Maintenance and Repair of Concrete Structures
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Lecture – 31
Structural Repair of Prestressed Concrete Systems

Hi, everyone. I am Prabha Mohandoss who recently completed my Ph.D., under the guidance of Prof. Radhakrishna G. Pillai in IIT, Madras. Today, I am going to talk concepts on structural repair for prestressed concrete.

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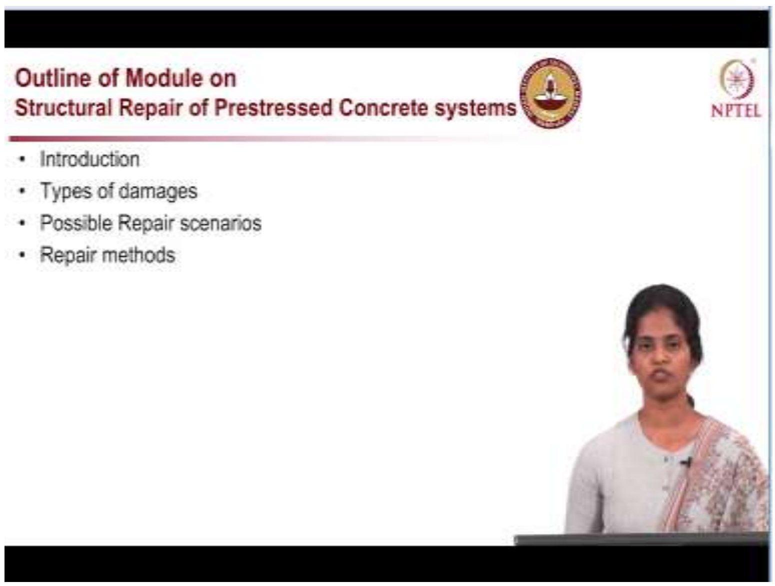

This is the outline of module on concepts of structural repair. We have seen introduction to concepts of structural repair and strengthening of beams, columns and walls, joints. In this lecture, we are going to look at strengthening of prestressed concrete to enhance its performance. Deterioration of prestressed concrete systems is often difficult to identify and repair. Most of the time these structures will not reveal its true condition until the failure becomes so evident. So in this lecture we are going to look at different types of strengthening methods available to enhance the performance of prestressed concrete systems.

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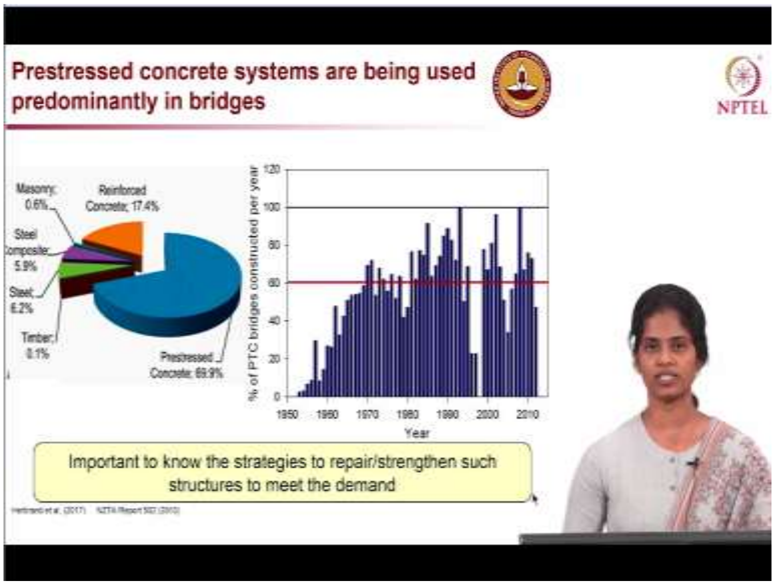

So we all know prestressed concrete systems are being used predominantly across the globe, especially in the construction of bridge. Here in the left the pie chart shows percentage of bridges constructed using different types of systems. This was the survey conducted by German federal highway system compressing of about 40,000 bridges. Among this we can see almost 70% of bridges are made using prestressed concrete.

The number is significant and the right side you can see the bar chart, where it shows the percentage of pretension concrete bridge was constructed per year over the past 5 decades. This was reported by New Zealand Transportation Authority. You can see in the late 1960s the construction of pretensioned concrete bridges has increased significantly almost 60 to 100 number of bridges are being constructed per year.

Again it shows the number is huge and it requires attention for such structures. Strengthening of bridges becomes more and more important due to the existing of bridges that are facing ageing and were constructed using old codes and we are seeing a lot of traffic volume increased over the past decade and expecting to increase even more in the coming future. So many of these prestressed concrete bridges are new and they expected to serve for 100+ design service life.

However, we are facing such prestressed concrete structures losing its structural performance due to loading or environmental conditions. Hence it is important to know the strategies to repair and strengthen such structures to meet its design demand.

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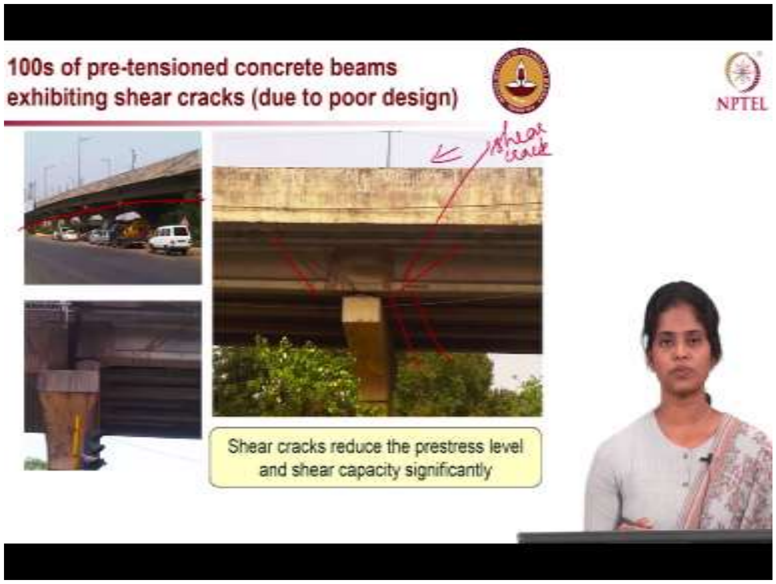

100 numbers of pretensioned concrete beams exhibiting shear cracks due to poor; the image here shows the prestressed concrete bridge in India which is located in one of the prime cities of India. Experiencing shear cracks at the ends of the girders. Almost all the girders at the ends have such shear cracks all along the length of the highway bridge. So this indicates 100 numbers of pretensioned concrete beams along the length of the bridge experiencing such shear cracks.

