Retrofitting and Rehabilitation of Civil Infrastructure

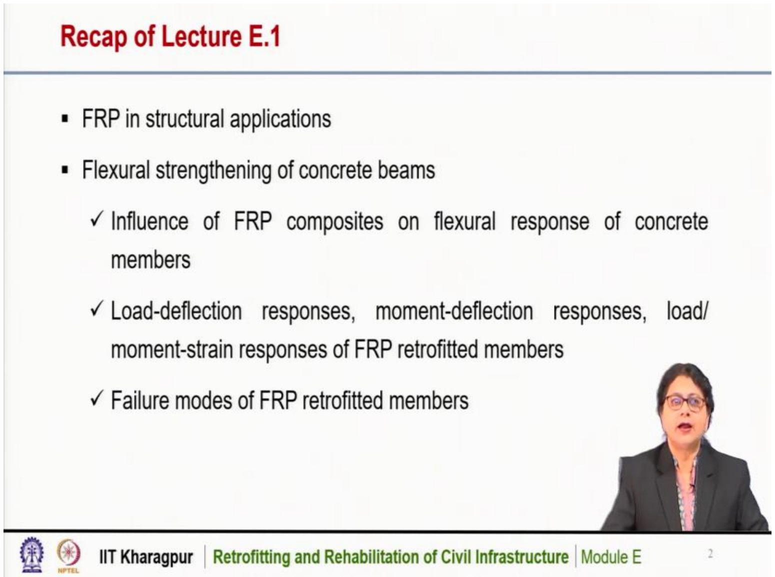
Professor Swati Maitra
Ranbir And Chitra Gupta School of Infrastructure Design and Management
Indian Institute of Technology, Kharagpur

Lecture: 24

FRPC In Flexural Strengthening of Structural Members-II

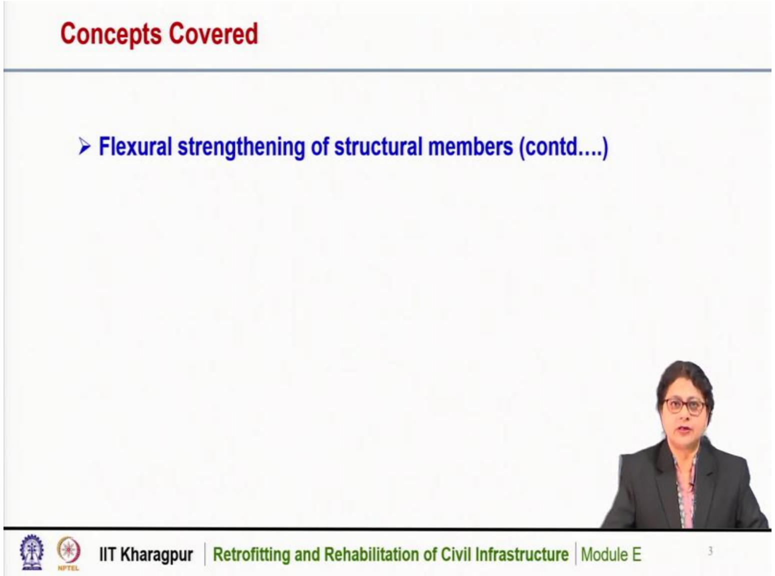
Hello friends, welcome to the NPTEL online certification course Retrofitting and Rehabilitation of Civil Infrastructure. Today we will discuss module E, the topic for Module E is Retrofitting using FRP composites.

(Refer Slide Time: 00:44)



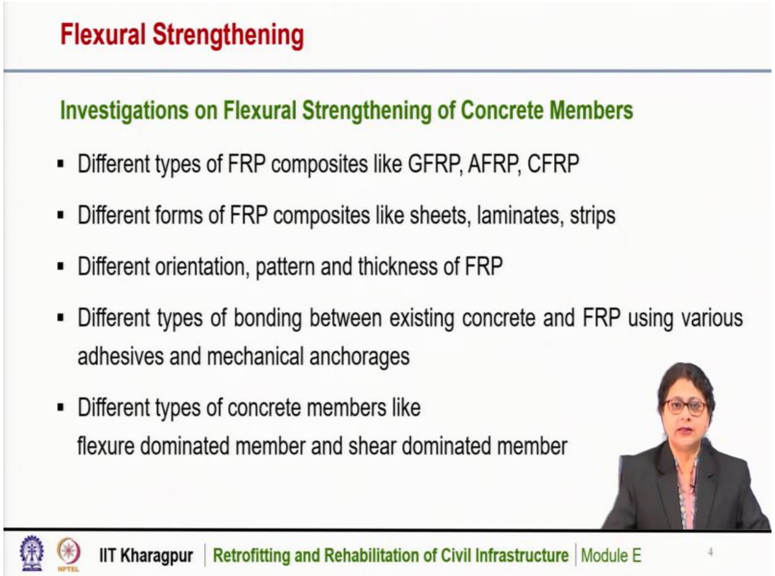
In the previous lecture, we have discussed several applications of FRP composites in structural area. We have discussed the flexural strengthening of concrete beams using FRP composites, there are several parameters that may influence the complex behavior of FRP retrofitted flexural members. There are several parameters of FRP composites and the concrete members. And we have discussed some of the experimental works in this area, the load deflection responses, the failure modes et cetera, have been discussed based on the experimental research carried out in this area.

(Refer Slide Time: 01:37)



Today, we will continue our discussion on flexural strengthening of structural members using fiber reinforced polymer composites and the effect of some other parameters on the response of FRP retrofitted flexural members.

(Refer Slide Time: 01:59)

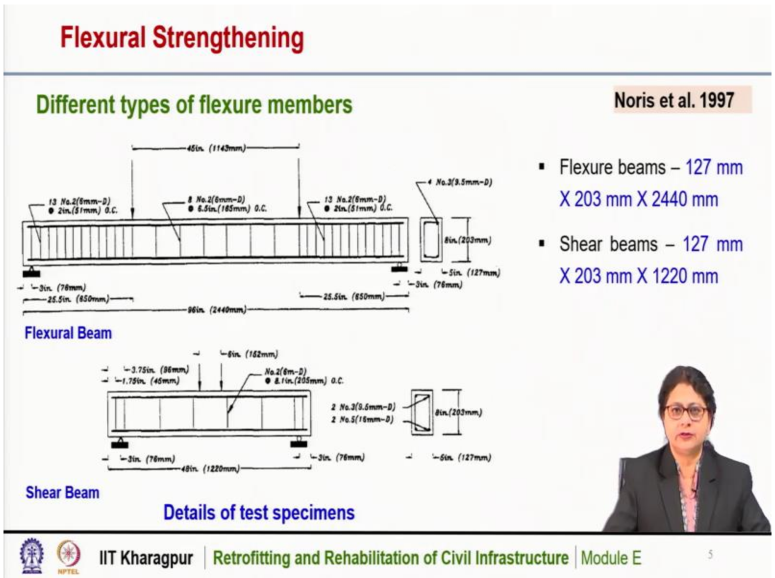


We have discussed earlier that there are several parameters that may influence the behavior of FRP retrofitted flexural members. The different types of FRP composites with its strength and stiffness may influence the load displacement response and failure modes of the members. Different forms of FRP composites are also used like sheets, laminates, strips et cetera.

