Retrofitting and Rehabilitation of Civil Infrastructure
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Lecture 29
FRPC in Strengthening of Beam-Column Joints

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 fiber reinforced polymer composites.

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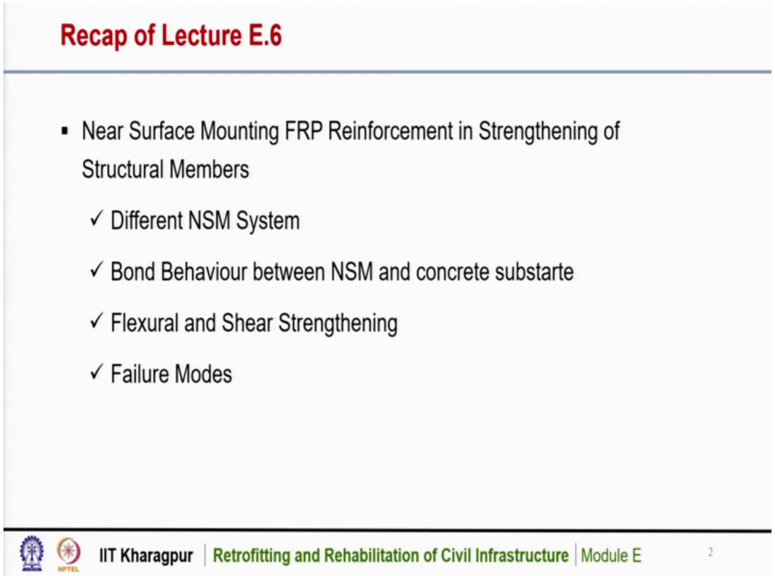

In the previous lecture, we have discussed the near surface mounting FRP reinforcement in strengthening of structural members. We have discussed the different NSM systems using FRP, the bond behaviour between NSM and concrete substitute, the flexural and shear strengthening using NSM FRP system and the different failure modes.

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Today we will discuss the strengthening of beam-column joints using fiber reinforced polymer composites.

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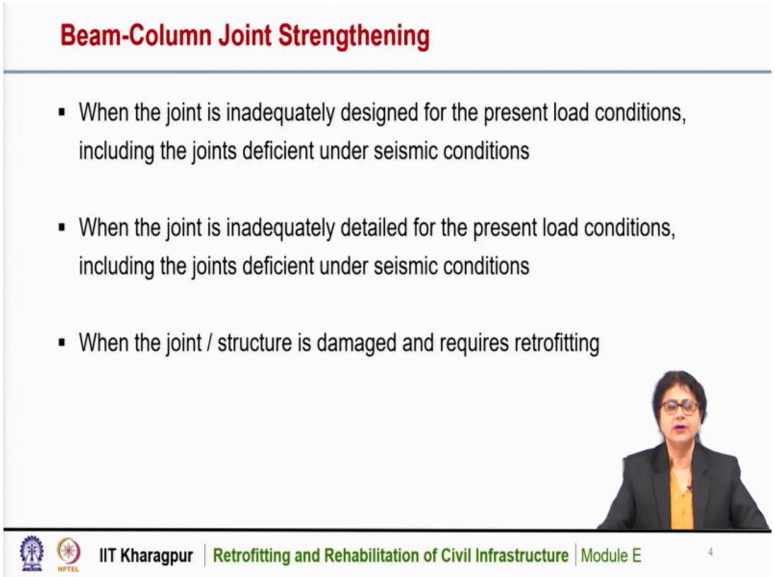

Beam column joint strengthening is carried out when the joint is inadequately designed for the present load conditions including the joints deficient under seismic conditions. It is also done when the joint is inadequately detailed for the present load condition including the joint deficient under seismic conditions and also when the joint or structure is damaged and requires retrofitting.

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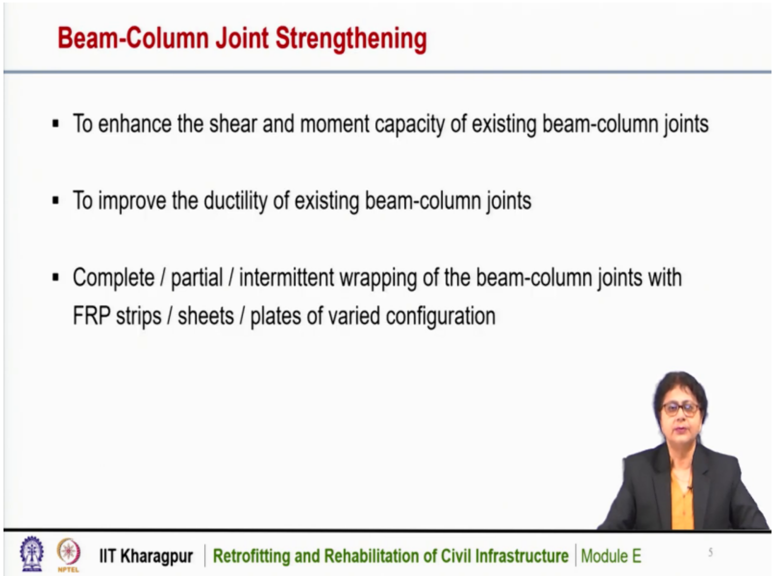

The beam-column joints strengthening is also an important retrofitting measure for existing structures. It is aimed to enhance the shear and moment capacity of existing beam-column joints, also to improve the ductility of the existing joints. In FRP retrofitting, we use different types of fibers and that may be of different forms like strips, sheets or plates, that are used for strengthening of beam-column joints with complete partial or intermittent wrapping of the beam-column joints with varied configuration. So, different investigations have been carried out to understand the complex behaviour of FRP strengthen beam-column joints.

