Retrofitting and Rehabilitation of Civil Infrastructure

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Lecture 37

Design Approach for Axial Strengthening

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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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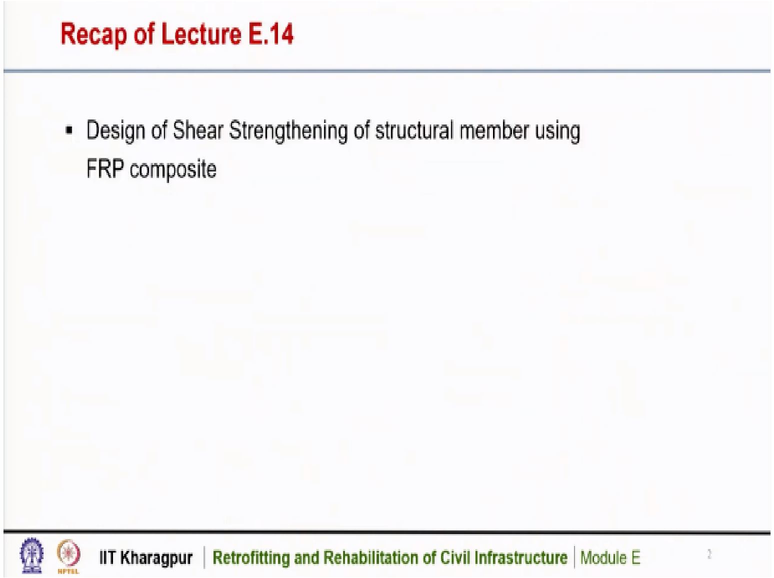

In the previous lectures we have discussed the design approaches of shear strengthening of structural members using FRP composites and also a design example of shear strengthening of structural member using FRP composite.

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Today we will discuss design approaches for axial strengthening by fiber reinforced polymer composites.

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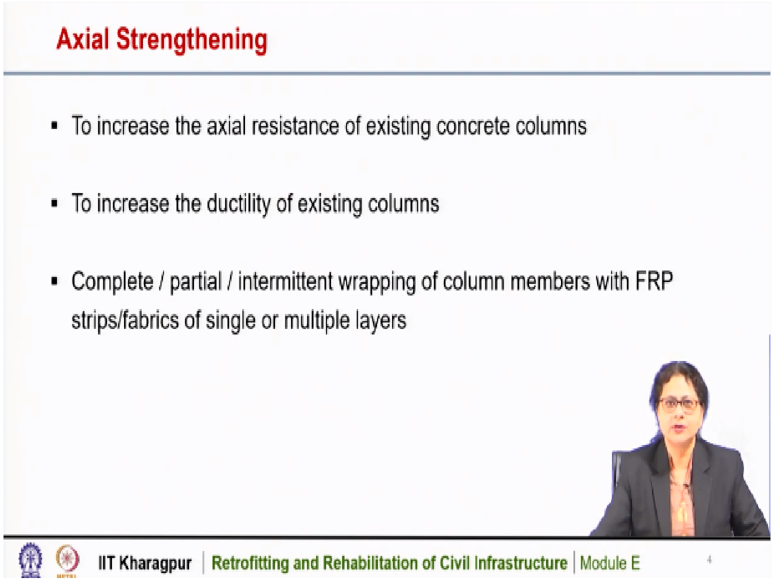

Axial strengthening as we have discussed earlier is aimed to increase the axial resistance of existing concrete columns, it is also aimed to increase the ductility of existing columns and for axial strengthening the FRP strips or fabrics can be used in single layer or with multiple layers and the FRP strips or fabrics can be wrapped completely or partially or intermittently around the column members.

So, to improve the axial capacity of the existing concrete columns to improve its axial resistance and ductility FRP strips or fabrics are wrapped around the columns in 1 layer or in multiple layers with complete wrapping or with partial or intermittent wrapping.

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Now, we will discuss the design approach for axial strengthening of structural members using fiber reinforced polymer composite. We will discuss the effect of confinement on columns, when the column is wrapped using fiber reinforced polymer composites either intermittently or completely the column is experiencing a multi-axial state of stress. When the column member is subjected to axial loading, with increase in axial loading it experiences an increase in its axial strain and along with the increase in axial strain it also experiences an increase in its lateral strain.

However, initially the increase in lateral strain or axial strain is uniform or elastic in nature, but when the axial strength or when the axial loading is increasing and it may reach up to 70 or 80 percent of its uniaxial strength then concrete is experience some cracking in the cement paste. And when it is cracked then it begins to dilate along its radial direction and when it begins to dilate in its radial direction, then the effect of confinement actually comes into play.

So, the confining effect is experienced by the column under the axial loading after the concrete has cracked and begins to dilate. So, when it is not cracked or when the load is not that high the effect of confinement is practically nothing.

So, when the concrete starts cracking with increase in its axial loading then only the effect of confinement is experienced by the column and that confinement effect creates a multi-axial state of stress to the column member and due to this multi-axial state of stress the axial capacity of the column increases significantly.

Now, this confining effect is experienced only when the concrete starts dilating in its radial direction, so that is why it is called passive confinement. So, this confinement effect is applicable when the concrete begins to dilate in its radial direction and the confinement is termed as passive confinement.

The confined concrete strength depends on this confinement effect, the strength of the confined concrete depends on the effectiveness of confinement, it also depends on the initial concrete strength and the dimensions of the concrete member. So, by providing passive confinement to the member the axial capacity of the member increases significantly and how much will be the increase in strength or how much is the strength of the confined concrete that depends significantly on the effectiveness of confinement, it also depends on the initial concrete strength and the dimension of the concrete columns.

The effect of confinement is dependent on the elastic modulus of the FRP that is used as a confining material, the ultimate strain of the FRP and the thickness of the FRP wrapping. So, the confinement effectiveness is dependent on the properties of the FRP, the elastic modulus of FRP, the ultimate strain of the FRP and the thickness of the FRP wrapping.

