Retrofitting and Rehabilitation of Civil Engineering

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Lecture 25

FRPC in Shear Strengthening of Structural Members

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 of Structural Members Using Fibre Reinforced Polymer Composites.

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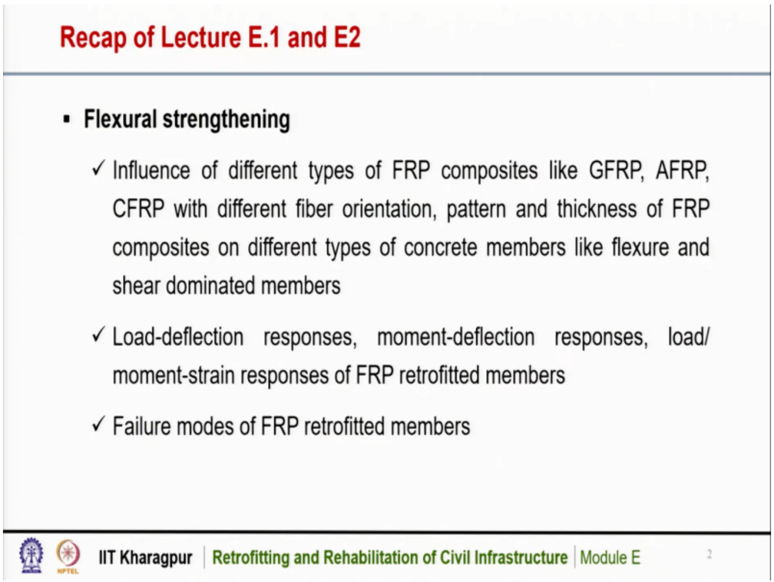

In the previous lectures, we have discussed the Flexural Strengthening of Structural Members Using Fiber Reinforced Polymer Composites. The influence of different types of FRP composites like GFRP, AFRP or CFRP have been discussed on the response of flexural strengthened beams.

The different fiber orientation, different fiber pattern, the thickness of FRP composites have been discussed. And their influence on the response of the FRP strengthened members have been covered. The responses of the FRP retrofitted beams in terms of load deflection plots or moment deflection plots or load versus strain variations have been discussed. The failure modes of FRP retrofitted members have also been discussed in the previous lectures.

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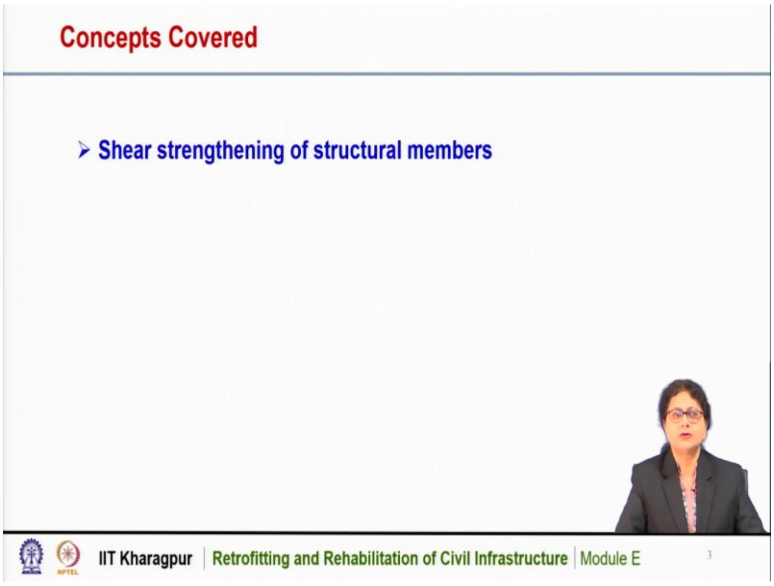

Today, we will discuss the Shear Strengthening of Structural Members using Fiber Reinforced Polymer Composites.

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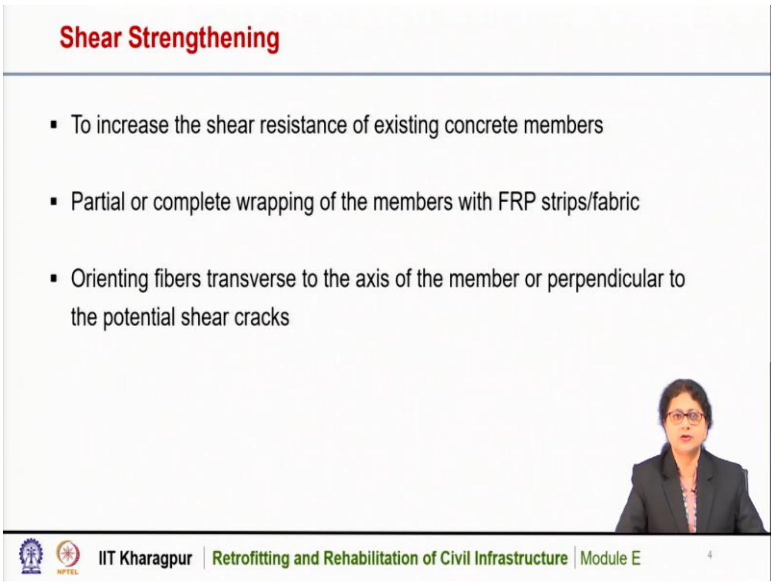

Shear strengthening of structural members aims to increase the shear resistance of existing concrete members. In this shear strengthening, the structural members are strengthened using FRP strips or fabrics with partial wrapping or complete wrapping around the member. The fibers may be oriented transverse to the axis of the member or perpendicular to it or perpendicular to the potential shear cracks or they can be of any angle.

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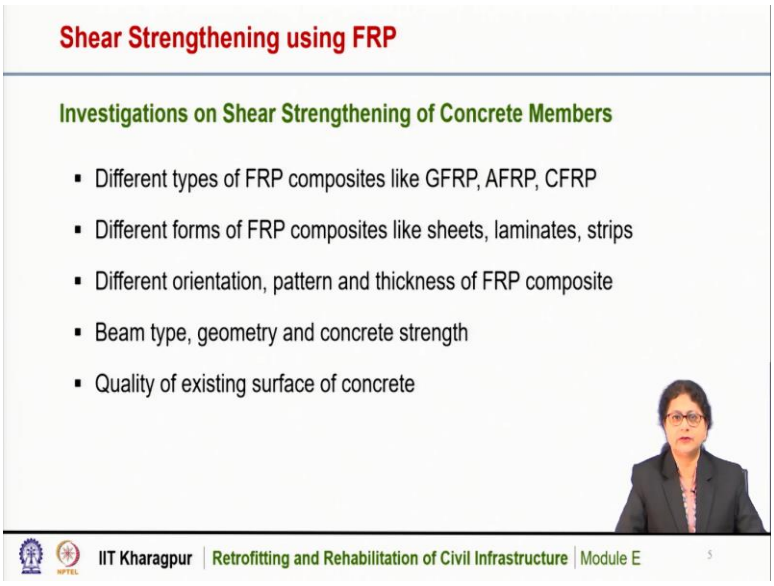

There are several investigations that have been carried out on shear strengthening of concrete members. Different research works have been carried out to investigate the influence of different types of FRP composites like Glass Fiber Reinforced Polymer Composites, Aramid Fiber Reinforced Polymer Composites or Carbon Fiber Reinforced Polymer Composites.

Different forms of FRP composites have also been considered like sheets, laminates, strips or fabric, etcetera. The different orientation of fibers, the different pattern of fiber and the thicknesses of fiber composites have also been considered in the stress-strain response of the FRP retrofitted members. The beam type, the different geometry and configuration and concrete strength has also been investigated in this research. The quality of existing surface of concrete has also been investigated in the research.

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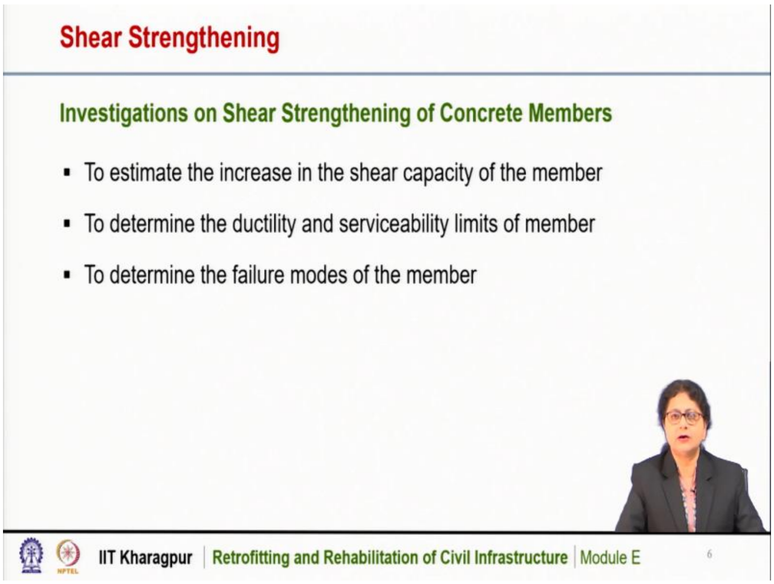

In the investigation of shear strengthening of concrete members, different types of investigations have been carried out to estimate the increase in the shear capacity of the member to determine the ductility and serviceability limit of the structural members and also to determine the failure modes of the members which are retrofitted with FRP composites.