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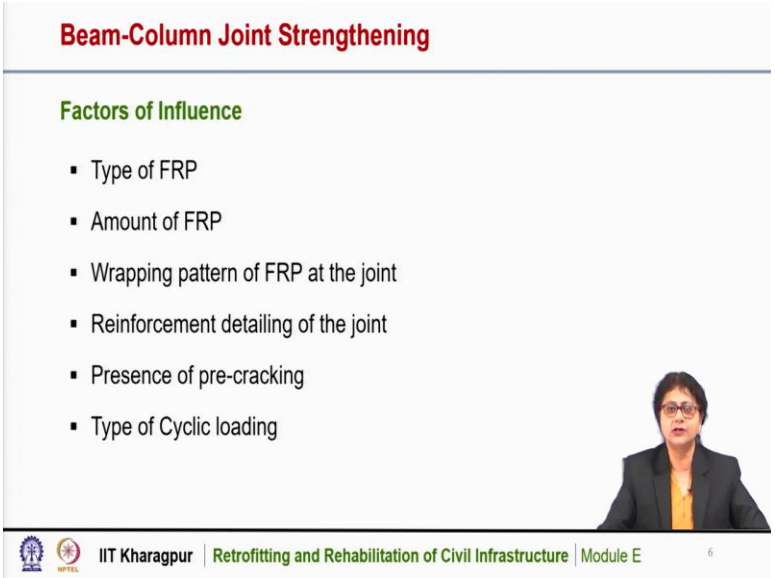

There are several parameters that may influence the response of beam column joint when it is retrofitted with FRP. The factors of influence are types of FRP, different types of FRP has been used like GFRP, CFRP, etcetera. The amount of FRP reinforcement, the wrapping pattern, there are different wrapping pattern that may be used for strengthening purpose at joints. The reinforcement detailing of the joint, the existing steel reinforcement detailing may also influence the response. The presence of pre-cracking at the joints, whether the joint is already cracked or it is not cracked or the type of cyclic loading that may influence the response of beam column joint when it is strengthened with FRP composites.

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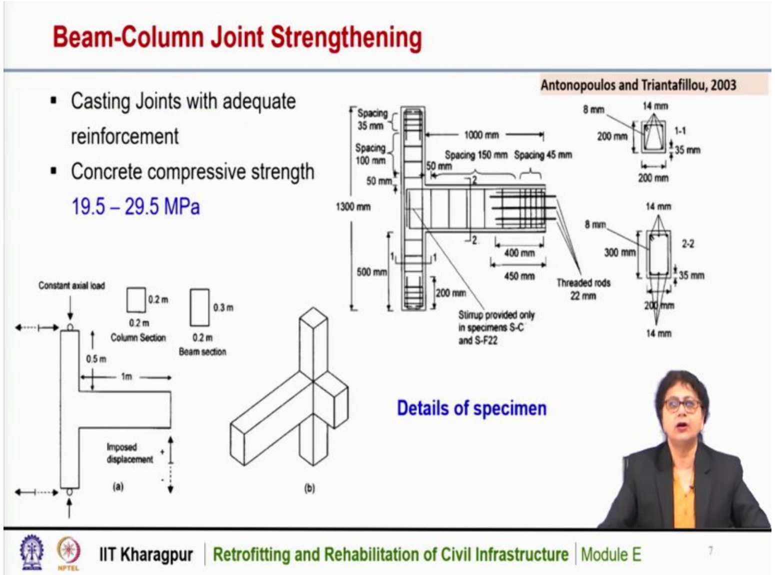

In many cases, the beam-column joints may fail, particularly during Earthquake, this is a vulnerable location where failure occurs. And it is important to retrofit these locations with FRP composites, so that the abrupt failure can be avoided. So, in this experimental research, different beam-column joints have been investigated with different parameters. As we can see here that this is a typical beam column joint specimen that is used for the experimental purpose.

The beam-column joint has reinforcement as we can see here, these are the reinforcements placed in the beam-column joints. The joints are casted with adequate reinforcement. We can see here, the concrete compressive strength varies from 19.5 to 29.5 MPa. And the dimensions of the specimens are also given and the steel reinforcement which has been used here in these joints have also been shown in this schematic diagram.

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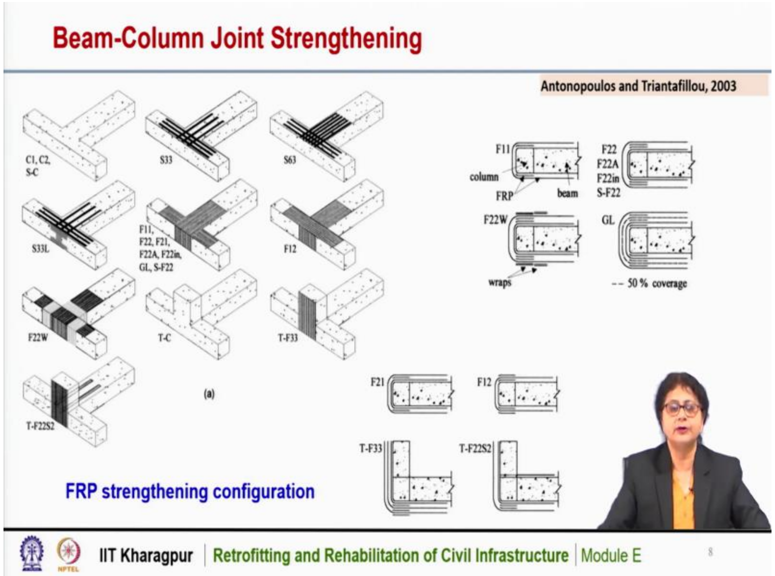

So, in this experiment a number of specimens have been prepared with different FRP strengthening configuration to understand the response of the joint when it is retrofitted with different types of fibers and with different pattern. So, here are the schematic diagrams of all these configurations that have been tested. Different layers of FRP has also been used one layer or two layer near the joints in the beam portion as well as in the column portion as we can see here, these different configurations of the specimen.

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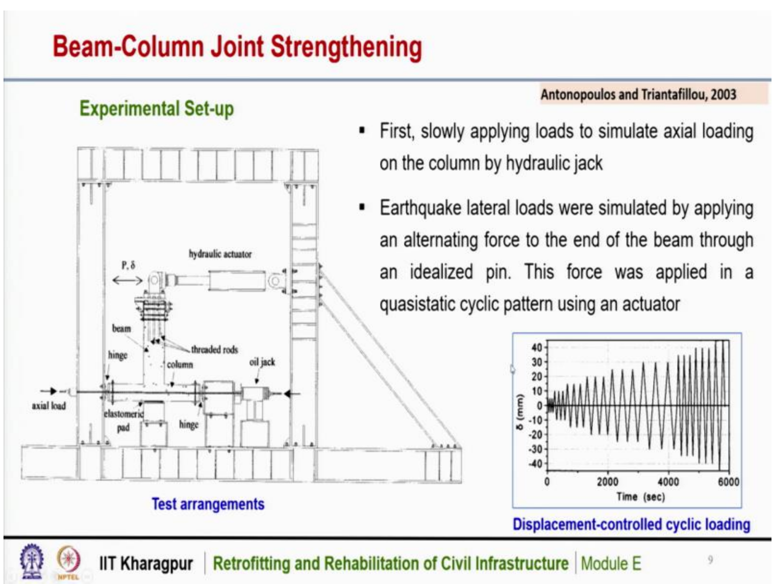

This is the experimental setup for testing the beam-column joints. We can see here this is the loading frame and this is the joint that has been placed in this frame. This is the specimen and the column are placed horizontally and it is subjected to axial loading by this jack and this is the beam. So, beam is placed vertically and here it is connected and with this hydraulic actuator the load is applied at the tip of the beam.

