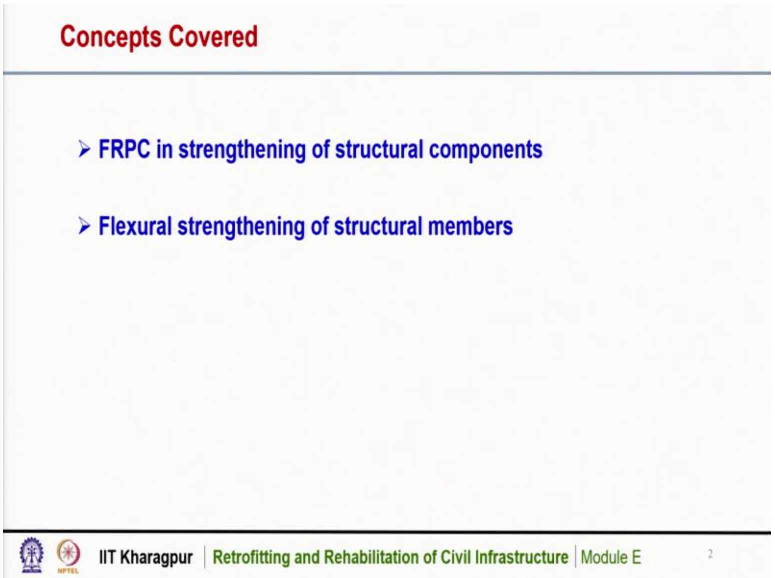
Retrofitting and Rehabilitation of Civil Infrastructure
Professor Swati Maitra
Ranbir and Chitra Gupta School of Infrastructure Design and Management
Indian Institute of Technology Kharagpur
Lecture 23
FRPC in Flexural Strengthening of Structural Members - I

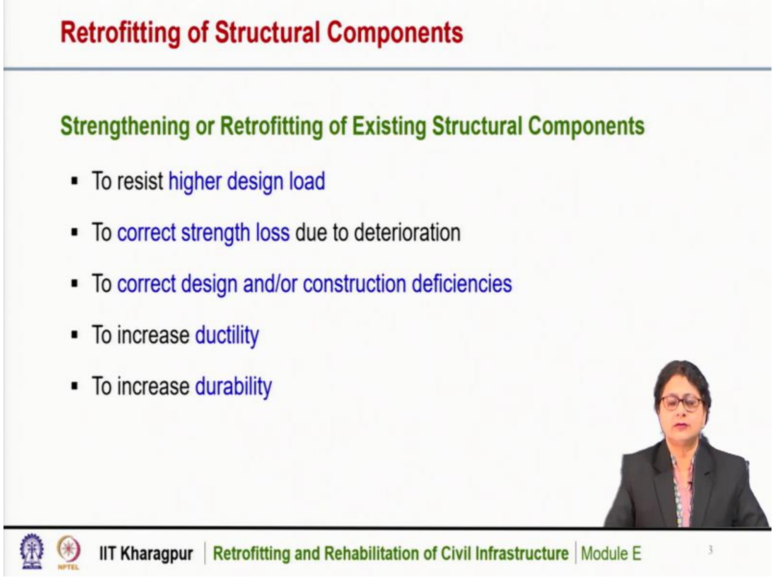
Hello friends, welcome to the NPTEL online certification course retrofitting and rehabilitation of civil infrastructure. Today we will discuss module E, the topic for module E is retrofitting using fibre reinforced polymer composites.

(Refer Slide Time: 00:45)



The topic that will be covered today are fibre reinforced polymer composites, in strengthening of structural components and flexural strengthening of structural components using fibre reinforced polymer composites.

(Refer Slide Time: 01:01)



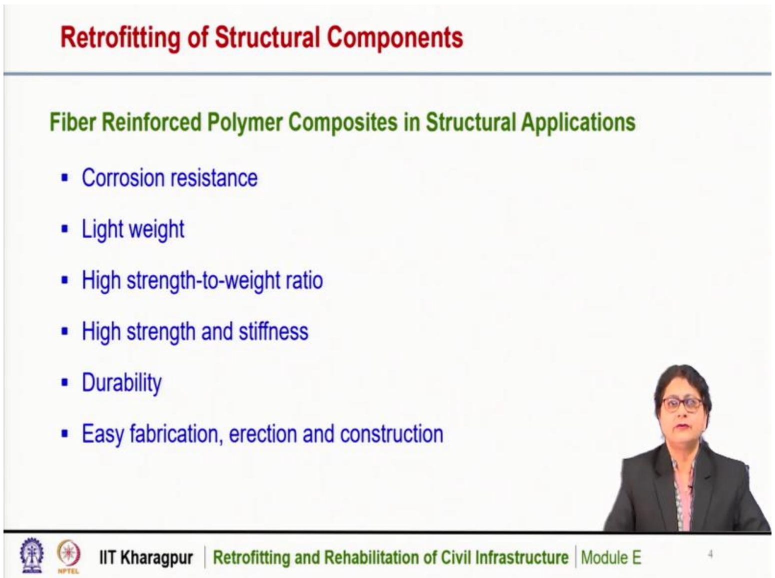
Strengthening or retrofitting of existing structural members are important considerations for infrastructure development. We have discussed earlier that retrofitting and rehabilitation of existing structures are important to improve their service life and performance. So, retrofitting of existing structural members are aimed to resist higher design load. A structure which is performing for several years may be subjected to a higher load and to take care of that higher load, we can retrofit an existing structure to correct the strength loss due to deterioration.

The deterioration of an existing structure may be due to several reasons; due to material degradation, due to weathering actions, due to climatic variations and that may result into loss of strength and performance. So, to correct the strength loss, we can retrofit an existing structure to correct the design or construction deficiencies. The deterioration may be due to some design related issues or construction deficiencies.

So, to correct those deficiencies, we can strengthen an existing structure to improve the ductility of the structural members. Structure may have high strength, but the ductility may be lower. So, to improve its ductility, we can strengthen an existing structural member. And to increase the overall durability of the member or the structure we can carry out strengthening or retrofitting an existing structure.

So, to improve the durability, service life of an existing structure, we can strengthen an existing structure. So, these are the major aims of retrofitting and rehabilitation of existing structures to resist higher design load to correct the strength loss due to deterioration and that deterioration may be due to design or construction deficiencies or due to material degradation or due to weathering actions and improve the ductility and overall durability of the structure. The strengthening or retrofitting of an existing structure can be done.

((Refer Slide Time: 03:26)



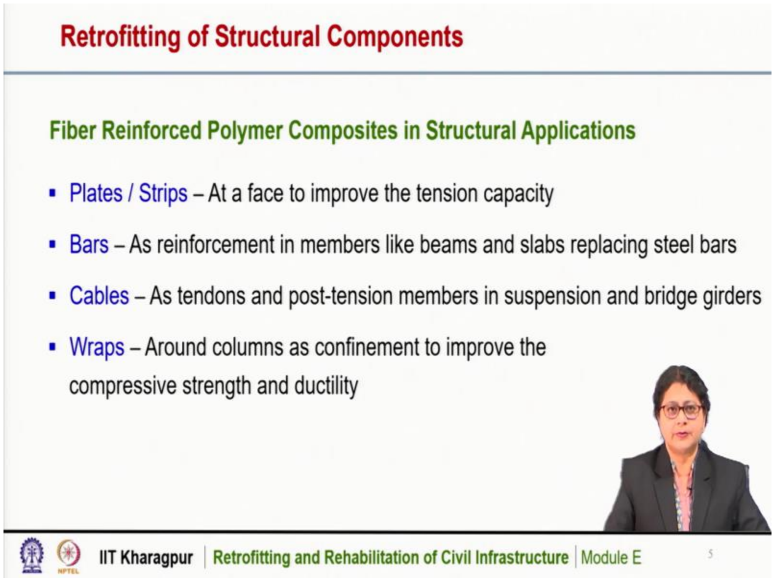
Fibre reinforced polymer composites have several applications in different fields. We have discussed earlier that it is used in marine industry, it is used widely in aerospace industries, in building aerospace structures, in automobile industry, in various manufacturing of sports goods and also in a civil infrastructure.