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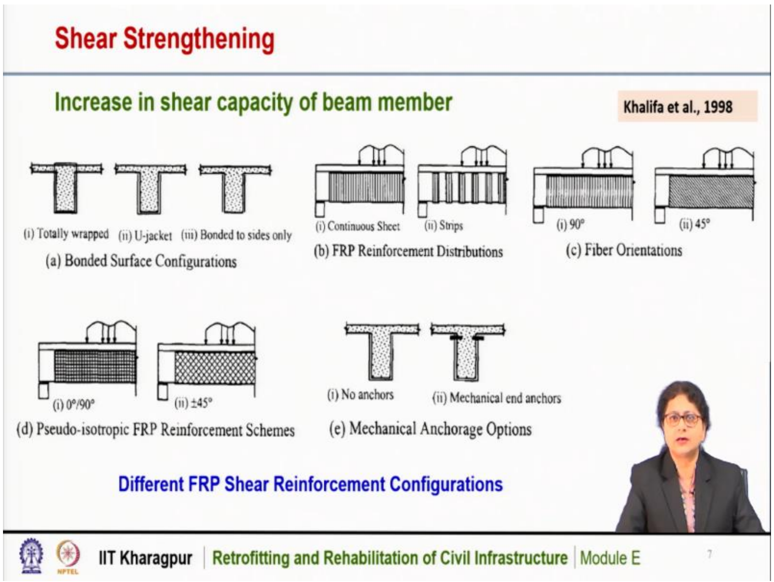

Several investigations have been carried out for shear strengthening to investigate the shear capacity of beam members which are strengthened by FRP. Different configurations of FRP reinforcement has been considered. Like in this figure it is shown that the FRP retrofitted members, this is the cross section of the beam members, it may be totally wrapped with FRP or it may be wrapped on three sided like U-jacket.

We can see here the FRP is placed around the member on three sides or it can be bonded to only at the sides. If we consider the length of the member, different configurations have also been considered here. We can see here the FRP may be placed continuous along the length of the member or intermittently with some spacing.

The orientation of FRP or orientation of fibers may be different. We can see here that research has been carried out when the fibers are oriented perpendicular to the axis of the member or maybe at certain angles, say 45 degree to the axis of the member or it could be a combination of 0 and 90 degree. So, here the fibers are oriented in 0 degree or 90 degree to the axis of the member or it could be plus minus 45 degree. So, all these configurations have been investigated to see the behavior of the FRP strengthened members.

In addition to that anchors have also been used. The variation with respect to presence of anchors or with only with adhesives and no anchors have also been investigated by the researchers. So, these are the different FRP reinforcement configurations that have been tried by the researchers to find out the response of the FRP retrofitted member to find out the shear capacity, the increase in the shear capacity of the members.

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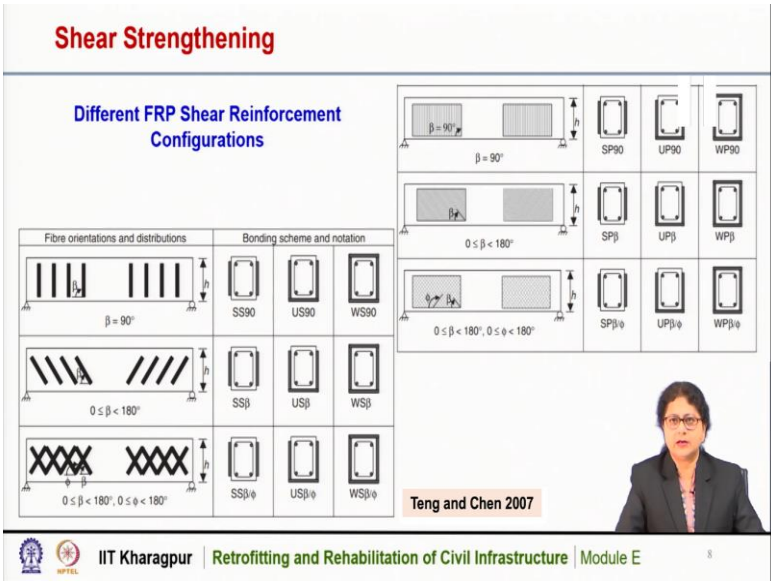

These are some other configurations, FRP shear reinforcement configurations along the length of the member. We can see here that research has been carried out when the FRP fabric is placed intermittently along the length of the member and it is 90 degree along its perpendicular to its axis or it may be of any angle.

We can see here, it can be placed at any angle and that is also near the support. Here cross plies have been used. One is say 45 degree another is minus 45 degree and near the support and it could be two sided three sided or all four sided. Here, this type of configurations have also been tried.

The FRP fabric is placed continuously near the support and the fibers are oriented 90 degrees to the length of the member or it could be at some angle. But it is continuous near the support or it could be at plus or minus any angle. So, these type of configurations have been investigated by the researchers to understand the behavior of the FRP strengthened members.

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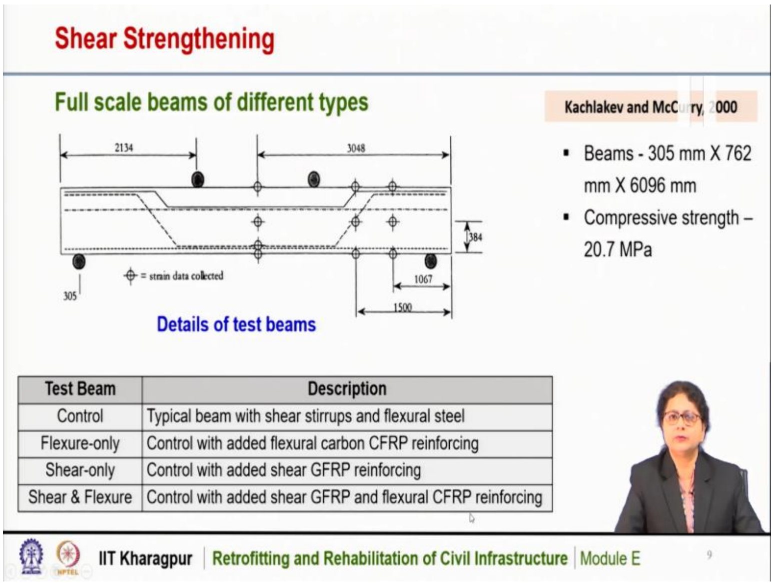

The researchers Kachlakev and McCurry has investigated the full-scale beams of different types. The beams are of dimension 305 millimeter × 762 millimeter × 6 meter. So, it is a full-scale beam. They have investigated and tested and the compressive strength of the beam was 20.7 MPa. This is the details of the test beam.

We can see here, the test beam is simply supported and the different types of beams, one is control beam that is without any FRP reinforcement but it has a steel reinforcement and steel stirrups. Another one is termed as flexure-only beam. It has reinforcement similar to the control beam but with added flexural carbon CFRP reinforcing. So, it has additional CFRP reinforcement at the external face, at the bottom of its face.

Another type of beam is shear-only beam. This beam is of same dimension as the control beam and the reinforcements are also same but this beam has an additional shear reinforcement with GFRP. And another type of beam was also tested. That is shear and flexure type beam. The dimension and reinforcements are same as that of control beam but this beam has added shear reinforcement with GFRP and additional flexural reinforcement with CFRP.