And their orientation pattern and thickness may affect the response of the FRP retrofitted member.

There are different types of bonding that may exist between the existing concrete and FRP using various adhesives and mechanical anchorages that may influence the response. And different types of concrete members also have been investigated by several researchers like flexure dominated member or shear dominated member or members with different lengths and dimensions. And their responses have been found out by carrying out experiments on FRP retrofitted members.

(Refer Slide Time: 03:15)



We will discuss some of important experimental works carried out by several researchers and these are the pioneering works that helped us in understanding the complex behavior of FRP retrofitted members. The FRP retrofitted members behave in a different way as compared to steel reinforced member.

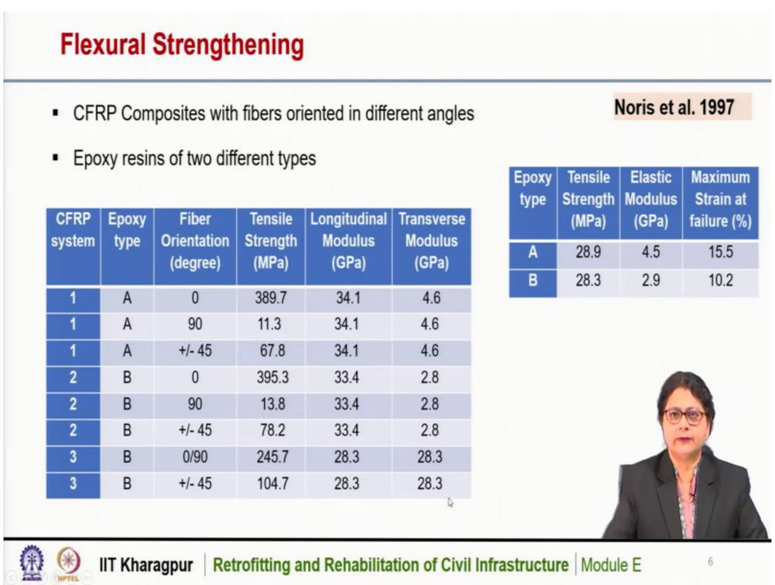
And to understand the behavior of the FRP retrofitted members a number of experiments have been carried out by several researchers, to understand the load carrying capacity and the failure modes of these members. We will discuss now, the different works and this is a research work by Noris et. al. the researchers have carried out experiments on different types of beam members. The different types of flexural members, one is a flexure dominated beam and the other is a shear dominated beam. So, two types of beam members have been considered and the beam members have been retrofitted with FRP composites to improve their flexural capacity.

The dimensions of the beams are given here for flexure beams, it is 127 millimeter × 203 millimeter × 2.44 meter in length, the shear beam sort of shorter length 127 millimeter × 203 millimeter × 1.22 meter in length. In case of flexure dominated beam we can see here this is the schematic diagram of the flexure dominated beam, which is of 2.44 meters length.

It has reinforcement, as we can see here top reinforcement and bottom reinforcements are provided and this is the cross section of that beam and it has shear reinforcement, the shear reinforcement is quite heavy, so, that if with increase in load, there may be a failure due to flexure. So, this is a flexure dominated beam and this is a shear dominated beam. The length is much smaller. Here also we have reinforcement at top and bottom of the beam and the shear reinforcement is also there, but that shear reinforcement is much less. So, with increase in load the beam may fail in shear.

So, this is a shear dominated beam, whereas, this is a flexure dominated beam. So, the behaviors of these two beams are different and when these beams are retrofitted with FRP composites, then also the behavior will be different. And to understand these two types of beam retrofitted with FRP composites experiments have been carried out.

(Refer Slide Time: 06:23)



These are the details of the composites that have been used to retrofit the flexure and the shear beams. CFRP composite has been used and here in this CFRP composite, the researchers have used the fibers which are oriented in different angles. And there are two types of epoxy resins and the properties of the epoxy resins are given here.

Two types of epoxy resins with different tensile strength and elastic modulus as we can see here and also with different strains at failure. So, two types of epoxy resin have been used and one type of CFRP composite has been used, but, they have made it differently like by orienting the fibers in different angles, in one type of CFRP the fibers are oriented along the length of the member.

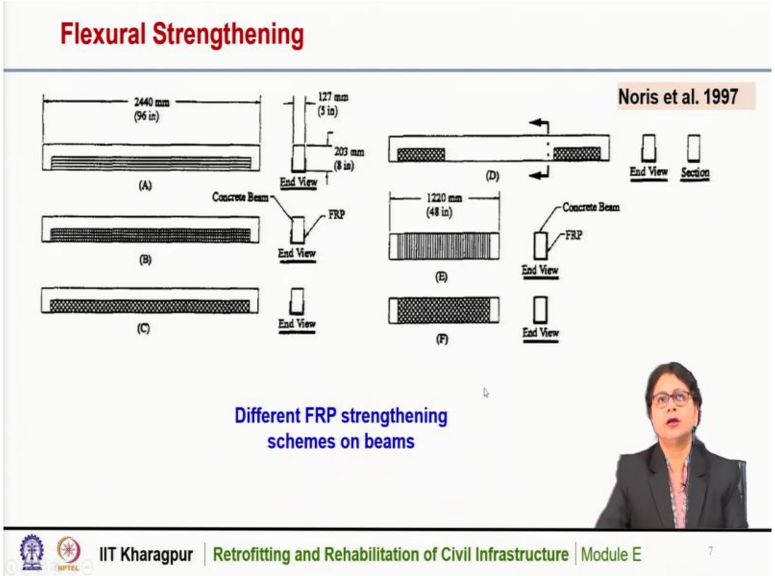
So, the fibers are oriented at an angle 0 degree. In another case, the fibers are oriented perpendicular to the length of the member. So, it is 90 degree. So, the fibers are oriented at 90 degree to the length of the member, in another case it is oriented at an angle of 45 degree. So, in one case it is in one direction plus 45 degree also minus 45 degrees in opposite direction.

So, in two ways the fibers are oriented one is plus 45 and minus 45 degree, in another case it is again 0 degree, but with different type of fiber then again 90 degree and here it is the epoxy is different here epoxy is type A here the epoxy is type B and the fibers are oriented in 0 degree, 90 degrees then plus minus 45 degree then again 0 and 90 degree.

So, the fibers are in perpendicular to each other in two sets, in one set it is along the length of the member and in another set it is perpendicular to the length of the member. So, 0 and 90 degree both type of fibers are there and in another case it is plus minus 45 degree. Accordingly, the tensile strength and Longitudinal Modulus, Transverse Modulus are also different, as we have discussed earlier that.

If the fibers are oriented along the length of the member the strength and modulus is high along the length of the fiber. So, here when the fibers are oriented at 0 degree along the length of the member, the tensile strength is, maximum. And when it is perpendicular to it, it is less intermediate when it is at 45 degree. So, like that the strengths are given, the modulus are given and the transverse modulus are also given, the properties of epoxy of two types are also given in this table.

(Refer Slide Time: 09:46)



So, these are the different schemes of FRP strengthening. As we have just mentioned in the previous slide that the fibers may be oriented in 0 degree or 90 degree or plus minus 45 degree or 0, 90 degree like that. So, these are the schemes this is the fibers are oriented along the length of the member.