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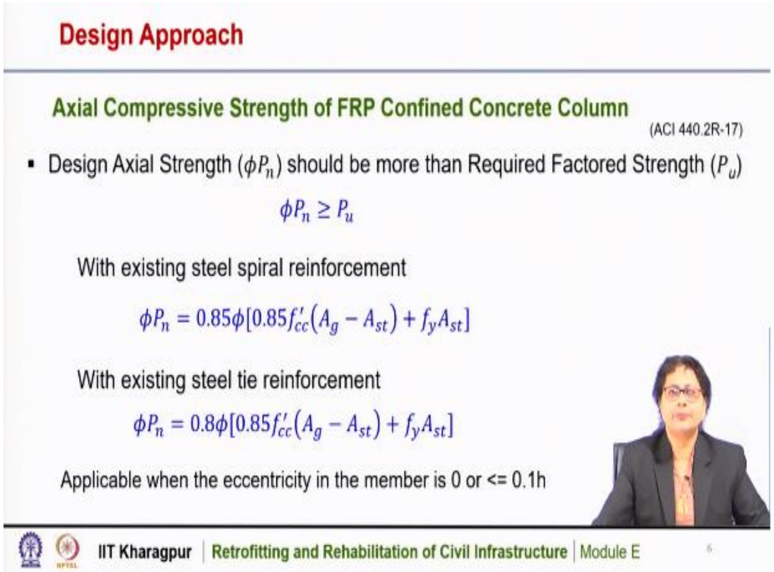

So, considering these things the design approach has been developed for the axial members, which are strengthened by FRP composites. So for the design of the axial members the first thing is that the design axial strength should be more than the required factored strength that is $\phi P_n \geq P_u$, ϕP_n is the design axial strength and with FRP composite the column should be strengthened by FRP composite and for that the design axial strength that is achieved should be more than the required strength.

And to find out the design axial strength we can use these equations for the columns when it is subjected to axial loading and it has steel reinforcement, when the lateral ties are used, we can use this expression and when there is still spiral reinforcement, we can use this expression for determining the axial strength, the design axial strength of the member.

So, this is the equation for determining the design axial strength of the confined concrete column f_{cc}' is the strength of the confined concrete, A_g is the area of the column, A_{st} is the steel area, f_y is the yield strength of steel.

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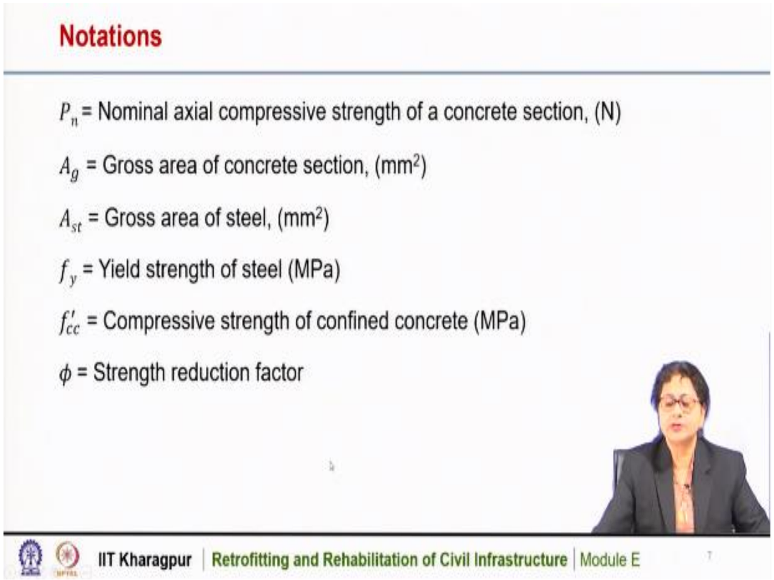

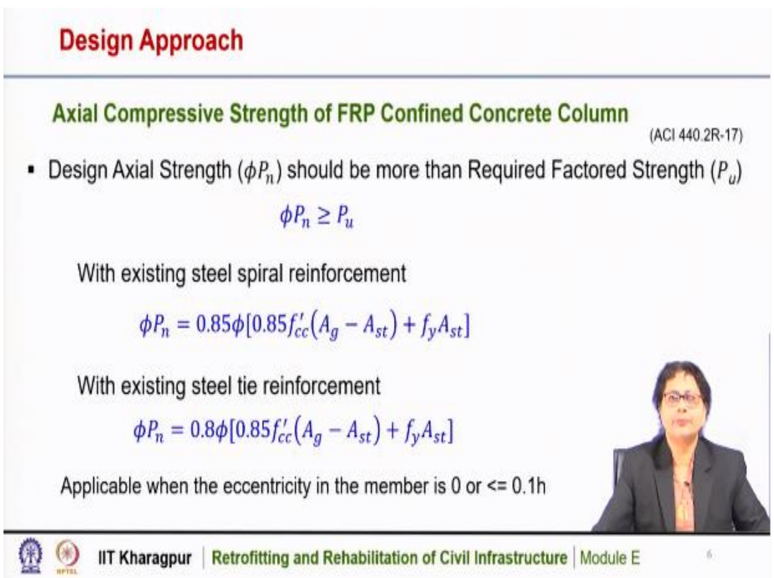

So, these are the notations that are used here, P_n is the nominal axial compressive strength of a concrete section, A_g is the gross area of the concrete column, A_{st} is the gross area of the steel, f_y is the yield strength of steel, f_{cc}' is the compressive strength of confined concrete and phi is the strength reduction factor that is used here.

So, for the 2 different types of lateral reinforcement, 1 is spiral reinforcement, 1 is tie reinforcement we are using these equations to determine the design axial strength of confined column. And these equations are applicable when there is no eccentricity or the eccentricity is less than equal to 0.1h. So, this we have to consider that when the column is subjected to axial loading only and if there is some eccentricity that must be 0 or less than 0.01 and for that condition these are the expressions for design axial strength.

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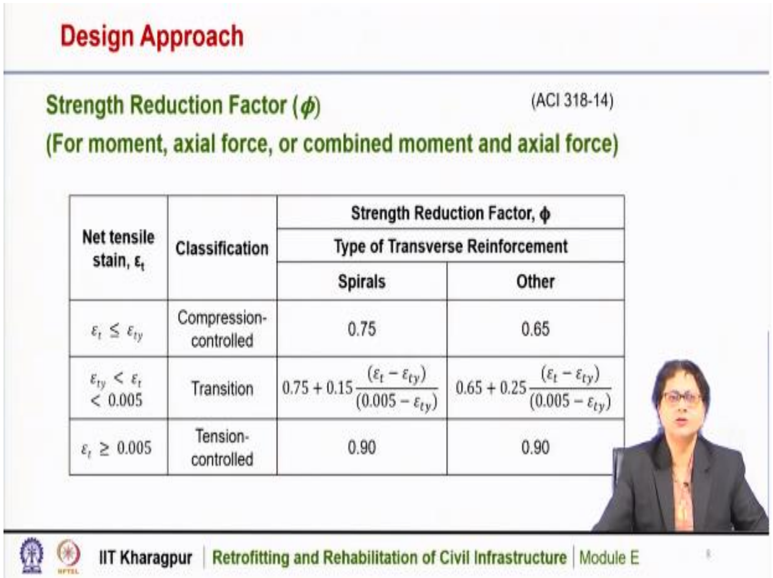

