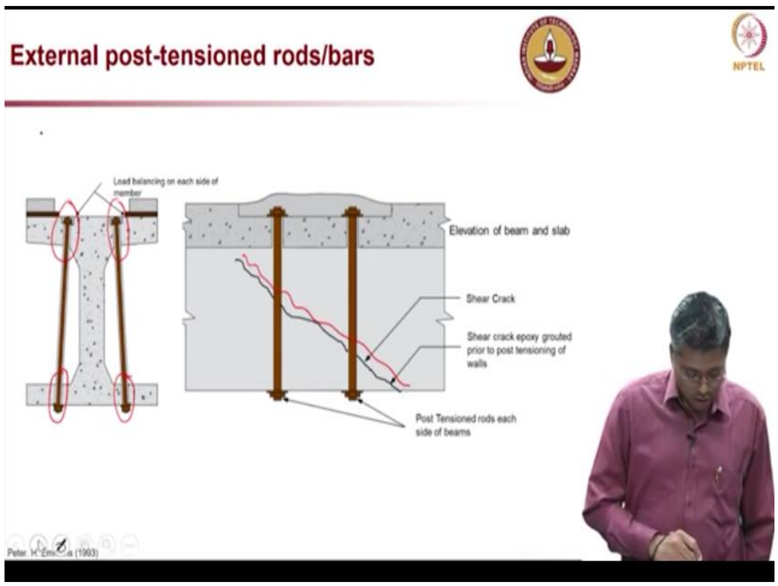

This is the external post-tensioning, because drilling that hole if it is a deep beam, it is a lot of work and sometimes it is not very easy and practical. So in such cases, we can go for external post-tensioning where drilling is required only for this much length very short amount of work and then you connect either a rod or a strand or a cable system, so that the shear resistance can be enhanced.

One thing to tell again, if you do this, the crack should be filled first with an epoxy injection or something before doing the post-tensioning of the element. And why we fill the crack first is, at the time of application of post-tensioning the load can be easily transferred and in an uniform manner all along the crack. That is the reason.

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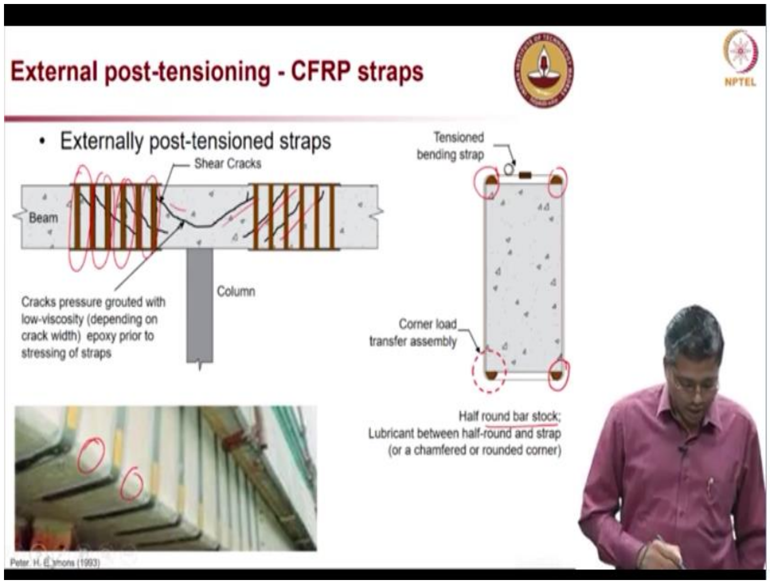

Now CFRP straps are also widely used for external post-tensioning for enhancing the shear strength. You can see the sketch here, all these brown color vertical thick lines, they all indicating the straps and you can see the inclined shear cracks over there. One important thing to notice here is when you talk about straps, these fibers should not get torn or the tear resistance of that should be considered. The best thing is and they are very good in tension, but sometimes they might get torn. So we have to provide a smooth surface or smooth corner, so that at the corner they also can slide over and then take that stress while prestressing and at the same time they do not get damaged. So half round bar stock is important, something which is curvy in nature can be provided or you can also chamfer the beam. As you can see in this photograph here, the beam is chamfered at the corner, not sharp 90 degree turn.

