Retrofitting and Rehabilitation of Civil Infrastructure
Professor Swati Maitra
Ranbir and Chitra Gupta School of Infrastructure Design and Management
Indian Institute of Technology, Kharagpur
Lecture 36
Design of Shear Strengthening

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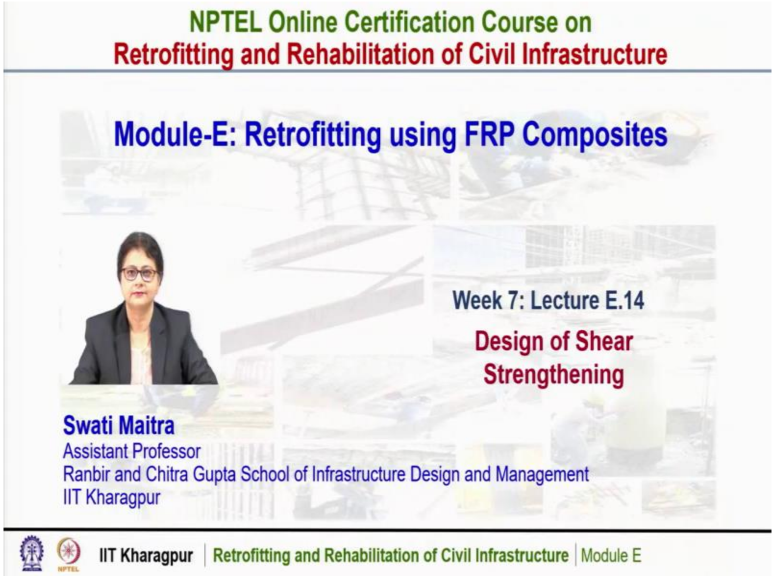

Hello friends, welcome to the NPTEL online certification course Retrofitting and Rehabilitation of Civil Infrastructure. Today, we will discuss module E, the topic for module E is retrofitting using fiber reinforced polymer composites.

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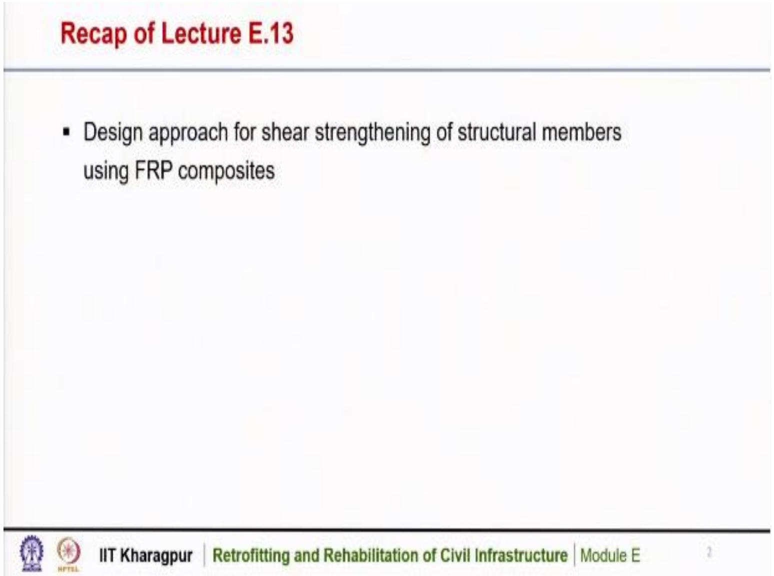

In the previous lecture we have discussed the design approaches for shear strengthening of structural members using fiber reinforced polymer composites.

