Retrofitting and Rehabilitation of Civil Infrastructure
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Lecture 27
FRPC in Axial Strengthening of Structural Members-II

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

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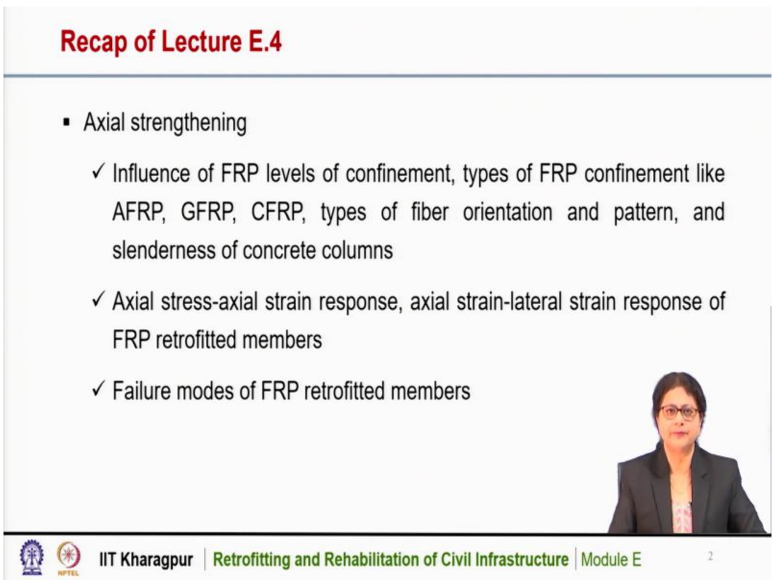

In the previous lecture, we have discussed axial strengthening of FRP retrofitted column members. We have discussed the influence of several parameters like FRP levels of confinement, different types of FRP confinement, example AFRP, GFRP or CFRP, different types of fibre orientation and fibre pattern and the slenderness of concrete columns.

The responses of FRP retrofitted column members were discussed in terms of axial stress versus axial strain response, axial strain versus lateral strain variation of FRP retrofitted members. We have also discussed the failure modes of FRP retrofitted members.

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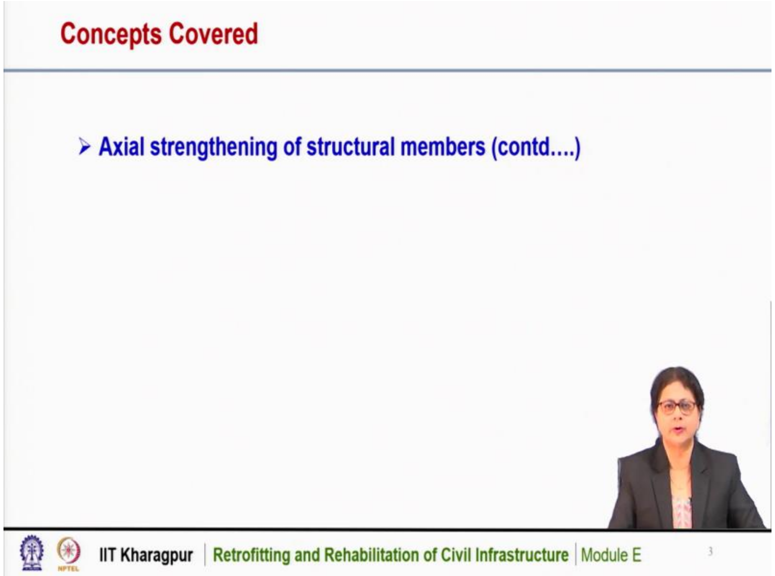

Today, we will continue our discussion with axial strengthening of structural members using fibre reinforced polymer composites.

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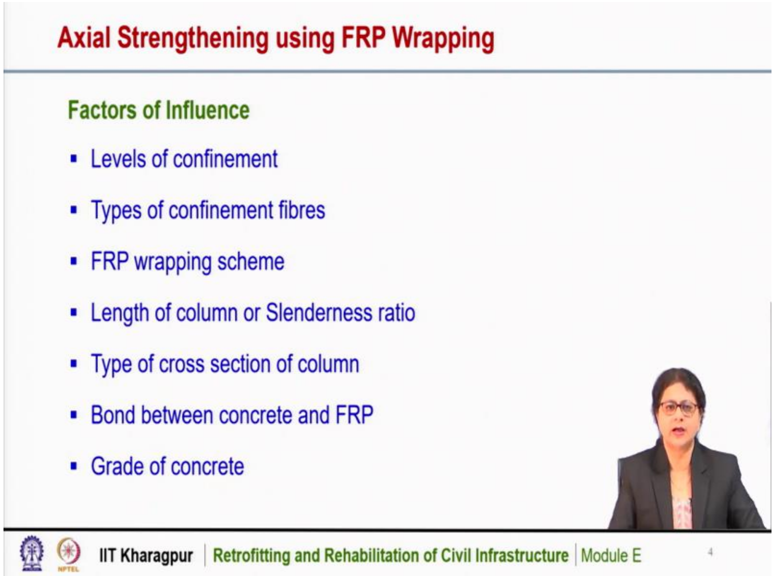

In the previous lecture, we have discussed that there are several factors that influence the performance of FRP retrofitted columns. The parameters that influence the behaviour of FRP retrofitted columns are levels of confinement, types of confinement fibres, FRP wrapping scheme, slenderness ratio of column, cross section of column, bond between concrete and FRP and grade of concrete. We have discussed the influence of several parameters in the previous lecture. And in today's lecture, we will discuss the influence of some other parameters.