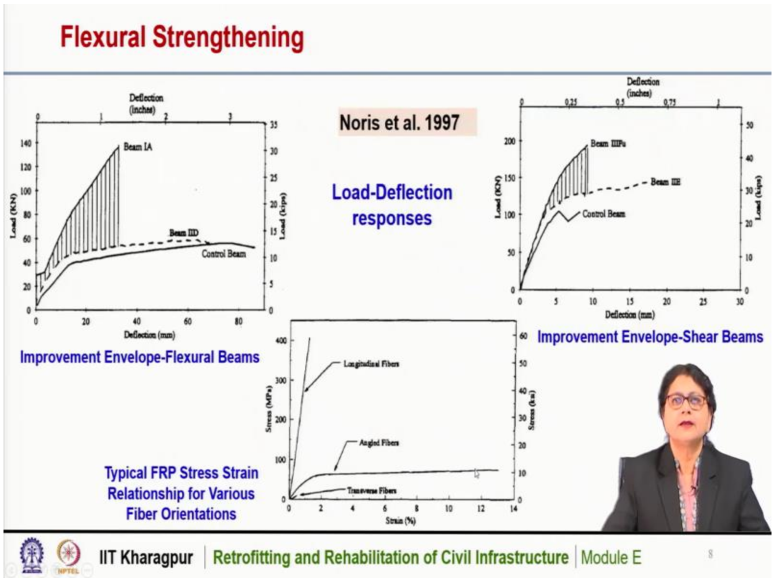
So, it is 0 degree and here it is in U-shape as we can see here that this is the U-shape here. Main purpose is to strengthen the bottom face and so, it is applied like this here it is 0 and 90 as we can see here one is 0 degree another is 90 degrees. So, and it is placed also like this attached with some epoxy and that epoxy is also given, here it is plus minus 45 degree one is plus 45 another is minus 45 degree here.

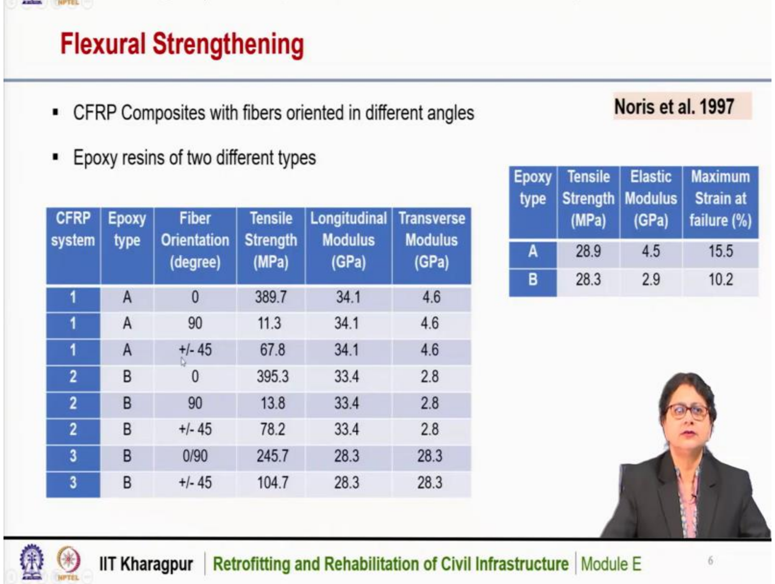
This is also plus 45 minus 45, but, it is only at these locations. So, this is near the support it is provided plus minus 45 degree. So, these are all flexure beams, these four are flexure beams, and these two are shear beams, so, in case of shear beams, the fibers are oriented as we can see here, along the entire length almost just only at the support it is not there.

But it is along the entire length and these are the fibers transverse to the length of the member. So, this is the orientation of the fibers as we can see and this is the length of the fiber, this is the length of the member. So, the fibers are perpendicular to the length of the member and here it is plus minus 45 degree as we can see here through the entire length of the member and through the entire web also it is provided.

So, here in the cross section we can see here the fibers are placed and which is perpendicular to the length of the member and here it is plus minus 45 degree to the length of the member. So, these are the different FRP strengthening schemes on the different types of beams, both flexure dominated beam and shear dominated beam and it is important to understand the behavior of these two types of beam with different wrapping scheme.

(Refer Slide Time: 12:18)





So, it has been seen that all the beams which are retrofitted with FRP with different angles, there is a significant improvement in the load carrying capacity of the members. And here it has been seen that in case of flexural beams, there are details are given here. So, that details are not shown here, but all the beams have shown significant improvement in their flexural capacity. So, in case of flexure dominated beams, there is an improvement over the control beam. So, this is the response of the control beam as we can see here load deflection response of the control beam is this and FRP retrofitted beam, this is beam 1A there are different notations and particularly for this beam there is an improvement in the load carrying capacity.

So, there is a significant improvement in the load carrying capacity when it is retrofitted with CFRP. And here possibly, it is at the fibers are oriented at 0 degree. So, there is a significant improvement in the load carrying capacity of the flexure dominated, in case of shear dominated beam there is also improvement in the flexural capacity and we can see here the comparison this is the response of the control beam and these are the response of the FRP retrofitted beam.

So, here also there is a significant improvement in the load carrying capacity of the shear dominated beam. This is a typical stress strain relationship of the composites having different fiber orientations. We have discussed earlier that the strength of the composite is maximum when the fibers are oriented along the length of composite, the least when the fibers are oriented perpendicular to the length of the member.

And intermediate strength is achieved, when the fibers are oriented at some angles. So, this is shown here in this diagram that the composite which has the fibers at 0 degree, the strength is maximum and when the fibers are oriented at 90 degree, the strength is much less and in between when the fibers are oriented at different angles.

So, here also this is shown here in this table that the tensile strengths are different, when the fibers are oriented at different angles. So, maximum strength is for the composite having fibers at 0 degree and minimum is when the fibers are oriented at 90 degree and intermediate when the fibers are oriented at plus minus 45 degree.

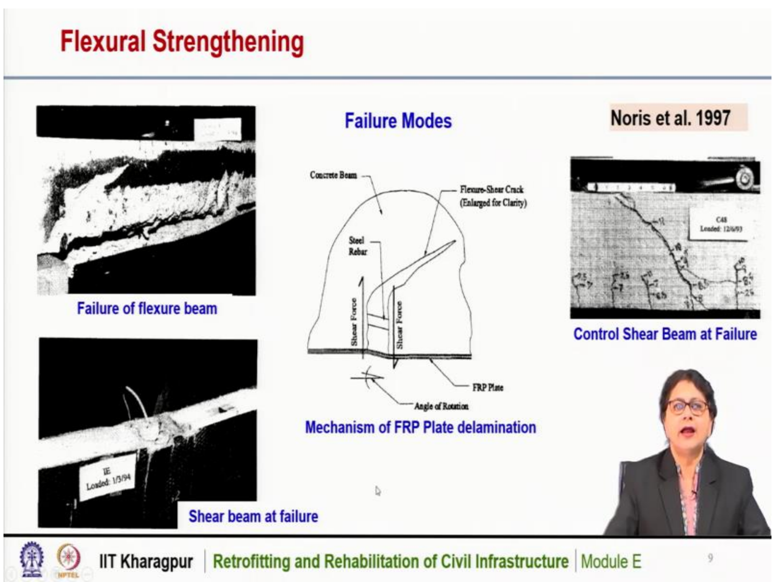
So, similar results are also obtained when the beams are retrofitted with FRP composites having fibers oriented at different angles. Maximum improvement in strength is possible when it is retrofitted with the composite having fibers at 0 degree with the length of the member and minimum improvement in strength is achieved when the fibers are at 90 degree to the length of the member and intermediate when the fibers are at different angles.