First slowly the load is applied on the column to simulate axial loading on the column by hydraulic jack. As we can see here, the load is applied on the column part by the hydraulic jack. And here, this is the beam where earthquake lateral load is simulated by applying an alternating force to the end of the beam through an idealized pin. Here, this force is applied in a quasi-static cyclic pattern using an actuator. So, this is the hydraulic actuator that is placed, so that the cyclic loading can be applied. This is the displacement control cyclic loading that is being applied on the beam. And this is the experimental setup for the tested specimens.

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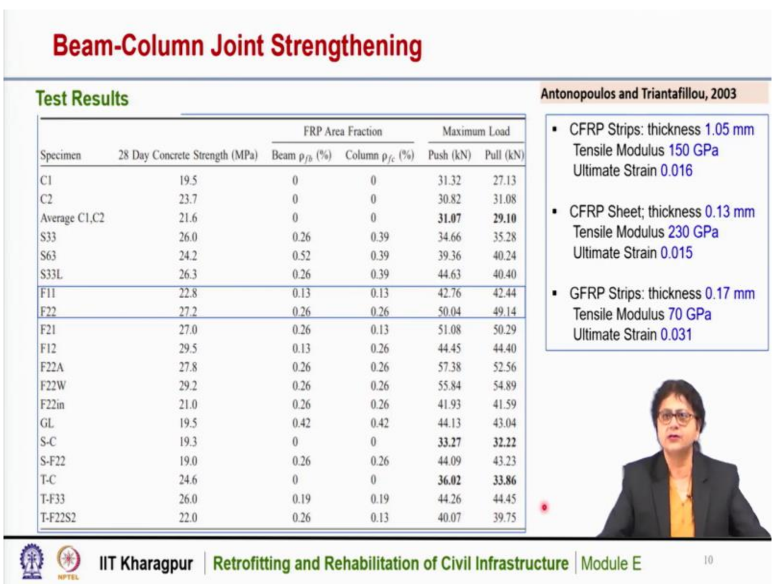

Specimen	28 Day Concrete Strength (MPa)	FRP Area Fraction		Maximum Load	
		Beam ρ_{fb} (%)	Column ρ_{fc} (%)	Push (kN)	Pull (kN)
C1	19.5	0	0	31.32	27.13
C2	23.7	0	0	30.82	31.08
Average C1,C2	21.6	0	0	**31.07**	**29.10**
S33	26.0	0.26	0.39	34.66	35.28
S63	24.2	0.52	0.39	39.36	40.24
S33L	26.3	0.26	0.39	44.63	40.40
F11	22.8	0.13	0.13	42.76	42.44
F22	27.2	0.26	0.26	50.04	49.14
F21	27.0	0.26	0.13	51.08	50.29
F12	29.5	0.13	0.26	44.45	44.40
F22A	27.8	0.26	0.26	57.38	52.56
F22W	29.2	0.26	0.26	55.84	54.89
F22in	21.0	0.26	0.26	41.93	41.59
GL	19.5	0.42	0.42	44.13	43.04
S-C	19.3	0	0	**33.27**	**32.22**
S-F22	19.0	0.26	0.26	44.09	43.23
T-C	24.6	0	0	**36.02**	**33.86**
T-F33	26.0	0.19	0.19	44.26	44.45
T-F22S2	22.0	0.26	0.13	40.07	39.75

Here in this experiment different types of FRP composites have been used CFRP strips, CFRP sheets and GFRP strips. The properties of the FRP composites are given as we can see here that CFRP strips have tensile modulus of 150 GPA, whereas, the CFRP sheet has higher tensile modulus of 230 GPa and GFRP has tensile modulus of 70 GPA. The ultimate strain values are also given. The GFRP has a higher ultimate strain as compared to the other two FRP sheet or strips. These are the test results we can see here that different concrete strengths have been used for these different types of specimens. And these are the FRP area fraction.

So, in beam part, this is the percentage of FRP and here in the column part, this is the percentage of the FRP reinforcement. And this is the loading that is carried by the specimens. So, each specimen carried the load and these are shown here in this table. We can see here that these two are the control specimen without any FRP reinforcement. So, here this is the average load on this control specimen. And these are the loads on the FRP retrofitted members. We can see here that all the FRP retrofitted members carry load much higher than the control specimen.

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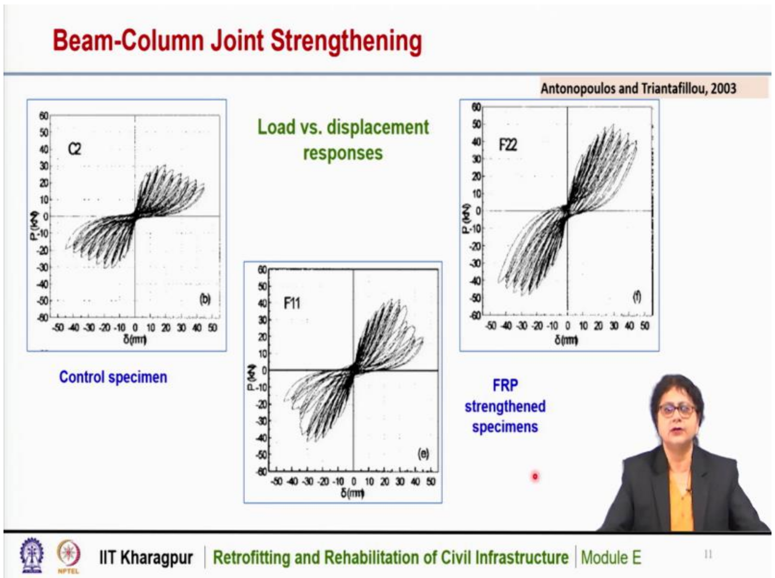

These are the load versus displacement response of some of the specimens. This is the response of the control specimen. This is the response of an FRP retrofitted member with one layer of FRP and this is a response of the FRP retrofitted specimen with two layers of FRP. Here when the load is applied, there is displacement. So, this is the load versus displacement plot. When the load is applied initially there is no stiffness degradation and the load versus displacement plot due to the cyclic loading is linear.