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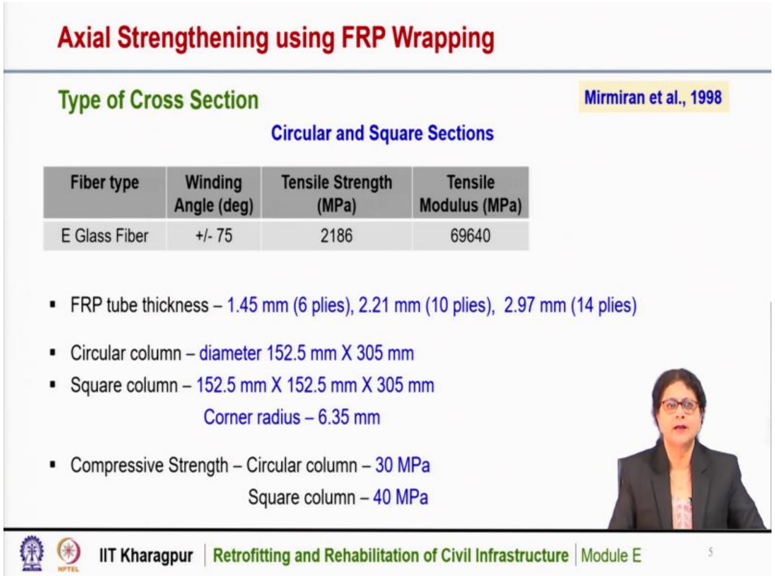

Type of cross section of columns has a significant influence on the behaviour of FRP retrofitted members. In this experiment by Mirmiran et al. in 1998, they have conducted experiments on circular columns and square columns. The glass fibres were used as E glass fibre with winding angle +/- 75º and the tensile strength of the fibre was 2186 MPa and the tensile modulus was 69640 MPa.

The FRP tube having different thicknesses of 1.45-millimetre, 2.21-millimetre and 2.97-millimetre. The circular column has diameter 152.5 millimetre with length 305 millimetre, whereas the square columns have dimension 152.5 millimetre and the length was 305 millimetre. The square columns had corner radius of 6.35 millimetre. Both the columns have different compressive strength. Circular columns have 30 MPa, compressive strength and for square column it was 40 MPs. The columns were confined with E glass fibre, with different levels of confinement having different FRP thickness and they were tested under axial loading.

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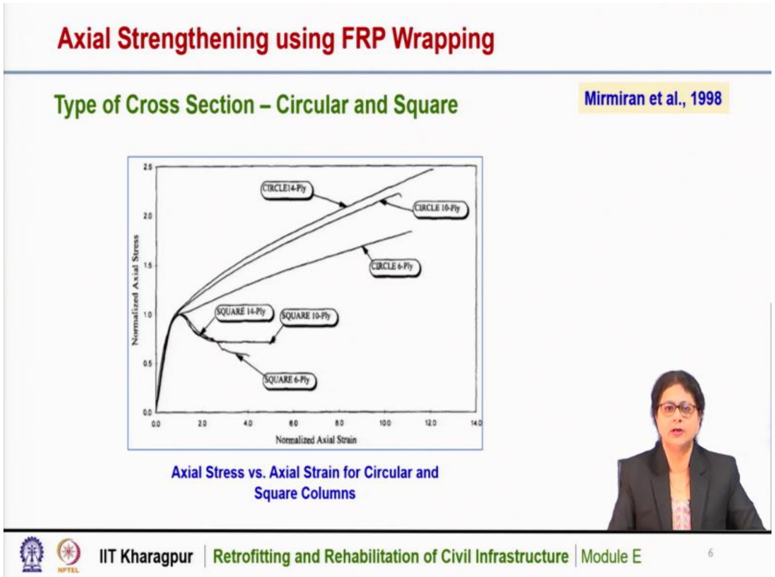

This is the response of the FRP retrofitted columns of circular as well as square columns, having different levels of confinement. We can see here that the this is the normalised axial stress versus normalised axial strain plots of the columns. The columns having circular cross section and with 14 plies have maximum improvement in the axial stress.

So, we can see here that this is the stress strain plot of the column having 14 plies and this is with 10 plies and both are circular, whereas this is the plot for the circular column having 6 plies and these are the plots for the square columns. This is for 6 plies, this is for 10 plies and 14 plies. So, we see here that there is a significant difference in the square column and the circular column response.

The improvement in strength is maximum for the circular columns, whereas, for square columns it is much less. It also depends on the levels of confinement. Higher is the level of confinement, higher is the improvement in the axial strength and for the difference in the cross section also there is a significant difference. The square column has much lesser strength as compared to the circular columns.

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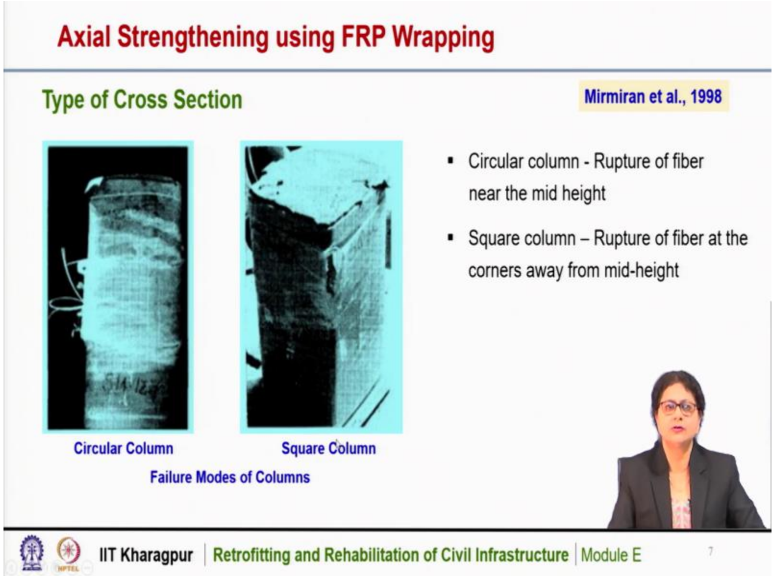

These are the failure modes of the square columns and the circular columns. We can see here that, this is a photograph of the circular column after failure and this is the photograph of the square column after failure.