This could be due to poor design that adapted while constructing or the poor construction materials used or due to improper codal provision. When such member experiencing shear cracks then this prestress level would be significantly reduced thus the shear capacity. So it is important to identify the sources or the; it is important to identify the sources for the damage whether it is due to loading condition or the aggressive environment or this is due to inadequate design or the poor construction materials used.

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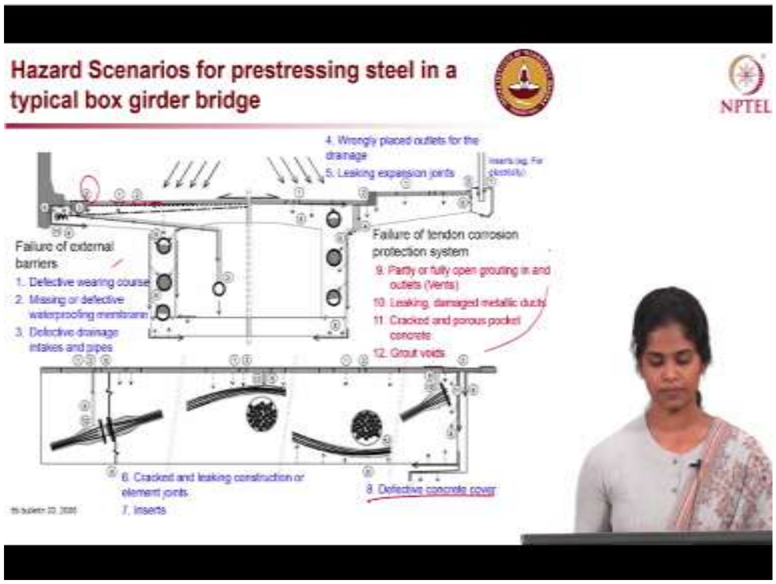

Here is one such hazardous scenarios for prestressing steel in typical box girder bridge provided in *fib* bulletin 33. So it shows how water can get into the prestressing strands due to different parts or resources. So based on the conditions it was divided into two categories one is the failure of external barriers where you can see the water can get in due to defective varying courses on the service on the surface or the missing or defecting waterproof membrane here or due to the defective damaged drainage intakes or the pipes that was placed to drain out the water.

And sometimes the wrongly placed outlets would lead to moisture ingress. And the joints at the ends or between members or crucial for water ingress for example, leakage in the expansion joints or the leakage in the construction joints would lead to water ingress and the inserts where water again get in. And another important factor is that concrete cover which was supposed to protect the tendon or the steel inside.

If that is defective, then it is easy for moisture to reach the steel surface. Then the second category is that failure of tendon corrosion protection systems. So here again we can see the outlets placed for placing the grouting. So if it is partially or fully open then that could lead to moisture ingress and then the ducts where we place the tendons and the surrounding concrete or the grout voids. These are the primary sources for moisture to reach the strand surface and eventually to corrode the steel.

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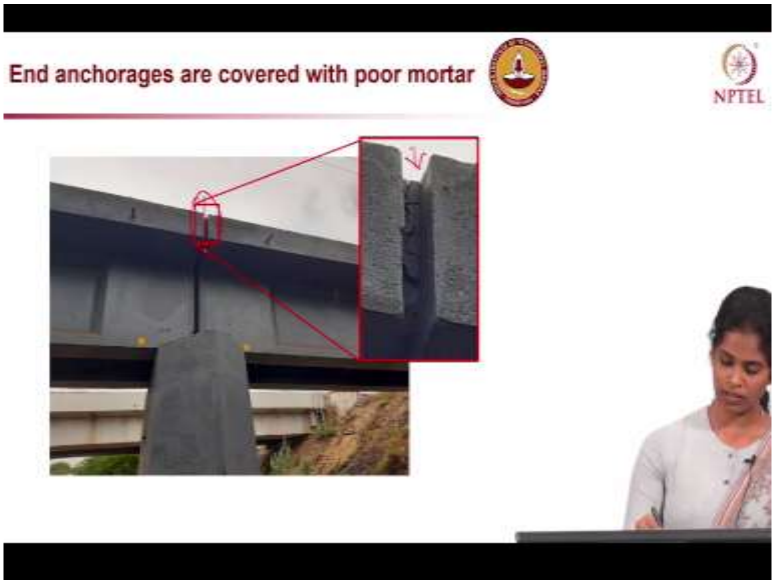

These are some real-life examples where we can see such scenarios. So here in this case in anchorages between the expansion joints are covered with the poor mortar. So you can see the region here, the mortar quality which is used to fill the joint was not good and you can see the cracks over it, so that will lead to the path for moisture to get in and to reach the strand surface.

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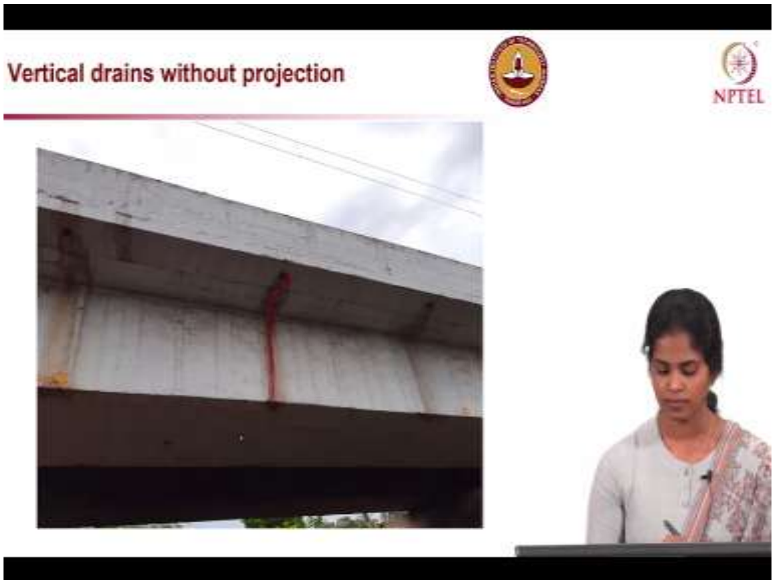

And here is another example, where the vertical drains which was supposed to drain out the water surface is not placed properly and hence the water flowed over the concrete surface and leading to damage or deterioration on the region.

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Let us look at what are the types of damages that we can see in prestressed concrete systems. The one most common damages is that concrete spalling when the concrete strength is not adequate enough to take the stress or we will see the concrete spalling, when the bridges experiencing sudden impact load, we could see the concrete spalling and here are the batches where you can see concrete has spalled and if the concrete has spalled then it is evident that the strand will be exposed.