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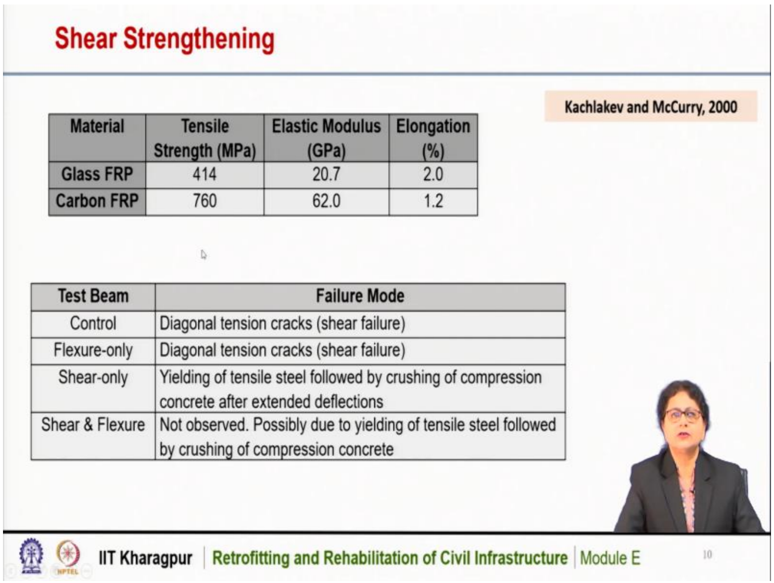

The material properties of the Glass FRP and the Carbon FRP are given. The tensile strength, the elastic modulus and the elongation of the two FRP system have been given. And the stress strain response and the failure modes were observed. So, we will discuss the failure modes little later.

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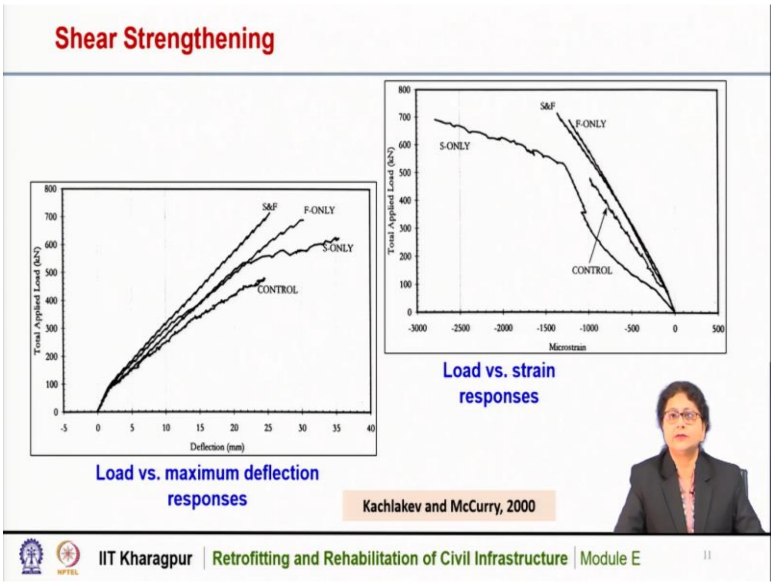

Let us discuss the load versus maximum displacement variations. So, this gives the load versus maximum displacement responses of all the four types of beams. We can see here that this is the response of the control beam. And these are the responses of the FRP retrofitted beam.

For all the FRP retrofitted beams, the load carrying capacity is much higher as compared to the control beam. The maximum load carrying capacity is obtained for the shear and flexure combination beam. Then the flexure only beam and then the shear only beam. So, here the load carrying capacity has been investigated. And it has been found that the load carrying capacity of the FRP retrofitted beams are much higher as compared to the control beam.

However, when we see the load versus strain variation of all these beams, we can see here that the control beam is having the least strain at failure. Whereas the shear beam has the highest strain at failure. So, we can see here. This is the response of the shear only beam and it has the highest strain as compared to the other beams. So, there is a significant improvement of the capacity of the FRP retrofitted beams.

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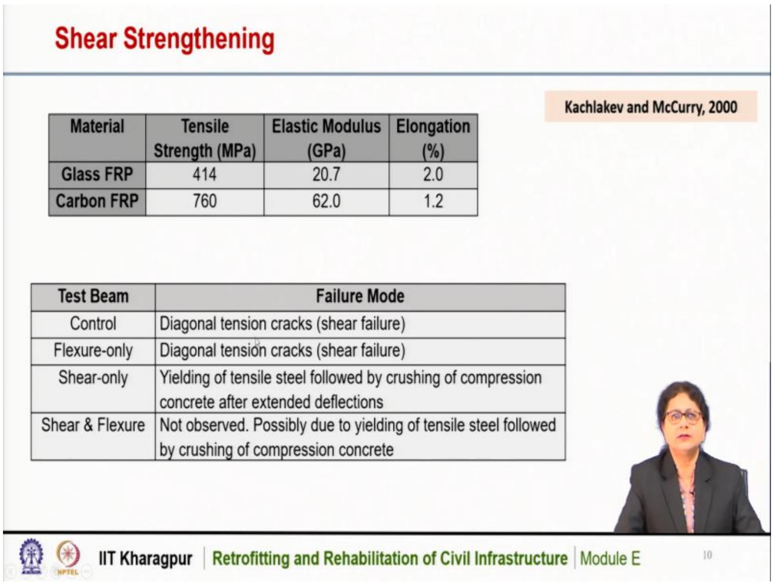

Now, we will discuss the failure modes of all these beams. The control beam failed due to shear with formation of diagonal cracks. The flexure-only beams failed due to the formation of diagonal cracks. So, here in this case the failure was ensured, because it has significant amount of flexural reinforcement. So, it did not fail in flexure but it failed in shear.

The shear-only beam failed due to yielding of tensile steel followed by crushing of compression concrete after extended deflection. So, this shear-only beam did not fail in shear but due to the yielding of tensile steel and followed by crushing of concrete. The shear and flexure beam did not fail but some cracks were observed. And it was estimated that possibly the failure was due to yielding of tensile steel followed by crushing off the compression concrete.

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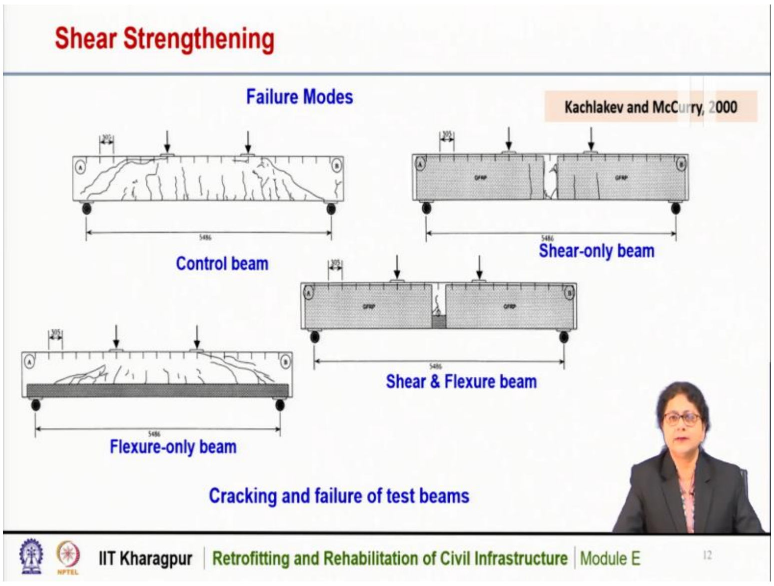

So, these are the schematic diagram of the cracking and failure modes of the tested beams. We can see here this is the control beam that fails due to the formation of these shear cracks. So, these are prominent shear cracks on these beams under loading and that beam failed due to shear. This is the schematic diagram of the flexure-only beam. Here, shear cracks have been developed and this beam failed due to shear.

Here, this is the shear-only beam. It has high shear reinforcement and that is why the failure is due to a flexure. So, flexural cracks have been observed and the steel also yielded and there is concrete crushing afterwards. This beam, shear and flexure beam did not fail, however some cracks were observed in the flexure zone. We can see here also the cracks in this zone.

So, these are the typical failures of the different types of beam. The control beam, the shear only beam, the flexure only beam and the shear and flexure beam. So, depending on the type of FRP reinforcement, the failure mode is also different. So, it indicates that if the beam is retrofitted with FRP and it is strengthened in shear, it can take much higher load and the failure mode is also, in flexure or due to steel yielding and not in shear.

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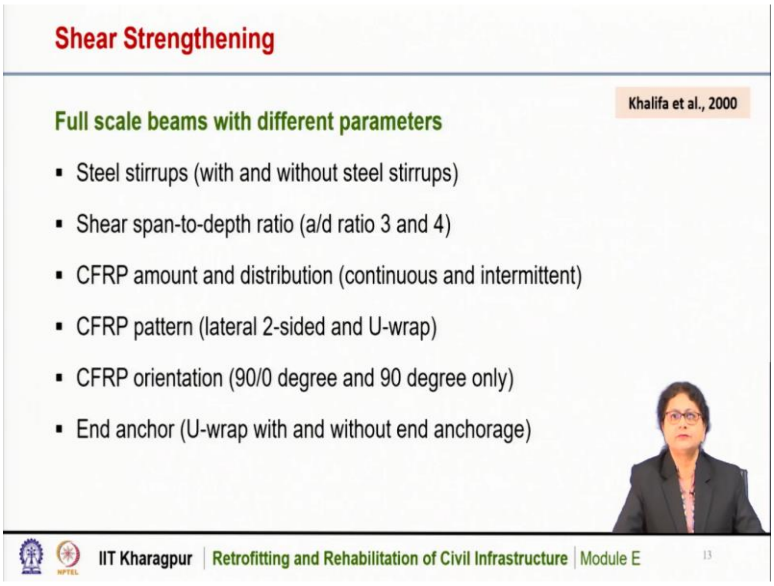

Khalifa et. al. in 2000 carried out experiments, number of experiments were carried out on full-scale beams with varied parameters. The parameters used were steel stirrups, where, there in the beam, so one set of beam was used where there is no steel stirrup and another one with steel stirrups.