Fibre reinforced polymer composites has several structural applications mainly due to its several advantages like corrosion resistance. The material is a non-metallic. So, it is highly corrosion resistance. So, in civil structures, one of the major problems is the corrosion of steel reinforcement. FRPC being a non-metallic material, it is highly corrosion resistant. So, that is why it is used in structural applications.

It has high strength and stiffness and at the same time it is lightweight. So, it has high strength to weight ratio. So, this is also another big advantage of using FRPC in civil infrastructure. The material is durable. All FRPCs are generally not susceptible to weathering actions or climate variation. So, they are much durable than other materials.

So, durability is also another advantage of FRPC and the material is easily transportable because it is lightweight, available in roles. So, fabrication and erection of the material at site is quite easy. So, in construction purpose, when we want to use FRPC, it is very easy to use this type of materials. So, because of these advantages fibre reinforced polymer composite is used in structural applications, and particularly in retrofitting of existing structures.

(Refer Slide Time: 05:37)

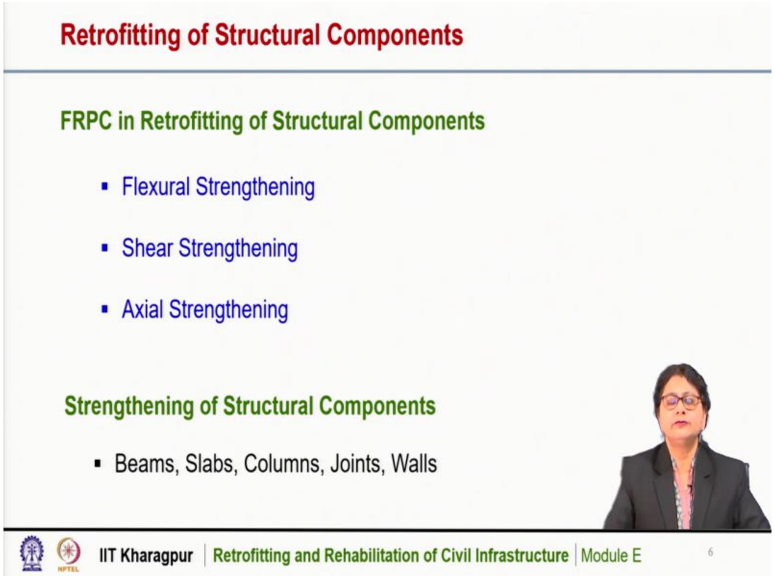


In structural applications there are various ways by which we can use FRPC. It can be used as plates or strips at a face to improve the tension capacity of the members. A thin plate or strip is available and that plate or strip can be attached at the tension phase of a member to improve its tensile capacity.

It can be used as bars, FRPC bars can be used as reinforcement, and that can be used in structural members like beams or slabs and that can replace the conventional steel bars. It can be used as cables, which can be used as tendons and post tension members in suspension and bridge girders. Or it can be used as it wraps around columns or other members as confinement to improve the compressive strength and ductility of the member.

So, FRPC can be used in various structural applications as plates or strips, or as wraps, or as bars, or as cables to improve their tension capacity of those members. We can use FRPC as in the form of plates, trips, bars, cables or wraps.

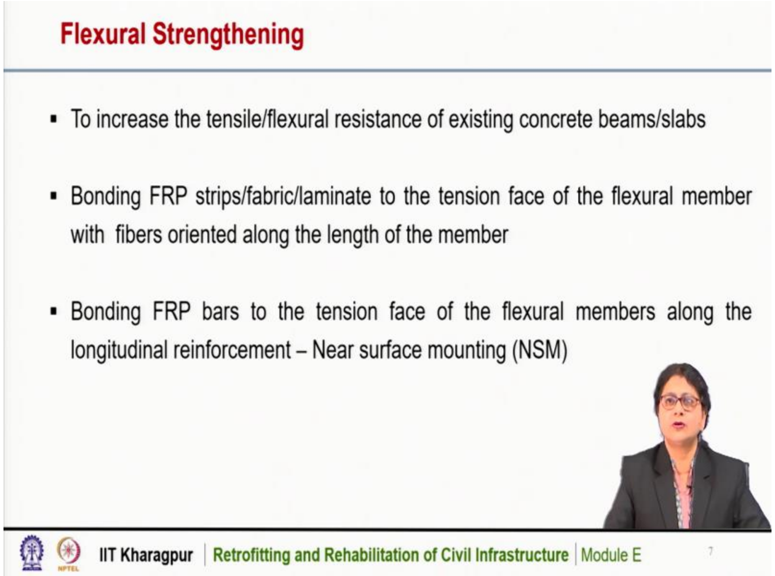
(Refer Slide Time: 07:08)



FRPC is used widely in recent years in the retrofitting of existing structural components. To improve the flexural capacity of the members, we can use, FRPC strips or plates or wraps. We can use FRPC in improving the shear capacity of the members and also to improve the axial capacity of the members.

So, to improve the flexural capacities, shear capacity and actual capacity, FRPC is used widely in structural members. And the structural components which are used for this purpose are beams, slabs, columns, joints or walls. So, these members can be strengthened using FRPC strips or wraps and the tensile capacity or the shear capacity or the axial capacity can be improved significantly.

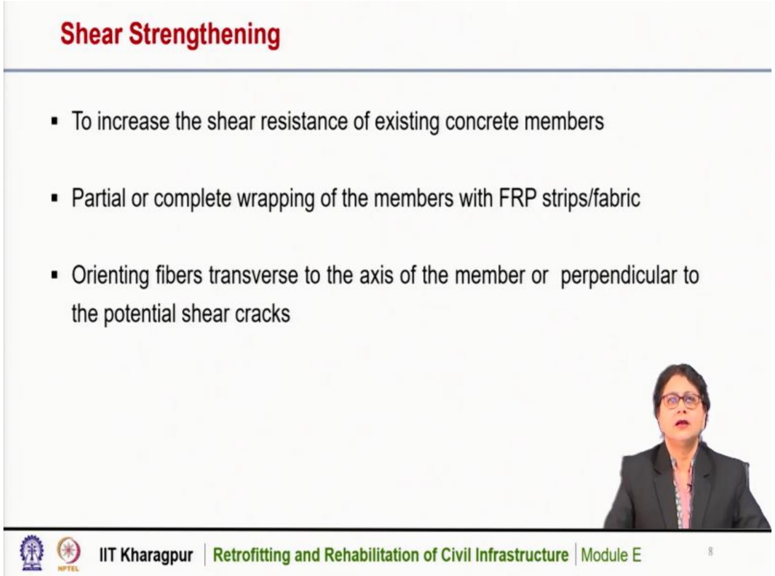
(Refer Slide Time: 08:11)



In flexural strengthening it is aimed to increase the tensile or flexural resistance of existing concrete beams or slabs. In flexural strengthening, FRP strips or plates or fabrics or laminate is bonded to the tension phase of the flexural member. And in that, composite, the fibres are generally oriented along the length of the member.