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I am going to show another photograph. You can see here this beam is chamfered and this strap is nicely curved so it can easily take that load and give very good shear enhancement.

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This is another example. Again you can see, the shear region is only the near support region. So this girder does not have any problem with the flexural resistance. The problem is mainly for the shear resistance, because shear cracks were probably observed in these elements like this and they wanted to fix that issue. So they provided this FRP laminates and that is only provided where the failure was observed not the entire bridge. So it is a good way of optimized use of repair materials.

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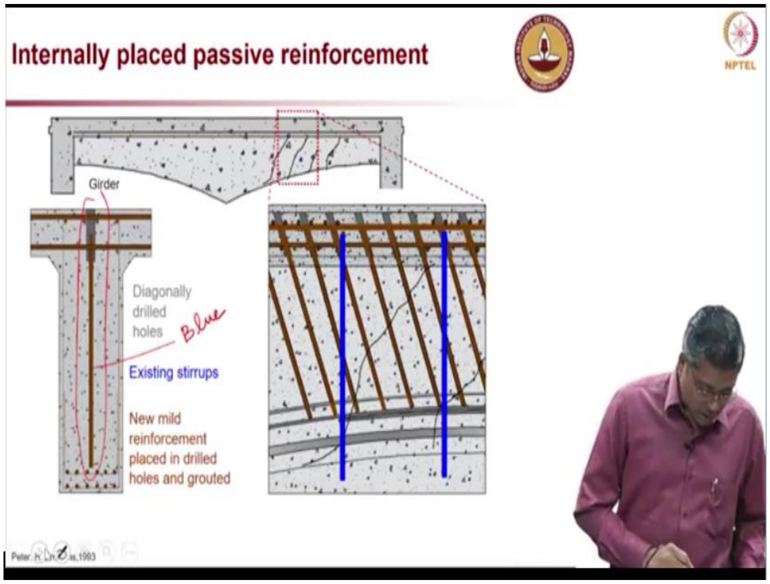

Now also internally placed passive reinforcement is also used, this is not an active system, it is just a passive system, which is in fact I should have made this (vertical rod in left most sketch) also blue in color, so that you can match. So this rod, vertical rod is also assumed it to be blue. So all the blue rod, they are actually passive reinforcement. So a small hole will be drilled, then placed and then hole and then grouted. So they will come into action when there is a requirement. So that is why we are calling it as a passive reinforcement. Unlike a post tension or a pre stress system, in a post tension system the moment you provide the anchoring or the prestress, then from that time onwards that is actually taking part in load sharing.

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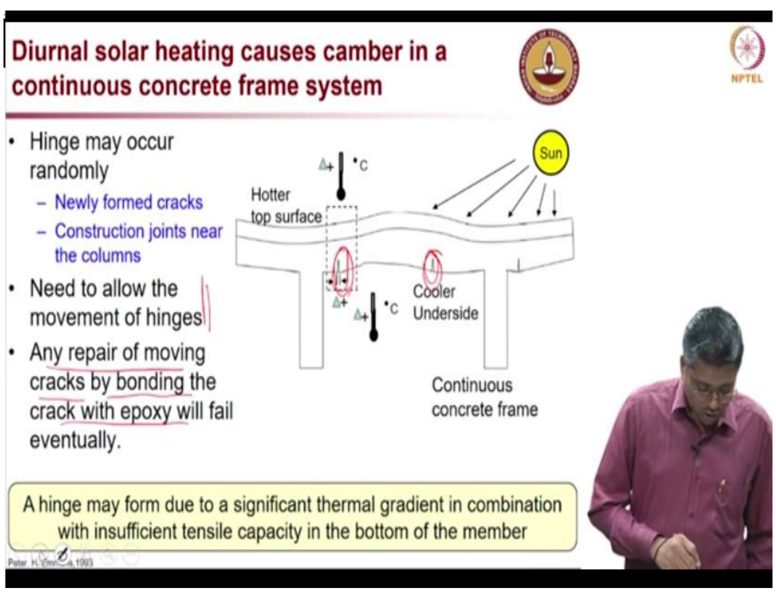