The circular column failed due to rupture of fibre near the mid height, you can see here there is a rupture of fibre and the square column also failed due to rupture of fibre, but at the corners. So, here at the corners there is high stress concentration and because of that, the square column failed at the corner location by rupture of fibre.

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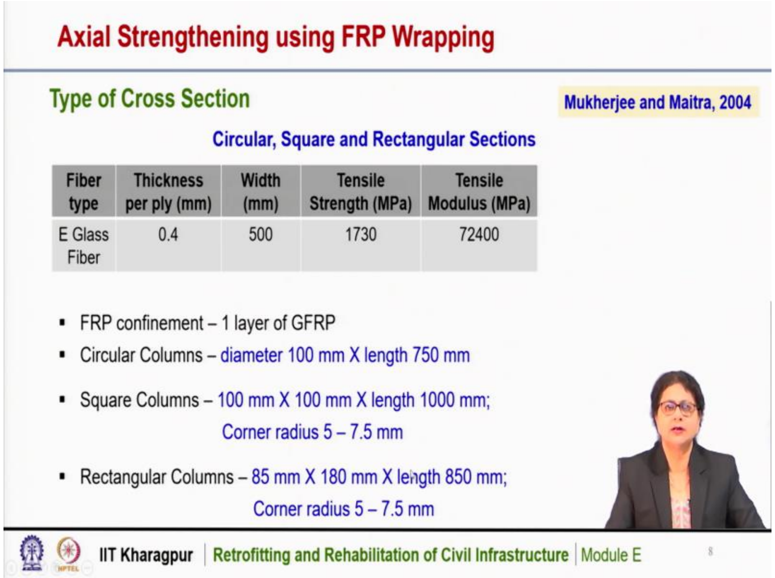

In this experiment, Mukherjee and Maitra, here also different types of cross sections were investigated. Circular columns, square columns and rectangular columns were tested under axial loading. The confinement was done by E glass fibre having thickness 0.4 millimetre and tensile strength 1730 MPa.

The circular columns had diameter 100 millimetre and length 750 millimetre, square columns had dimension 100 millimetre and length 1000 millimetre and rectangular columns had dimension 85 millimetre × 180 millimetre and length 850 millimetre. The corners were rounded off and for square column the corner radius was kept at 5 to 7.5 millimetre. Whereas, for rectangular columns, it was 5 to 7.5 millimetre. Both for square columns and rectangular columns, the corner radius was maintained at 5 to 7.5 millimetre.

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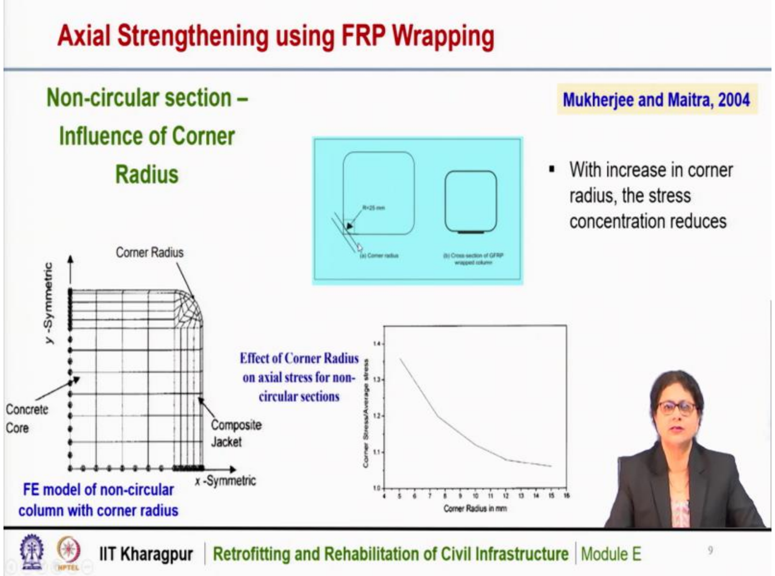

This is a schematic diagram of the non circular columns, we can see here that the corners are rounded off, corners are rounded off to reduce the stress concentration at these locations. With increase in the corner radius, actually the stress concentration reduces. A FE model has been developed for non circular columns, we can see here that this is the one fourth of the column has been modelled in finite element and this is the concrete and this is the FRP jacket.

In this model, the model was analysed to understand the influence of corner radius on the stress development. So, based on this analysis, it was found that corner radius has a significant influence on the stress. This is the plot of the corner radius and the corners stress with average stress.

So, effect of corner radius on axial stress for non circular section shows that with increase in corner radius, there is a significant decrease in the corner stress. So, this variation is nonlinear and this shows that higher is the corner radius lower is the stress at the corners for non-circular sections.