And in some cases where the member is corroding we can see; we can see rusted strands also. But the corroded prestressing strands itself has different stages where first we will have a even surface with no pitting corrosion, so in that case the capacity of the member will be around 240 kN. Here it is mentioned in kips about 60 kips and with increasing corrosion level the pitting has slowly formed and the surface of the strand becomes slightly uneven and the load carrying capacity was slightly reduced.

And with further increase in corrosion level the pitting becomes severe and with further increase in corrosion level we could see highly uneven surface on the strand. Well the capacity of the strand has reduced significantly. So with increasing level of corrosion further, it leads to partial or complete loss of strand area. When the member is experiencing huge load or when it is experiencing sudden impact load then we could see strand ruptured failure and in most common we will have this structural crack due to inadequate shear or flexural performance or inadequate fatigue performance of the member.

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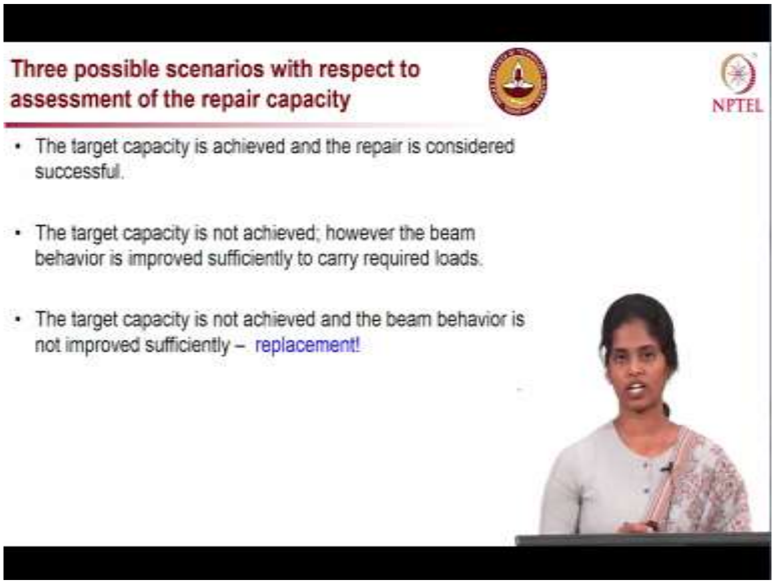

Having seen or having assessed this damage in the prestressed concrete systems, we have three possible scenarios to repair the capacity of the member. The first scenario is that the; to achieve the target capacity. When I say target capacity it means the capacity; design capacity of the member before it got damaged. So the first scenario is to meet the target capacity in that case repair is considered successful, so after repair the capacity of the member is equivalent to the capacity of the member or the undamaged member.

And the second scenario is that the target capacity is not achieved but still the member can be strengthened to enhance the performance of the structure that is here in this case after strengthening or after repair the capacity of the member is not met the design capacity of the member before it is damaged but still we can increase the capacity of the member adequate enough to meet its purpose.

The third case is where we have the members were severely damaged, so in that case we cannot even enhance the performance just to meet the purpose, so in that case we need to replace the member to meet the conditions. So here the target capacity is not achieved and the behavior of the member cannot be improved by repairing, so in that case we have to replace the member.

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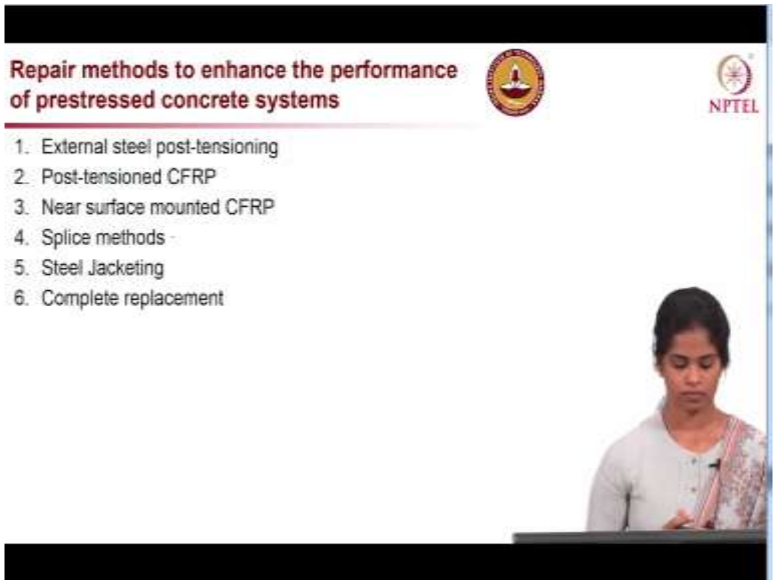

Having all those let us see what are the typical methods to enhance the performance of prestressed concrete systems. The first and most commonly used method is External steel post-tensioning and a second method is post-tensioned CFRP, CFRP is Carbon Fiber Reinforced Polymer and the third one is near surface mounted CFRP, where CFRP is placed but not prestressed.

And the fourth method is sliced tendons, splice methods if the tendons are broken or if the tendon is damaged then we can repair those things using splice method and another method is steel jacketing and which is commonly used in RC or conventional reinforced concrete systems also and if the member is severely damaged then none of these methods will work then we have to go with complete replacement of the member.

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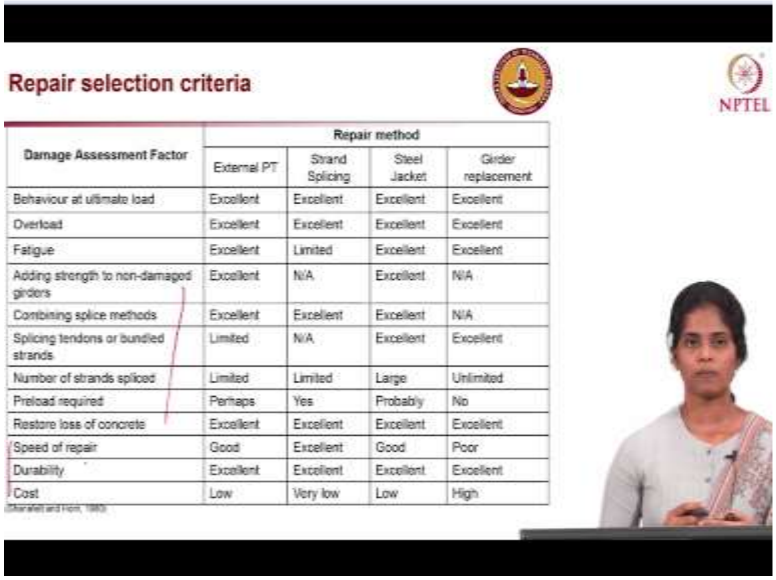