However, when the number of load cycles increases, then in that beam potion some cracks appear, and these cracks appear with a greater number of cycles and this is due to the yielding of the reinforcing steel. As the reinforcing steel yields, it is unable to take any further loading. However, the specimen will still take some loading and beyond this yielding of steel, the load is carried by the FRP.

So, when there is a stiffness degradation, this linearity of the load displacement plots is lost. So, there is nonlinear variation of the load displacement response and we can have this type of nonlinear variation of the response. So, this type of hysteresis loop is obtained from the experiment and so, this is called Hysteresis loops due to the cyclic loading when there is stiffness degradation beyond the yielding of the steel.

Now, for a structure, the ability of that structure in resisting the earthquake load depends on its ability to release the input energy and this release of this input energy can be done by this hysteresis damping. Here, we can see that this hysteresis damping can be estimated by the area of this hysteresis loop. So, larger is the area of this hysteresis loop, more is the hysteresis damping, that means more is the energy dissipation.

So, here also in this diagram, we see that there is significant hysteresis damping because of this nonlinear variation of the load displacement plots and there is significant energy dissipation due to the FRP strengthening of the members. These curves show that as compared to the control specimen there is much higher load carrying capacity of the FRP retrofitted member with one layer of FRP and it is further more for the specimen having two layers of FRP.

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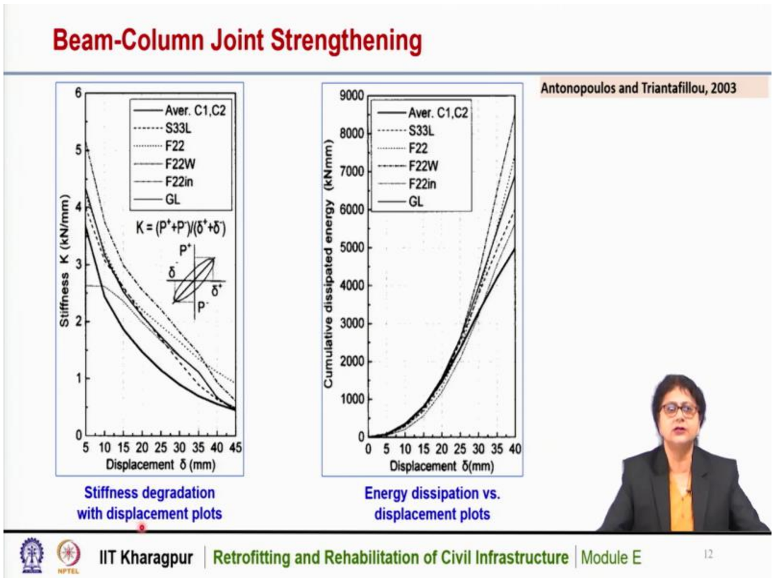

This plot shows the stiffness degradation with displacement. Here due to the cyclic loading, when the steel yields and FRP starts taking up the load, the specimen stiffness deteriorates. So, this is the plot of the stiffness with displacement and we can see that with increase in displacement there is the significant degradation of the stiffness. So, with increase in displacement, the stiffness also degrades.

So, for all the FRP retrofitted members, there is significant deterioration of the stiffness with large displacement. This graph shows the energy dissipation versus displacement plot. We have seen that in these plots also that with larger displacement there is more dissipation of the energy. So, this is very much advantageous because it shows that with larger amount of dissipated energy, it reduces the chance of sudden failure of the member.

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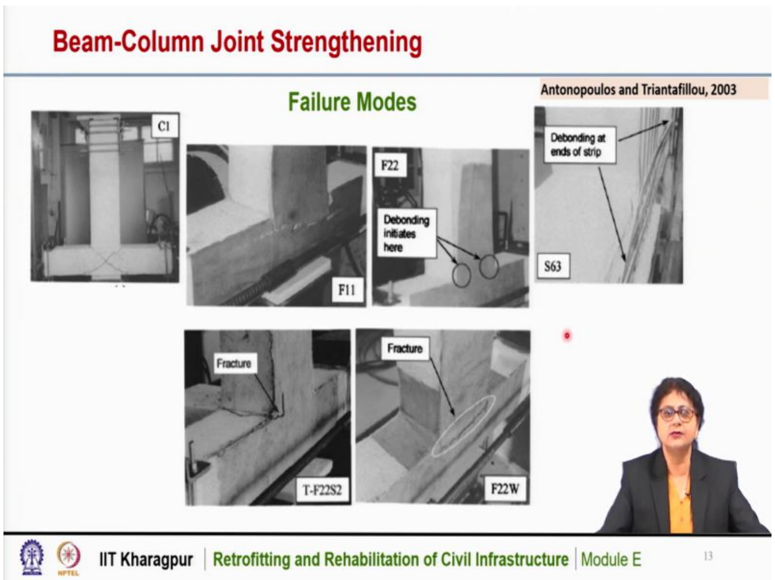

These are the failure modes of some of the specimens. This the failure mode of the control specimen, typical shear cracks diagonal cracks appeared on this specimen because of this cyclic loading. These are the failure modes of the FRP retrofitted members with one layer of FRP and with two layers of FRP. Here the failure occurs due to debonding of the FRP strips.

In this specimen also, we can clearly see that debonding occurs, at the end of the strip in this specimen. These specimens have additional anchorages. So, in these cases there is no debonding, but the specimens fail due to fracture of the FRP. So, in these two specimens, there is a fracture of FRP and because of that the specimen failed.

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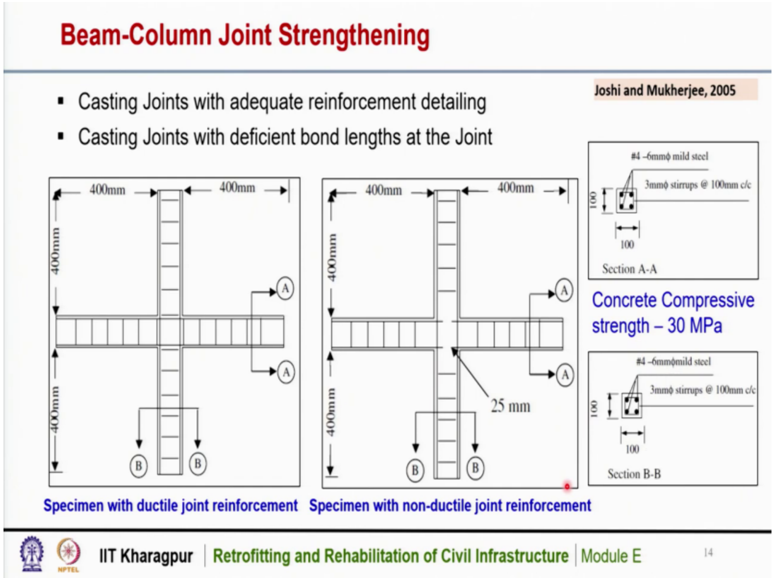

This is another extensive experimental research carried out by Joshi and Mukherjee in 2005. Here a number of specimens were prepared and the joints were having reinforcement. So, some joints were cast with adequate reinforcement detailing and some joints were cast with deficient bond length at the joint. These are the schematic diagrams of the joints with reinforcement, we can see here that these are the main reinforcement and the stirrups are given and, in this specimen, the bond lengths are inadequate.