So, here in this present experiment, a number of beams have been tested with different types of FRP composite having different fiber orientation, it is either 0 degree or 90 degree or a combination of 0, 90 or plus 45 minus 45 et cetera. So, a number of FRP combinations have been used with various fiber orientations.

And we have seen that the maximum improvement in strength is possible for the beam which has external reinforcement with FRP composite having fibers at 0 degree and least improvement is there for the beam which is retrofitted with FRP having fibers oriented at 90 degree and intermediate improvement is achieved for the beams retrofitted with FRP having fibers at plus minus 45 degree.

So, fiber orientation has a significant influence on the response or behavior of the FRP retrofitted member, maximum improvement is achieved when the fibers are at 0 degree. And if the fiber orientations are other than the 0 degree, the strength improvement is much less as compared to the previous one. So, fiber orientation has a significant influence on the strengthening of beams which are retrofitted with FRP composites.

(Refer Slide Time: 18:01)

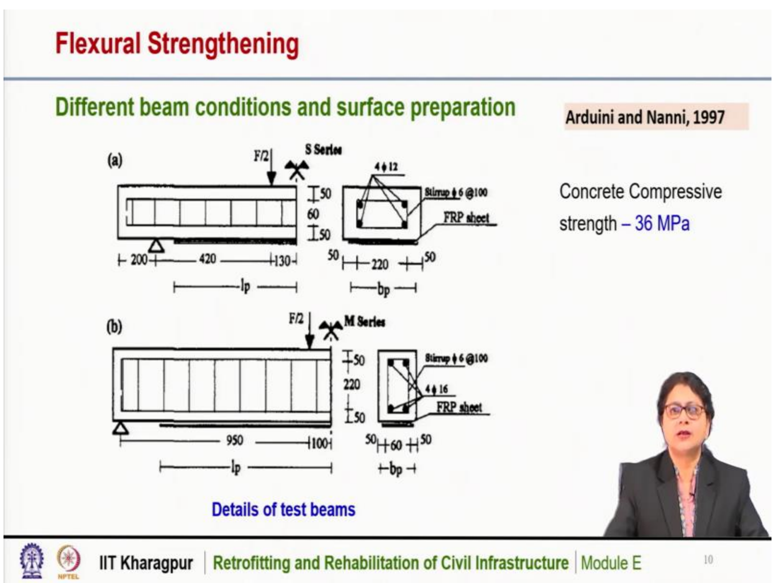


These are the failure modes of different types of member, we can see here in this picture, this is the failure mode of the control beam, control shear beam and that fails due to the formation of shear cracks as we can see here, these are the typical shear cracks that has been developed and the control beam and these are the failure modes for the flexure dominated beam and this is for the shear dominated beam. So, the flexure dominated beam there is a delamination as we can see here at the here at this edge of the member. So, this is a delamination and this is due to the formation of flexure cracks or flexure shear cracks on the member, and this is the shear beam which fails due to the crushing of concrete at this location.

So, this beam fails due to the compression crushing at this location. And this is a schematic diagram of the mechanism of FRP plate delamination. As we can see here, this is delamination occurs. So, this is the schematic diagram, this occurs when there is formation of cracks and that cracks is a flexure shear crack.

Initially the crack is vertical but with increasing load as the load increases, there is the beam is also loaded and the crack moves inclined to the member. So, that is the flexure shear crack and that is formed and if there are more number of this type of cracks occur then there is delamination of the FRP from the concrete substrate. So, this is the cracks that is formed and it is inclined with increased in loading and that results into delamination of the FRP from the concrete.

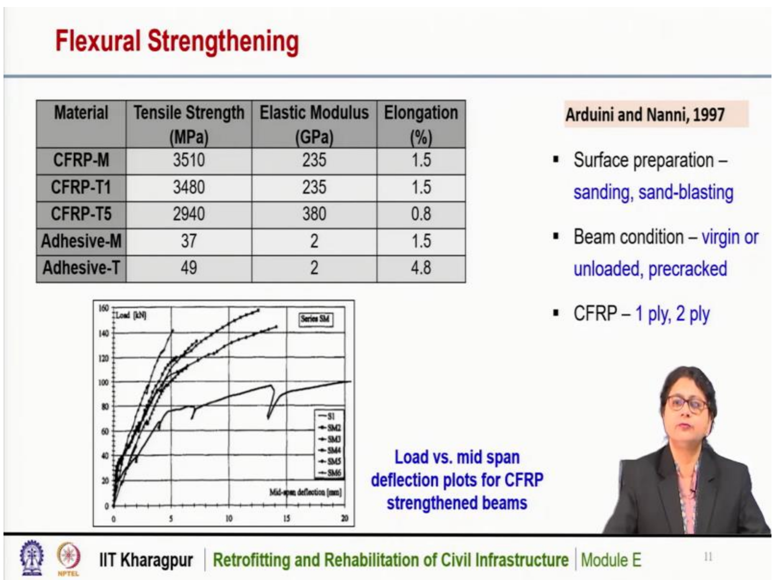
(Refer Slide Time: 20:09)



This is another research work by Arduini and Nanny. And they have also investigated the performance of FRP retrofitted members and with different beam configuration. So, here we can see here that these are the two different types of beam members, the dimensions are given here and the beams are also with steel reinforcement, the details are given here and the concrete compressive strength is 36 MPa.

So, these beams are retrofitted and here we can see that the beam dimensions are different and the researchers have also used different surface condition, the surface preparation were also different. So, to find out the effect of bonding condition, these experiments have been carried out because in many cases it is the debonding that occurs and that is a cause of failure. So, to investigate that, these experiments have been carried out.

(Refer Slide Time: 21:25)



And the surface preparation that has been used in this experiment is sanding and sand-blasting and another is for control beam there is no surface preparation. The beam condition also was different one is virgin or not loaded at all. And another set of beams were pre-cracked that means the beams were already loaded and there are some cracks on the beams and those beams were retrofitted and the responses were observed.

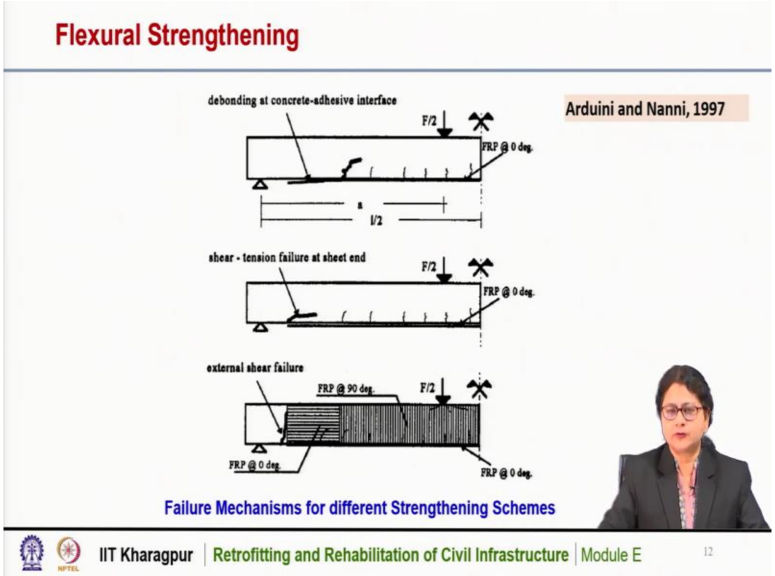
The CFRP was used as external reinforcement and both 1 ply and 2 ply reinforcements were used. The properties of the CFRP are given here in this table we can see here the three different types of CFRP with different Tensile Strength, Elastic Modulus and Elongation in percentage and two different types of adhesives we are also used for attaching the CFRP to the concrete.