The beams have varied shear span-to-depth ratio. The ratio was 3 to 4. CFRP amount and distribution was also different. It may be intermittent and continuous the pattern of CFRP is also different, lateral 2-sided FRP strips and U-strips, both were used. The orientation of fibers were different in the CFRP system. One was 90 degree and 0 degree combination and in another one it is only 90 degree. And end anchorages were also used and in some beams it was not used.

So, U-wrap with end anchorage or without end anchorage was used. So, the experimental parameters were different, use of steel stirrups or not, and varied shear span-to-depth ratio, the different amount of CFRP, different orientation of fibers and different CFRP pattern and also with and without end anchorages.

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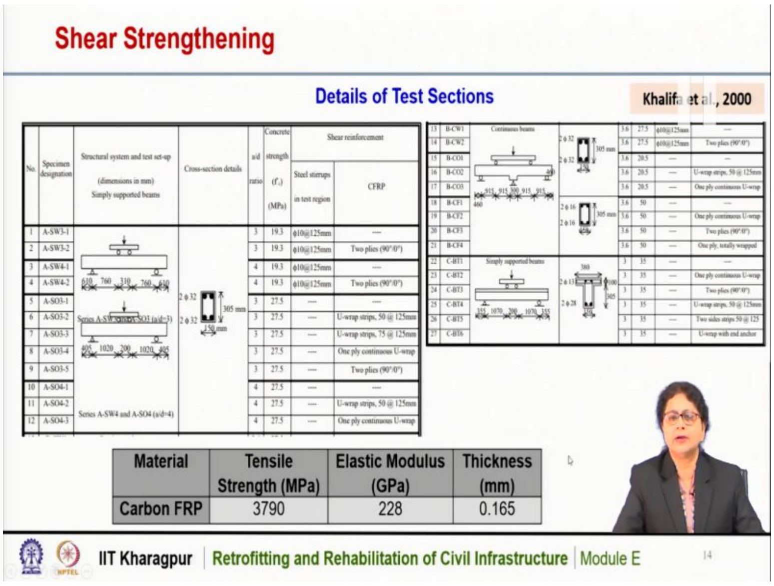

So, these are the details of test sections. Different types of beams were tested. These are simply supported beams. And this is also simply supported but with varied a by d ratio that is span-to-depth ratio. This is continuous beam and this is a T beam. So, different types of beams were tested and different a by d ratios that is span-to-depth ratios and also varied compressive strength.

The fiber orientations and the fiber patterns are different and these are mentioned here. Some beams were control beams. There is no FRP reinforcement. Some were with CFRP reinforcement and the orientations of fibers or the pattern of FRP reinforcement were also different and as mentioned in these tables. The properties of carbon fiber reinforced polymer composites are mentioned here.

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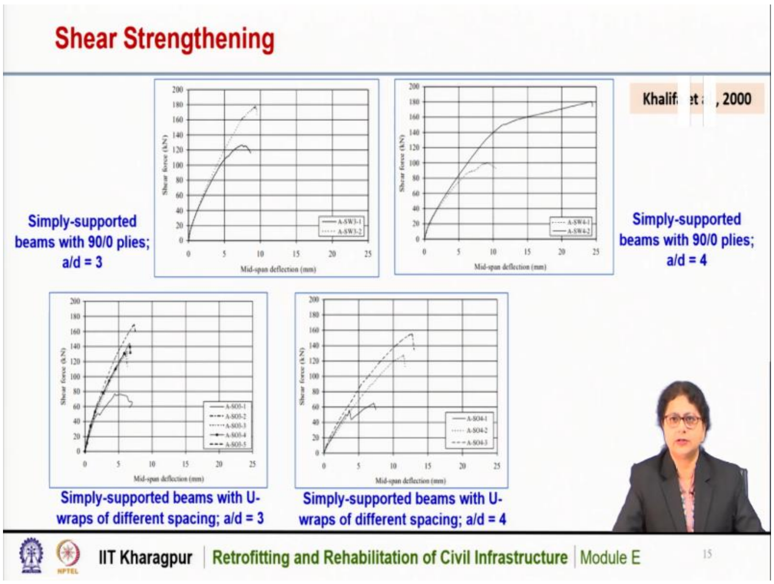

And these are the responses of the FRP strengthen beams. This is the response of the simply supported beams with 90, 0 combination plies. So, two plots are there. One is the beam with no FRP reinforcement. So, this is the response of the control beam and this is the response of the FRP retrofitted beam with 90, 0 plies.

So, it is the, we can see that there is a significant improvement of the shear capacity of the FRP retrofitted beam and this graph shows the plot of the shear force versus the mid-span deflection of the simply supported beam with 90, 0 plies and one is the control beam with a different a by d ratio, that is a by d is 4 here.

And here also we can see that there is a significant improvement of the shear capacity of the FRP retrofitted beam. This plot shows the variation of the shear force with mid-span deflection of the simply supported beams with U-wraps of different spacing. The spacing was also varied in the experiment. And this is the response of the control beam when the a by d ratio is 3.

So, here, we can see that when the spacing is less then the shear capacity of the beam increases, significantly. And this increase is much higher as compared to the control beam. This plot also shows the improvement in the shear capacity of the simply supported beam with U-wraps of different spacing when the a by d ratio is 4. So, this is the response of the control beam and these are the responses of the FRP retrofitted beam. So, significant improvement in the shear capacity has been observed in all cases.

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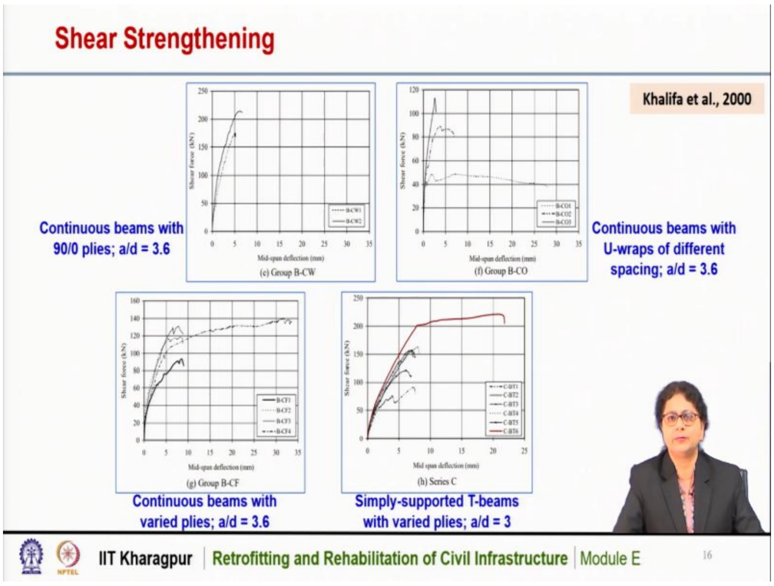

These are the responses of the continuous beam and the T beams. We can see here that this is the response of the continuous beam and this is the response for the control beam when the a by d ratio is 3.6. And this is the response of the FRP retrofitted beam when the FRPs are given as 90, 0 combination. This is the response of the continuous beam with U-wraps of different spacing and one is for the control beam and when the a by d ratio is 3.6.

So, here also we can see that with decrease in spacing, the capacity is higher. Similar responses have been observed for the continuous beam with varied plies. The number of plies or the thickness of the plies are different. And it has been seen that as the amount of reinforcement is increasing, the shear capacity also increases. This is with T beams.

The variation of the load versus mid-span deflection for the T beams of different variation of the plies with a by d ratio 3. And this shows that there is a significant improvement of the shear capacity of the FRP retrofitted beam as compared to the control beam. This is for the beam width end anchorages and it shows that the shear capacity is the maximum in this case. So, all these things shows that there is a significant improvement in the shear capacity of the FRP retrofitted beam as compared to the control beam.