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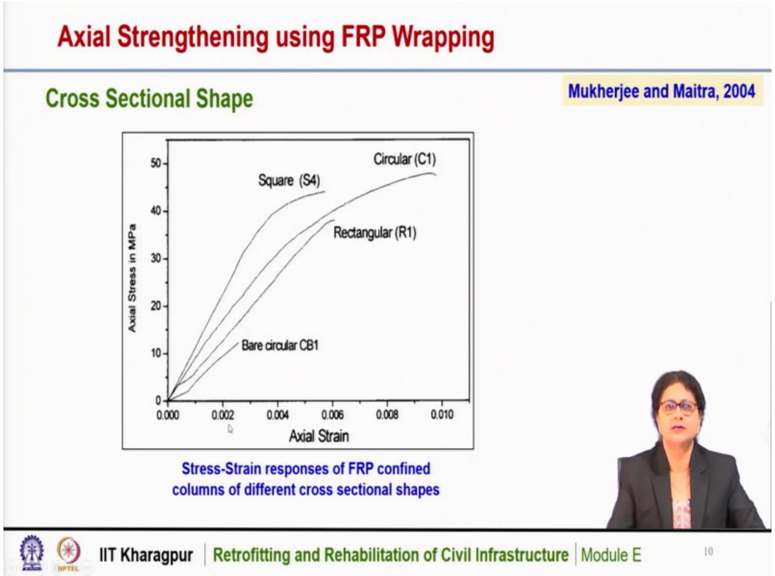

The experiments were carried out for circular columns, square columns and rectangular columns. And these are the stress strain responses of the FRP confined columns of different cross-sectional shapes. So, here we can see that, this is for the square column, this is for the circular column and this is for the rectangular column and this is the bare column or the control column that is circular without any FRP confinement.

So, the plots show that there is maximum increase in axial stress is for circular columns, next is for square columns and next is the rectangular column. So, the cross-sectional shapes have significant influence on the stress strain behaviour of the columns. In case of circular column, the confinement is uniform and that is why the increase in strength is maximum for circular column. In case of square and rectangular columns, the confinement is not uniform and corner radius plays a significant role. So, the increase in strength is much less as compared to circular columns.

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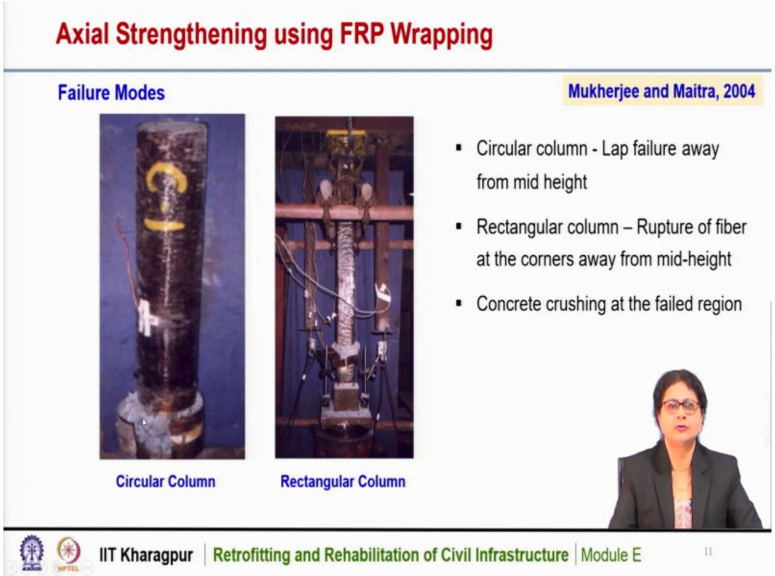

These are the failure modes of circular column and non circular column, here this shows that this is the circular column which fails due to lap failure away from the mid height and there is also concrete crushing at the failed region. Here, this is the failure mode of the rectangular column. In case of rectangular column, the column fails due to rupture of fibre at the corners and that is away from the mid height.

You can see here, that it is near the end there is rupture of the fibres and due to that the column failed. There is concrete crushing also at the failed region as we can see here from the picture. So, there is significant difference in the behaviour of circular column and non circular column. In case of circular column, the confinement effect is uniform and that is why the gain in strength is also much more as compared to non circular sections.

In case of non-circular sections, the corner radius plays a significant role. Higher is the corner radius, lower is the stress concentration. If the corner radius is not provided, then there is high stress concentration and the column fails due to rupture of fibre at those locations.

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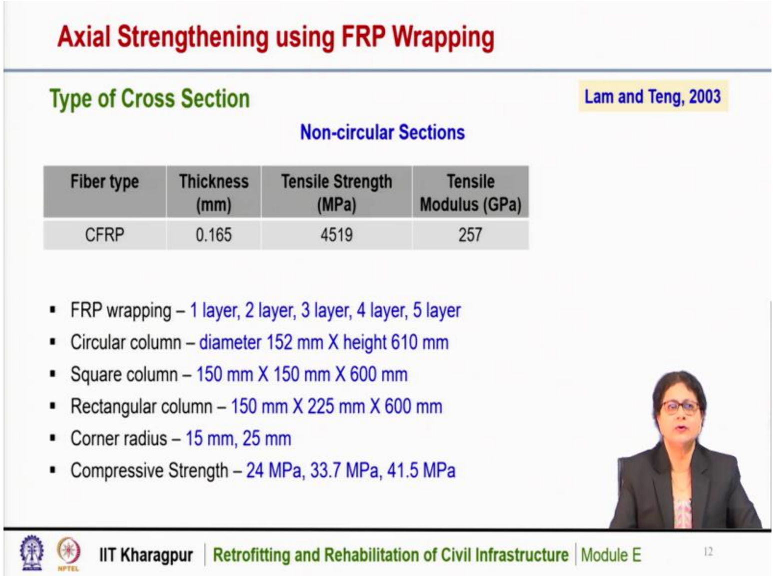

In this experimental research, the researchers have also reviewed some of the previous works. The experiment was done with CFRP confinement material. And these are the properties of the CFRP composites. Thickness was 0.165 millimetre and tensile strength was 4519 MPa with tensile modulus as 257 GPA.

Different layers of FRP wrapping were used for confining the columns 1-layer, 2-layer, 3-layer, 4-layer and 5-layers of confinement. Circular columns, square columns and rectangular columns were tested. The dimensions are given here and for the non-circular columns, the corners were rounded off and two corner radius were tried. One is 15 millimetre and the other is 25 millimetres. The compressive strength of the columns varied as 24 MPa, 33.7 MPa and 41.5 MPa.