Damage Assessment Factor	Repair method			
	External PT	Strand Splicing	Steel Jacket	Girder replacement
Behaviour at ultimate load	Excellent	Excellent	Excellent	Excellent
Overload	Excellent	Excellent	Excellent	Excellent
Fatigue	Excellent	Limited	Excellent	Excellent
Adding strength to non-damaged girders	Excellent	N/A	Excellent	N/A
Combining splice methods	Excellent	Excellent	Excellent	N/A
Splicing tendons or bundled strands	Limited	N/A	Excellent	Excellent
Number of strands spliced	Limited	Limited	Large	Unlimited
Preload required	Perhaps	Yes	Probably	No
Restore loss of concrete	Excellent	Excellent	Excellent	Excellent
Speed of repair	Good	Excellent	Good	Poor
Durability	Excellent	Excellent	Excellent	Excellent
Cost	Low	Very low	Low	High

So before selecting the methods there are certain selection criteria that we have to look and based on that we can choose the repair method for enhancing the performance. And these are the damage assessment factors that we have to consider while selecting repair methods whether we are going to increase the capacity to meet the overloading demand or the fatigue performance and if the tendons or the strands got captured or damaged in the existing member whether we need to splice or combine the strands and if so how many strands have to be spliced.

And if there any prestressed loss, if there is a loss how much pre-load is required, condition of the concrete how much it has to be restored or it has to be enhanced and speed of the repair. Apart from these things above all, these three are the primary factors that is that we have to give consideration, how speed that we can do the repair of the existing member that is basically the interruption of the service while repairing that has to be as minimum as possible.

And the next category is the durability and cost. In repair philosophy it is meant that if the structure is repaired then it has to meet its service life beyond its intended design service life. So the repaired members should have high durability to serve its design service life.

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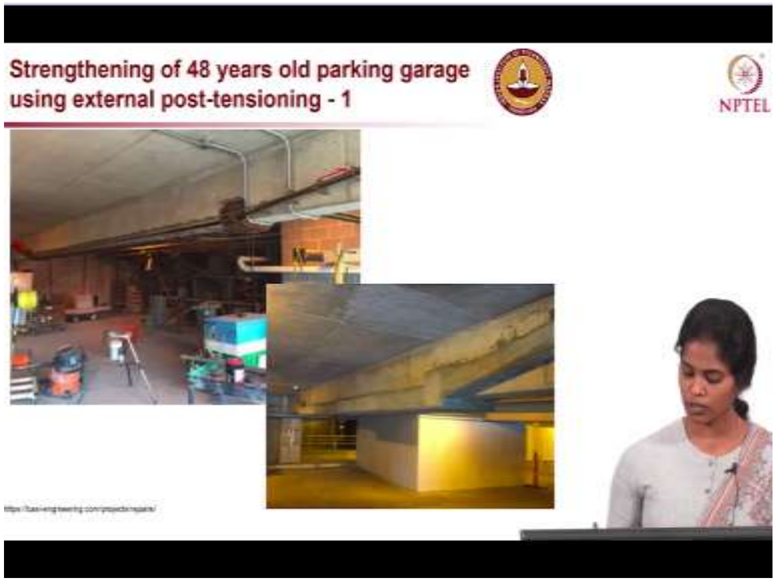

So let us get into the case 1 that is external post-tensioning. Here is the case of strengthening of 48 years old parking garage using external post-tensioning. So I am not going to get into details of this method as this was elaborately covered in the previous lectures. So here is the case so I will just get into briefly explain the scenario here. The girder of the parking garage was deteriorated due to aging and loading conditions.

So external prestressing strands were placed outside and it was stressed at both ends to enhance the capacity of the; flexural capacity of the member. Once it is stress, once the stressing applications all done this region was covered using concrete, so that the externally placed tendons can be protected.

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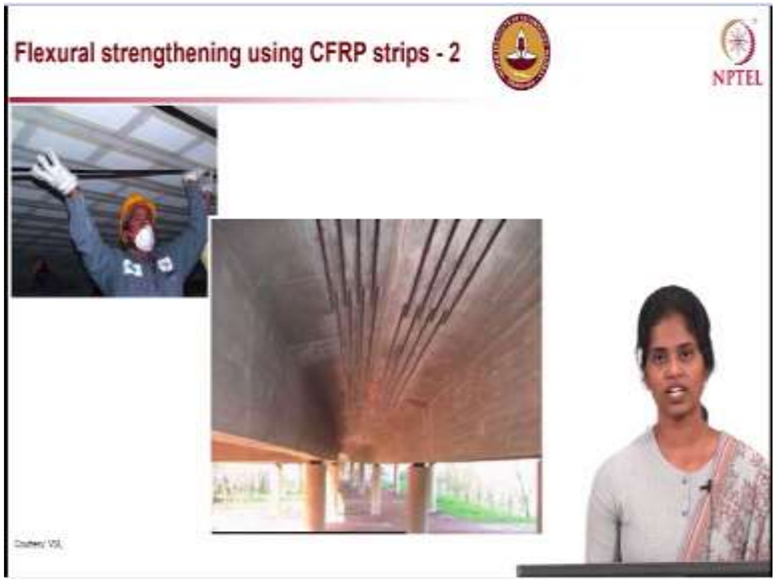

So the most common and preferred method is that flexure strengthening using CFRP that is carbon fiber reinforced polymer strips. Because the carbon fiber reinforced polymer strips has high stiffness and strength to enhance the flexural capacity or the required performance of the member. This CFRP strips are highly orthotropic in nature so the stiffness and strength is in higher magnitude in one direction than the other.

This due to its high strength and stiffness it becomes a good alternative for prestressing purpose. However, the CFRP strips has certain challenges for gripping and prestressing. So we have commercially available components for the effective prestressing CFRP system.

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So these are the four components first one is the CarboStress prestress CFRP and the second one is jacking end anchoring movable frame and live end anchors, how the anchoring is there at live; and stress head system.

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So let us look at the first component CarboStress prestress CFRP. So when CFRP comes it comes with the; so in this region it comes with the potted anchorages that is called stress heads which basically helps us to anchor that region using steel clamps anchors or this will be fixed to the concrete surface. So usually this end where it is attached to the slab or the member surrounding it, it is called fixed end or dead end.