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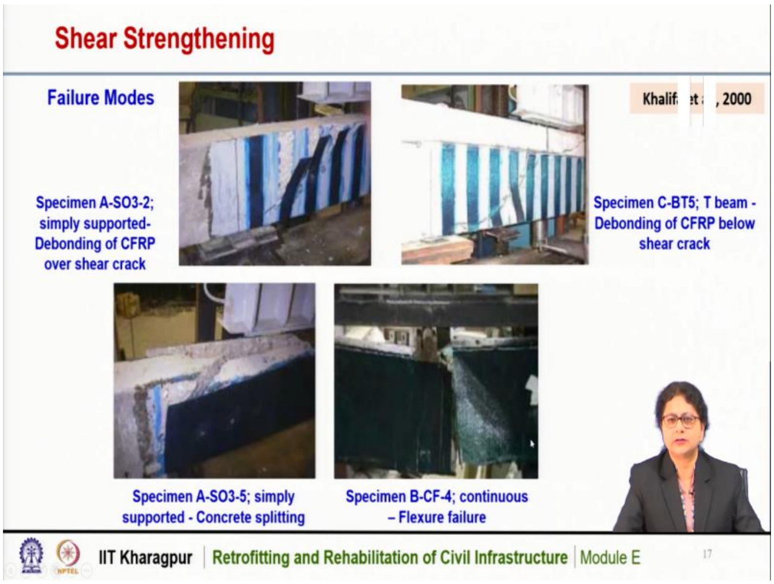

These are the typical failure modes. We can see here that this is the simply supported beam. The failure is due to the debonding of the CFRP over the shear cracks. So, shear crack is visible and the debonding occurred over the shear crack. This is the failure mode of the T beam. Here also debonding occurs. And this is the debonding of the CFRP below the shear crack. So, a clear shear crack is visible in this beam and there is debonding below the shear crack.

Here in these two cases, the FRPs were placed continuously along the length of the member. So, the failure is due to concrete splitting. We can see here that the there is a splitting of the FRP from the concrete surface. Here also we can see that the FRP was applied along the full length and continuous. Here, the failure is due to flexure.

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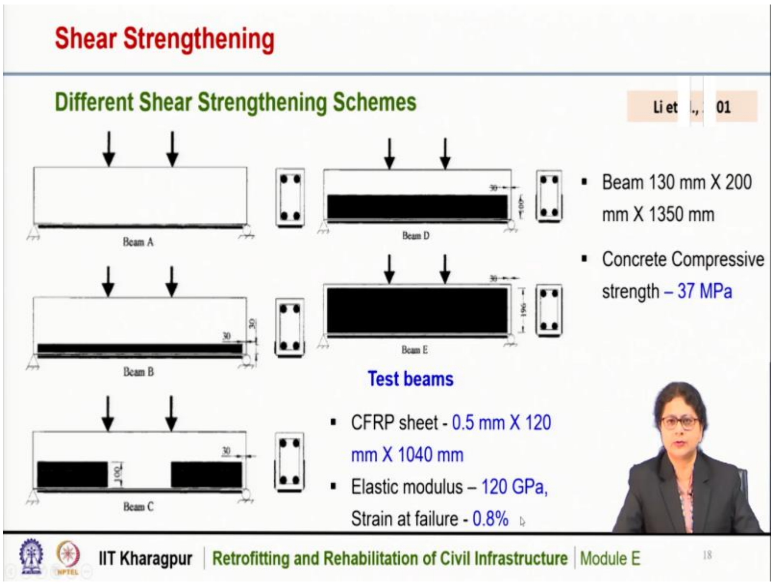

These are another experimental research by Li et. al. in 2001. Different types of beams were tested with different FRP strengthening. The beams were of dimension 130 millimeter × 200 millimeter × 1350 millimeter and of compressive strength of concrete as 37 MPa. Different types of shear strengthening were investigated.

We can see here that here, only flexural strengthening has been done in case of beam A. In case of beam B, it is also flexural strengthening but a small amount of FRP has been given at its sides. We can see here that only near the support, the FRP has been provided continuously up to this depth. And in this case, it is along the entire length of the member and the U-strips have been provided.

And here the complete width, complete depth of the member has been considered and along the full length of the member the FRP sheets have been provided. The FRP sheet is carbon fiber reinforced polymer composite of thickness 0.5 millimeter, 120 millimeter in width and 1.04 meter in length which is available and the elastic modulus and strain at failure are also given.

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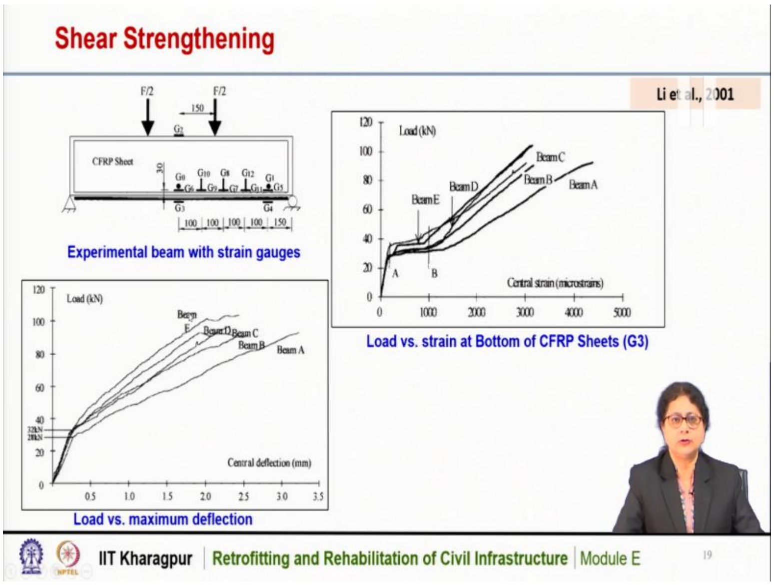

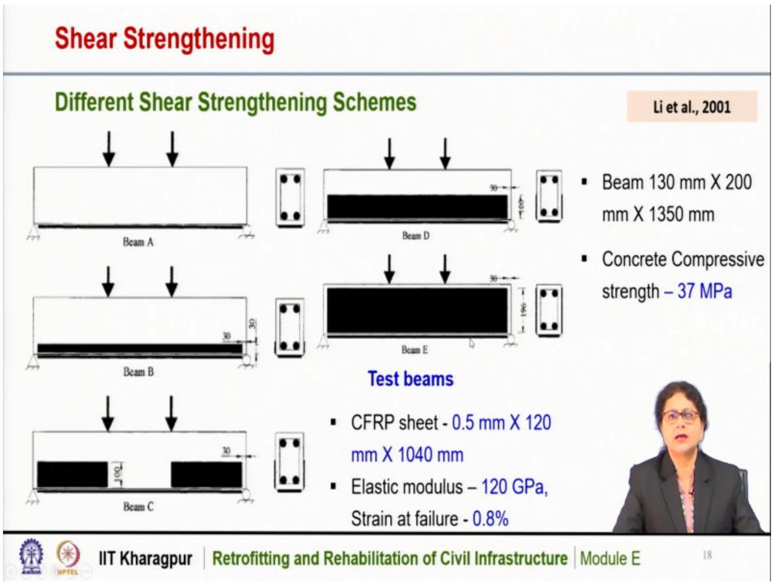

So, these are the responses of the different types of beams, strengthened with FRP composites. We can see here that this is the load versus maximum deflection plot. And the beam B, this is the response of the beam A and these are the responses of the other beams retrofitted with FRP.

So, the maximum load carrying capacity has been obtained for beam E which is this one it has the flexural reinforcement as well as the shear reinforcement maximum with U-strips and for the entire length. So, these are the responses of the beams and with increase in the shear reinforcement and also the flexural reinforcement, the load carrying capacity of the beams increasing.

This is the load versus strain variation at the bottom of the CFRP sheets. Here also it shows that there is an improvement in the strain as the CFRP reinforcement increases. However, when the FRP reinforcement increases, there is a lesser strain at failure as compared to the beam A.