Now another mechanism which some of the long span structures experience is hinge formation, because of the temperature variation and we do not know where this hinge might form exactly, region wise we can tell but exact location may not be possible to predict. So when you have very significant variations in temperature at different points, in this particular case, the top portion is getting heated and is expanding where the bottom portion is still under cool or in low temperature under shade. So because of the expansion, these kinds of hinges might form, where there is a bending action also coming.

Now the repair system which we adopt should allow the movement of these hinges. If it does not allow, then what will happen is, it will just transfer that stress to some other location and then it will form hinges elsewhere. So it is better to allow these hinges to form and then design your repairs material system in a way so that the system will function.

So, if you provide epoxy, if that epoxy is very brittle or very rigid, that epoxy is not really a flexible material. So you have to really think about what type of material to be used. So any repair of moving cracks, if the cracks are forming, closing, forming, closing or moving, then by bonding the crack with epoxy will definitely fail. If not in short term, in long term it will fail. So, it is not a good practice to adopt.

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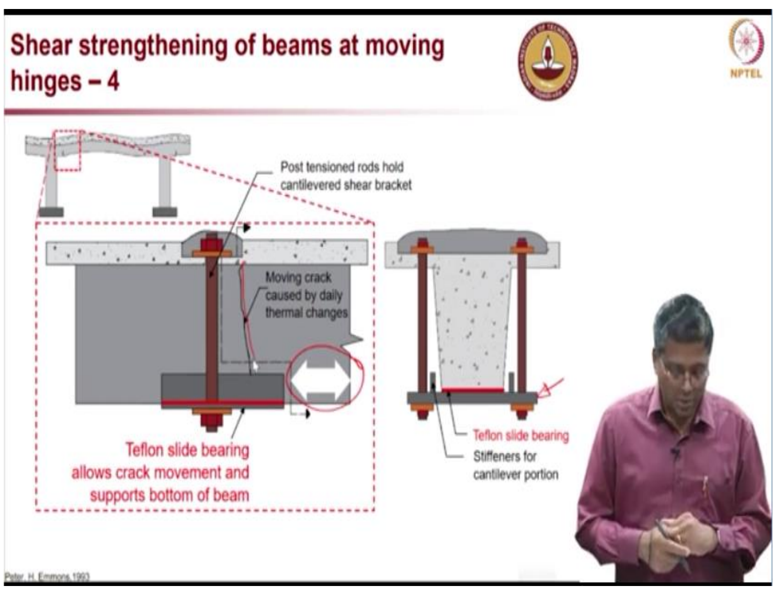

In such cases, what we should do is something like this, where you provide a steel support, because our idea here is to transfer the shear stress. So you can provide a vertical rod like this and then main idea is to provide a horizontal plate, the dark grey region (in the bottom of right sketch) is the horizontal plate and there is a thick thick red horizontal line, that is the teflon slide which helps the concrete element to slide or move horizontally (showing the arrow) so that the shear stress is transferred, but not the other stresses. So it is essentially like an L-shape steel plate on which the element on the right side or the concrete on the right side of this moving crack, concrete on the right side is resting on that and whatever that vertical load is transferred through the plate and the left side of the element is taking that load.