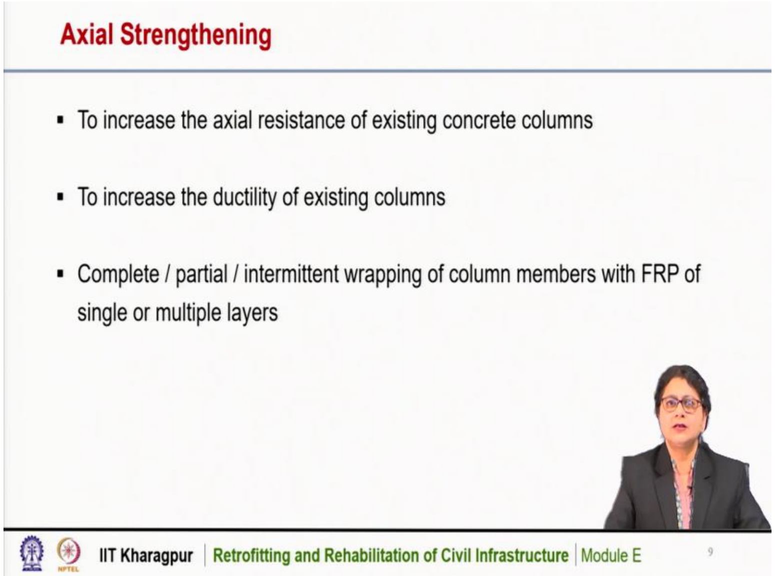
The bonding of the FRP bars can also be done on the tension phase of the flexural members along the longitudinal reinforcement to improve the tensile capacity of existing members and it is termed as near surface mounting. In near surface mounting, we can improve the tensile capacity of the existing member by bonding FRP bars to the tension face of the member or for the existing beams, we can bond the FRP strips or laminate or fabrics to the tension face of the member to improve its flexural capacity. So, in flexural strengthening the aim is to improve the overall tensile or flexural capacity of the existing members.

(Refer Slide Time: 09:45)



In case of shear strengthening, it is aimed to increase the shear resistance of the existing concrete members. In this case, the FRP strips or fabric is wrapped partially or full wrapping around the members to improve its shear capacity. The fibres are generally oriented, transverse to the axis of the member or perpendicular to the potential shear cracks. So, in case of shear strengthening it is aimed to increase the shear resistance of the existing concrete members using FRP strips or fabric.

(Refer Slide Time: 10:33)



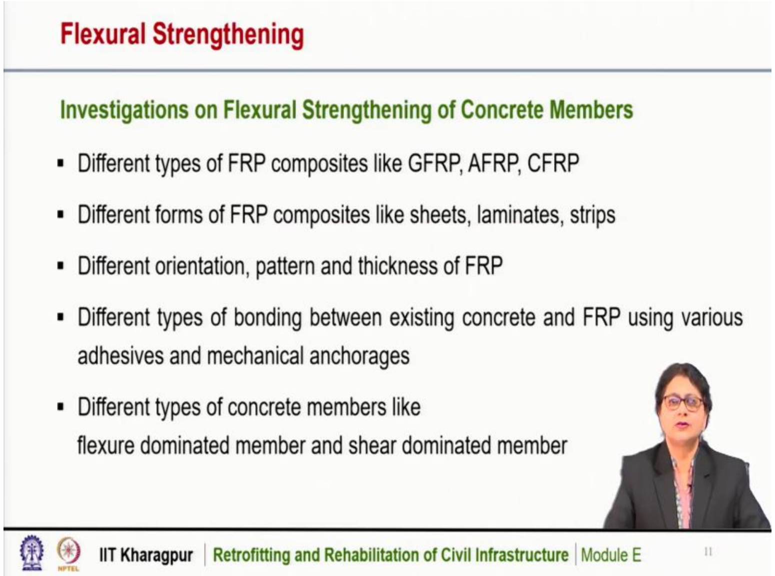
In case of axial strengthening using FRP composites, it is aimed to increase the axial resistance of existing concrete columns. It is also aimed to improve the ductility of the existing columns using FRP straps. And in this case, the FRP strips or wraps are used by partial or intermittent wrapping or complete wrapping around the member.

So, FRP strips or wraps are used around the member either intermittently or complete wrapping around the member. So, it is aimed to improve the overall axial resistance and the ductility of the existing columns and for that, we can wrap the FRP strips around the column either partially or completely.

(Refer Slide Time: 11:39)

Now, we will discuss in detail about the flexural strengthening of existing members.

(Refer Slide Time: 11:46)



Flexural strengthening of existing members using fibre reinforced polymer composites has gained interest in the research community and there are several research works have been done on this. Fibre reinforced polymer composite is comparatively a new material. So, the behaviour of FRP strengthened members is also different as compared to the steel reinforced or steel plate retrofitted existing members.

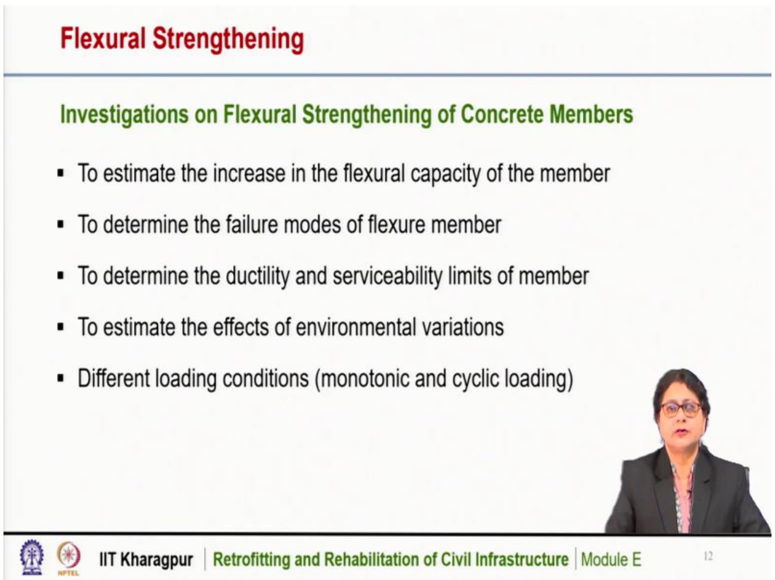
So, several investigations have been done by researchers on flexural strengthening of concrete members and different parameters have also been considered in the research. Researchers have used different types of FRP composites like glass fibre reinforced polymer composite, aramid fibre reinforced polymer composite or carbon fibre reinforced polymer composites, in retrofitting of existing members to improve its flexural capacity.

Different forms of FRP composites have also been used. Researchers have used FRP sheets or FRP laminates, strips, wraps etcetera for improving the flexural capacity, the fibres may be oriented at different direction and that has also been investigated. The fibres may be oriented along the length of the member or perpendicular to it or maybe at some angle.

So, the orientation of the fibres, the pattern of the wrapping scheme or the thickness of the FRP has also been considered while determining the behaviour of flexural members, strengthened with if FRPC. Different types of bonding between existing concrete and FRP using various adhesives and mechanical anchorages have also been studied.

And different types of concrete members have also been studied like flexural dominated member and shear dominated member and with those different types of FRP's are used. So, to improve the flexural capacity of the existing members, different research works have been done and these are based on different types of FRP, different forms of FRP, different fibre orientation, different pattern of FRP, placement and different types of concrete members like flexure dominated member or shear dominated member have been considered in the investigation.