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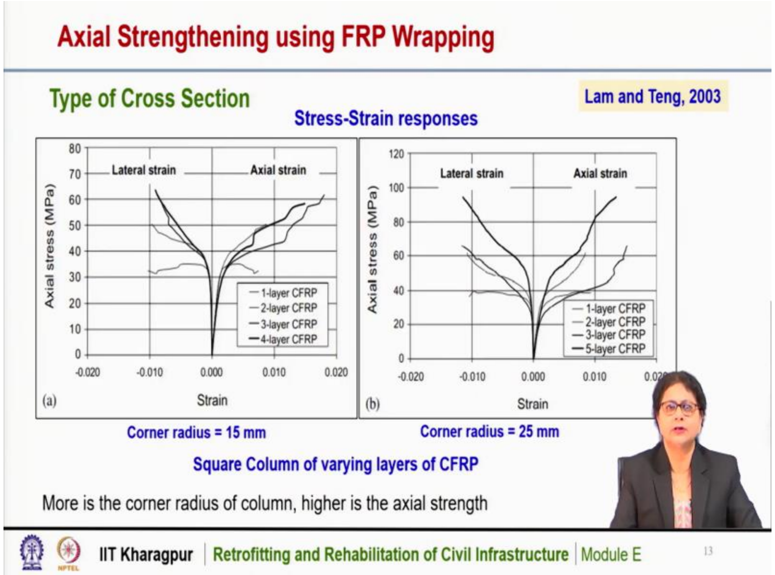

These are the responses of the square columns of varying layers of CFRP composites. We can see here that this is the plots of axial stress versus axial strain and this is the axial stress versus lateral strain for square columns. And here, in this case, the corner radius was 15 millimetres. So, this shows that there is a significant improvement in the axial stress for the confined columns.

And with increase in confinement as expected, the axial stress also increases as compared to the bare column. So, this shows that there is a significant improvement when the corner radius was 15 millimetre and lateral strain also increases with axial strain. This is the plot for square columns having corner radius of 25 millimetre and with different layers of CFRP confinement. This shows that with increase in confinement, the increase in axial stress is there.

And here it shows that there is more increase in the stress as compared to columns having corner radius 15 millimetre. So, here the maximum increase in stress is about 60 MPa whereas, when the corner radius is 25 millimetre, the improvement in axial stress is about 90 Mpa.

So, there is significant increase in the actual stress when the corner radius increases. This has also been observed from the numerical studies by Maitra and Mukherjee and that shows from the finite element model that minimum 15 millimetre radius is desirable and 25 millimetre can be maximum.

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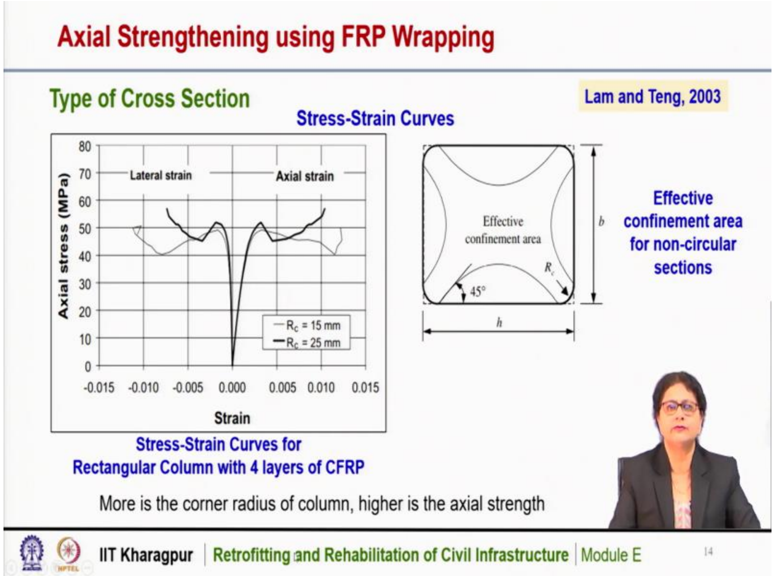

These are the stress strain responses of the rectangular columns with four layers of CFRP and with a different corner radius. So, here it shows that the plots are for two different corner radius one is for 15 millimetre and the other is for 25 millimetre. So, here also it shows that for the rectangular column when the corner radius is 25 millimetre, the increase in axial stress is more as compared to the column having corner radius of 15 millimetre.

So, corner radius plays a crucial role in case of non circular sections and we have to provide the corners to be rounded off, so that, the stress concentration is reduced and it can take higher load. The researchers have mentioned that the for non-circular section the effectiveness of confinement is like this.

So, in case of a non circular section, the effectiveness of confinement is not uniform as compared to circular section, where the effect of confinement is uniform, whereas, for non circular section the confinement is like this. So, this is the corner radius and the effectiveness depends also on the lateral dimension of the member. So, this is the effective confinement area for the non circular sections.