So, three different types of CFRP we are used, two different types of adhesives, three different types of surface preparation including the control condition and the beam condition where cracked already and un-cracked, and this is the load versus mid span deflection plots of the CFRP retrofitted beams. So, here we can see that this is the mid span deflection and this is the load and these are the different beams. So, here we can see that this is the response of the control beam and these are the response of the CFRP retrofitted beams. So, here also we can see that the CFRP retrofitted beams have higher flexural capacity or higher load carrying capacity as compared to the control beam.

So, as the number of plies increases, that means, the amount of CFRP reinforcement increases, higher is the load carrying capacity. So, this also shows that, with improvement or with increase in the amount of reinforcement external reinforcement the flexural capacity increases. The surface preparation also shows that when the surface is sand-blasting.

There is an improvement in the load carrying capacity as compared to the control specimen. And in case of pre-cracked on unloaded beams, there is not much difference, that means the pre-cracked beam also showed significant improvement in the load carrying capacity. So, that shows that this is an effective technique by which we can improve the performance of a cracked beam also. So, these are the responses that show, that there is a significant improvement in the load carrying capacity of the members which are retrofitted with CFRP composite.

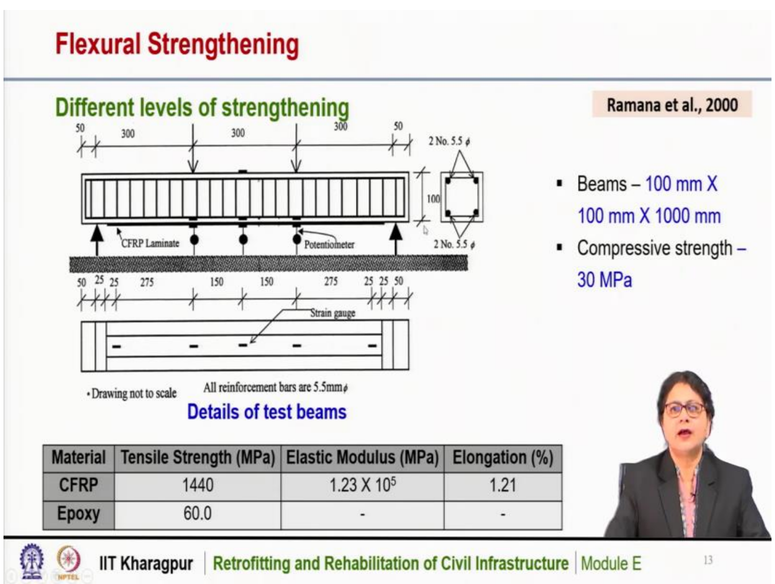
(Refer Slide Time: 24:49)



These are the schematic diagrams of the failure mode, here also there may be debonding with formation of cracks we can see here there may be flexure shear cracks on the member and because of more number of cracks, there may be debonding at the concrete adhesive interface. So, when the bond strain exceeds the limiting value, there is a debonding and with more number of cracks debonding may occur. So, this is a, flexure shear cracks that is formed near the support and there is a failure at this end. And here also the FRPs are oriented one is 90 degree to the length of the member and another is 0 degree to the length of the member and this is the formation of shear cracks.

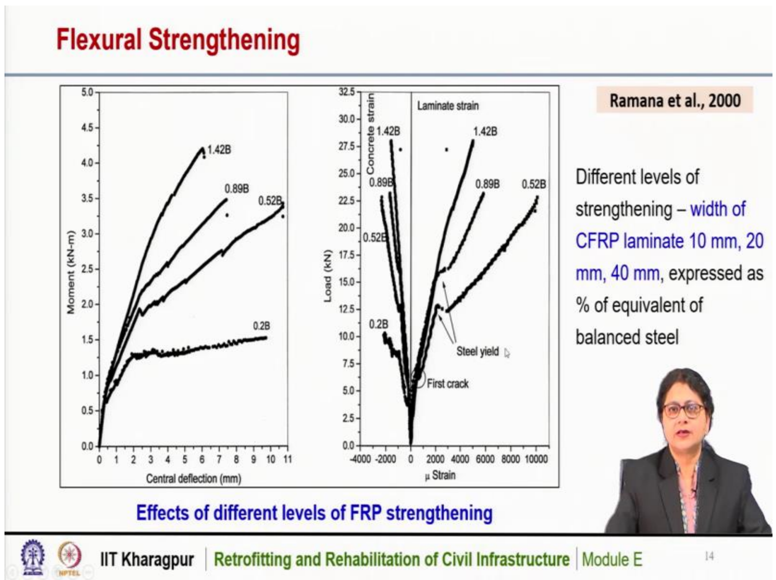
So, there may be debonding at this end. So, this is the schematic diagram of the failure mechanism of different strengthening schemes. So, it shows that in many cases, there may be debonding type of failure, that means, the FRP and the concrete may lose its contact and the failure is at the concrete adhesive interface or they are may be rupture of FRP or they are may be concrete crushing. So, here in this case it is mostly debonding type of failure that has been observed from the experiments.

(Refer Slide Time: 26:24)



Ramana et al. has performed experiments on concrete beams and the beams were 100 millimeter × 100 millimeter × 1 meter in length and the compressive strength for the concrete was 30 MPa. So, they have carried out experiments using CFRP composite and that is attached at the bottom face of the beam members. This is a simply supported beam we can see here and these are the load points, the beam is having steel reinforcement and it is given here with stirrups and the properties of CFRP and epoxy are shown here. So, these are the properties of the CFRP composite and the epoxy adhesive that is used for this purpose and they have carried out experiments to find out the behavior of FRP retrofitted members.

(Refer Slide Time: 27:29)



So, these are the responses of the FRP retrofitted beam members. Here in this, experiments the researchers have used different amount of FRP reinforcement and that has been done by varying the width of CFRP laminate, they have used different CFRP width like 10-millimeter, 20 millimeter and 40 millimeter and expressed as percentage of equivalent balanced steel area. So, it is like 0.52B, 0.89B, 1.42B et cetera. So, these are the different amount of FRP reinforcement that has been used in this case.