Net tensile stain, ε_t	Classification	Strength Reduction Factor, ϕ	
		Type of Transverse Reinforcement	
		Spirals	Other
$\varepsilon_t \le \varepsilon_{ty}$	Compression-controlled	0.75	0.65
$\varepsilon_{ty} < \varepsilon_t < 0.005$	Transition	$0.75 + 0.15\frac{(\varepsilon_t - \varepsilon_{ty})}{(0.005 - \varepsilon_{ty})}$	$0.65 + 0.25\frac{(\varepsilon_t - \varepsilon_{ty})}{(0.005 - \varepsilon_{ty})}$
$\varepsilon_t \ge 0.005$	Tension-controlled	0.90	0.90

Now, the strength reduction factor that we have used in the previous equations that we have to consider and for moment, axial force, or combined moment in axial forces these are the factors that depends on the strain levels. So, this is the strength reduction factor and these factors have been obtained from American Concrete Institute guideline 318. And we can see here that when the strain levels are varying we can use these strength reduction factors for spiral transverse reinforcement or tie transverse reinforcement.

So, these are the factors that need to be considered for estimating the design axial strength of the member.

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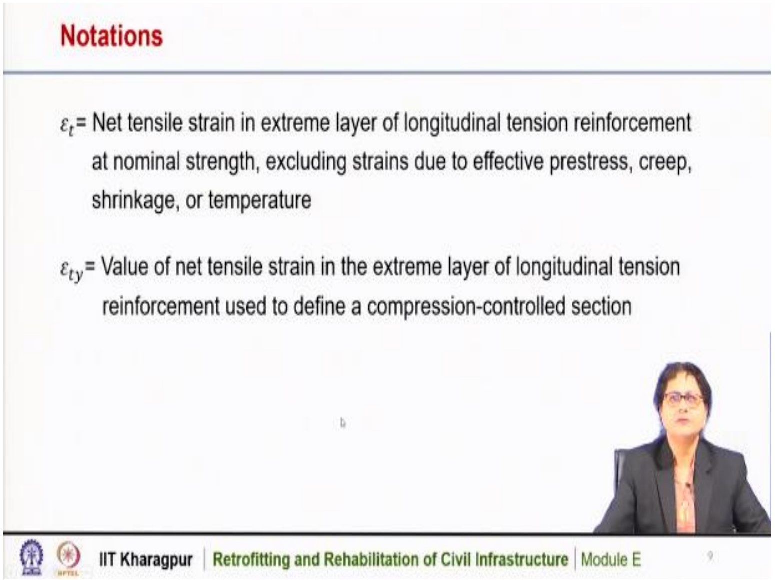

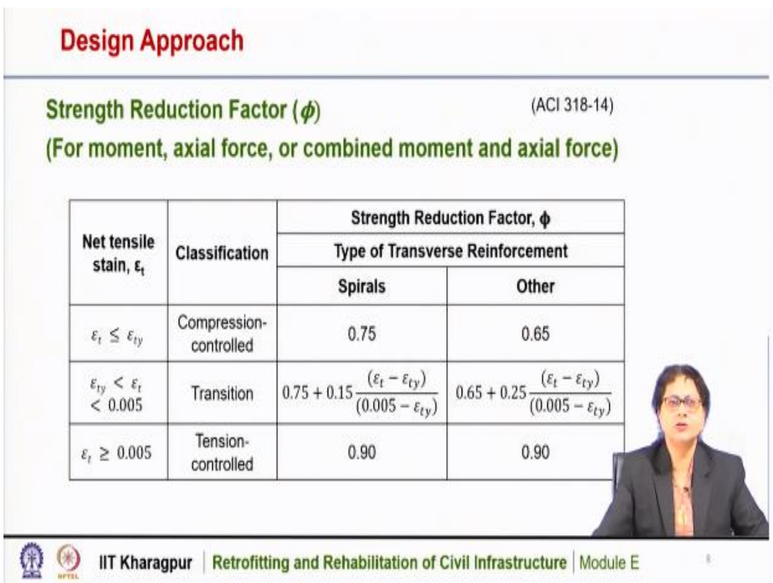

Epsilon t is the net tensile strain in extreme layer of longitudinal tension reinforcement at nominal strength, excluding the strains due to effective pre-stress, creep, shrinkage or temperature etc., and ε_{ty} is the value of net tensile strain in the extreme layer of longitudinal tension reinforcement used to define a compression control section.

So, these are the notations and using these values of strains in these ranges we can obtain the strength reduction factor for determining the design axial strength.

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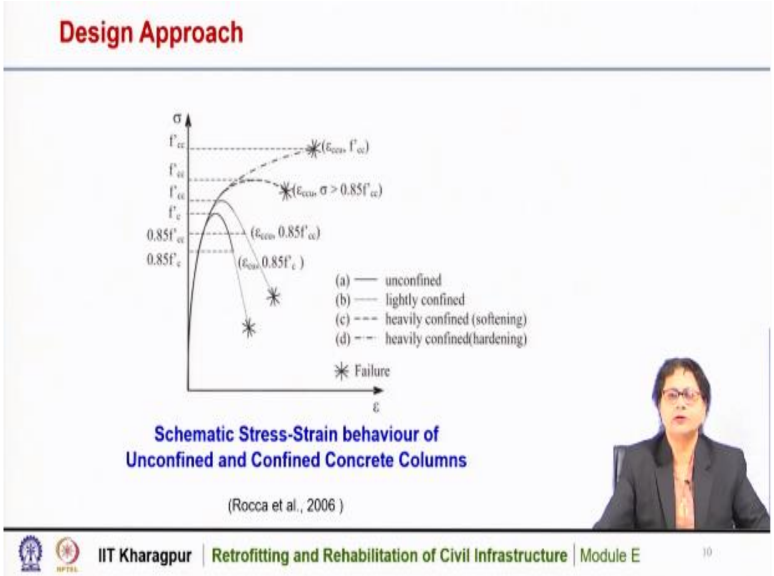

This is the schematic diagram of the stress strain behavior of unconfined and confined concrete columns. We have discussed these things in the previous lectures a number of research works have been done on confined concrete column with different types of FRP composites with different wrapping scheme, with different thicknesses of FRP to understand the behavior of the confined concrete column. How much is the increase in strength, how much is the increase in the strain or ductility of the member that have been obtained from various research works.