So, here this specimen is termed as non-ductile joint whereas, here it is termed as ductile joint specimen. The cross section of the specimens is given here 100 × 100, here also it is the same and concrete compressive strength was 30 MPa in both cases. The reinforcements that have been provided are also given here.

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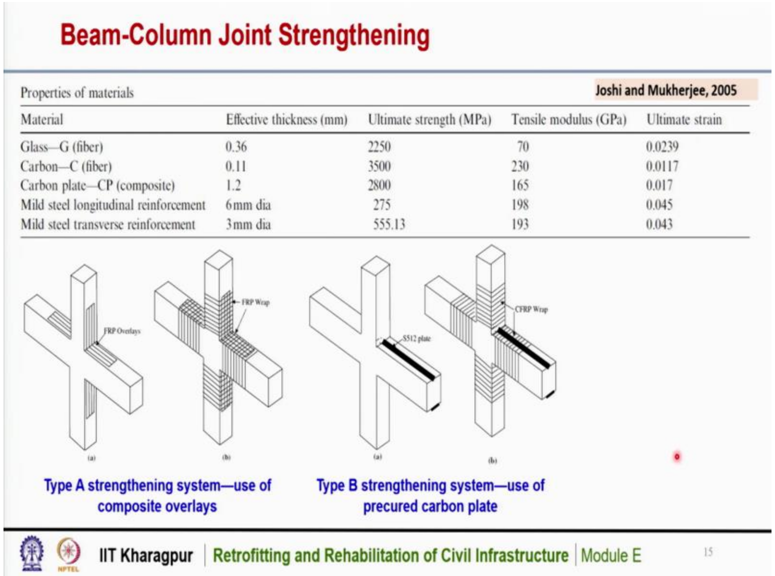

Material	Effective thickness (mm)	Ultimate strength (MPa)	Tensile modulus (GPa)	Ultimate strain
Glass—G (fiber)	0.36	2250	70	0.0239
Carbon—C (fiber)	0.11	3500	230	0.0117
Carbon plate—CP (composite)	1.2	2800	165	0.017
Mild steel longitudinal reinforcement	6mm dia	275	198	0.045
Mild steel transverse reinforcement	3mm dia	555.13	193	0.043

And, these are the schematic diagram of the strengthening system using FRP. Different types of FRP has been used with different wrapping pattern. Glass fiber has been used, carbon fiber has been used and also carbon fiber plates have been used here in this experiment. And with different configurations, here are the properties of the different FRP composites, the glass fiber properties, carbon fiber properties and the carbon fiber plates are also given. And the properties of the steel reinforcement as well.

This is type A strengthening system that has been used for strengthening the joint and this is type B system with pre-cured carbon plates. So, here the FRP strips are provided L shaped and then on that joint, the FRP strips are wrapped. And here in this system, FRP plates are used, and then it is wrapped, so, on all four legs of these joints, the FRP wrapping has been done, but in some portion, the FRP plate has been used and in some portion it is not. So, these are the different types of strengthening system that has been used in the different specimens with carbon fiber strips, glass fiber strips and carbon fiber plates.

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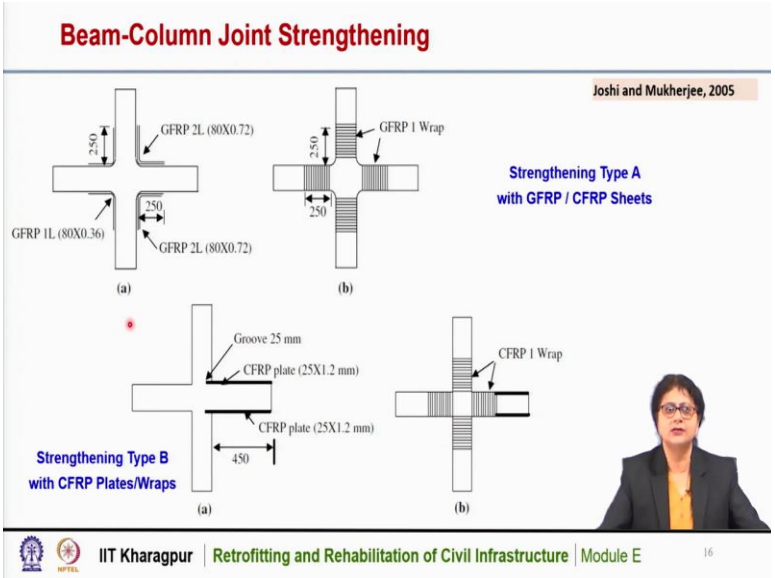

These are some more schematic diagrams of the strengthening system. The dimensions are given here. And in some cases, one layer of FRP has been used and in other cases, two layers of FRP has been used. And this has been done to understand the behaviour of the joint under different wrapping scheme, under different amount of FRP reinforcement and different types of FRP reinforcement.

So, here we can see that GFRP has been used and the dimensions for wrapping these are kept as 250 mm. And in this case when CFRP plate was used. Here one group was made during the casting and the CFRP plate was inserted and then it was filled with epoxy so that the bonding is better. So, here the CFRP plate was given on the full length of this member and then it is wrapped with CFRP strips. So, these are the different configurations and pattern of FRP reinforcement for the beam column joint and those were tested.