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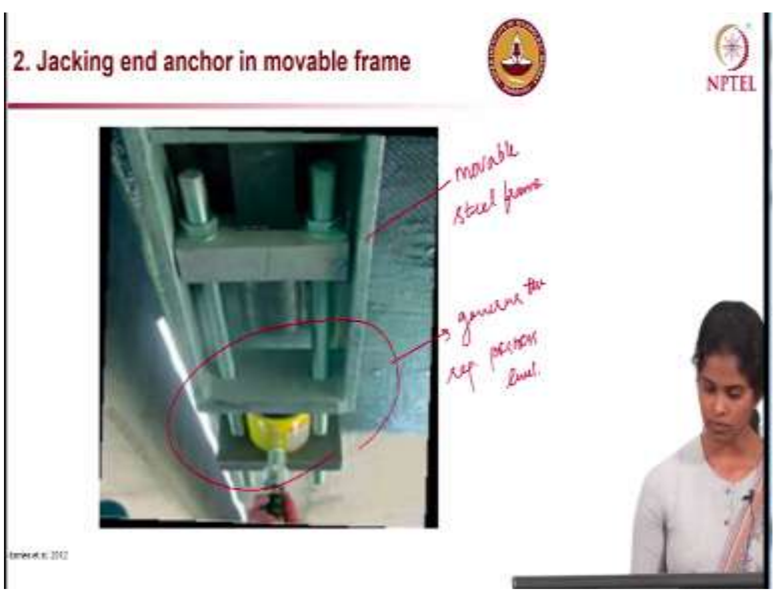

Whereas the other end where the stressing will be applied is called jacking end and that end the strips in this end is inserted or replaced in the movable steel frame. Basically the CFRP strips comes with stress heads, so this end is clamped or anchored at their region. The capacity of the anchorage would be around 300 kN and we can apply maximum of about 240 kN depending on need for strengthening. Basically, the member in this region governs the required prestress level, that is the strength of the member at that region determines how much prestress has to be applied for strengthening purpose.

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And this image shows the live and anchors once the strips are placed and anchored at the live end. And here shows the clear image of how it was done for a bridge deck. So where you can see a steel frame and the CFRP strips are placed inside and clamped it for stressing.

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And these are the stress head system, which helps us to apply the required prestress and basically for gripping and stressing. So you can see the wedges and anchorages for gripping and locking the stress and here is the hydraulic jack, which will help us to apply the required prestressing force. So this image right here shows the assemblage of this stress head system at the live end for stressing application. So these are the components that help us to prestress the CFRP system for enhancing the structural performance of the member. Next case that we are going to see is for near surface mount CFRP system.

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Let us consider a case where the bridge member experiencing sudden impact failure. So when member expect experience such sudden impact failure it is obvious that this concrete is going to get fall off so here you can see the intensity of the damage and the concrete spot. So once the concrete has fall the stands will get exposed and in some case depending on the load if it is huge then the strand in that region get rupture. So let us see how that is going to affect the performance.

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When we have such vehicle impact or corrosion damage so the member could significantly lose its prestressing level. Here you can see the red mark, the right to the red mark where you can see the ruptured strands and rusted steel. The left to the red mark you can see the bright steel. So when the member has such strand failure or reduction in capacity it does not represent the scenario of the whole length of the girder; it is very localized.

In that case, we need to account the other region, where the strands are in good condition and embedded in a good concrete. So this leads to a question; so in general in pretension concrete systems stress will be transferred from strand to the concrete. If the strand is ruptured or damaged in this region the stress transfer mechanism will be failed but here in this region this strands are in good condition and embedded in concrete.

If that is the case then can the prestress force be redeveloped over the transfer length of the strand, if so then we need to account the prestressing level available in this region to determine the capacity of the member. So for any strengthening methods first we have to evaluate the condition and the capacity of the member by doing the analysis, so in that analysis we need to account for this redevelopment also if it is occurring.

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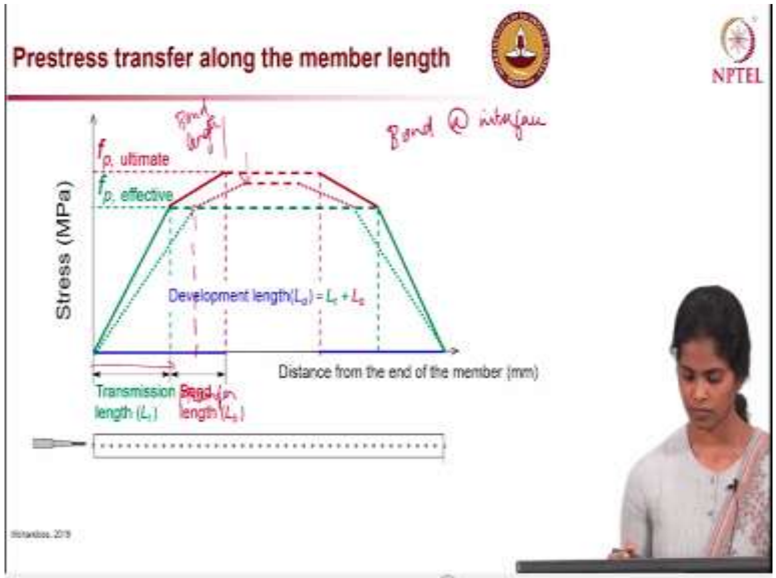

So before getting into that let me explain about the transfer mechanism along the length of the member. As I said earlier in pretentioned concrete systems, we have stress transfer from strand to the concrete. So when the stress is getting transferred it get transferred from the end of the members and it gradually increases to along the length and reaches the effective prestress. The length required to reach the effective prestress is called transmission or transfer length.

And further under service the effective prestress will be developed to reach the ultimate stress and the length required to reach the ultimate stress is called development length. Basically, the length of this region alone is called Bond length, and together the length of transmission or transfer length and the bond length is called development length which is the length required to is the ultimate stress from zero.

So this transfer mechanism is significantly depends on the bond at interface. Hence this will be affected if the interface is getting damaged or disturbed due to the external loading or due to aggressive environments in case of corrosion. So for example you are assuming that the member is experiencing corrosion or near the damage this bond interface gets affected. So in such cases to transfer the effective prestress we may need a longer or the member will need a longer transmission length.

So in that case the transmission length will get moved from this region to that region. If it is the corrosion damage then the prestress level will also get reduced due to loss of strands. This is the simple hypothesis for this transfer mechanism, what happens if it is affected by corrosion or any bond damages at the interface.