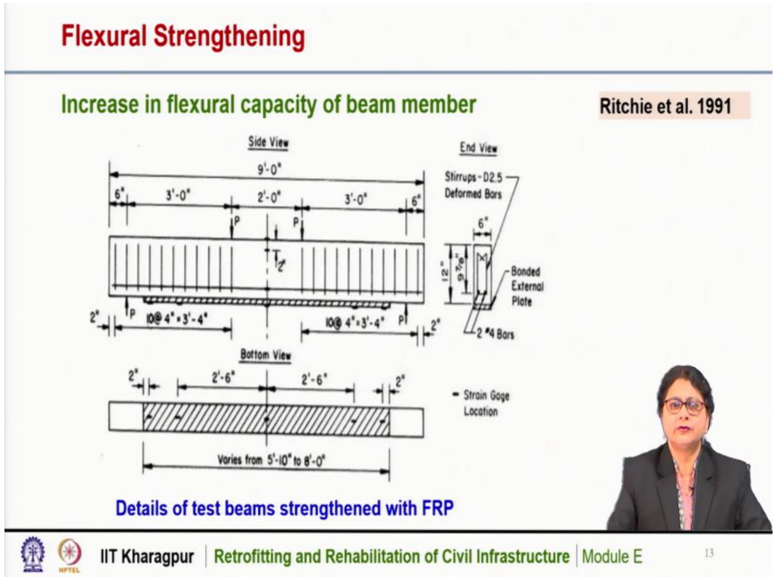
(Refer Slide Time: 14:41)



Investigations have been carried out on FRP retrofitted concrete members to estimate the increase in the flexural capacity of the member, to determine the failure modes of flexural members because the failure modes are different from the members retrofitted with steel plates or steel members, to determine the ductility and serviceability limits of members, to determine the effects of environmental variations and different loading conditions have also been considered like monotonic or cyclic loading. Because the structure may be subjected to different types of loading.

So, all these things have been considered while investigating the behaviour of the FRP retrofitted members. So, to investigate the flexural strengthening of existing concrete members, which are retrofitted by FRP strips or plates or laminates, several research works have been carried out to estimate the increase in the flexural capacity of the member to understand the load displacement response to determine how the members fail due to increase in load and how much is the ductility improvement or serviceability limit etcetera. Several works have been carried out.

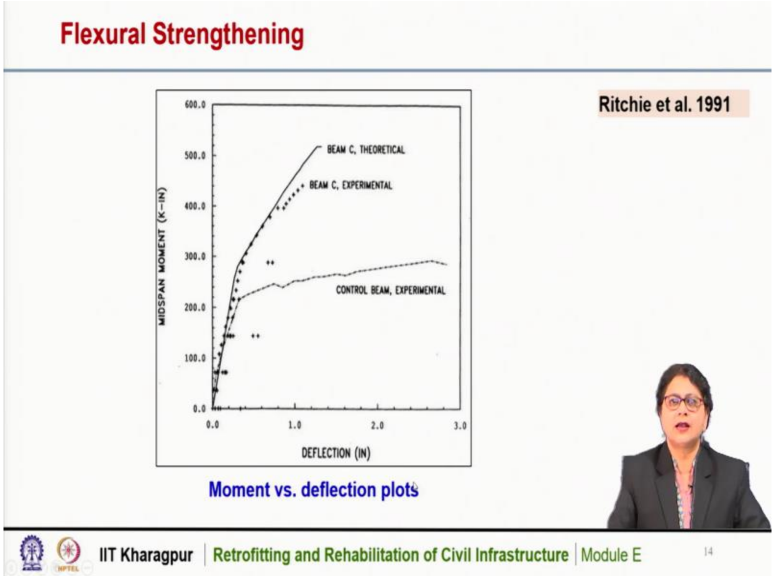
(Refer Slide Time: 16:12)



This is a picture of some experimental work carried out by researchers Ritchie et al. and in this work, the researchers have investigated the behaviour of FRP retrofitted flexural members. So, this is a reinforced concrete beam member with reinforcement at its bottom and these are the shear reinforcement.

Now, we want to improve its flexural capacity and that has been done by attaching a FRP strip at the tension face of this member. So, in this experiment, the researchers have put some FRP strips at the bottom of the simply supported beam, at the tension face of the beam to see the improvement in the flexural capacity. The beam dimensions are also shown here.

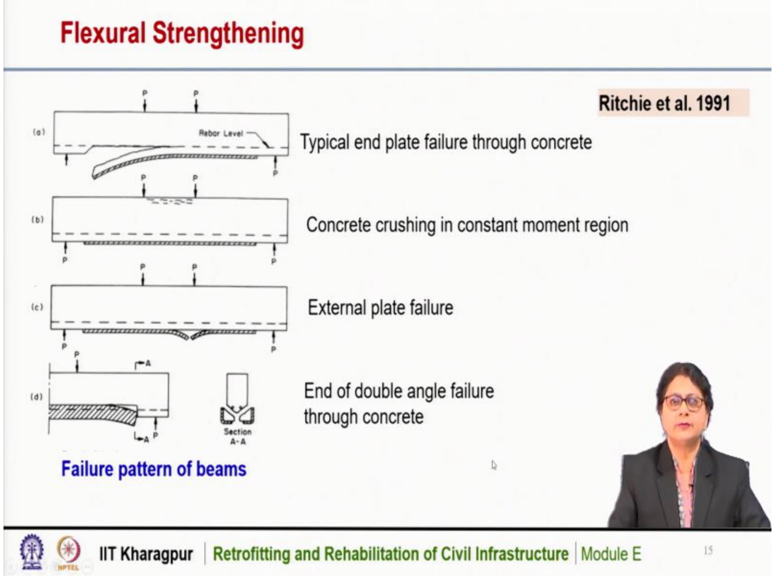
(Refer Slide Time: 17:18)



This is the response of the moment versus deflection plots as obtained from the experiment carried out by this Ritchie et al. Here the two plots are shown one is the control beam and one is the retrofitted beam. The control beam is the beam which has no FRP at its tension face. So, it is the conventional beam with steel reinforcement and this is the response of the beam which is retrofitted with FRP composite.

So, it has been seen that there is a significant improvement in the midspan moment for the FRP retrofitted beam. The control beam has much lower moment capacity, which is without FRP, whereas the FRP retrofitted beam has significantly high moment capacity as compared to the control beam. So, this shows the improvement in the flexural capacity of the FRP retrofitted member.

(Refer Slide Time: 18:31)



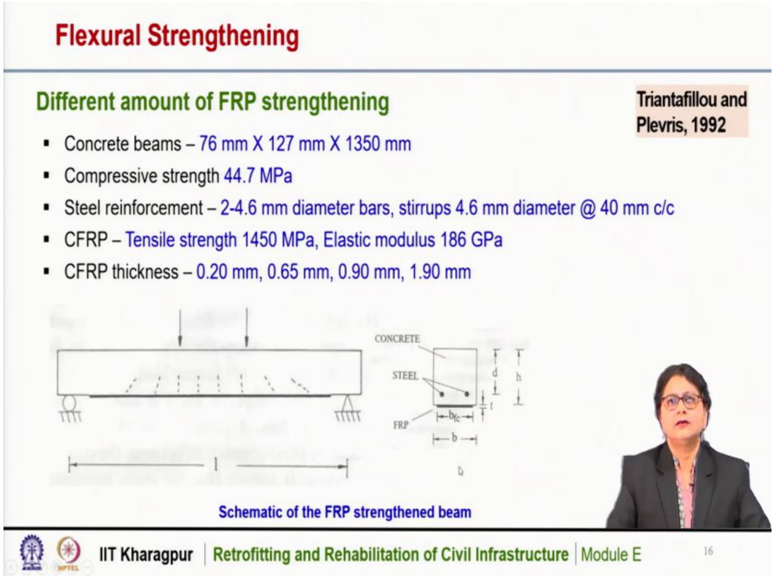
These are the failure pattern of the beams which are retrofitted with FRP composite. These are the schematic diagrams as obtained from the experiments by Richie et al. Here, this is the simply supported beam and these are the lines for reinforcement and this is the FRP which is attached at the bottom of the member.