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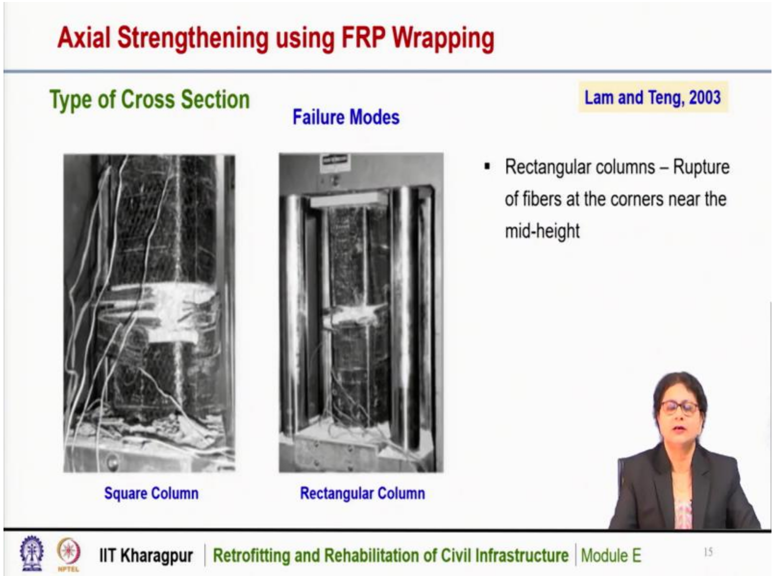

Since the effective confinement area is less in case of non circular sections, therefore, increase in the actual stress is also less as compared to circular cross sections. These are the failure modes of the square columns and the rectangular columns. Both the columns failed due to rupture of fibres at the corners near the mid-height. So, in both cases the fibres break near the mid-height and due to the breakage of the fibres the column failed.

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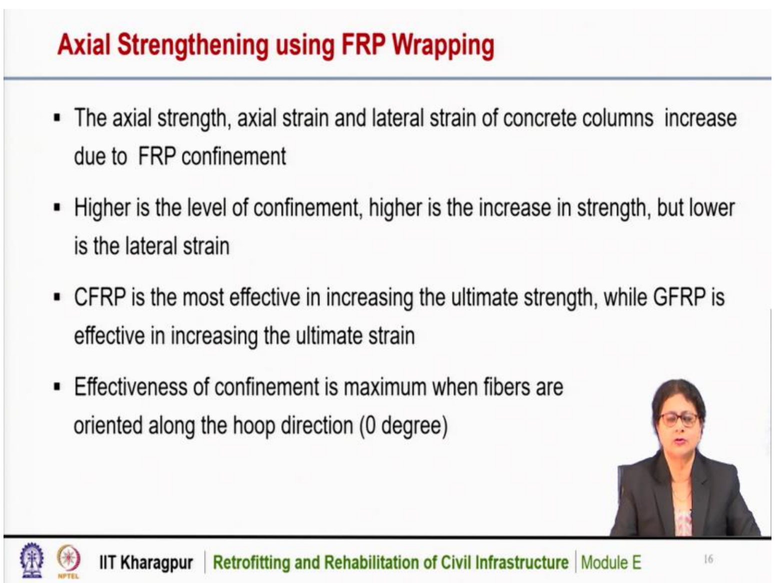

So, we have discussed several research works that investigated the influence of different parameters on the stress strain behaviour of FRP confined concrete columns. We have discussed the effect of levels of confinement, different types of FRP, different wrapping pattern and different cross sections, slenderness ratio etcetera.

Now, the major observations for axial strengthening using FRP composites are summarised here. The axial strength, axial strain and lateral strain of concrete columns increase significantly due to the FRP confinement. If the column is confined with fibre reinforced polymer composites, the axial strength increases significantly. Axial strain and lateral strain also increase significantly due to confinement.

Higher is the level of confinement, higher is the increase in strength that we have seen from several experimental works, but lower is the lateral strain. That means, if the level of confinement increases, the lateral strain actually decreases. That means, with increase in confinement the ductility actually decreases.

CFRP is the most effective in increasing the ultimate strength as compared to the other two types of composites like AFRP and GFRP. However, GFRP is more effective in increasing the ultimate strain, because the strain at failure for GFRP is generally much higher as compared to AFRP and CFRP. So, the columns which are confined with GFRP, generally has higher strain at failure. So, they are more ductile as compared to CFRP or AFRP confined columns.

However, the strength increase is more in case of AFRP and CFRP as compared to GFRP confined column. The effectiveness of confinement is maximum when the fibres are oriented along the hoop direction that is 0° with respect to the length of the member. And that we have seen that when the fibres are oriented along the length, the strength of the composite is maximum. So, the effectiveness of confinement is also maximum when the fibres are oriented along the hook direction.

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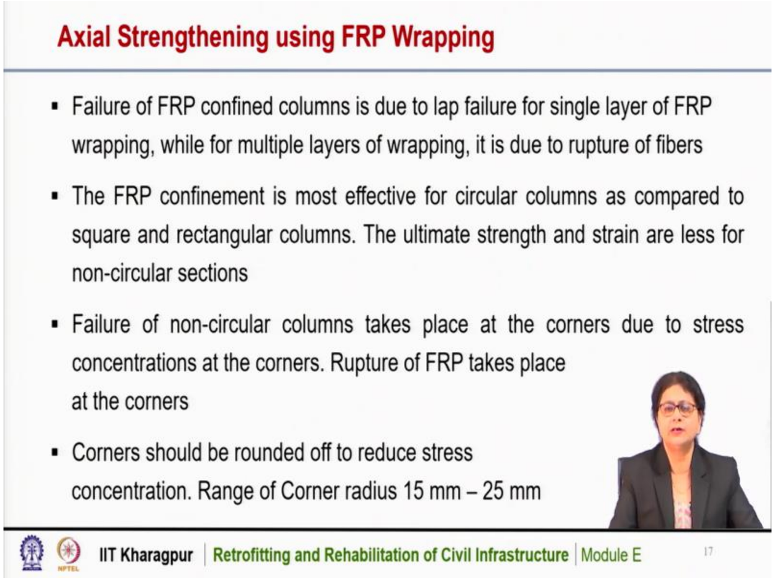

Failure of FRP confined column is due to lap failure for single layer of fibre composite. While for multiple layers of wrapping it is due to rupture of fibres. So, in many cases, it has been seen that when the column is wrapped with one layer of FRP composite, there may be lap failure. While in case of multiple layers of wrapping, it is due to rupture of the FRP.