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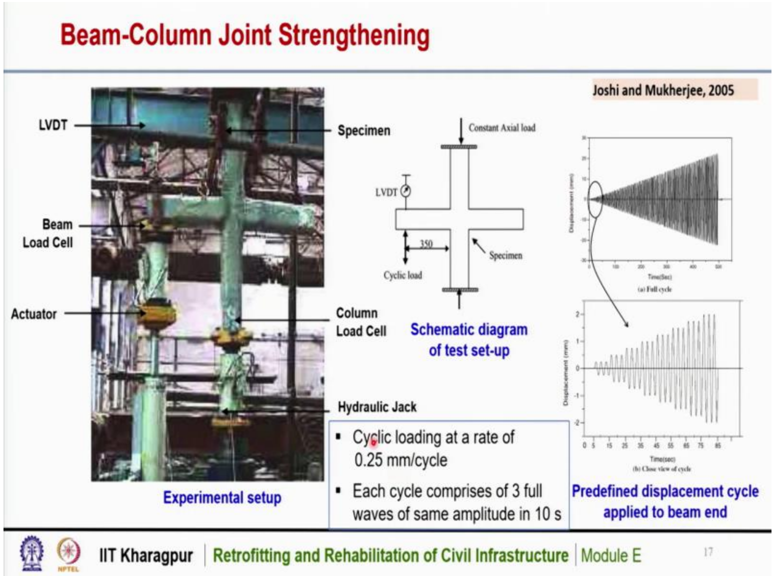

This is the experimental setup for the beam column joint. This is the typical beam column joint and it is wrapped with FRP composites. This is the hydraulic jack for applying the load on the column. So, this is the column and this is the hydraulic jack. So, that axial load can be applied through this and this is the beam part. Here there is an actuator and through this actuator the cyclic loading is applied. It is displacement control and here it is applied cyclically and this is the predefined displacement control cyclic loading on the beam.

So, it looks like this. With increase in time the displacement is increased and this is the larger view of one part of it. So, here the cyclic loading is applied at a rate of 0.25 millimetres per cycle and each cycle comprises of three full waves of same amplitude in 10 seconds and then again, another side.

And this is the schematic diagram of the test setup. This is the column which is under axial loading, and that axial loading is applied to this hydraulic jack and this is the beam where the cyclic loading is applied and this is by the actuator. Now, the displacements are measured by the LVDTs here. So, LVDTs are attached and the displacements are measured.

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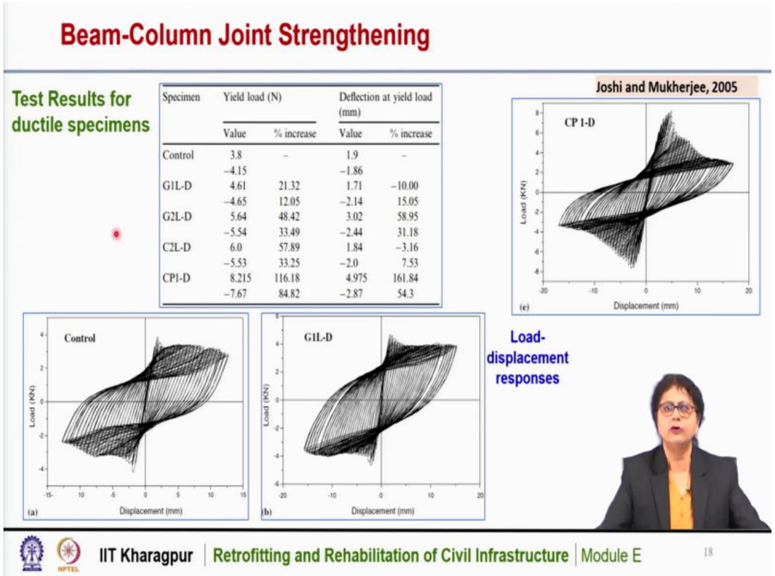

These are the test results for ductile specimens. A large number of experiments were carried out we are showing some of the results. So, here are the test results for ductile specimens, that means with reinforcement detailing with adequate bond length and here it shows that this is the response of the control specimen and these are the response of the FRP retrofitted members. So, this G stands for GFRP retrofitted members and C stands for CFRP retrofitted members and there are different members.

So, the load carried by the control specimen is 3.8 in one side and another side it is 4.15 and we see that for all the retrofitted members, the load carried is much higher than the control specimen. So, there is an increase in the load carrying capacity from 12 percent to 116 percent. So, significant improvement in the load carrying capacity for all the retrofitted members as compared to the control specimen. Now, here also we have seen that hysteresis loops. Initially when there is no stiffness degradation, the response is linear.

And this is shown here, this is for the control specimen and these are for the GFRP retrofitted members and this is for the CFRP retrofitted member. So, here initially there is no stiffness degradation, but with a greater number of cycles, there is steel yielding and cracks appear on the member and because of these cracks appeared on the member and the steel yielding the stiffness of the members degrades. So, with more and more stiffness degradation, there is more displacement and there is non-linearity in the load displacement plots that we can see here very clearly.

So, as there is non-linearity in this load displacement plots or this hysteresis loop, the steel is unable to take any further load because it is already yielded. So, beyond this point the FRP is Taking the load. So, for the FRP retrofitted member, it takes much higher load as compared to the control specimen, because when the steel yields it carries further loading.

And we can see the nonlinear response of the specimen and with more and more loading, there is more nonlinearity of these specimens and this shows that there is the energy dissipation of the member. So, here we can see that the load carried by the CFRP retrofitted member is higher as compared to GFRP retrofitted member and that shows that more energy dissipation is there in the CFRP retrofitted members.

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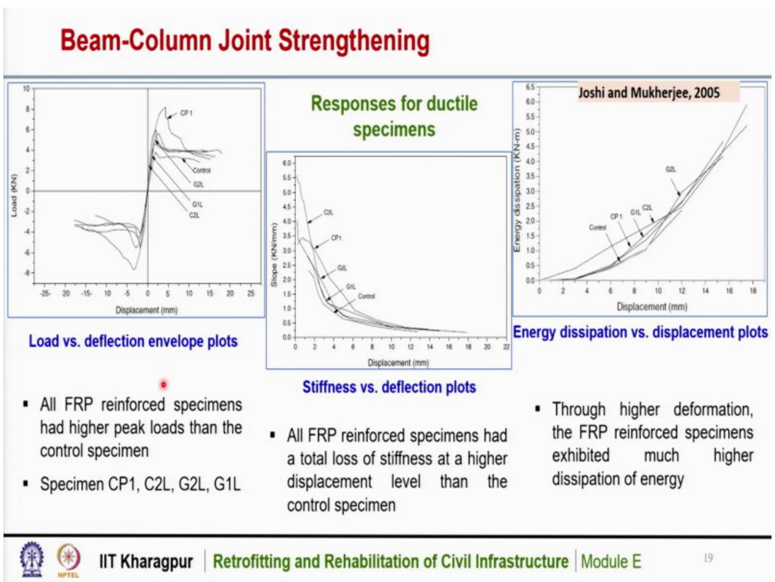

This curve shows the load versus deflection envelope plots for the different types of specimens, the control specimen, the CFRP retrofitted members and the GFRP retrofitted members. So, the plots show that all FRP retrofitted specimens had higher peak loads than the control specimen. The maximum load is taken by the CFRP retrofitted member the specimen CP1, here we can see. CP1 has the highest load followed by the specimen, C12 with carbon fiber two layers of wrapping, then with glass fiber two layer of wrapping and then glass fiber wrapped with one layer.