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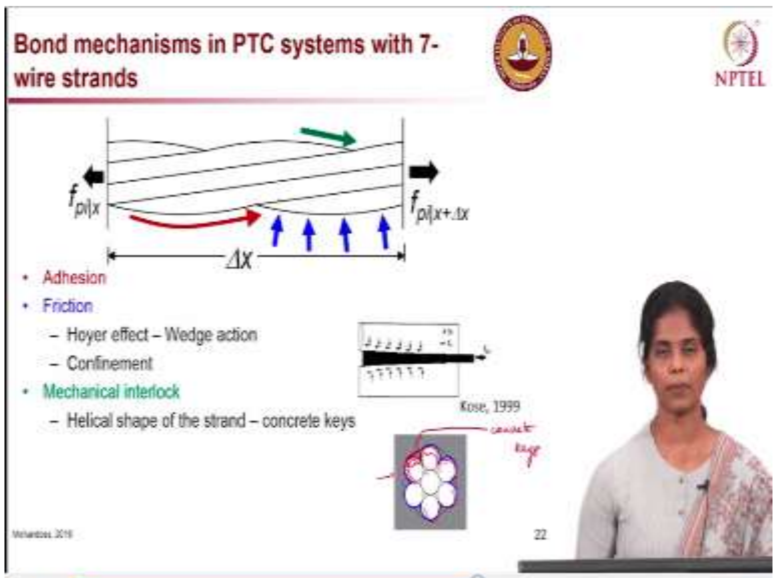

So just to have an idea what is the bond mechanism in prestressed concrete systems with 7 – wire strands, this shows the schematic of the strand surface. The bond mechanism in prestressed concrete systems were contributed by adhesion, friction and mechanical interlock. Adhesion is due to the lubricant presence of lubricant on the surface which plays a minor role when the strand gets sleep then the effect of adhesion will be lost and friction and mechanical interlock plays a huge role in transferring or for a bonding action.

So friction is mainly contributed by the Hoyer effect. I am not getting detail about this, and the confinement of the surrounding concrete and mechanical interlock is basically due to the shape of strand here, you can see how the cross-section of the strand in concrete. So in the gap between the strand and concrete it forms the concrete keys. This concrete key plays a major role in providing a confined interface.

So they said, if the interface gets damaged or if the strand is experiencing corrosion this cross-section is going to get affected and that is going to affect the bond between the strand and concrete. So it is important to know the bond strength between the strands and concrete while performing or while evaluating the capacity of the member.

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So how do we determine the bond strength of potential concrete systems? Here is the experimental setup that we developed here in IIT-Madras to determine the bond strength for especially pre-tensioned concrete systems. We have such long members of about 1 meter accounting the transmission length or the transfer length from both ends of the member. So we do a simple pullout test and to measure the bond stress slip behavior to obtain the bond stress bond strength of the member. So here we measure the bond stress and slip behavior to determine the bond strength of prestressed concrete systems.

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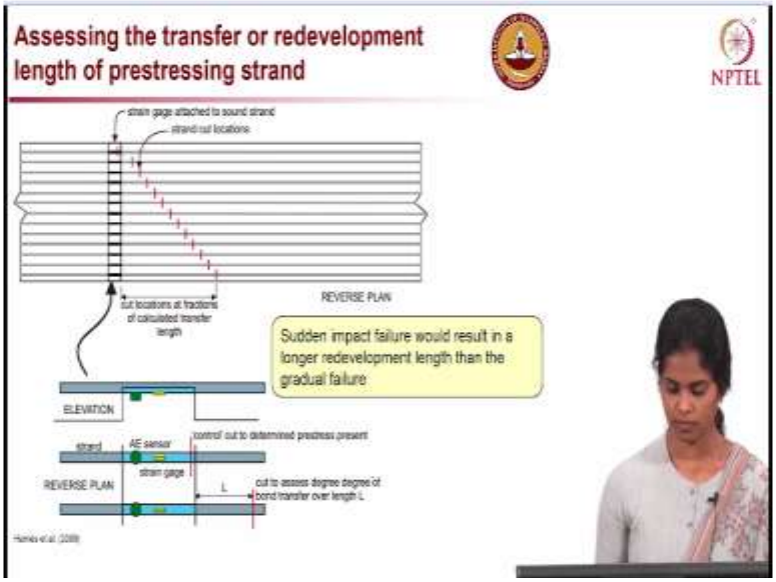

Now let us see assessing the transfer or redevelopment length of prestressing strands on the existing system. People have proved that we can measure the transmission length or the prestress can be redeveloped along the length of the member in the undamaged portion of the damaged structure. So here to determine the transmission length what we have to do is we need to select the cut location at fractions of distance and then we can place the strain gage to the good quality or the undamaged strand and measure the stress or strain acting on it.

Here in this case acoustic emission sensors were placed to determine the strength. So by measuring or by monitoring the stress on acting on the surface so based on this we can easily determine the transmission and based on the concept transmission length is the length required to attain the effective prestress, effective prestress can be obtained by the sensors that we placed on the existing surface.

So from the observed results we have seen that the transmission length of the existing member is large if it is due to the sudden impact load comparing to the gradual failure. That means sudden impact failure could result in longer transmission length or redevelopment length comparing to the gradual failure.

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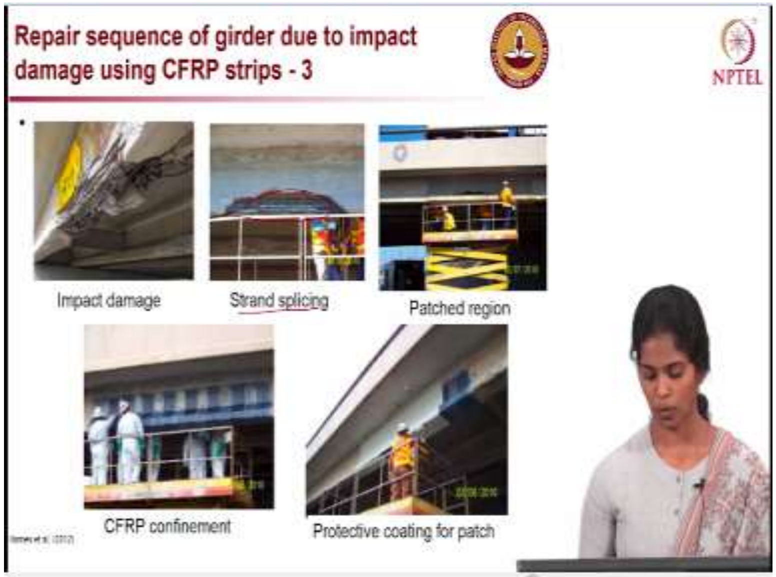

And this is the sequence of repair how we are going to strengthen the member in case of impact damage using CFRP strips. Basically, this is near mount surface CFRP strips. First step is that to fix the damages of strands the exposed strands. If the strands got ruptured, then we need to do the strand splicing; I will explain this in the following slides how to do this strands splicing and once the strands splicing is done, we need to apply the prestress to meet the required level.