The FRP confinement is most effective for circular sections as compared to square and rectangular sections. In case of circular sections, the confinement effect is uniform. Whereas, in case of square and rectangular sections, it is not uniform. The ultimate strength and strain are less for non circular section as compared to circular sections.

Failure of non circular columns takes place at the corners due to stress concentration at the corners. And because of the stress concentration rupture of FRP takes place at the corners. And it has been seen that for non circular sections, the failure is due to rupture of FRP at the corners. The corners should be rounded off to reduce the stress concentration and the range of corner radius is 15 millimetre to 25 millimetre. So, it is very important that the corners of the non circular section should be rounded off to reduce the stress concentration and the range of corner radius is 15 millimetre to 25 millimetre.

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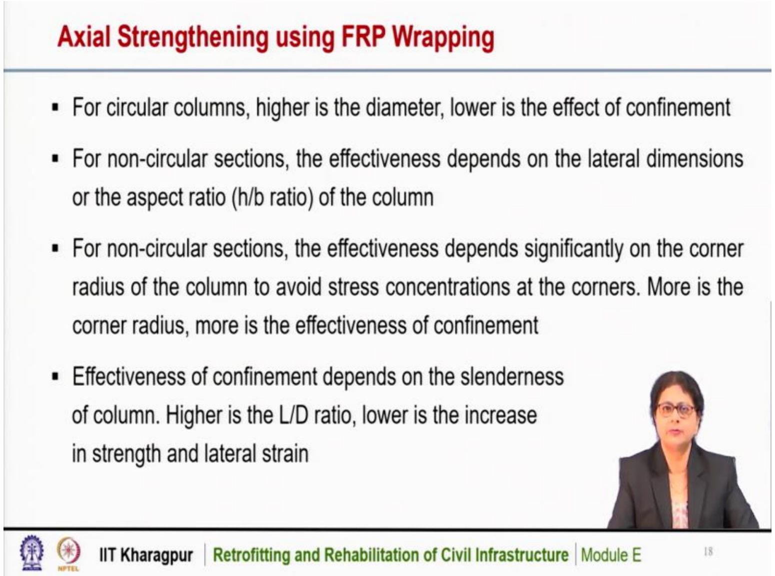

For circular columns, higher is the diameter lower is the effect of confinement. For non circular sections, the effectiveness depends on the lateral dimensions or the aspect ratio of the column that is h/b ratio. So, dimension of the columns also influences the behaviour. For circular section, more is the diameter, less is the effect of confinement and for non circular section, it depends on the ratio of the two sides.

For non circular sections, the effectiveness depends significantly on the corner radius of the column to avoid stress concentration at the corners. More is the corner radius; more is the effectiveness of confinement. Effectiveness of confinement depends on the slenderness of the column. Higher is the L/D ratio, lower is the increase in strength and lateral strain.

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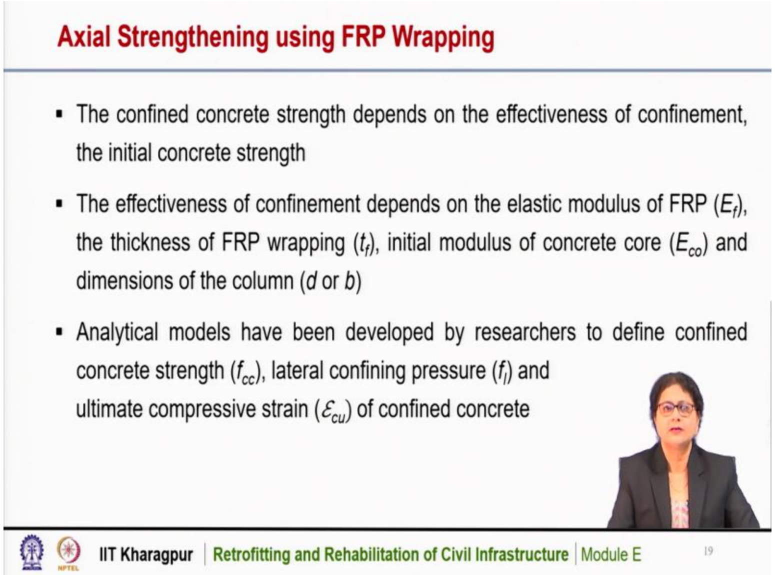

The confined concrete strength depends on the effectiveness of confinement and also on the initial concrete strength. The effectiveness of confinement depends on the elastic modulus of the FRP, the thickness of FRP wrapping and the initial modulus of the concrete core and also on the dimensions of the column.

So, for FRP confined column, how much will be the increase in the strength or strain, that depends on the effectiveness of confinement. The effectiveness of confinement depends significantly on the stiffness of the confining material and the elastic modulus of FRP, the thickness of FRP all plays a significant role in this.

The initial modulus of concrete and the dimensions of column also influence the behaviour of the FRP retrofitted columns. Analytical models have been developed by researchers to define the confined concrete strength, lateral confining pressure and ultimate compressive strain of confined concrete.

So, to understand the behaviour of FRP confined columns, based on the different experimental works analytical models have been developed by researchers, to define the confined concrete strength, how much will be the increase in the strength, what will be the confining pressure and what will be the ultimate compressive strain of confined concrete that has been modelled by several researchers.