So, these are the load versus deflection envelope plots and this plot shows the stiffness versus deflection for the different types of specimens. So, here also it shows that all FRP retrofitted specimens had a total loss of stiffness at a higher displacement level than the control specimen. So, we can see here that the stiffness degrades and the displacement also increases.

So, this is advantages because that reduces the chance of abrupt failure of the specimen. This graph shows the energy dissipation versus displacement plots of the different types of specimens. Here it shows that through higher deformation, the FRP retrofitted specimens exhibited much higher dissipation of energy. So, here we see that this is the control specimen but the FRP retrofitted specimens exhibited much higher dissipation of energy with higher displacement.

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These are the failure modes of different types of specimens, which are ductile. Here is the failure mode of the control specimen. Here it is seen that the control specimen failed due to the formation of hinge at this joint and this portion the concrete is spalled out. So, there is a hinge that is formed and that may cause rotation of the beam member with respect to the joint. So, this control beam fails due to this formation of hinge at this location.

And these are the failure modes of the FRP retrofitted members. This is GFRP retrofitted member and these are the CFRP retrofitted members. Here these members failed due to cracks appeared at the joint because of significant amount of FRP wrapping. There is no formation of this type of hinge at the joint and the specimen failed due to this formation of cracks at the joint here.

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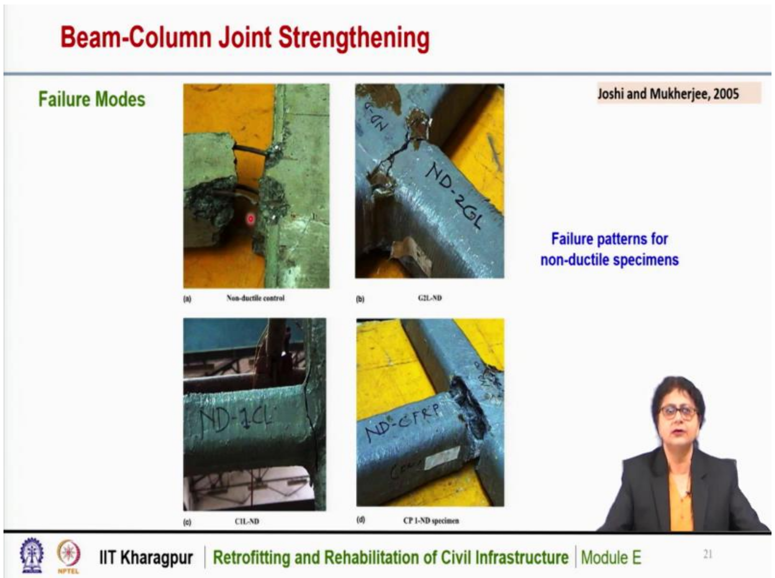

These are the failure pattern of non-ductile specimens. This is the control specimen and the specimen fail due to the pull out of this reinforcement here at the joint. These specimens failed due to the formation of cracks at the joints and this specimen with carbon fiber strips failed when the strips came out at the joint and also the strip was not experiencing any failure or debonding but it was pulled out from the joint. So, with that the specimen failed. So, these are the typical failure patterns of the non-ductile specimens.

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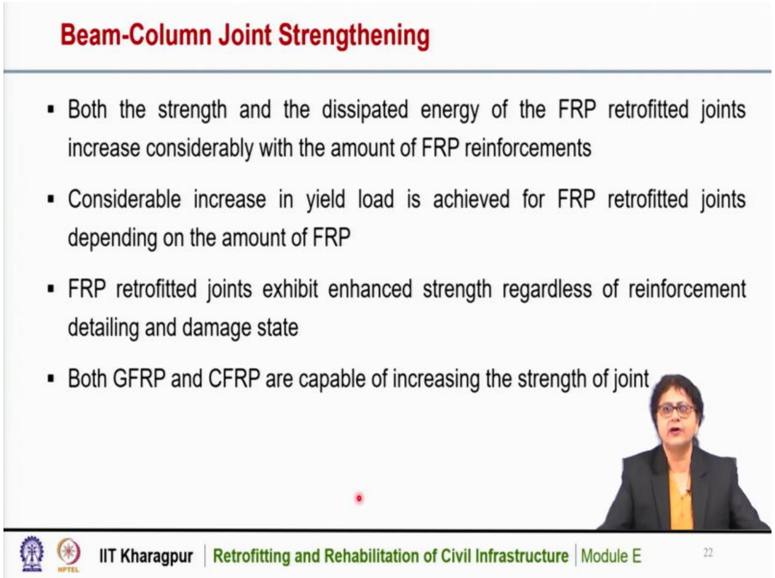

So, beam-column joints strengthening with FRP is a complex thing and the response is important to understand. So, here is the summary of the observations obtained from different experiments and research. Both the strength and the dissipated energy of the FRP retrofitted joints increase considerably with the amount of FRP reinforcement. As the level of FRP reinforcement increases, the strength and the dissipated energy of the FRP retrofitted members increase considerably. The considerable increase in the yield load is also achieved for FRP retrofitted joints, depending on the amount of FRP.

The FRP retrofitted joints exhibit enhanced strength, regardless of the reinforcement detailing and the damaged state. So, whether the reinforcement detailing is inadequate or not, or whether there is any cracking in the joint or not, the FRP retrofitted joints with sufficient amount of FRP that show enhanced strength and performance. Both GFRP and CFRP are capable of increasing the strength of joint.