So, here in this schematic diagram we can see that there is a significant increase in the strength of the member when it is confined with FRP composites and with more and more confinement level that means if the confining reinforcement is more then there is increase in the strength of the confined concrete.

So, with respect to the unconfined concrete strength, there is significant improvement in the strain and the strength of the confined concrete. So, this has been shown schematically in these diagrams and this has been considered in developing the design methods for confined concrete columns.

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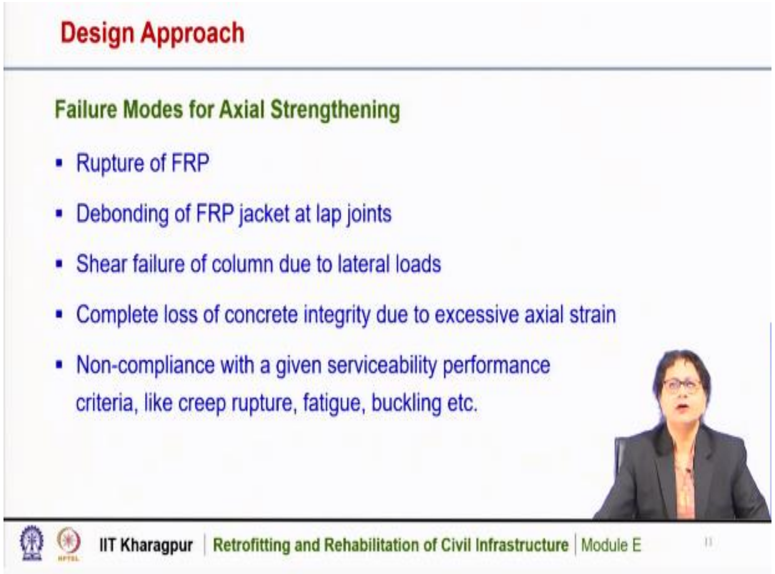

Now, while developing the design methods, we have to consider the different failure modes for axial strengthening, different experiments have been done on concrete columns considering different parameters and we have seen that there may be different types of failure a confined concrete column may experience.

The different failure modes are rupture of FRP or it could be debonding of the FRP jacket at lap joint, that means there is lab failure. There may be shear failure of column due to lateral loads. There may be complete loss of concrete integrity due to excessive axial strain. Or there may be non-compliance with the given serviceability performance criteria like creep rupture, fatigue, buckling etc.

So, in most of the cases it has been seen that when the concrete column is wrapped with FRP composite there may be rupture of FRP and that is the most common type of failure for column members, for circular member the rupture could be at any location where there is high stress. Whereas in case of non circular section it has been seen that the corners are the locations where there is high stress concentration.

So, in most of the cases rupture of FRP takes place at the corners and that is why it is important to round off the corner by grinding or so, so that the stress concentration is reduced. So, the failure modes could be rupture of FRP, it could be debonding or it could be shear failure of columns or there could be complete loss of concrete integrity.

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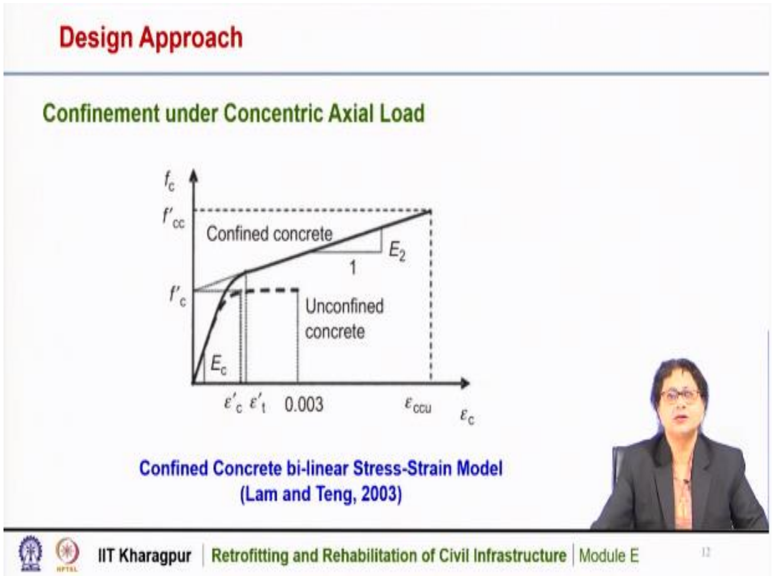

Now, based on the number of research works the behavior, the stress strain behavior of confined concrete column have been obtained by the researchers and we have seen that, while carrying out the experiments we have seen that there is significant improvement in the compressive strength of confined concrete as compared to the unconfined concrete.

So, with different types of FRP or with different schemes there is significant improvement in the strength as well as the strain of the columns. So, it is more or less a bilinear stress strain behavior for the confined concrete column and several researchers have obtained similar observations.

And for developing the design methods for confined concrete column this has been considered in several guidelines American Concrete Institute guideline or Australian guidelines or British Standard etc., several guidelines they have considered and accepted that this is the stress strain relationship, this type of bilinear stress strain relationship is possible for confined concrete column.

So, here also it is shown and the model developed by Lam and Teng has been used finally for the development of the design methods. So, here we can see that this is the response of the unconfined concrete, whereas this is the response of the confined concrete. So, more or less a bilinear relationship we get and this is the point where there is failure and this is the ultimate strength of the confined concrete member, this is the ultimate strain, the maximum strain level reached by the confined concrete.