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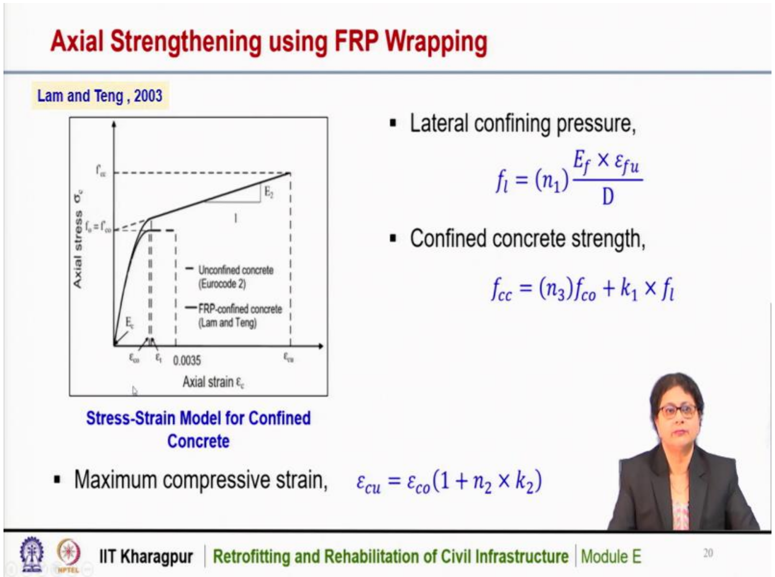

And the model for confined concrete is bilinear model. We can see here this is a typical bilinear model for confined concrete. This is the response of the unconfined concrete and this is the response of the confined concrete. So, different research works have been carried out to estimate the lateral confining pressure.

So, lateral confining pressure depends on the stiffness of the confining material, the elastic modulus of the FRP, the ultimate strain of the FRP composite and the diameter or the dimension of the concrete column. The confined concrete strength can be expressed in this form it depends on the initial concrete strength f_{co} and also on the lateral confining pressure.

So, the confined concrete strength has been obtained from the different research work. It depends on the effectiveness of confinement. So, it depends on the lateral confining pressure and also on the initial concrete strength and maximum compressive strength ε_{cu}.

Lateral confining pressure, $f_l = (n_1)\,(E_f \times \varepsilon_{fu})/D$

Confined concrete strength, $f_{cc} = (n_3)\,f_{co} + k_1 \times f_l$

Maximum compressive strain, $\varepsilon_{cu} = \varepsilon_{co}\,(1 + n_2 \times k_2)$

So, these are the forms of maximum compressive strain, lateral confining pressure and confined concrete strength. Different researchers have developed different stress strain model and that has been used to design the FRP confined concrete columns.

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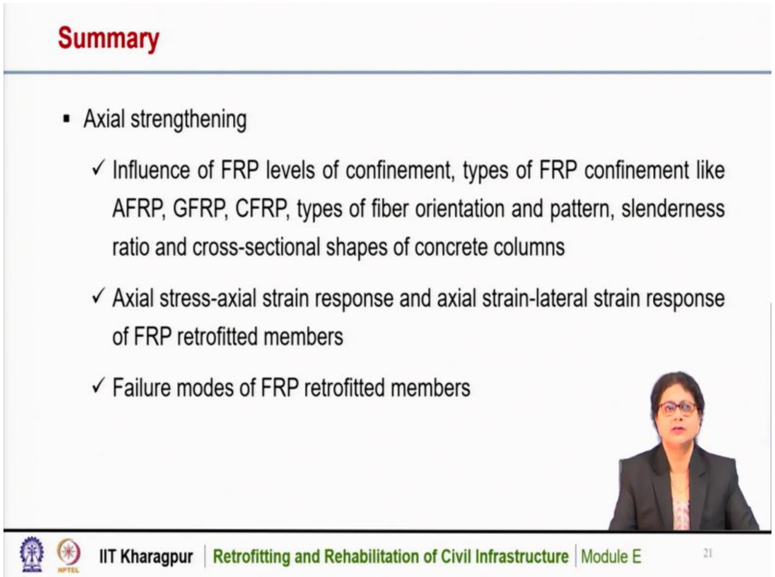

So, to summarise, we have discussed today the axial strengthening of concrete columns confined by fibre reinforced polymer composites. And in these two lectures, we have discussed the influence of different parameters, the different levels of FRP confinement, different types of FRP confinement like AFRP, GFRP or CFRP.

The different types of fibre orientation and different FRP patterns. The slenderness ratio of column and cross-sectional shapes also have been discussed. The responses of the FRP confined columns were discussed in terms of axial stress versus axial strain curves and axial strain versus lateral strain curves of FRP retrofitted members. We have also discussed the failure modes of FRP retrofitted columns.

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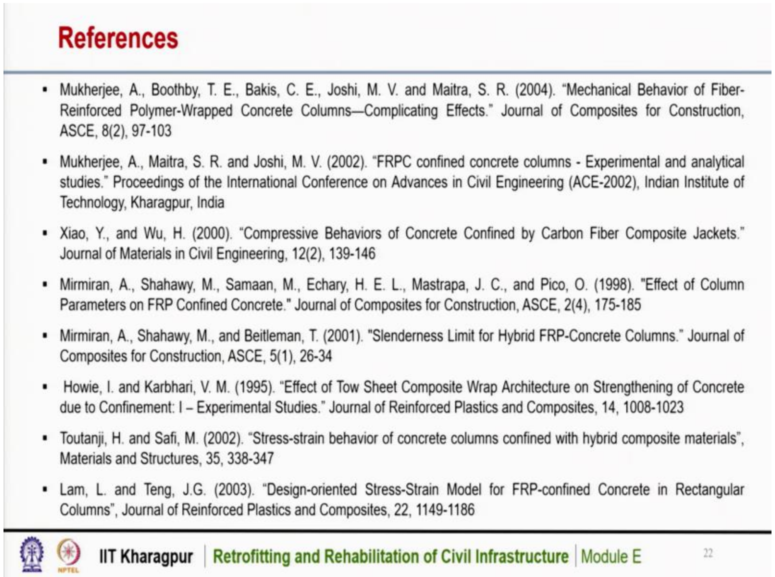

These are the references for axial strengthening of columns by FRP composites. Thank you.