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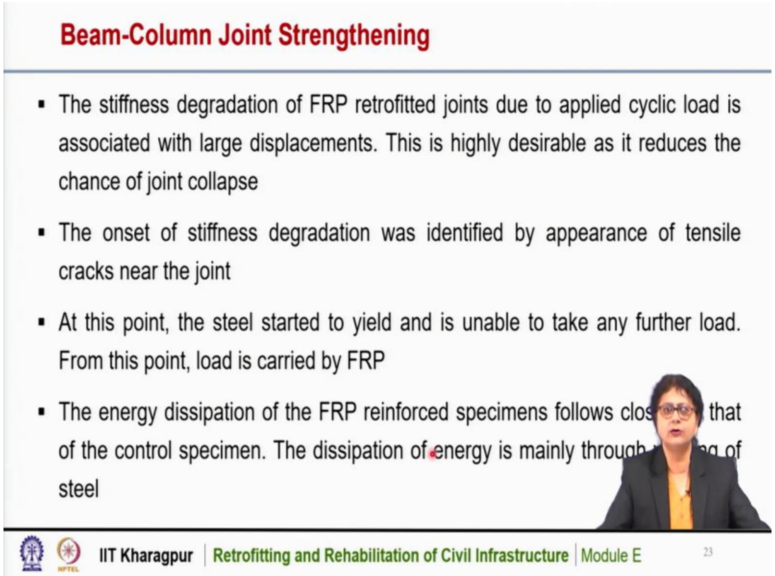

The stiffness degradation of FRP retrofitted joints due to the applied cyclic load is associated with large displacement. So, this is also advantages and highly desirable as it reduces the chance of joint collapse. The onset of stiffness degradation was identified by the appearance of tensile cracks near the joint and at this point the steel started yielding and is unable to take any further load. And from this point the load is carried by the FRP. The energy dissipation of the FRP retrofitted specimens follows closely to the control to that of the control specimen. The energy dissipation of the FRP reinforced specimens follows closely to that of the control specimen. The dissipation of energy is mainly through yielding of the steel.

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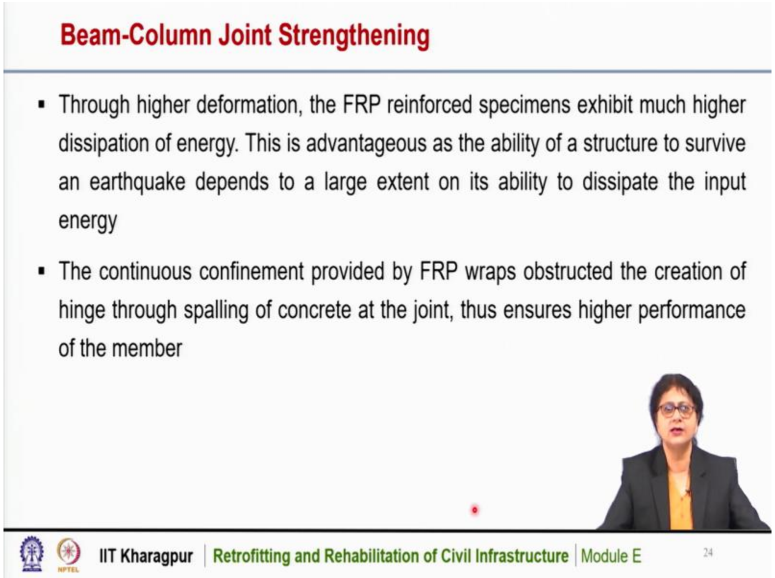

Through higher deformation, the FRP reinforced specimens exhibit much higher dissipation of energy. This is advantageous as the ability of a structure to survive an earthquake depends to a large extent on its ability to dissipate the input energy. The continuous confinement provided by FRP wraps obstructed the creation of hinge through spalling of concrete at the joint thus ensures higher performance of the member.

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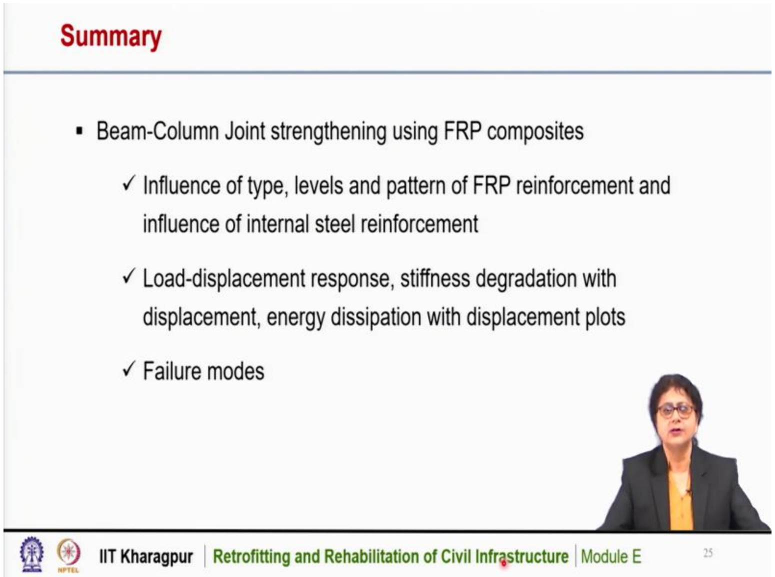

So, to summarize we have discussed beam column joint strengthening using FRP composites.

We have discussed the influence of different parameters like, types of FRP reinforcement, levels of FRP reinforcement and the different patterns of FRP reinforcement. We have also discussed the influence of internal steel reinforcement on the load displacement, response of the members. The stiffness degradation with the displacement and the energy dissipation with the displacement plots.

So, these are the responses that has been discussed and it shows that when the beam-column joint is retrofitted with FRP composites, there is a significant energy dissipation with large deformation and that is advantageous to restrict or reduce the sudden failure of the member. We have also discussed the sudden failure modes of the beam-column joints which are retrofitted with FRP composites.

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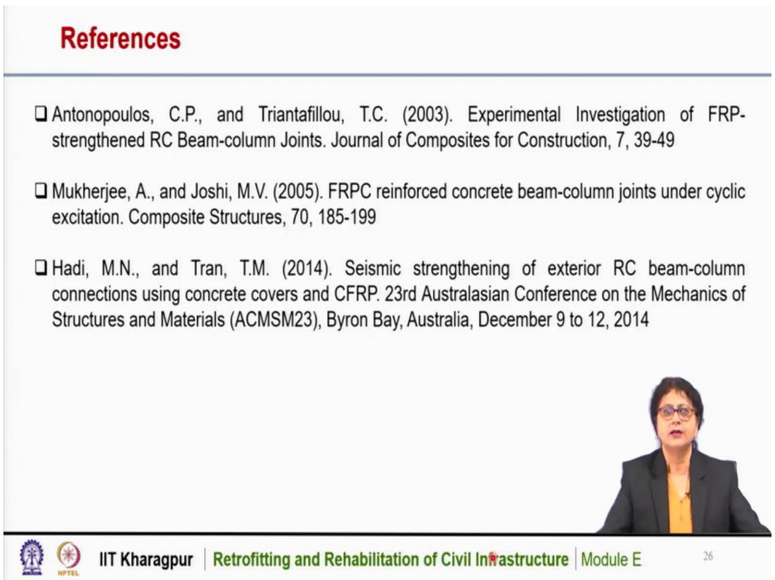

These are the references for this lecture. Thank you.