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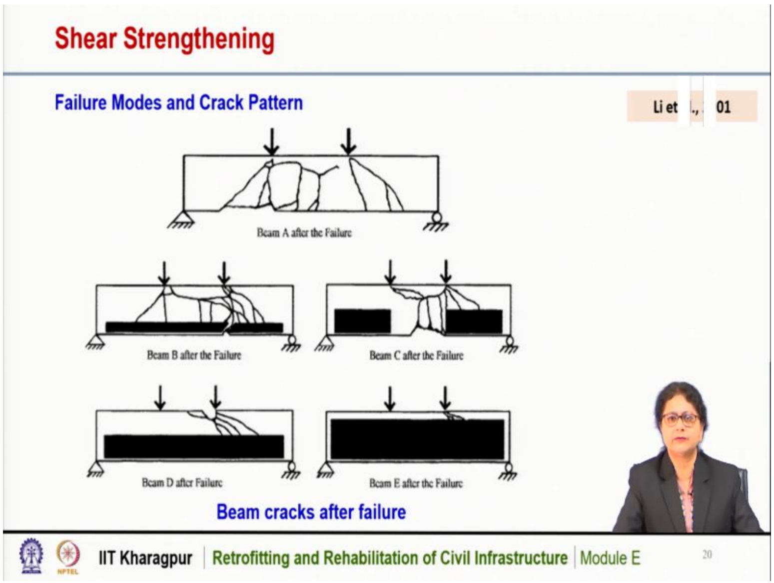

These are the schematic diagram of the failure modes and crack patterns of the various beams. Here, we can see that this is the beam A which has only flexural reinforcement at its bottom. So, this beam fails in flexure and there are several fractural cracks and then the concrete crushing was observed.

This beam is also having flexural reinforcement due to FRP and this beam fails due to the formation of flexural cracks and also concrete crushing at these points. And in this beam, there was, FRP rupture was observed. So, we can see here that there is a FRP rupture due to concentration of stress at these points.

This beam with this type of FRP reinforcement failed due to flexural cracks at these regions. These two beams failed in shear and it is taking higher load. So, these shear cracks have been observed and here also shear cracks have been observed at these locations. So, these are the schematic diagram of the failure modes and crack patterns of the different beams.

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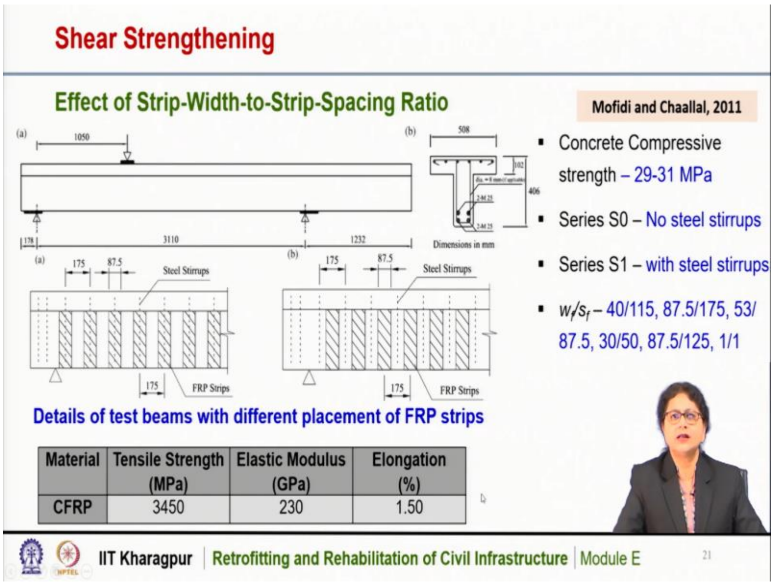

Another research in this area carried out by Mofidi and Chaallal in 2011. They have investigated the effect of strip-width-to-strip-spacing ratio. This is the configuration of the concrete beam having compressive strength of 29 to 31 MPa. Two series of tests were done. In series S0 there were no steel stirrups and in series S1 there were steel stirrups. Different strip-width-to-strip-spacing ratio were considered as given here. And the FRP strips were given intermittently along the length of the member.

Here also two different patterns have been followed. In one case, the FRP strips were provided in the same line of steel stirrups. And in another case, the FRP strips were provided in between the two stirrups. So, these are the two patterns have been followed in the experiment. The properties of the CFRP are given here. The tensile strength, the tensile modulus and the elongation at failure.

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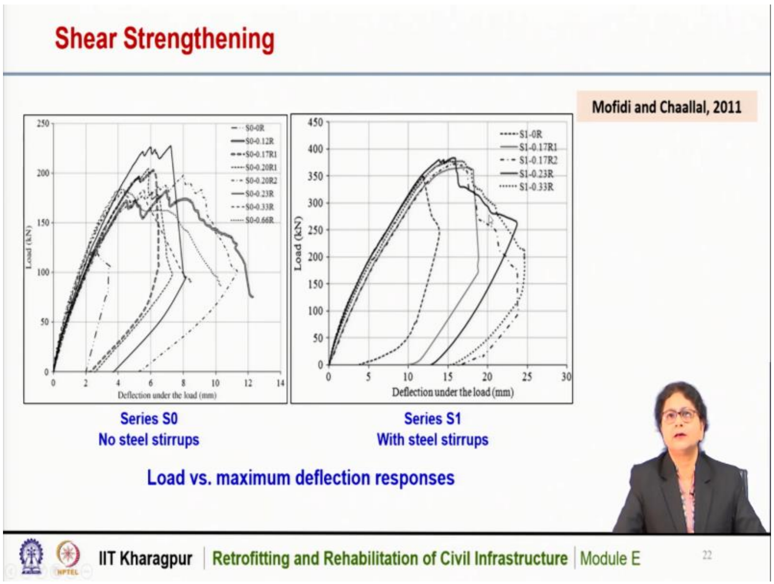

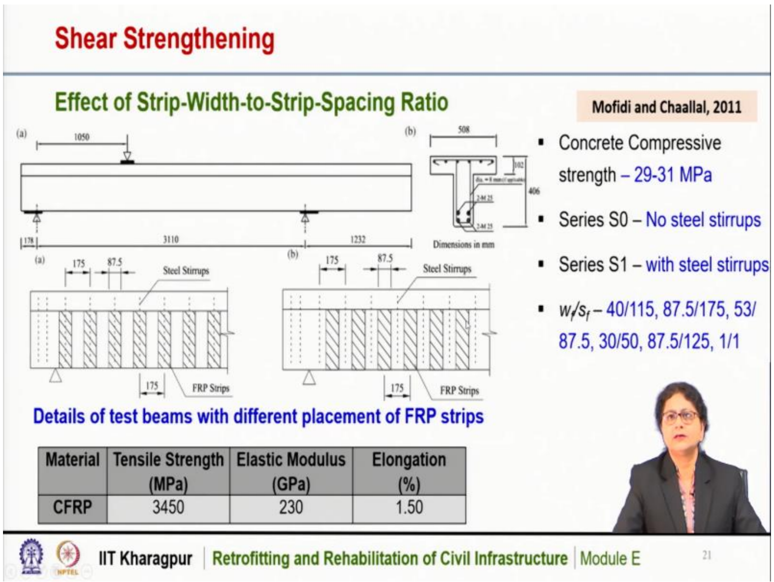

These are the responses of the tested beams. These are the load versus maximum deflection responses for both series, series S0 and series S1. So, this is the response of the control beam and these are the responses of the FRP retrofitted beam when there is no steel stirrup and with different strip-to-width ratio. So, here we can see that there is a significant improvement of the load carrying capacity of the FRP retrofitted members as compared to the control beam.

Here, this is the response of the beams of series S1 with steel stirrups. This is the response of the control beam. And these are the responses of the FRP retrofitted beam. So, here also we have seen that there is a significant improvement in the load carrying capacity of the FRP retrofitted beams. However, the increase as compared to the control beam is higher in case of beams with no steel stirrups, as compared to the beams having steel stirrups. And as the ratio increases, there is lesser capacity of the, load carrying capacity of the members.

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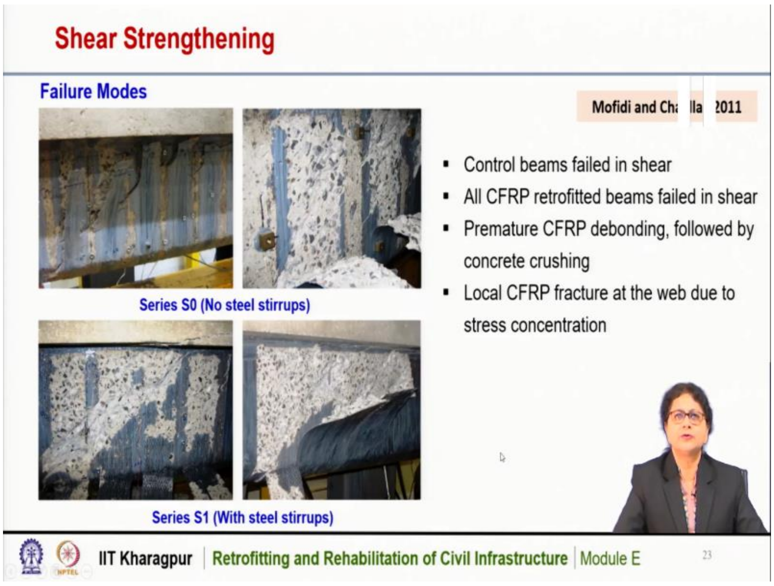

These are the failure modes of the different types of beams of both series S0 and S1. Here we can see that these cases, there are shear cracks have been developed and in some cases the FRP ruptures. The control beams failed in shear as expected and all the CFRP retrofitted beams also failed in shear. The premature CFRP debonding was also observed, followed by concrete crushing. And there may be local CFRP fracture. We can see here local CFRP fracture at the web due to stress concentration. So, these are the different types of failures that have been observed on the tested beams.