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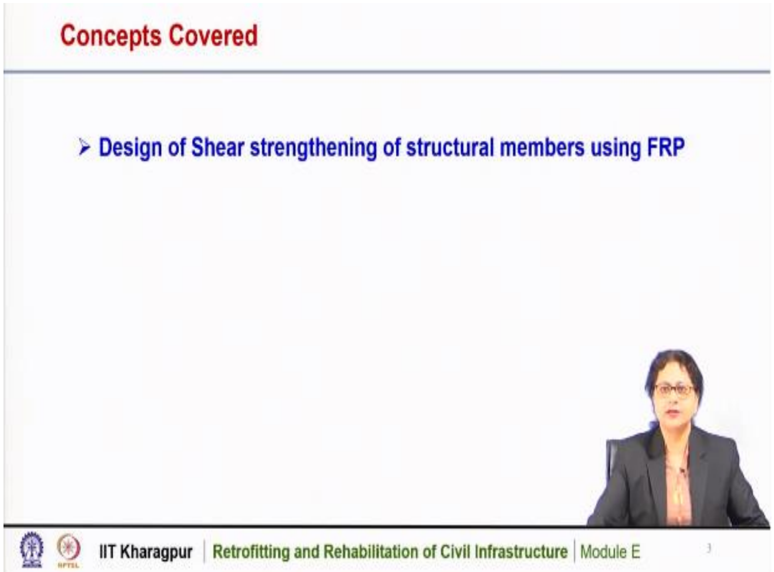

Today, we will discuss design example of shear strengthening of structural members using FRP composites based on the design approach what we have discussed in the previous lecture.

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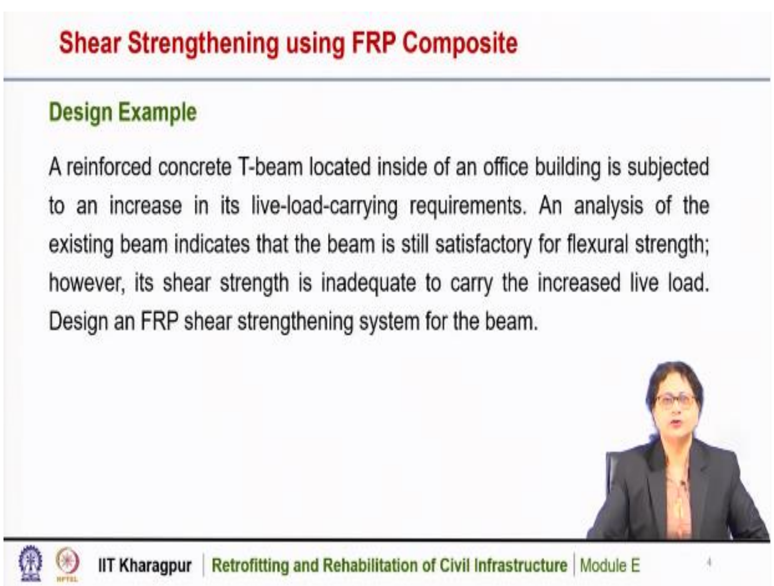

So, let us start the design example for shear strengthening of a structural member using fiber reinforced polymer composite. The problem is a reinforced concrete T-beam located inside of an office building is subjected to an increase in its life load carrying requirements. An analysis of the existing beam indicates that the beam is still satisfactory for flexural strength, however, its shear strength is inadequate to carry the increased live load. Design an FRP shear strengthening system for the beam.

So, this design example says that reinforced concrete T-beam is there, which is inside of an office building. So, the exposure condition is for internal environment, the live load carrying capacity of the beam has increased but the flexural strength of the member is still satisfactory to carry that excess load, but its shear strength is inadequate to carry that load.

So, we have to provide a shear strengthening system using FRP composite so that the beam can take up that additional load coming on it and for that we have to use an FRP composite system as shear strengthening for the beam.