And this region has to be covered or patch work has to be done by placing the concretes. And once that is done then the member is strengthened or confined using CFRP wrap. Here you can see U-wrapping strengthening has been provided to improve the performance. So once that is done protective coating on the CFRP surface has to be provided to enhance the durability of the repair.

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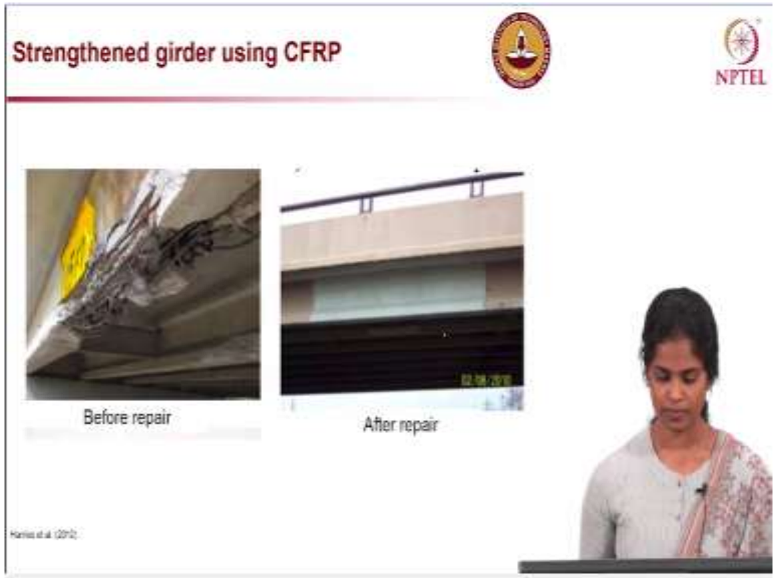

And finally, this is how the structure looks before and after repair. Before repair you can see the concrete spall and the strand damaged everything here and now it looks like need completely strengthened structure.

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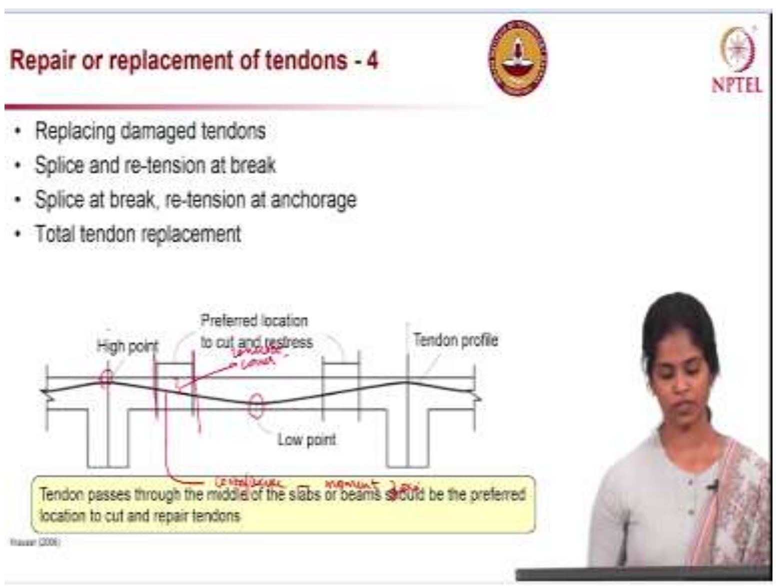

So let us look at repair and replacement of tendons. So here we have four cases, the first case is to just replace the damaged tendons and the second case you can place a new tendons to the existing one and splice it at intervals or a splice and retention and breaks, and the third method is splice at break and retention altogether splicing has to be done at their intervals and all together we can retention.

fourth method is complete replacement of tendons, if the tendons is severely damaged that we cannot repair by splicing. So now it is important when we select; when we do a repair for tendons it is very important to find out the location where we need to repair or where we need to do the strengthening or cut work. Let us look at the repair and replacement of tendons.

So we have four cases for repairing tendons, the first one is to replace the damaged tendons and the second one is to splice and retention at breaks, and the third one is like splice at breaks and all together we can retention at anchorages and the final one is to complete replacement of tendons if possible in the case where the strands are severely damaged. For replacing tendons its foremost important to select the location of repair.

And here it; the schematic shows the profile of cable in the prestressing systems where you can see the high points at the support region and the low points are the mid span of the member and the preferred location would be somewhere in between where you can have enough concrete cover for repairing if there is any need for cutting, and also it matches with contraflexure of the member where moment is zero. Hence, it is always preferred to select the location where tendon passes through the middle of the slab or beams for the repair work.

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When we repair the tendons it is important to detention the stress available in the tendons. If the strands are ruptured or cut, then there will not be any prestressing force acting on it then we can directly go or get into the repair process.

If the strands are not completely ruptured or still there is some residual prestressing force available in the strands then we need to detention the prestress force before splicing the strands. What are the different ways of detensioning strands? So we have three ways, the first one is through anchorages and the second one is by drilling into the strand and third one is burning through strand.

Here is the case of the first one where we can use this anchors at the ends and then slowly detention the strands. And sometimes we can use some special jacking arrangement where such can such jack systems can be placed at the ends, so this is for a member which has an accessible length; the both ends can be gripped by jack grippers and the middle of the regions we can cut the strands and slowly it will release the jack; this region will take care of gradual release of prestressing or detensioning the strand.

And the second method is like drilling into the strands where we have to drill directly into the strand and in this case the location of concrete sorry the location of strand has to be known before we start the process or the exact location has to be known for drilling into the concrete. On the third method is that exposing these strands and the anchorages to the heat by allowing heat, the prestress can be reduced; detensioning of prestressing involves high risk as we are dealing with the huge amount of forces.

Hence in this case the strands or tendons can pop out or the concrete surrounding concrete can blown out, so it is important to ensure people are not surrounded by that to avoid any injuries.