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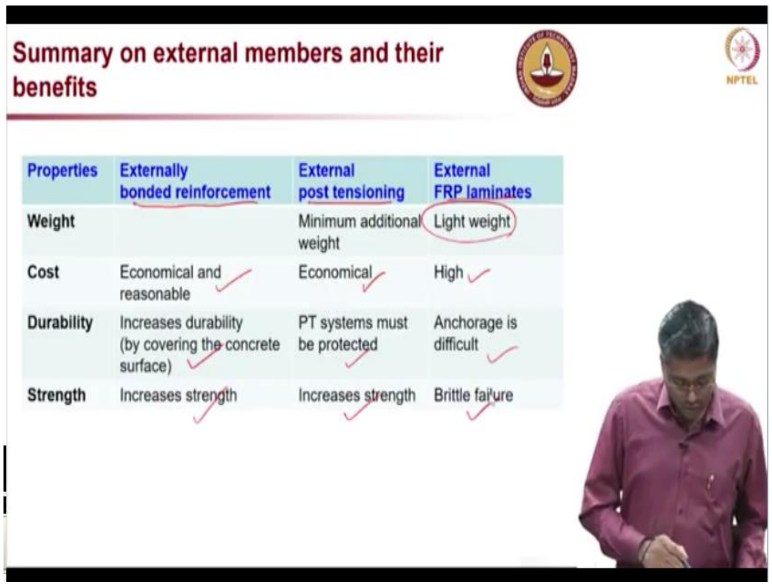

Now look at what are these different external members which we talked about as strengthening systems. So we talked about bonded reinforcement, post-tensioning using either straps or strands etc., and also post-tensioning using FRP laminates. So bonded reinforcements, strands and laminates, these are the three systems we are going to compare. Weight wise bonded reinforcement has negligible weight and post-tensioning has minimal additional weight, but laminates very lightweight. So it does not really add anything to the dead load.

Cost, economical and reasonable if it is bonded reinforcement, strands economical but also it depends on the span or the amount of work and laminates are costly and also they may not be good for significant increase in the strength.

Now durability, in the case of bonded reinforcement durability is enhanced, because the bonded reinforcement itself will provide that additional protection, it will cover the concrete surfaces in some cases. And post-tensioning systems, in that case they must be protected, they are very vulnerable to corrosion sometimes, so they must be protected. And in case of laminates the anchorage is the most important part, how well they are anchored to the system is important, If the anchorage fails, the entire, the system does not function.

In case of strength, bonded reinforcement and strands enhances the strength and FRP laminates, it enhances the strength, but there is a possibility of brittle failure. So multiple laminates or system should be designed in a way that the brittle failure of the structure is not going to happen, maybe one of the straps can fail in brittle in way, but the structure should not fail in a brittle way.

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So to summarize, we talked about different techniques adopted for flexural strengthening and for shear strengthening of beams and slabs.

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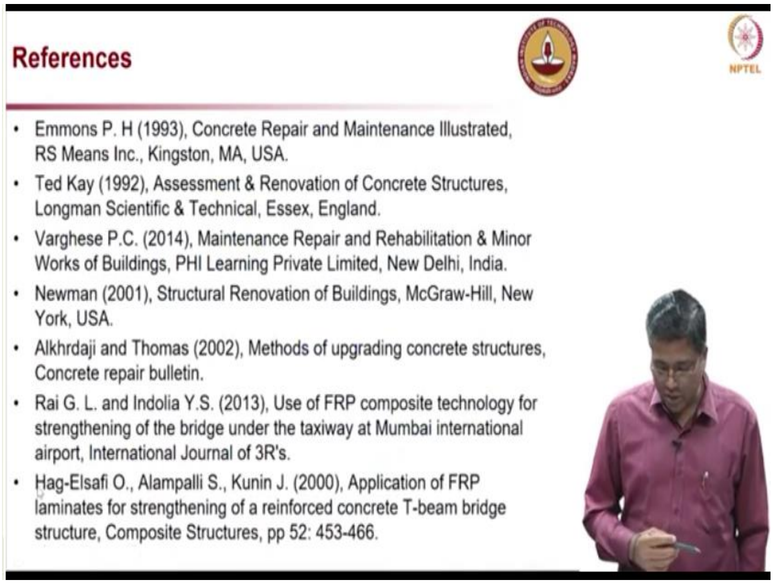

I think these are the references which we used. Thank you.