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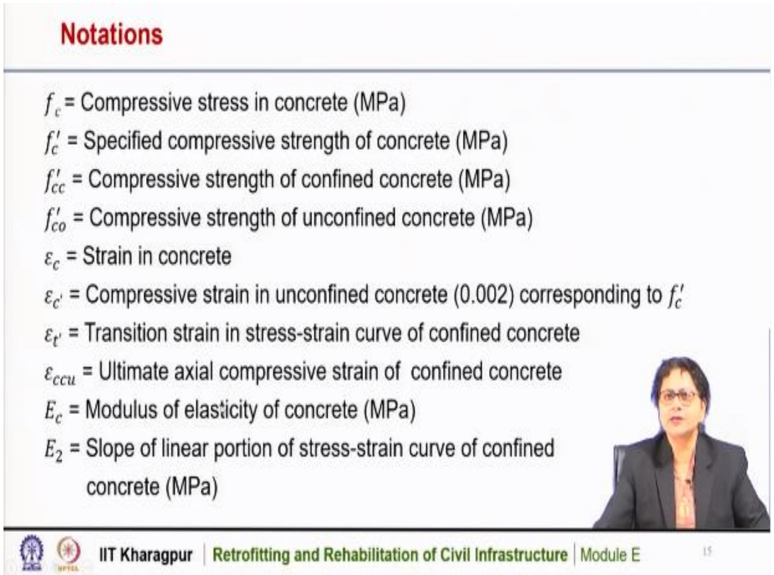

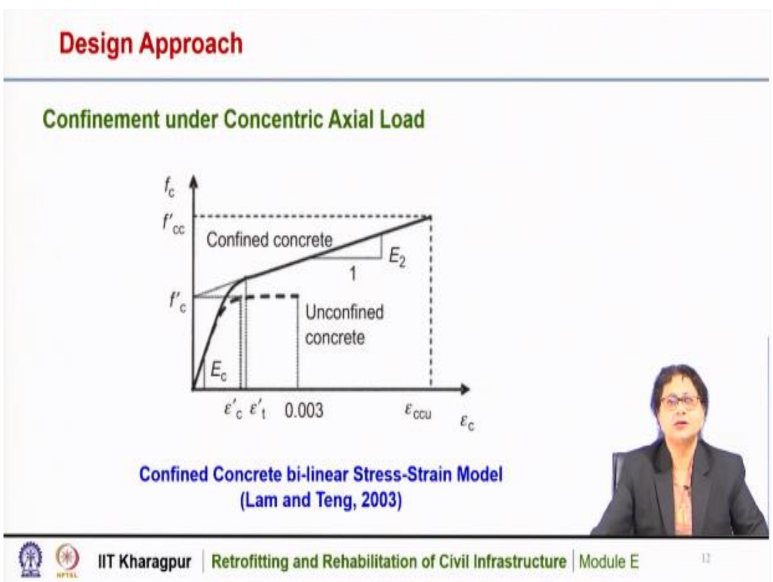

These are the notations f_c is the compressive stress in concrete, f_c' is the specified compressive strength of concrete, f_{cc} is the compressive strength of confined concrete, f_{co}' is the compressive strength of unconfined concrete. So, these are the notations that we will follow, ε_c is the strain in concrete, ε_c' is the compressive strain in unconfined concrete and generally it is taken as 0.002, ε_t' is the transition strain in stress strain curve of confined concrete, ε_{ccu} is the ultimate axial compressive strain of confined concrete, E_c

is the modulus of elasticity of concrete and E_2 is the slope of the linear portion of the stress strain curve of confined concrete.

So, let us see these things so this is E_c here, this is E_2, this is ε_{ccu} the maximum strain in confined concrete, f_{cc}' is the maximum strength of the confined concrete, f_{co}' is the unconfined strength and f_c' is the strength of the confined concrete. So, these are the different notations that are used to define the stress strain behavior of the confined concrete.

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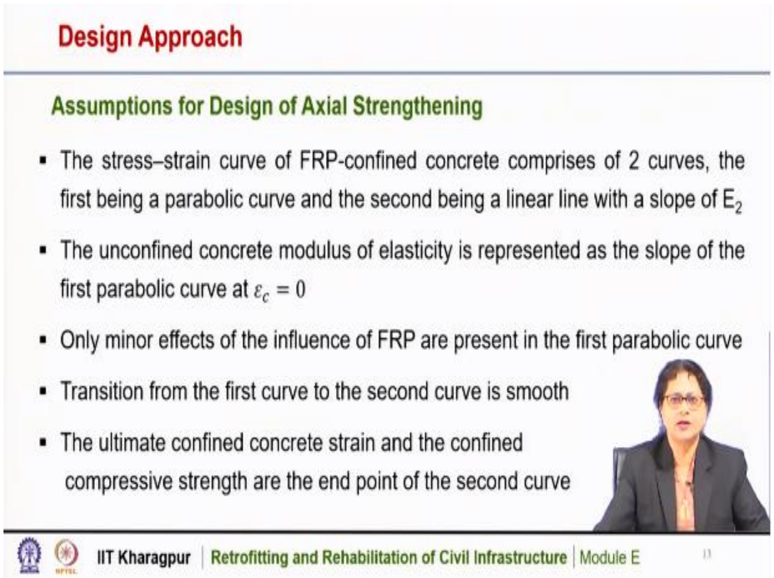

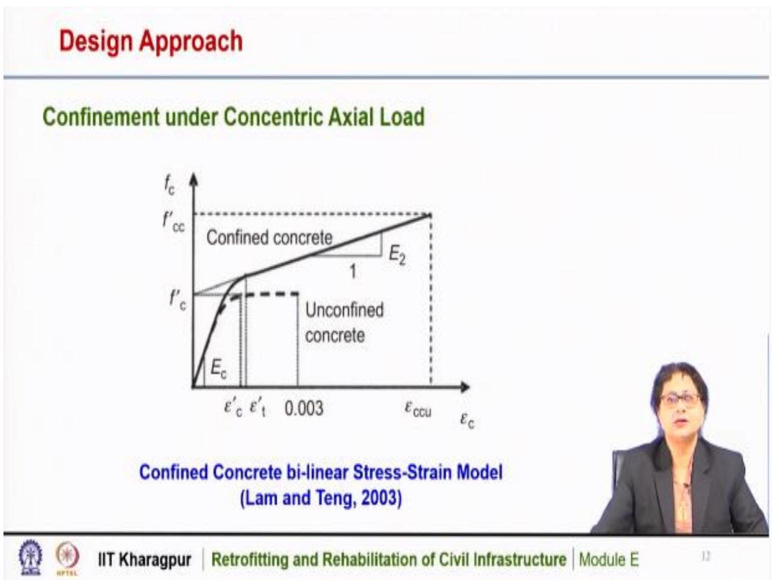

Now, to develop the design methods we need to follow several assumptions, there are several assumptions for the design of axial strengthening. The stress strain curve of FRP confined concrete comprises 2 curves. The first being a parabolic curve and the second being a linear line with a slope of E_2.