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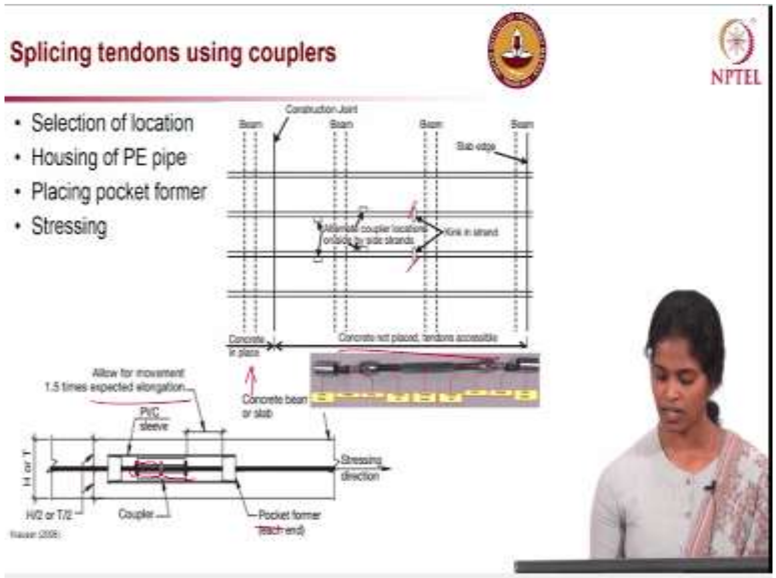

So let us get into the splicing method using couplers. So as I said earlier the first method is to replace damaged tendons completely if possible, this is the case when the concrete is not placed and when you identify the damage in the strand. where concrete is not placed and tendons can be easily accessible. Suppose in this case, where you can see the concrete in place of the beam and the tendons are embedded.

Now when you identify the damage, when the concrete has placed here in this region you can see kink in the strand. So if that is a case splicing help us to repair the tendons. So let us see how to splice the tendons. First, I mentioned we have to select a proper location, where we have sufficient concrete cover to access and it should be like not in the middle or end of the member, so where we have moment zero or the contraflexure is there.

So for proper gripping for proper gripping of coupler we are placing this PE pipe with a sufficient diameter and length to grip the coupler which will be placed inside the PE pipe and we have to select the length in such a way that it allows the movement while stressing. So roughly there has to be about 1.5 times of the expected elongation and then we have this Pocket former to be placed at the ends and we need to ensure there is no voids by providing prestressed tendon coatings.

Once this is all fixed you can see here, where the part of existing strand or tendon is inside the coupler and here is the part of new tendon that has to be spliced with the existing one. And this shows the image of the coupler arrangement, where you can see anchorages wedges and spring just to allow the movement and threaded rod and the coupler for connecting the old and the new strands.

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This image here shows couplers placed to join the old or the existing tendons with the new tendons. This work is for a slab work, where the tendons are spliced using couplers and stressed to meet its required performance.

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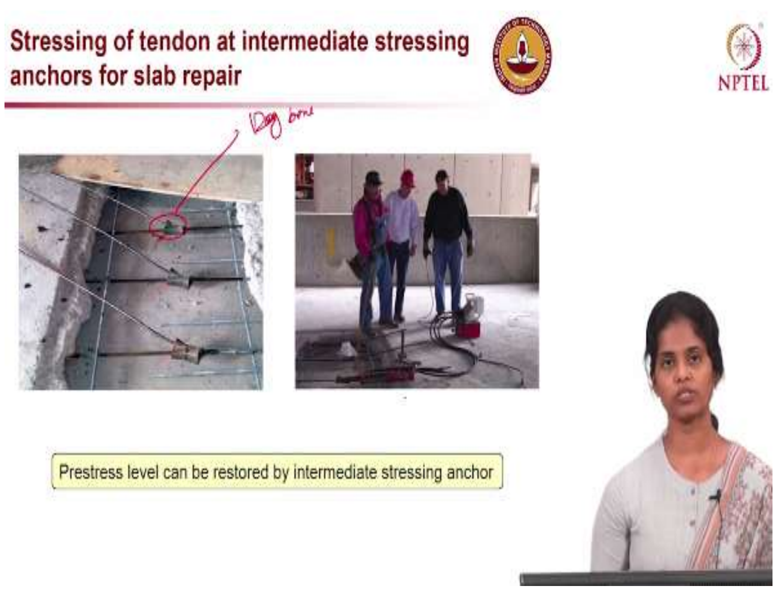

Now another method for stressing the strands is that the intermediate stressing using intermediate stressing anchors for slab repair. This is being followed or used when we cannot access the end anchorages but still we need to stress the strands at the intermediate. So here in this region so we have excavated the concrete over it; the size of excavation depends on the stressing equipment that we use or the type of anchorages that we use.

Here is the case you can see Dog bone system has been; arrangement has been placed to provide stressing tile for intermediate stressing anchors while detentioning the strands for repairing the length of the strands will get shortened but for this intermediate stressing anchors we need to have a stressing tail to provide stressing. Since the existing tendons will not have sufficient length new tendons has to be spliced to increase the length such that, will provide tail for intermediate stressing anchors.

So here is an arrangements how the whole tendon was embedded in a concrete and the dog bone system was placed to enhance the length of the tendons for intermediate stressing anchors. So once this is done; right image shows how the strands were stressed at the intermediate using hydraulic jack. So by doing so we can restore the prestress level in the member.

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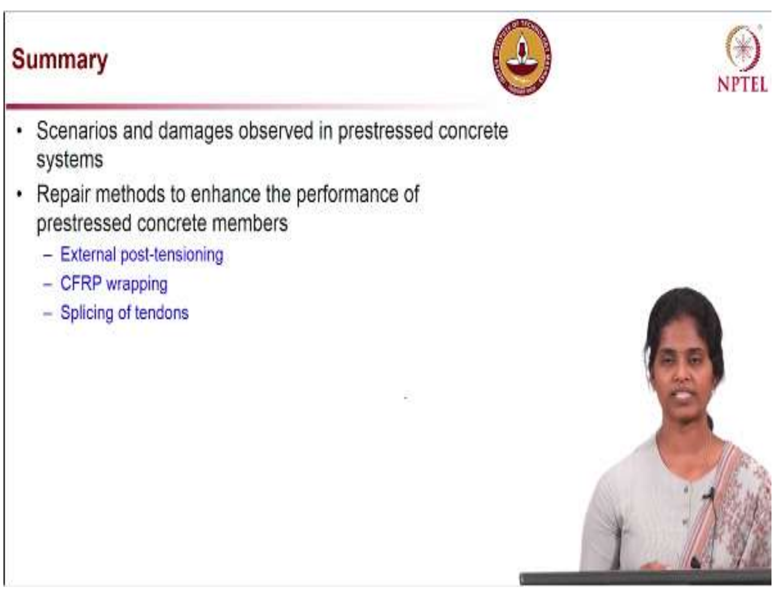

And here is the summary. So far we have seen the scenarios and damages observed in prestressed concrete systems and the repair methods to enhance the performance of prestressed concrete systems using external post-tensioning and CFRP wrapping in that using post-tensioning CFRP wrapping and near surface mount CFRP wrappings and splicing of tendons.

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And these are the references for further reading.

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