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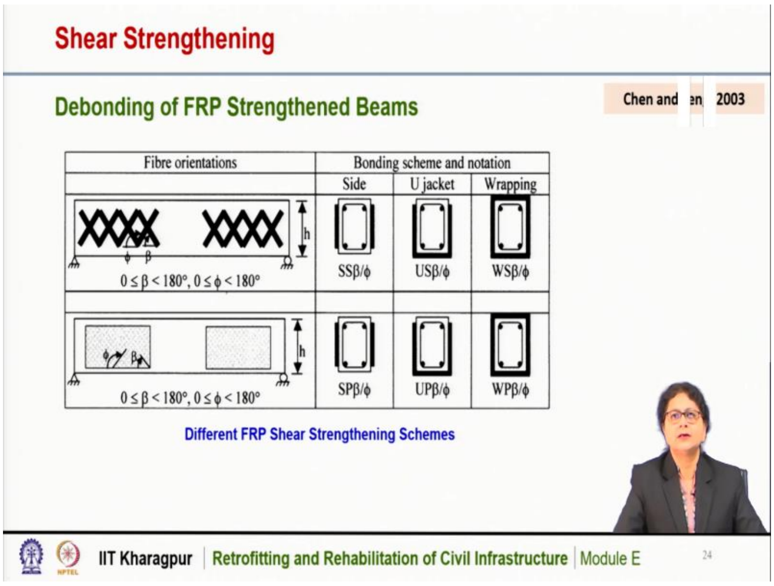

Chen and Tang investigated the behavior of FRP strengthened beams. And they have also reviewed some of the earlier works. They have investigated different fiber orientations as given here. We can see here the different fiber orientations and fiber patterns have been investigated. And the fibers were placed on two sided or three sided like U-wrap or complete wrapping. So, all these types of configurations have been investigated by Chen and Tang.

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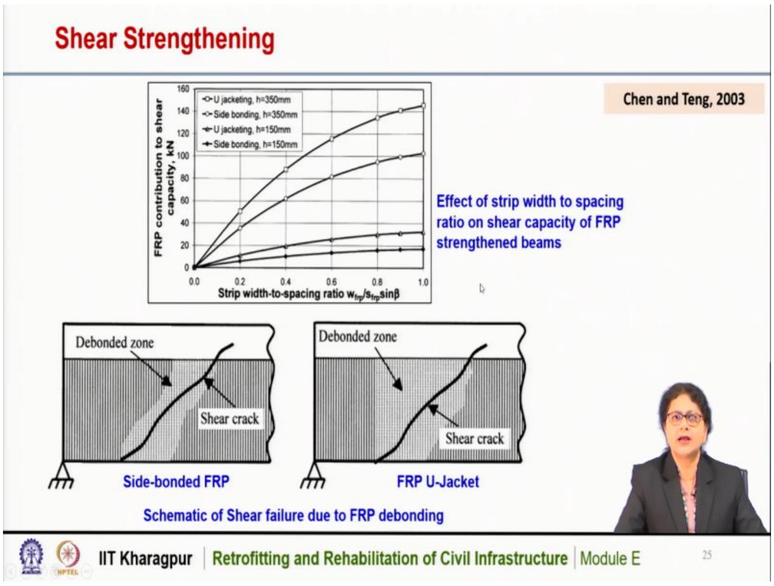

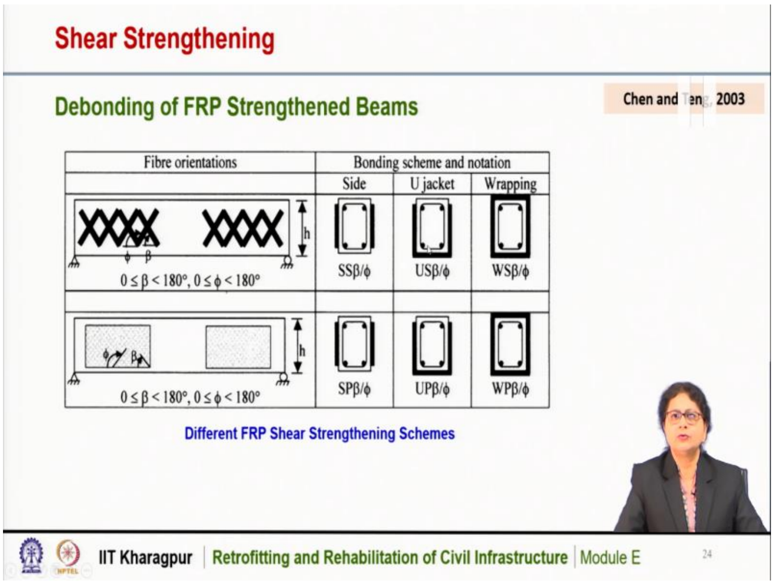

And the responses have been observed. These are the responses of the FRP strengthen beams. This is the effect of strip-to-width-to-spacing ratio on shear capacity of FRP strengthen beams. As the strip-to-width-to-spacing ratio increases, there is the FRP contribution also increases. And it has been seen that the effectiveness of FRP is more when it is U-wrapped as compared to the side wrapped. So, in case of side bonding that means two-sided bonding only and it is U-wrapped. So, the effectiveness is much more in case of U-wrap as compared to two-sided wrapping.

So, here we can see that the, FRP contribution is more in case of U-wrap. And this has been observed for two different types of beams having two different depths. So, for both the cases, the effectiveness of FRP is more in case of U-wrap as compared to side wrap. These are the schematic diagram of the shear failure due to FRP debonding.

We can see here that this is due to the side bonded FRP and this is due to U-wrap FRP. So, here it is seen that this is the debonded zone. So, with high amount of load application there may be debonding. And this is the proximity-bonding zone, in case of side bonded FRP. And this is the debonded zone in case of U-bonded FRP. And here in this case, the area is much more. So, this may be the debonded zone, in case of U-bonded FRP in a beam.

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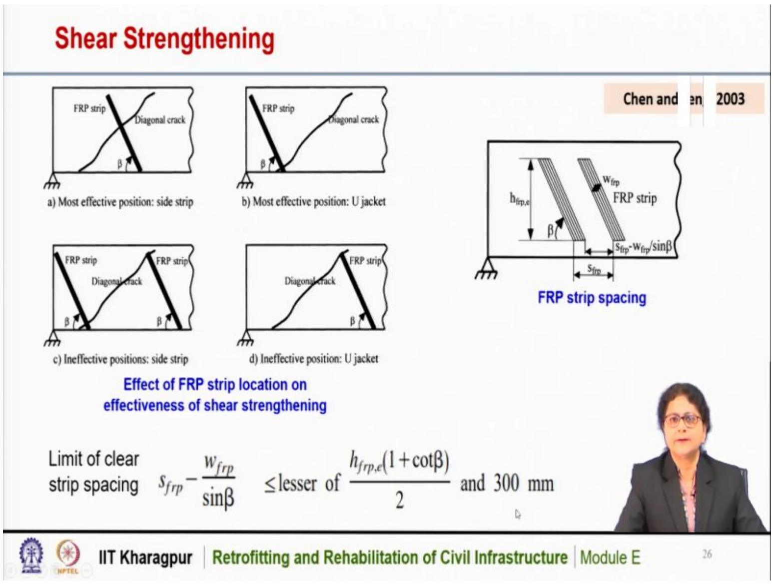

The researchers have investigated different FRP configurations and they have developed that there may be a limit for clear strip spacing. And this is the effect of FRP strip location on effectiveness of shear strengthening. So, if the shear crack or diagonal crack is formed like this near the support, so, the most effective position of the side strip will be like this. So, it has to be almost at the middle of the crack and then the effectiveness will be achieved.

And if we can provide the FRP strip like this, so that, this is the possible location of the diagonal crack and the FRP strip is this, then the effectiveness of FRP will not be achieved. So, this is the inactive position of the FRP in case of side strips. So, this is for the side strip when the FRP is bonded on two sided. The most effective position is this, when it is placed nearly a midway to the diagonal crack.

In case of U-bonded FRP, if this is the possible location of the diagonal crack, the FRP strip should be placed this way and making an angle to the beam axis and this way it is the most effective position. So, it should be at the beginning of the crack. It should be placed and with several spacing it can be placed.