So, it is almost a bilinear curve and that is why it has been written as this comprises of 2 curves. The unconfined concrete modulus of elasticity is represented as the slope of the first parabolic curve at ε_c is 0 and the only minor effects of the influence of FRP are present in the first parabolic curve.

So, in the initially there is hardly any effect of the FRP confinement, the transition from the first curve to the second curve is smooth, the ultimate confined concrete strain and the confined compressive strength are the end point of the second curve. So, that has been considered the ultimate confined concrete strain, that is ε_{ccu}, confined concrete compressive strength that is f_{cc}' are the end points of the second curve.

So, this and this, so these are the assumptions for the design of axial strengthening using FRP composites.

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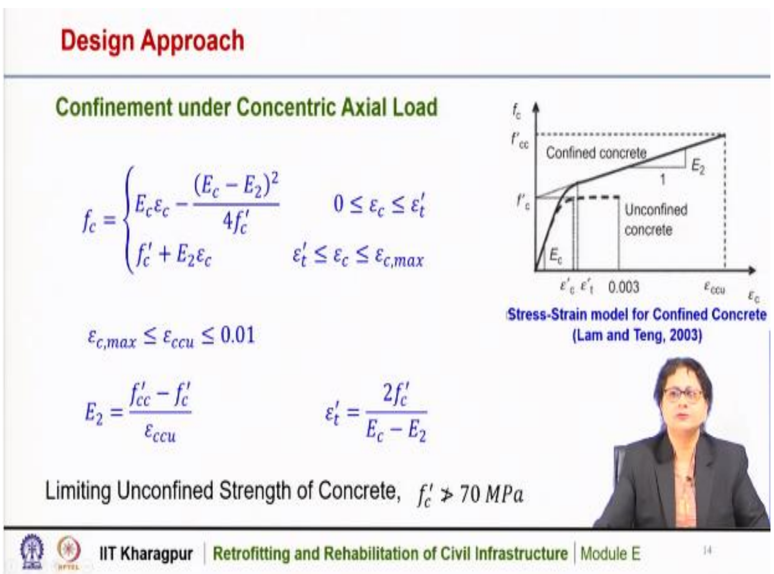

Now, we need to find out the relationships based on this bilinear stress strain curve. So, here the equations have been written, confinement under concentric axial loading, the fc that is the strength of the concrete column is written as with 2 different equations have been written based on this geometry, you can see here that since we have assumed that it is comprising of 2 linear components. So, based on this simple geometry we can obtain the value of the confined concrete strength and the strains.

So, when the strain level is between ε_t' and $\varepsilon_{c,max}$, so we can use this equation that is $f_c = f_c' + E_2\varepsilon_c$. So, this is from the just the simple geometry, we can use this equation and when ε_c is between 0 to ε_t' that is in this region we can use this equation. $f_c = E_c\varepsilon_c - [(E_c - E_2)^2/4f_c']$

So, this is from this triangle we can find out these equations and $\varepsilon_{c,max}$ must be less than ε_{ccu} because this is the ultimate strain in the confined concrete and that should be less than 0.01. So, this value of strain has been considered as the ultimate strain value beyond it should not be, we should not consider the strain value beyond this.

So, E_2 can be found out similarly $E_2 = (f_{cc}' - f_c')/\varepsilon_{ccu}$. So, this triangle we can just find out the E_2 equation. So, ε_t' similarly is obtained as $\varepsilon_t' = 2f_c'/(E_c - E_2)$. So, these are the equations that have been developed from this bilinear stress strain model and it has been seen that these equations are valid or that can be applicable for the unconfined concrete strength of not more than 70 MPa because most of the research works that have been done are for concrete strength less than 70 MPa. So, these equations are also for the concrete strength less than 70 MPa.

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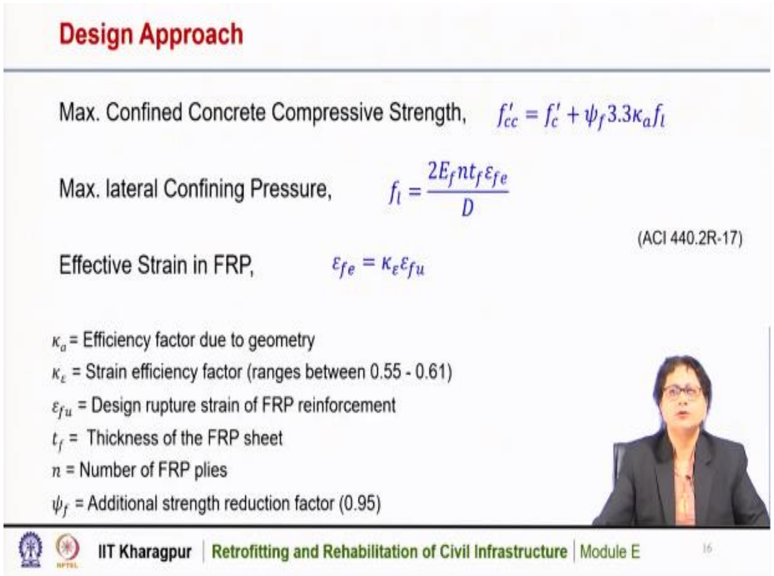

So, we have discussed these notations, so in the several research works that we have discussed in our earlier lectures that researchers have tried to develop the confined concrete model and it is more or less bilinear, that has been accepted. So, what is the confining pressure, what is the effect of confinement on the confined concrete column?

So, that is the question and researchers have tried to develop expressions for determining the confining pressure and by estimating the confining pressure only then we can find out what is the strength of the confined concrete column. So, based on the several works as we have discussed and we have shown in several research works and we have done also some of the experiments that has been discussed in our previous lectures, this is the equation that has been developed for determining the lateral confining pressure.

So, the maximum lateral confining pressure that is f_l is expressed by this equation, $f_l = 2E_f n t_f \varepsilon_{fe}/D$. So, this is the expression that has been developed for determining the maximum lateral confining pressure on the concrete column. The effective strain level in FRP is expressed as $\varepsilon_{fe} = \kappa_\varepsilon \varepsilon_{fu}$ and the maximum confined concrete compressive strength is expressed by this equation that is $f_{cc}' = f_c' + \psi_f 3.3\kappa_a f_l$.

So, this expression has been developed based on a number of experimental works on confined concrete column to determine the confined concrete strength. So, this confined concrete strength as we have discussed earlier that it is a function of the initial concrete strength and the effectiveness of confinement or the lateral confining pressure.