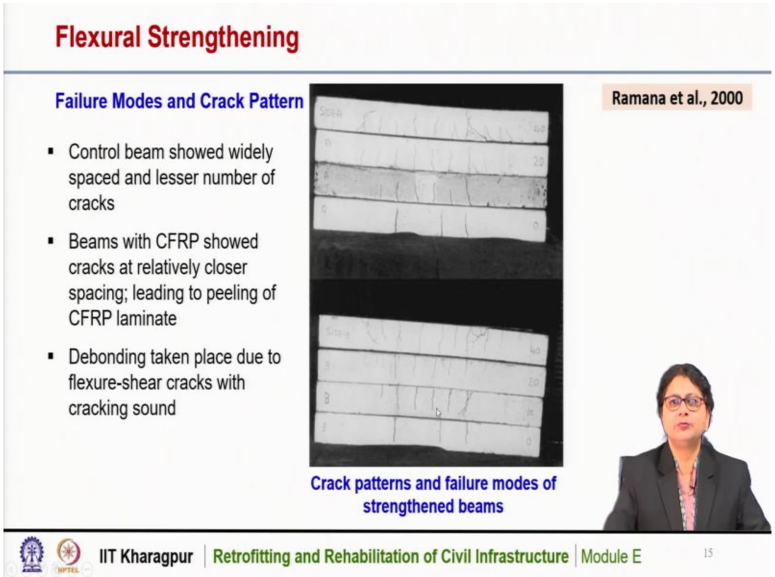
So, they have carried out experiments to understand the behavior of FRP retrofitted member having different amount of FRP reinforcement. So, this is the moment versus central deflection response of the members, this is with the least reinforcement and then the reinforcements exceeds. So, we can see here that as the amount of FRP reinforcement increases, the moment capacity of the members also increases significantly.

So, here we can see that, there is a significant improvement in the moment capacity with improvement in the amount or level of strengthening. Though the initial stiffness of the members is more or less similar, but the ultimate capacity is improved significantly. This is the plot of the load versus strain for all these members. So, we can see here this is the concrete strain is expressed here and this is the laminate strain.

And we can see here that also the strain improves with increase in the amount of strengthening, here is the point where there is yielding of steel occurs and but the member is still able to carry much higher load. So, we can see here that with increase in the amount of strengthening, there is an increase in the load carrying capacity. However, the strain at failure reduces with increase in the level of strengthening.

So, the ductility of the members actually reduces with increase in the amount of external reinforcement that has also been observed by other researchers. So, here we can see that, though there is an improvement in the load carrying capacity, but there is a reduction in the ductility if the level of reinforcement is increased.

(Refer Slide Time: 30:28)



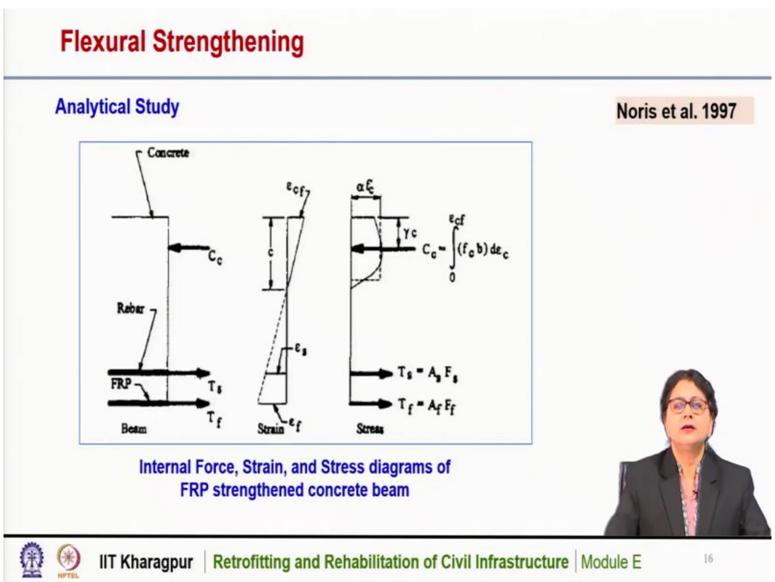
These are the Failure Modes and Crack pattern of the experiments. The control beam showed widely spaced and lesser number of cracks, here the control beam fails due to shear and other beams, which are retrofitted with CFRP those beams showed more number of cracks and at relatively closer spacing.

So, here we can clearly see that the FRP retrofitted beams, there are more cracks and those cracks are closely spaced, these closely spaced cracks lead to the peeling of the CFRP laminate or the debonding of the CFRP laminate, if there are more cracks, then they are may be debonding from the concrete stuffs to the FRP. So, that leads to peeling of the CFRP laminate. So, debonding takes place due to flexure shear cracks with cracking sound.

So, debonding has taken place in those members which are retrofitted with a CFRP. So, this shows the crack pattern and the failure modes of the FRP strengthened beams. So, these are what we have discussed some of the pioneering works in this area to understand the flexural behavior of FRP strengthened beams.

When the beams are retrofitted with FRP members and load is applied. So, the load carrying capacity improved significantly for the FRP retrofitted members, however, the ductility reduces and that has been observed from various experiments and the number of FRP layers or the stiffness of the FRP also influences significantly the performance of the FRP retrofitted beam members.

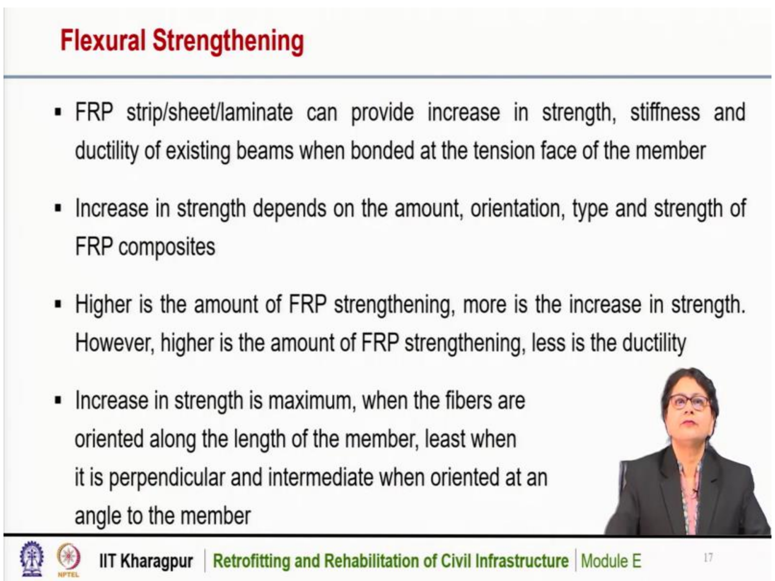
(Refer Slide Time: 32:35)



Now, analytical studies have also been carried out to estimate the capacity of the FRP retrofitted member. And here is the diagram that shows the internal force strain and stress diagrams of FRP strain then concrete beams. So, this is schematically shown as in traditional analysis also it has been mentioned.

So, here also this is the strain diagram, we can see here, this is the strain diagram and this is the stress diagram, the compressive stress is taken by the concrete and the tensile stress is taken by the steel members as well as the FRP members. So, this is the total force taken by the steel members and this is the total force taken by the FRP and that has to be balanced. So, the neutral axis depth can be obtained by iterative process and that can be estimated. So, based on this the design has been developed and that we will discuss later on which is based on the experimental works and analytical works that we will discuss in subsequent lectures.