But, if it is placed in this way that the beginning of the crack is here and the FRP is placed at some distance then the effectiveness of FRP will not be achieved. So, this is the ineffective position of the U-wrap and this will not give a good shear strengthening. And it has to be like this; at the beginning of the shear crack the FRP strip should be provided. So, if this angle is beta then the researchers have suggested that there should be a limit of clear strip spacing and as given in this equation, it can be provided.

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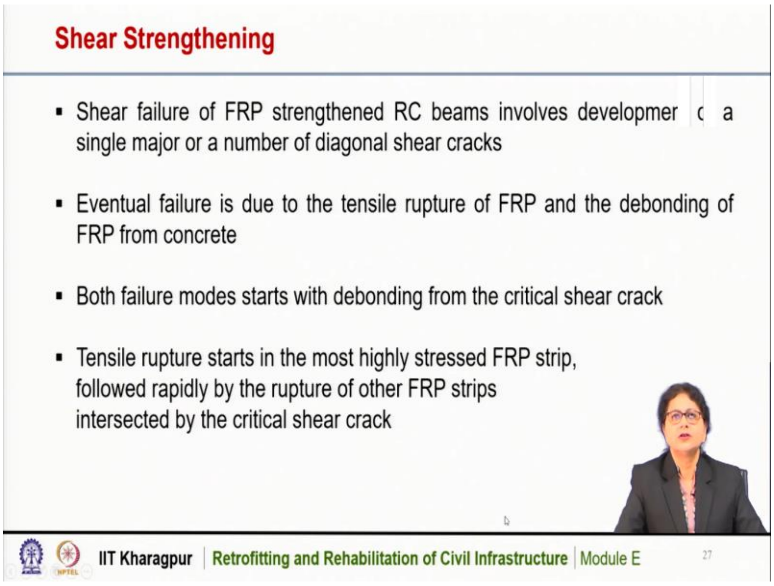

So, the major observations from these pioneering works on FRP retrofitted members to observe the behavior of the FRP retrofitted beams, there are shear failures of FRP strengthened RC beams involves development of a single major or a number of diagonal shear cracks.

The FRP retrofitted beam may undergo shear failure and that involves development of a single major or a number of diagonal shear cracks. The eventual failure may be there that is due to the tensile rupture of the FRP and the debonding of the FRP from concrete. Both failure modes starts with debonding from the critical shear crack.

There may be tensile rupture of the FRP in the most highly stressed FRP strip region that followed by rapidly by the rupture of other FRP strips intersected by the critical shear crack. So, there are major type of failure. One may be due to debonding; one may be due to the rupture of the FRP or due to shear failure.

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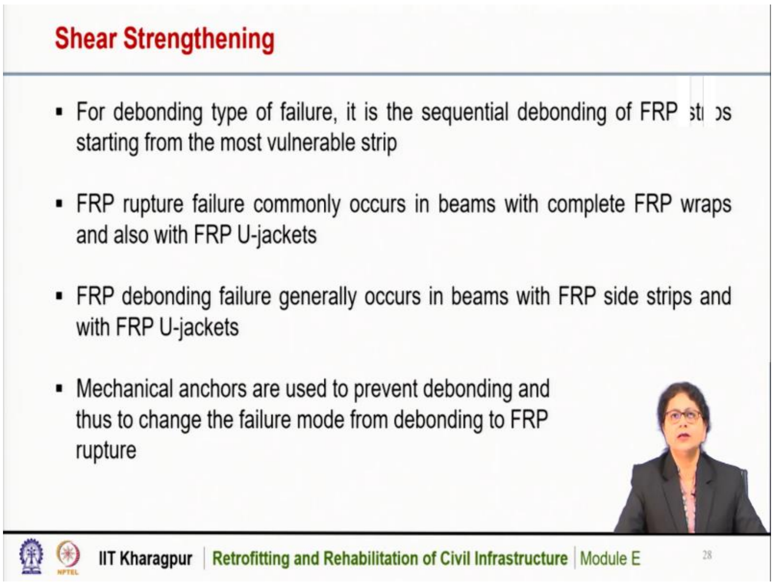

For debonding type of failure, it is the sequential debonding of FRP strips, starting from the most vulnerable strip. FRP rupture failure commonly occurs in beams with complete FRP wraps and also with FRP U-jackets. FRP debonding failure generally occurs in beams with FRP side strips and with FRP U-jackets. Mechanical anchors are used to prevent debonding and thus to change the failure mode from debonding to FRP rupture. So, if we use FRP, if we use mechanical anchors then the failure mode may be shifted from debonding to the FRP rupture.

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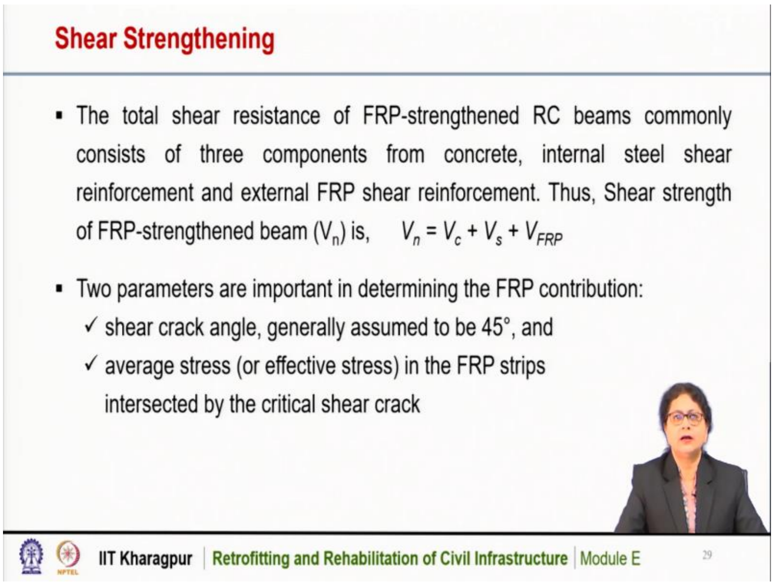

So, we have seen from the previous research works that the total shear resistance of FRP strengthened RC beams commonly consists of three components, from concrete, from internal steel stirrups and from the external FRP shear reinforcement. So, the shear strength of FRP strengthened beams can be written as that V_n that is the shear strength of the FRP strengthened beam is the total shear contribution of the concrete, the shear contribution of the steel stirrups and the shear contribution of the FRP. Two parameters are important in determining the FRP contribution. One is the shear crack angle, generally assumed to be 45 degree and the average stress or the effective stress in the FRP strips intersected by the critical shear crack.

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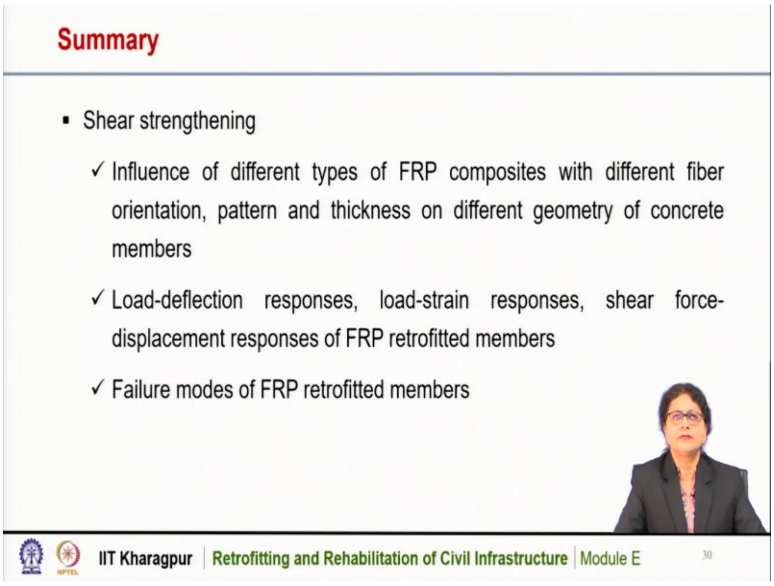

So, to summarize, we have discussed the shear strengthening of FRP retrofitted beams. We have discussed several research works that investigated the influence of different types of FRP composites with different FRP configurations having different fiber orientation, different FRP pattern and different FRP thickness on different types of beams having different geometry and configuration and steel stirrups.

The responses were observed in terms of load deflection responses, load strain responses; shear force displacement responses of the FRP retrofitted members. The failure modes of FRP retrofitted members have also been observed in those works and it could be due to debonding or it could be due to rupture of the FRP or it could be due to concrete crashing.

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These are the references for this lecture. Thank you.