Now, with increase in load, the capacity increases. However, with further increase in load, the beam may fail and in this case the failure may be due to the typical end plate failure through concrete. So, here we can see that this is the failure of the beam. So, the here at this point there is a delamination of the member here at this point.

The failure may be also due to crashing of concrete at this location. Because this is the location where there is compressive stress. So, concrete may crash at this location in the constant moment region we can see here, if the FRP is strong enough, then it may not fail or it may not delaminate or debond and concrete may crash at these locations. There may be another type of failure this is external plate failure; we can see here that the FRP strip may fail at this point.

So, here it may fail due to rupture of the FRP, that means, the FRP may break due to high tensile strength and there may be a rupture of the FRP or there may be end of double angle failure through concrete. So, here also there may be some debonding type of failure of the FRP. So, there may be different types of failure of the FRP retrofitted beams and that can be schematically shown here as bar Ritchie et al.

(Refer Slide Time: 20:59)



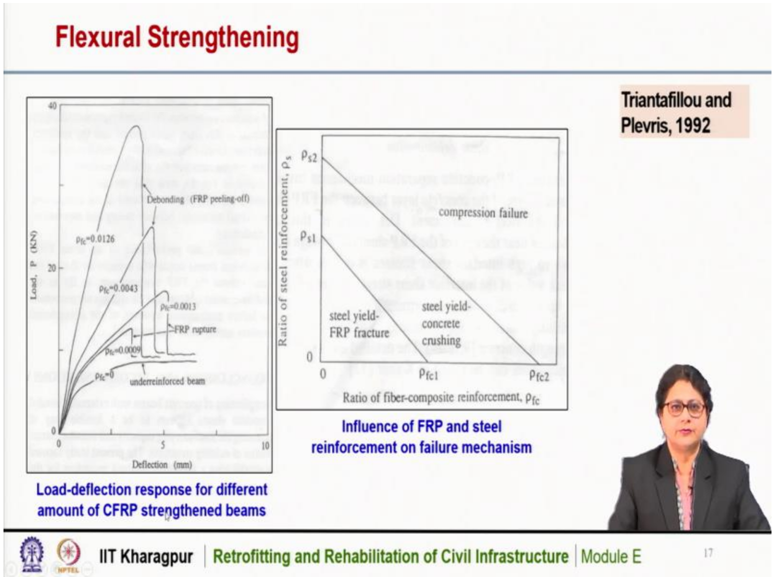
To understand the behaviour of FRP retrofitted flexural members, several researchers have carried out a number of experiments. So, here we are showing some of those experimental results which are pioneering works in this area. And based on their works, the behaviour of FRP retrofitted members can be understood and with that, further research has been carried out to understand the complicated effects that we will discuss in subsequent lectures.

So, here in this research works by Triantafillou and Plevris. The researchers have investigated and performed experiments on concrete beams. The size of the concrete beam is 76 mm × 127 mm depth and 1.35 metres in length. The compressive strength of concrete is given us 44.7 MPa.

The beam has steel reinforcement, 2 bars are there at the bottom and stirrups are there as mentioned here. And to improve the flexural capacity of this beam, CFRP or carbon fibre reinforced polymer composite has been used. The properties of CFRP are given here, the tensile strength the elastic modulus along the length of the fibre are given and the researchers have used different types of CFRP with varied thickness. The CFRP properties that means, the strength and elastic modulus are the same for all members, but the thickness may vary.

So, the 4 different types of CFRP thickness have been considered 0.2-millimetre, 0.65-millimetre, 0.9 millimetre and 1.9 millimetre. So, to understand the behaviour of FRP retrofitted beam members, experiments have been carried out with CFRP composites retrofitted at the tension face of the member and it has been attached by some epoxy material at the bottom face of the simply supported beam.

(Refer Slide Time: 23:32)



This is the load deflection response for different amount of CFRP strengthen beams. Here we can see that this is the deflection of the beams, that are plotted here and this is the load. With increase in load all the beams are carrying higher load as compared to the control beam. The control beam has no FRP reinforcement and so, the unreinforced or the control beam carries the least load and with increase in the FRP amount that can be considered by the improved or the increased thickness of the members.

So, when the beam is retrofitted with FRP, the load carrying capacity improves significantly as we can see from this load deflection plots. So, this is the plot for the control beam and these are the plots for the FRP retrofitted beam. So, the different plots are for the beams with different FRP thicknesses.

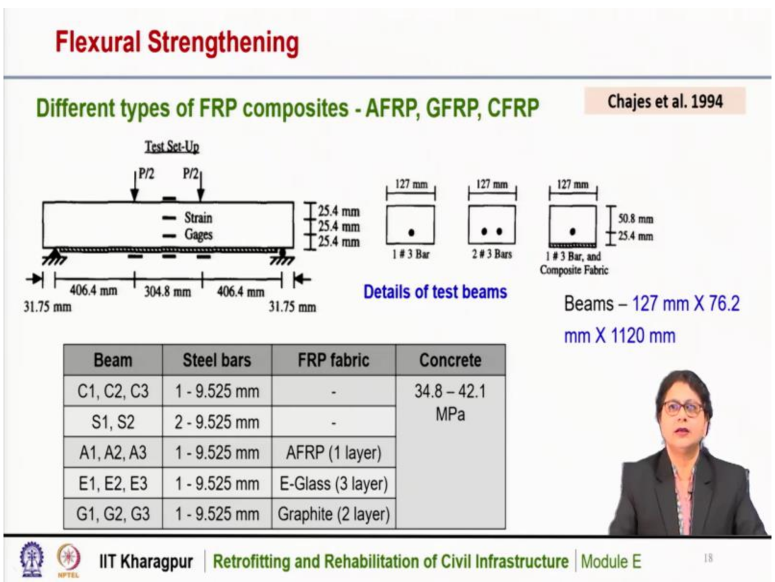
As the FRP thickness increases, the load carrying capacity of the beam also increases. So, we can see here that when the thickness is less, there is improvement in the load carrying capacity. But if the thickness of FRP is further increased, there is further increase in the load carrying capacity of the member.

And also, interestingly the mode of failure also is different. So, if the thickness of the FRP is increasing, then also the failure mode is different and the failure mode changes from concrete crushing to debonding. So, the control beam fails due to crushing or due to formation of shear cracks and with increase in the FRP reinforcement, there is FRP rupture and then there is debonding of the FRP.

Here in this plot, it is the variation of the ratio of fibre composite reinforcement with the ratio of steel reinforcement. So, here we can see that as the ratio of fibre composite reinforcement increases, and that can be identified with the improved thickness of the FRP. So, the failure mode also changes.

So, initially if the FRP reinforcement area is less that is with lesser thickness, the failure is due to FRP rupture. With increase in thickness that means, the amount of FRP reinforcement is more, then FRP ruptured to debonding and then to concrete crushing and then compression failure of the member. So, this has the variation of the influence of FRP and steel reinforcement on failure mechanism.