(Refer Slide Time: 33:57)

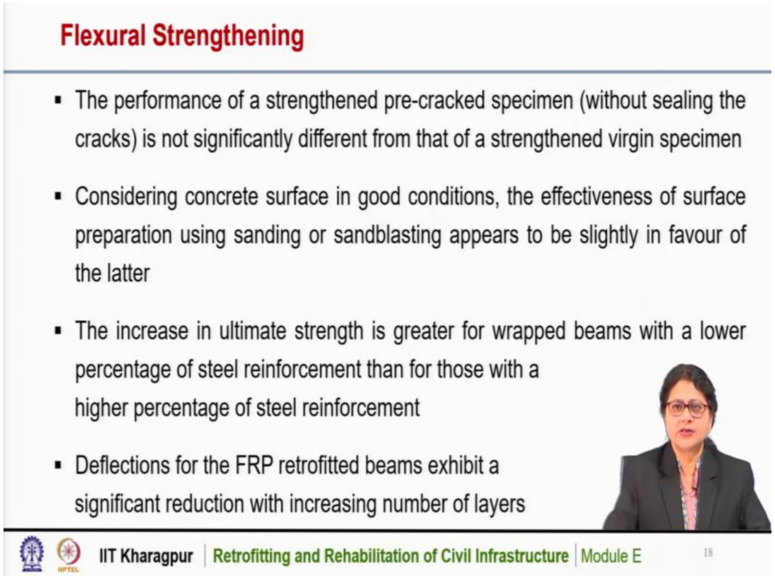


So, the major observations from various research works based on experimental works and analytical works, it has been found out on inferred that, FRP strips, sheets or laminates can improve the strength, stiffness and ductility of the existing beam members, when it is bonded at the tension face of the member. So, there is a significant improvement in the strength, stiffness and ductility of the existing members.

When FRP strips or sheets or laminates are attached at the tension face of the member. The increase in strength depends on the amount of FRP, orientation, type and strength of FRP composites. Different types orientations of fibers and different strengths of FRP composites have been investigated and it shows that there is a significant increase in strength and that depends on the amount orientation type and strength of FRP composites, higher is the amount of FRP strengthening more is the increase in strength that has been observed very clearly from the experiments. However, higher is the amount of FRP strengthening less is the ductility.

So, if the amount of FRP reinforcement is increased, there is an increase in strength, but the ductility is reduced. Increasing strength is maximum when the fibers are oriented along the length of the member and least when it is perpendicular to the length of the member and intermediate when the fibers are oriented at an angle to the member.

(Refer Slide Time: 35:46)

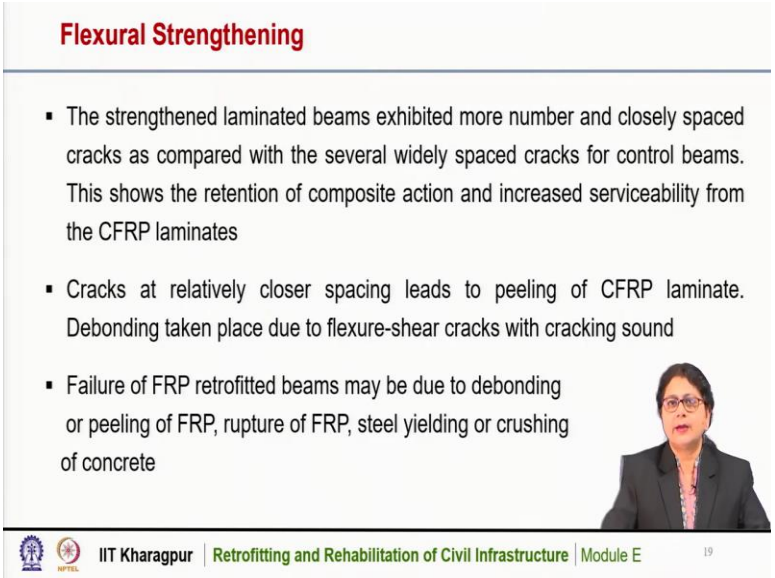


The performance of a strengthened pre-cracked specimen without sealing the crack is not significantly different from that of a strengthened virgin specimen. So, if there are minor cracks on the member that can be also retrofitted and the performance is also similar to the un-cracked specimen that has been observed from the experiments.

Considering concrete surface in good condition, the effectiveness of surface preparation using sanding or sandblasting appears to be slightly in favor of the letter. So, sandblasting can be an improved way of providing bonding. So, that can improve the performance of the FRP retrofitted member, the increase in ultimate strength is greater for wrapped beams with a lower percentage of steel reinforcement than for those with a higher percentage of steel reinforcement.

If there is steel reinforcement and the steel reinforcement is of lower area then the improvement is much better as compared to the member which is having high percentage of steel reinforcement. Deflection for the FRP retrofitted beams exhibit a significant reduction with increase in the number of layers that has been also observed from the load deflection plots.

(Refer Slide Time: 37:04)



The strengthened laminated beams exhibited more number and closely spaced cracks as compared with the several widely spaced cracks for control beams. That has been seen from the experiments that there is a difference in the failure modes of the control beam and they FRP retrofitted beams.

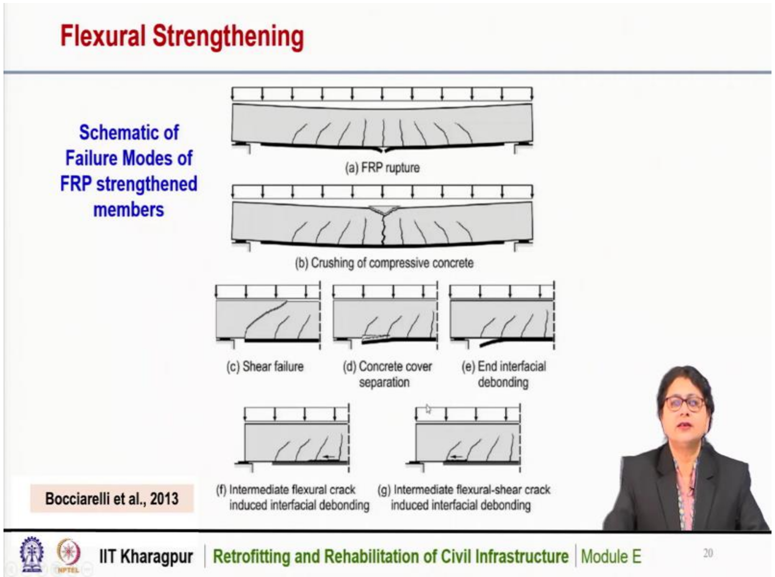
The FRP retrofitted beams, there are more number of cracks, they are closely spaced as compared to the control beam that has less number of cracks and widely spaced cracks. This shows the retention of the composite action and increased serviceability from the CFRP laminates because the FRP retrofitted beams now behaves as a one member.

So, that shows its composite action, cracks at relatively closer spacing leads to peeling of CFRP laminate. And debonding takes place due to flexure-shear cracks with cracking sound. That has been observed that if the cracks are closely spaced, and particularly this is for the CFRP retrofitted members or any FRP retrofitted members, and with close spacing of cracks, there is debonding that is taking place.

Debonding or peeling of the FRP that is taking place and that is due to the formation of more number of flexure-shear cracks. The failure of FRP retrofitted beams may be due to debonding or peeling of FRP, rupture of FRP, steel yielding or crushing of concrete that has been observed and these are important considerations and particularly, that has to be taken into consideration while designing the FRP retrofitted members.