We need to estimate what is the effective strain in the FRP, whether there will be rupture or there will be debonding. So, we need to find out what is the effective strain in the FRP and here also several parameters have been used and these parameters one is κ_a that is efficiency factor due to geometry.

So, the geometry may be different for a column, it may be circular or it may be non-circular section or it may depend also on the size of the members. κ_ε is also another parameter that has been introduced that is termed as strain efficiency factor and from several experiments it has been found that the value of this κ_ε is ranging between 0.55 to 0.61. ε_{fu} is the design rupture strain of FRP reinforcement and t_f is the thickness of the FRP sheet, n is the number of FRP layers and ψ_f is the additional strength reduction factor for the FRP.

So, we have discussed earlier that there is an additional strength reduction factor need to be considered for FRP and that is ψ_f and here we are using the value of 0.95 for ψ_f. So, these are the expressions that have been developed and accepted in the ACI guidelines for estimating the lateral confining pressure, the effective strain in FRP and the confined concrete compressive strength.

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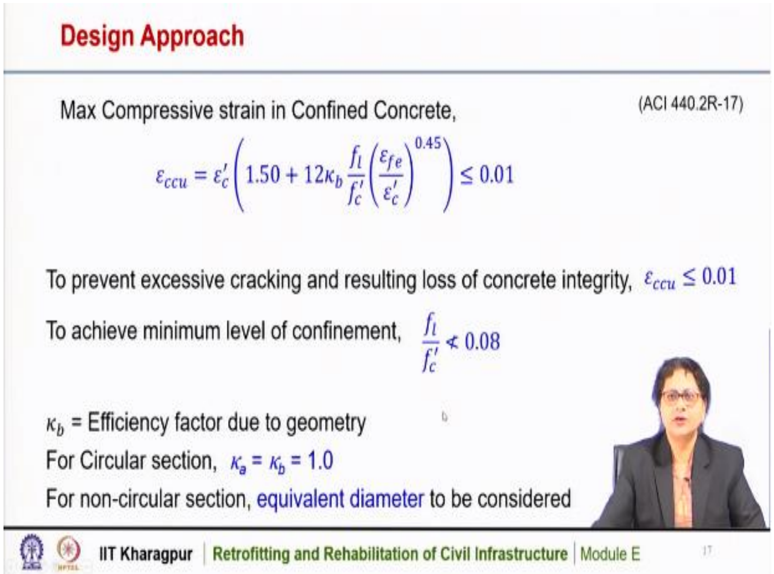

So, we also need to estimate the maximum compressive strain in confined concrete so that is ε_{ccu} that is the maximum strain in the confined concrete member and that is expressed by this equation. So here this is the ultimate strain of the confined concrete member and that should be less than 0.01 and this value has been considered and taken to prevent the excessive cracking and resulting loss of concrete integrity.

So, to prevent excessive cracking in the concrete member or to the resulting loss of concrete integrity we have defined this ε_{ccu} as less than 0.01. So, this has to be considered for the design that the ultimate strain of the confined concrete should be less than 0.01.

And to achieve minimum level of confinement also there is one limitation that is $f_l/f_c' \nless$ 0.08, that means if the confinement is very small, that means the level of confinement reinforcement if it is very less, then the confinement effect will not be achieved. So, there is a limit for the minimum confinement reinforcement.

So, minimum level of confinement is given here with this equation $f_l/f_c' \nless 0.08$. So, here also some parameters have been introduced one is κ_b, that is efficiency factor due to geometry and this efficiency factor depends on the geometry of the concrete column. For circular column these parameters are 1 that is κ_a and κ_b, κ_a we have used earlier for determining the f_{cc}'.

So, for determining the ε_{ccu} we are using κ_b, so this factors are taken as 1 for circular section because the effect of confinement is maximum for circular section then that has been obtained from several experimental works. But for non circular section the effectiveness of confinement is not uniform.

So, we have to use certain factors to determine the effectiveness of confinement. So, for the non-circular section we have to use an equivalent diameter because for the same area of columns having circular cross section or square or rectangular cross section the effectiveness of confinement is not same.

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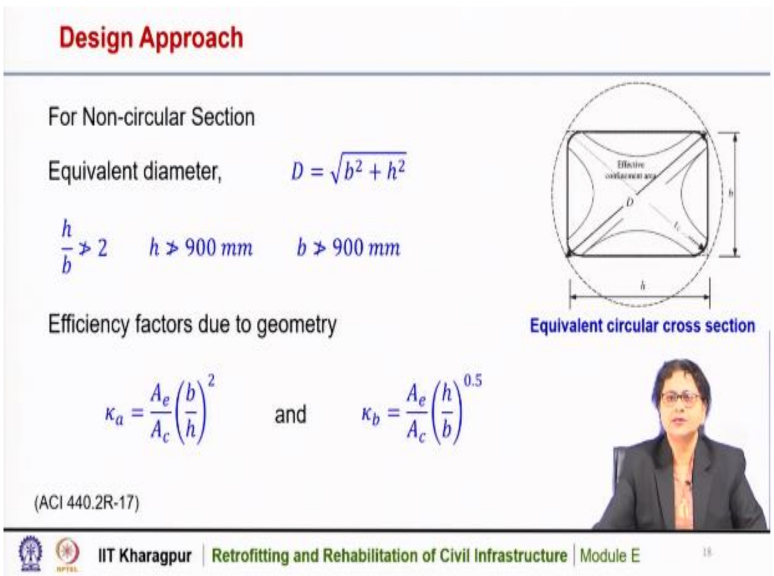

So, for non-circular section an equivalent diameter has been suggested because we have seen that and we have discussed also in the previous lectures that for circular columns the increase in strength is much more as compared to non-circular sections, because for non-circular sections the confinement effect is not the same, it is not uniform and as we have seen in this diagram and we can see that this is the effective confinement area.

So, for that we require an effective diameter and this effective diameter is $D = \sqrt{(b^2+h^2)}$ where b and h are the two lateral dimensions of the columns. So, we have to use this when the h by b ratio is not exceeding 2 and the lateral dimensions are also not more than 900 millimeter.

Two efficiency factors due to geometry have been used one is κ_a and κ_b and as we have mentioned that for circular sections κ_a and κ_b is equal to 1, but for non-circular sections it depends on the lateral dimension of the members. So, κ_a is expressed by this equation and κ_b is expressed by this equation based on several works on non-circular sections.