(Refer Slide Time: 27:07)

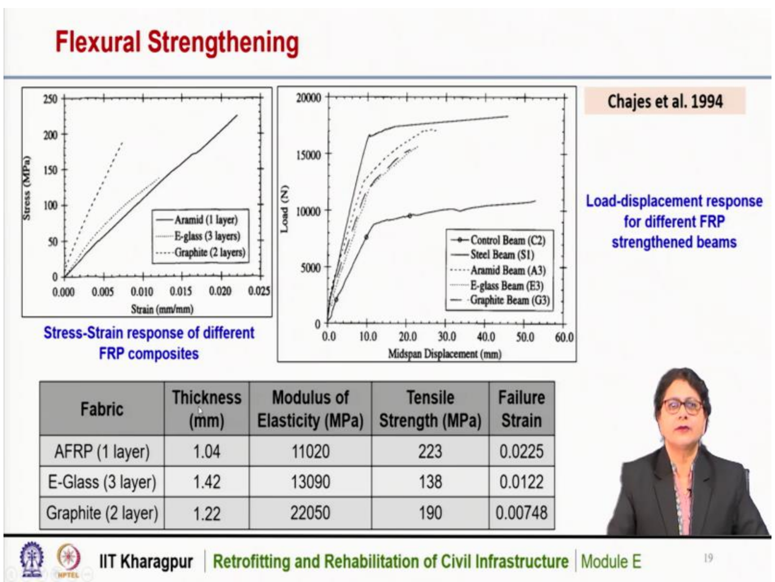


This is the result of another experimental work by researchers Chajes et al. These researchers have performed experiments on simply supported concrete beams and with different types of FRP composites. The different types of FRP composites that are used are aramid fibre reinforced polymer composite, glass fibre reinforced polymer composite and carbon fibre reinforced polymer composite.

Different beams have been tested. The dimension of beams have been given here 127 mm × 76 mm depth × 1120 mm in length and three different types of FRP composites have been used. The test beams have steel reinforcement as well. So, there are two control beams one control beam has one reinforcement, one steel bar as we can see here and the other control beam has 2 steel bars.

The FRP retrofitted beams also contain steel bars, but 1 steel rebar and the dimensions also are mentioned for the steel bars and the FRP layers are also of different thicknesses. AFRP is 1 layer. In case of another set of beam we have 3 layers of E glass fibres and in another set of beam, 2 layers of graphite fibres have been used graphite or carbon fibre reinforced polymer composites have been used.

(Refer Slide Time: 28:42)



And these are the responses. This table shows the properties of the 3 types of FRP composites, the AFRP composite and glass fibre reinforced polymer composite and the graphite fibre reinforced polymer composite, the thicknesses are given here, the modulus of elasticity, the tensile strength and the failure strains are given as mentioned by the research works by Chajes et al.

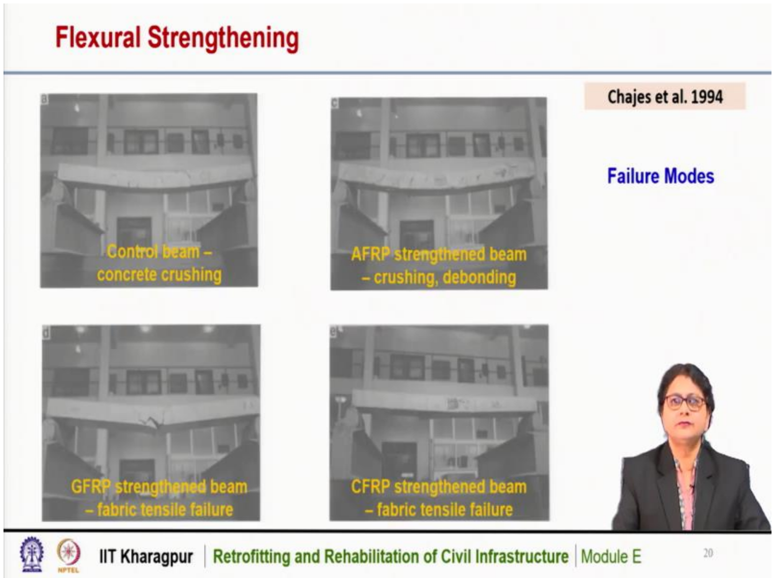
So, this is the property of the three FRP composites. We can see here that the graphite composite has the highest modulus value as expected, then the E glass fibres because it has 3 layers and aramid fibres also has this elastic modulus. And this is the stress strain response of the different FRP composites, aramid fibre composite, E glass fibre composite and graphite fibre composite.

So, this is the response of the graphite fibre composite. Next is the glass fibre and this is the aramid fibre. Now, when the beams are retrofitted with AFRP or GFRP or CFRP the flexural capacity of the members improved significantly and this is observed from this graph. So, here midspan deflection versus load is plotted and also the response of the control beam with no FRP reinforcement.

So, this is the response of the control beam and this is the control beam with one reinforcement and we can see here that these are the responses of the FRP retrofitted beams. So, we can see here that there is a significant improvement of all the beams retrofitted with AFRP, GFRP or carbon fibre reinforced polymer composites.

So, all the beams have significantly high load carrying capacity as compared to the control beam with one reinforcement. This is the response of the control beam with two reinforcements, the other control beam and these are the responses of the FRP retrofitted beams. So, we can see here that the FRP retrofitted beams have significantly high load carrying capacity as compared to the control beam. So, by attaching the FRP strips at the tension face of the member, the load carrying capacity of the member is improved significantly that can be observed from these experiments.

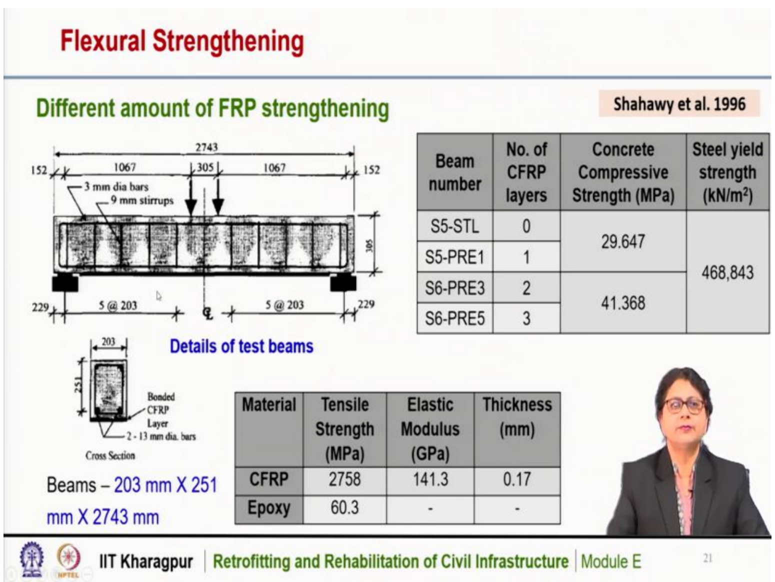
(Refer Slide Time: 31:42)



These are the failure modes of the members; we can see here that this is the failure mode of the control beam it is due to concrete crushing. So, this is the beam which is failed due to concrete crushing, this is the failure mode of the AFRP strengthen beam, it is due to debonding of the FRP strips and then by crashing of concrete.

Here is the failure mode of the GFRP strengthen beam, it is due to fabric tensile failure that means the GFRP ruptures. So, the GFRP breaks due to the tensile stress. So, this is due to the fabric tensile failure and this is the failure mode of the CFRP strengthened beam and that failure is due to fabric tensile failure. So, the rupture of the FRP strips. So, this is due to the rupture of the FRP strips the member failed. So, these are the failure modes of the experimental beams as carried out by Chajes et al.