So, when there is debonding and that debonding may lead to the failure of the FRP retrofitted member and because of the debonding, there may be the failure. Failure may be also due to rupture of FRP when the FRP strain exceeds its limiting strength, then there may be a rupture of FRP, the reinforcing steel may yield and that may also cause some failure of the members and crashing of concrete due to compression. So, that may lead to failure of the FRP retrofitted members.

(Refer Slide Time: 39:24)



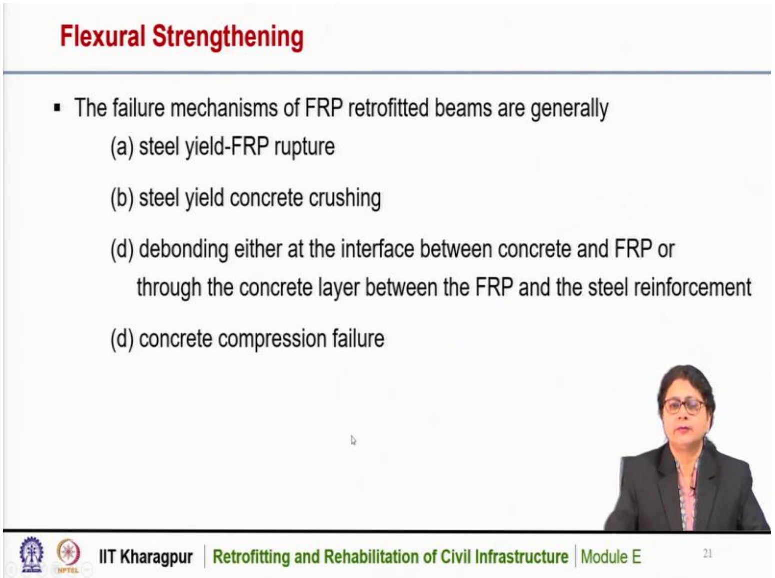
So, these are the schematic failure modes of FRP retrofitted members, we can see here that this is an FRP retrofitted beam, this is the FRP and it is under loading. So, with increase in loading, the FRP may rupture that means, the strain in FRP exceeds its limiting strain. So, there may be a rupture at the FRP at this most strain stress location.

So, there may be a rupture of FRP that may lead to failure of the member there may be crushing of the compressive concrete. So, this portion is under compression. So, if the concrete fails here due to crushing that may lead to the failure of the members are crashing of the concrete that may lead to failure of the member there may be shear failure you can see here the FRP is attached here.

And these are the typical shear cracks that may lead to failure of the member concrete cover the separation as you can see here, there is a delamination type of thing and with more number of cracks on the member there may be delamination of the FRP from the concrete substrate. So, this is also an interfacial debonding that occurs this is the debonding that occurs due to formation of cracks on the member. This is intermediate flexural crack induced interfacial debonding.

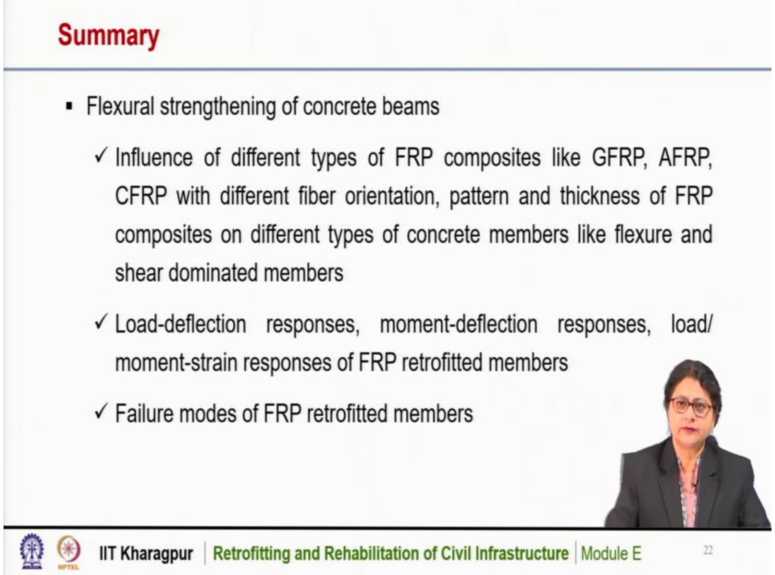
So, this is also debonding and this is also intermediate flexure shear cracks that may form that induce interfacial debonding of the FRP members. So, all these may cause failure of the FRP retrofitted member. So, these are the typical failure modes, that has been observed from the different experimental research that we have discussed. Some of them there are several research in this area to understand the complex behavior of FRP retrofitted flexural members.

(Refer Slide Time: 41:34)



So, the failure mechanism of FRP retrofitted beams are generally can be mentioned as steel yield then FRP ruptures, steel yield concrete crushing, debonding either at the interface between concrete and FRP or through the concrete layer between the FRP and the steel reinforcement or delamination or there may be concrete compression failure. So, all these may lead to failure of the FRP retrofitted beams.

(Refer Slide Time: 42:04)

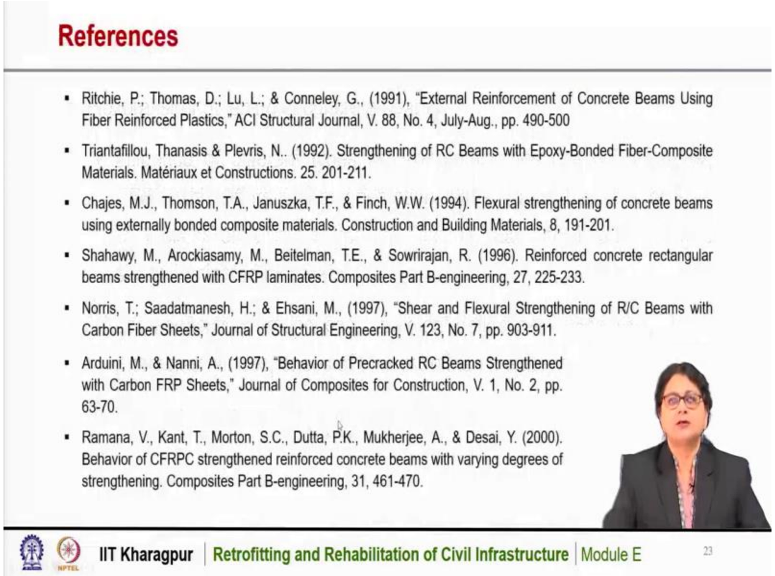


So, to summarize, we have discussed the flexural strengthening of concrete beams and the influence of different parameters like the different types of FRP composites like GFRP, AFRP CFRP, with different fiber orientation the fiber orientation may be 0 degree 90 degree or maybe a combination of 0 and 90 or maybe plus minus 45 degree et cetera.

Or there may be different pattern of FRP there may be entire length or there may be at some length near the support or maybe only at the bottom or maybe in the U-shape it. So, there will be different patterns and that may influence the performance, there are different thickness of FRP that also influenced the performance of FRP retrofitted member, different thickness means different amount of strengthening.

And different types of concrete members also behave differently like flexure dominated member or shear dominated member behave differently and the responses also are different. So, the responses have been discussed in terms of load displacement response or moment displacement response or load moment or versus strain responses of FRP retrofitted members. And we have also discussed, what are the different failure modes of FRP, retrofitted flexural members.

(Refer Slide Time: 43:33)



These are the references for this lecture. Thank you.