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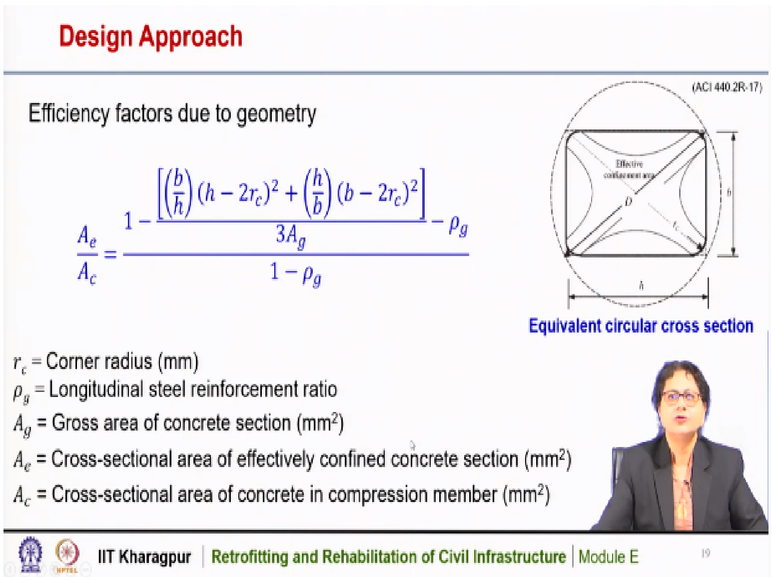

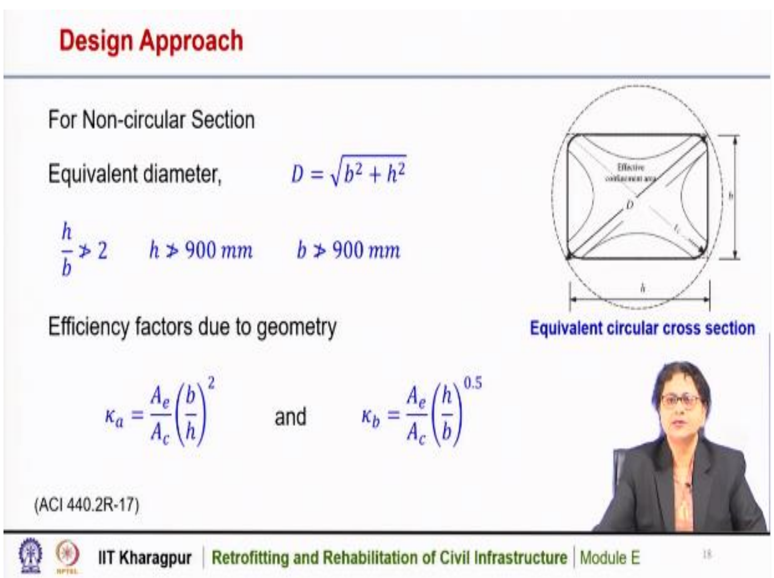

So, the efficiency factor due to geometry that is κ_a and κ_b and for that we have another term that is A_e/A_c. So, this A_e/A_c can be expressed by this equation so these equations have been developed considering the different corner radius, the amount of steel reinforcement, cross sectional area of concrete and the FRP reinforcement. So, here we are using several parameters r_c is corner radius, rho g is longitudinal steel reinforcement ratio, A_g is the gross area of concrete section, A_e is the cross-sectional area of effectively confined concrete section and A_c is the cross-sectional area of concrete in compression member.

So, these are the notations that are used and with that we have obtained this A_e/A_c ratio. So, for the non-circular section to determine an equivalent parameters κ_a and κ_b we can find out this A_e/A_c ratio and from that we can find out the κ_a and κ_b efficiency factors due to geometry of the concrete columns.

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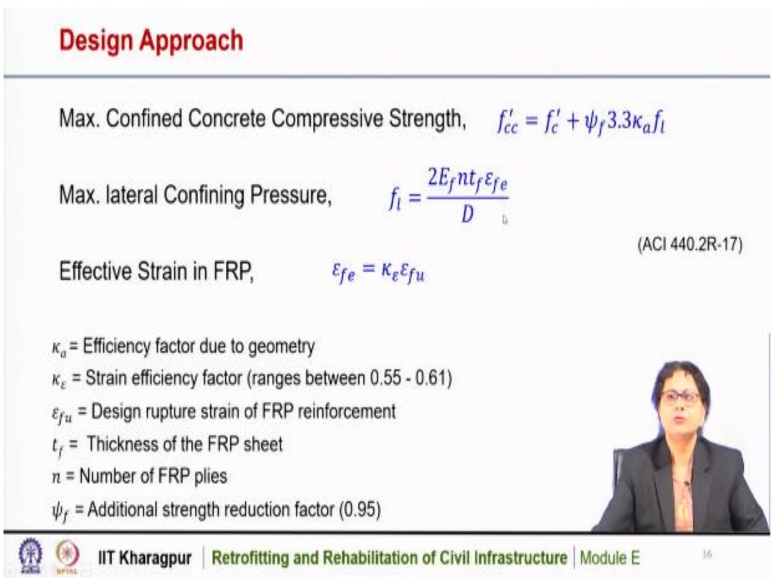

So, we have to use those parameters, we have to determine those parameters and from that we have to calculate the f_l, that is the lateral confining pressure, the strain in the confined concrete and then from that what is the f_{cc}', that is what is the ultimate strength of the confined concrete that can be derived or that can be determined from these equations. So, this equation can tell us the strength of the confined concrete by estimating the lateral confining pressure and the effective strain level in the FRP.

Now, we also need to consider the serviceability considerations as loads approach the factored load levels, damage to the concrete may be there in the form of significant cracking in the lateral direction. So, that may occur and when that cracking occurs then the effect of confinement is experienced, to avoid radial cracking under the service loads the transverse strain in concrete should remain below the cracking strain at service load levels.

So, the stress in concrete should be less than 0.65 f_c' and to avoid plastic deformation under sustained or cyclic loading the service stress in longitudinal steel should be less than 0.6 f_y. So, these are the 2 serviceability considerations that we can consider and while designing a confined concrete column along with the determination of strength we will see the serviceability criteria as well.

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So, to summarize we have discussed the design approach for actual strengthening of structural members using fiber reinforced polymer composites, the design approach has been developed based on several experimental works that we have discussed earlier and those experimental works have been done on circular concrete column or rectangular concrete column and different parameters were used. And based on the experimental works a number of parameters are introduced to define the confined concrete strength. Thank you.