(Refer Slide Time: 33:01)



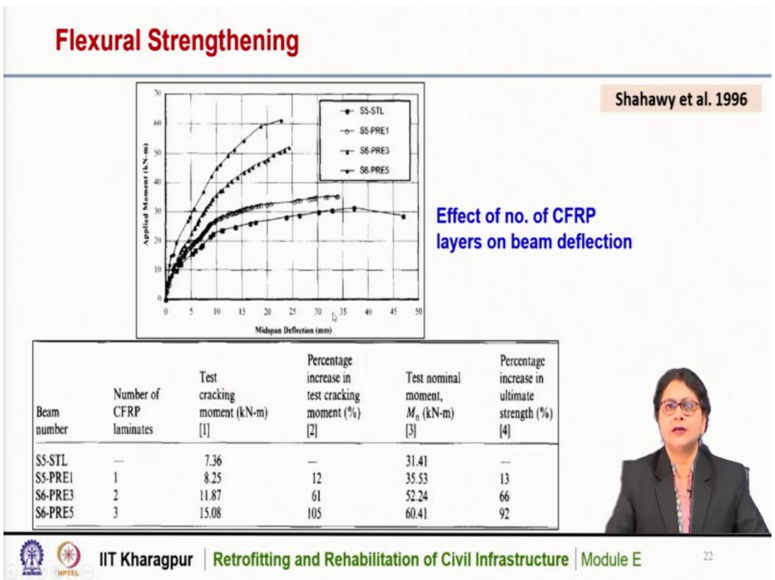
We will discuss and other experimental results as performed by Shahawy et al. Here also a number of beams have been tested. These are simply supported beam, we can see here this is a simply supported concrete beam the dimensions are given here 203 mm × 251 mm in depth and the length is quite big, it is 2.743 metre in length and it is subjected to these 2-point loading.

So, a 4-point bending test is carried out and the beam also has a reinforcement. Now, to improve its flexural capacity researchers have attached FRP strips at the tension phase of this member. So, CFRP has been used here and the properties of CFRP has been mentioned in this table.

So, the thickness of CFRP strip is very small 0.17 millimetre and that is attached here. So, here the parameter is used, different amount of FRP strengthening, that means, different layers of FRP has been used here. In the control beam there is no FRP, in 1 beam, there is only 1 layer of CFRP and another beam there is 2 layers of CFRP and in another beam there is 3 layers of CFRP, a composite as tensile reinforcement.

So, the amount of FRP reinforcement is increasing and the researchers have investigated the effect of the increasing reinforcement on the FRP retrofitted member. The concrete compressive strength is also mentioned and the steel strength is also mentioned as given by the researcher.

(Refer Slide Time: 35:02)



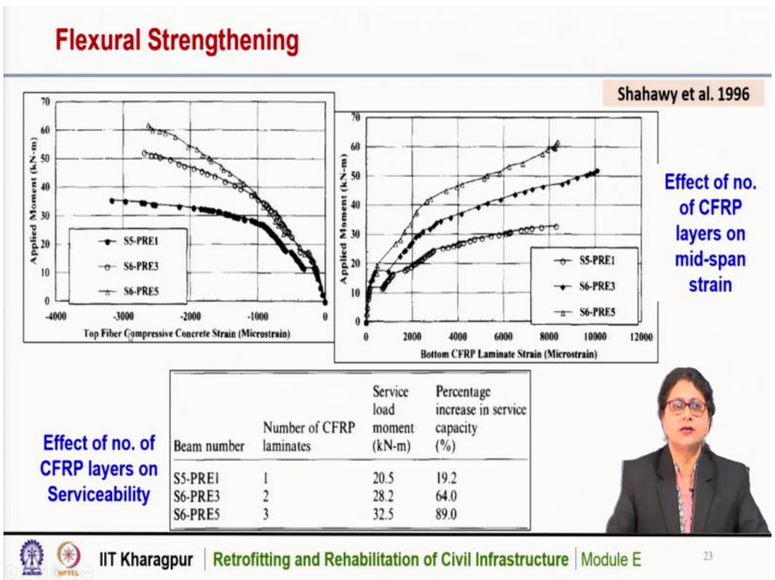
So, here, this is the applied moment versus deflection plots of the different beams. One is the control beam and the other are FRP retrofitted beams with different amount of FRP. So, in 1 case it is one layer of FRP and in another case it is 2 layers that means, the thickness is doubled and, in another case, it is 3 layers of FRP that is added.

So, to find out the effect of number of FRP layers or the amount of FRP layers on beam response, these plots have been made. So, we can see here that the least strength or the least moment capacity is for the control beam. So, this is the response of the control beam and these are the responses of the FRP retrofitted beam.

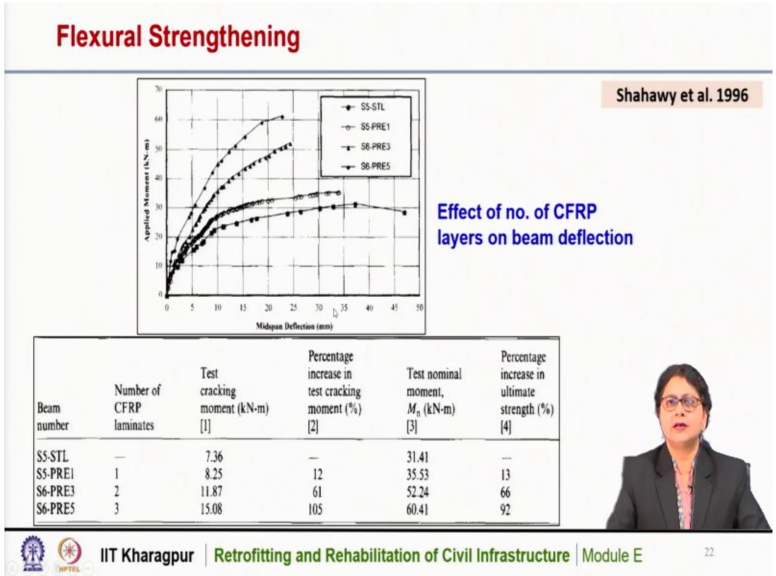
Now, as we increase the amount of reinforcement, amount of FRP thickness, the strength capacity or the applied moment capacity also is increasing. So, higher is the thickness of FRP, higher is the moment capacity of the member. So, this is very clearly seen from these experimental results and here this table shows the values of this improved moment capacity, the first cracking moment is also improved in case of FRP retrofitted members.

So, the percentage improvement, we can see here from 12 to 105 percent. The nominal moment capacity is also improved and these are the improvement in the ultimate strength. So, there is a significant improvement in the ultimate strength as we can see here from this experiment from 13 percent improvement when there is only 1 layer of FRP to 92 percent improvement when there is 3 layers of FRP. So, a significant improvement of the flexural capacity is possible, if we can attach FRP at its tensile face of the member.