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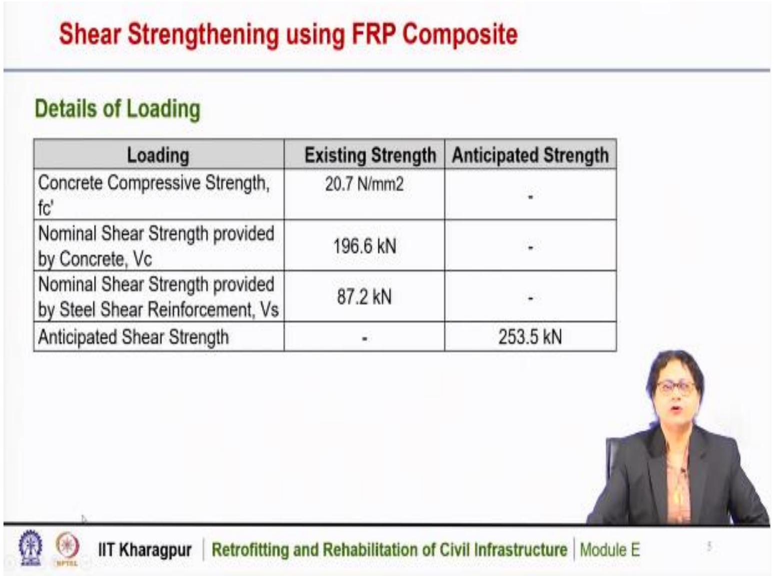

Loading	Existing Strength	Anticipated Strength
Concrete Compressive Strength, fc'	20.7 N/mm2	-
Nominal Shear Strength provided by Concrete, Vc	196.6 kN	-
Nominal Shear Strength provided by Steel Shear Reinforcement, Vs	87.2 kN	-
Anticipated Shear Strength	-	253.5 kN

The details of loading are given in this table, for the existing concrete the compressive strength is 20.7 Newton per millimeter square, the nominal shear strength provided by the existing concrete is 196.6 kilo Newton, the steel has reinforcement as well as stirrups, the nominal shear strength provided by the steel shear reinforcement is 87.2 kilo Newton and the anticipated shear strength is 253.5 kilo Newton, that is the extra load or the new load that is coming on the beam.

So, this is the required shear strength the beam needs to carry. So, you can see here that the summation of these 2 is less than that, so for this additional shear strength we have to design an FRP composite system.

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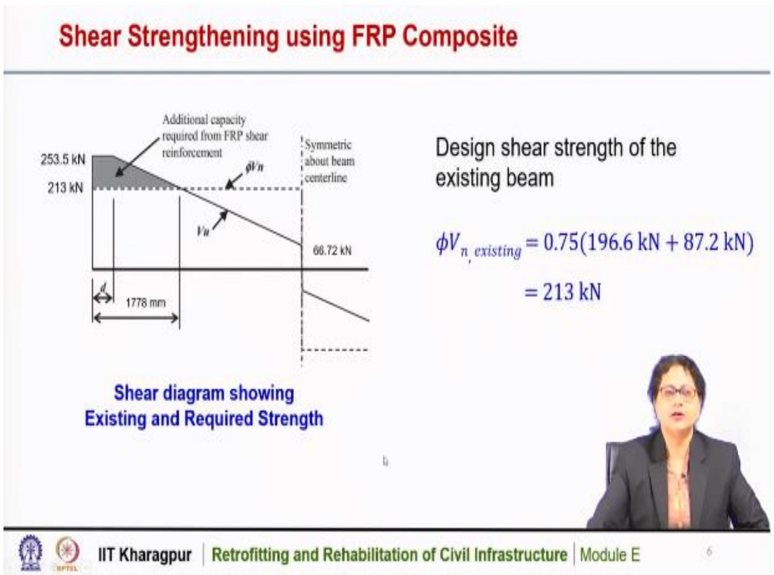