(Refer Slide Time: 37:23)



Beam number	Number of CFRP laminates	Service load moment (kN-m)	Percentage increase in service capacity (%)
S5-PRE1	1	20.5	19.2
S6-PRE3	2	28.2	64.0
S6-PRE5	3	32.5	89.0



Beam number	Number of CFRP laminates	Test cracking moment (kN-m) [1]	Percentage increase in test cracking moment (%) [2]	Test nominal moment, M_n (kN-m) [3]	Percentage increase in ultimate strength (%) [4]
S5-STL	—	7.36	—	31.41	—
S5-PRE1	1	8.25	12	35.53	13
S6-PRE3	2	11.87	61	52.24	66
S6-PRE5	3	15.08	105	60.41	92

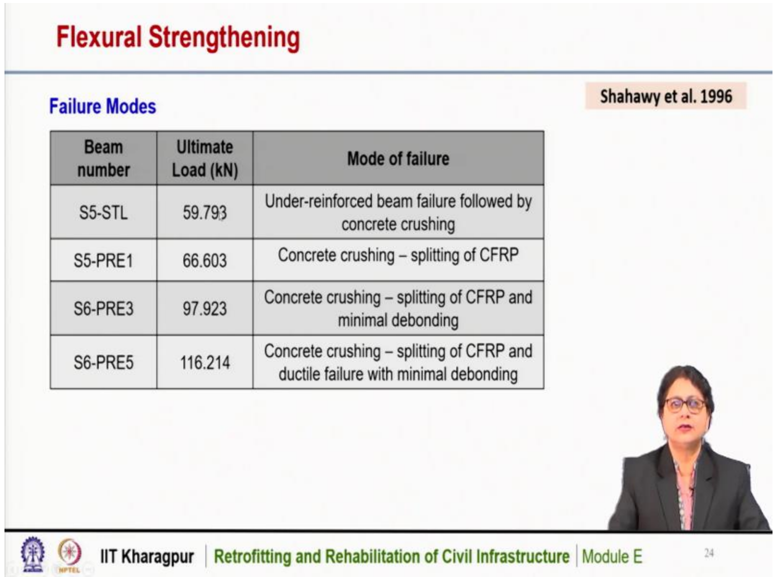
We can see here, these are the plots to find out the effect of number of CFRP layers on midspan. So, this is the strain at the top fibre of the concrete member and this is the bottom CFRP laminates strains and the strains are in micro strain. So, we can see here that as we increase the thickness of the FRP the moment capacity increases. However, the strain at failure actually decreases.

So, this shows that here in this plots, so this is the strain for the beam retrofitted with 1 layer of CFRP, this is the response of the beam with 2 layers of CFRP and this is for 3 layers of CFRP. Similarly, at the top fibre also. So, as we increase the number of layers or the amount of FRP, the strength increases or the moment capacity increases, but the strain at failure decreases.

So, it becomes less ductile, if we increase the number of layers or the amount of FRP. So, that is shown here. So, increase in strength actually reduces the ductility of the member. This table shows the effect of number of CFRP layers on serviceability, we can see here for the control beam the serviceability limit is approximately 17 as we have seen here from this plot.

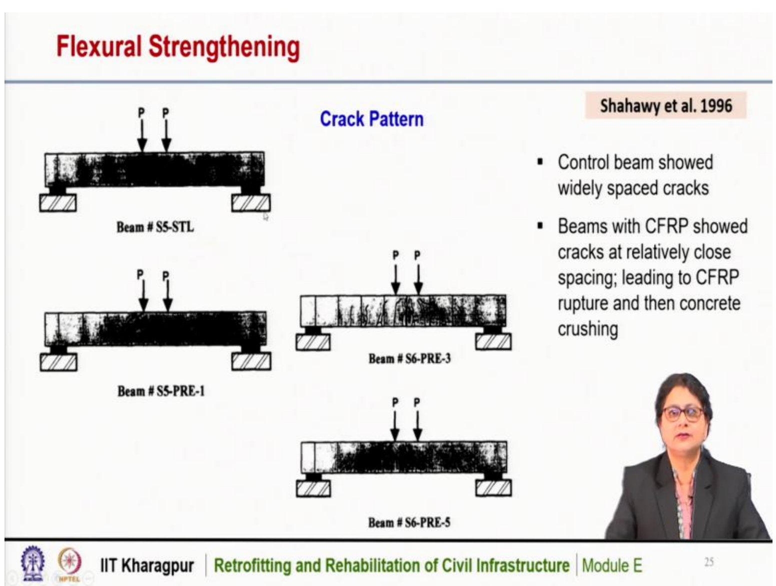
Now, with the increase in the CFRP at the bottom face of the members the serviceability limit also increases. So service load moments also increases and this is the percentage increase in the service capacity. So, here also there is a significant improvement of the serviceability of the members as the FRP is attached to the member or its thickness is improving.

(Refer Slide Time: 39:47)



The failure modes have also been noted by the researchers and it has been mentioned that these are the ultimate failure load and these are the modes of failure. The under reinforced beam, that is the control being fails due to concrete crushing, whereas the FRP retrofitted beams failed mostly due to the rupture or the splitting of the CFRP and then concrete crushing occurs. So, in the beams which are retrofitted with CFRP, the failure is mostly due to splitting of CFRP or rupture of CFRP or debonding of the CFRP from the concrete substrate and then concrete crushing.

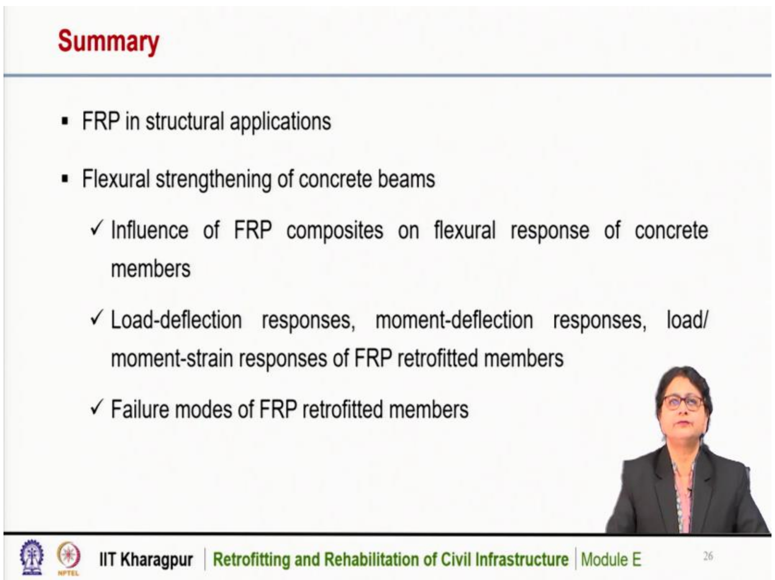
(Refer Slide Time: 40:35)



These are the crack pattern, the pictures are not very good, but it has been given by the researchers. So, here the control beam fails due to concrete crushing as we have mentioned earlier. So, there are cracks on the beams, the control beam showed widely spaced cracks. So, this is the control beam though cracks are widely spaced and there are a lesser number of cracks. Whereas, the FRP retrofitted beams and there are more number of cracks and closely spaced cracks.

Beam with CFRP retrofitted showed cracks at relatively close spacing that leads to CFRP rupture because at the when the cracks are closely spaced, there is delamination, so, there may be also rupture of the FRP. So, that leads to CFRP rupture and then concrete crushing. So, these are the schematic diagram of the cracked pattern of the FRP retrofitted beams and also for the control beam.

(Refer Slide Time: 41:45)



So, there are several other research works that we will continue in the next lecture. So, to summarise today we have discussed the various structural applications of FRP and FRP strengthening to improve the flexural capacity of concrete beam members. We have discussed some of the research works that shows the influence of FRP composites on flexural response of concrete members.

And the responses in terms of load deflection responses, moment deflection responses, load or moment to strain responses of FRP retrofitted members have also been discussed, and the failure modes of FRP retrofitted members have also been shown as obtained from several research works in this area. Thank you.