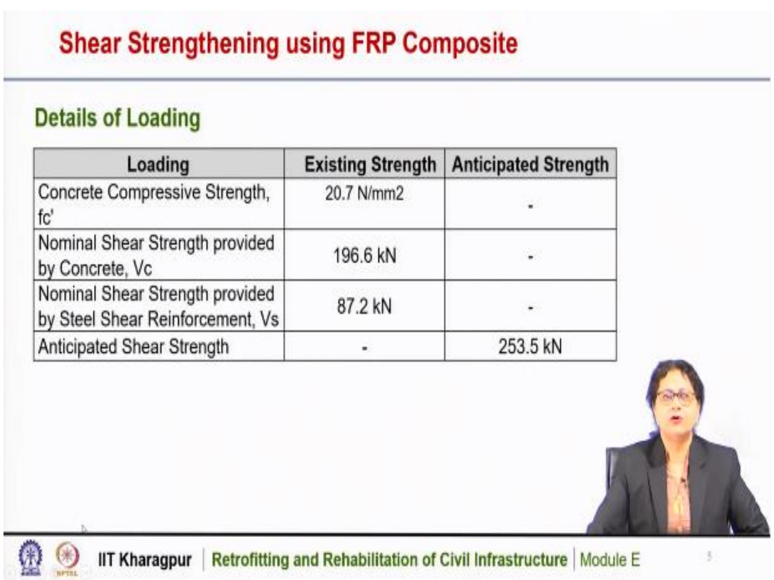

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So, this is the shear diagram showing the existing and the required strength. So, here we can see that the existing strength is 213, which is 196.6 kilo Newton that is the contribution of the existing concrete and 87.2 is the contribution from the steel stirrups as has been mentioned here. And so, the design shear strength of the existing beam is 213 kilo Newton considering that strength reduction factor ϕ.

So, this is the existing beam's design shear strength. So, this is shown here 213 kilo Newton and the additional one is shown here, we can see the required strength is 253 kilo Newton and it is shown in this shear diagram. So, this is the additional shear strength that is to be carried by the new system by FRP composite. So, this is the additional capacity required from the FRP shear enforcement and for that we have to suggest a suitable FRP strengthening system.

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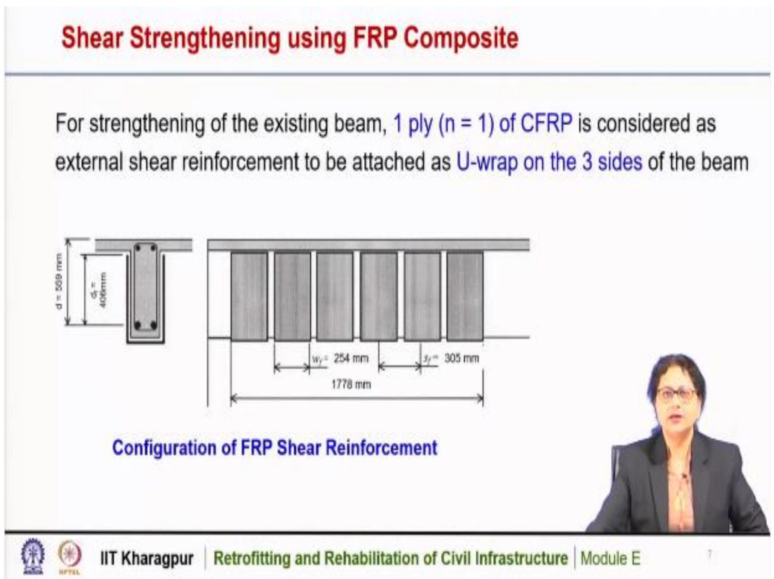

Now, for the strengthening of the existing beam to take up the additional shear strength let us try one layer of CFRP strip as shear reinforcement and that is to be provided as U-wrap on 3 sides of the beam and the CFRP shear reinforcement pattern is shown here in this diagram, this CFRP let us place it along the length of the beam up to 1.778 meter and the strip is to be placed intermittently with a spacing of 305 millimeter, the width of each strip is taken as 254 millimeter and it is to be bonded on the 3 sides of the beam using epoxy adhesives to increase its shear capacity.

So, for strengthening of the existing beam let us use 1 layer of CFRP as external shear reinforcement attached to the beam as U-wrap on 3 sides of its beam and it is bonded with epoxy adhesive.

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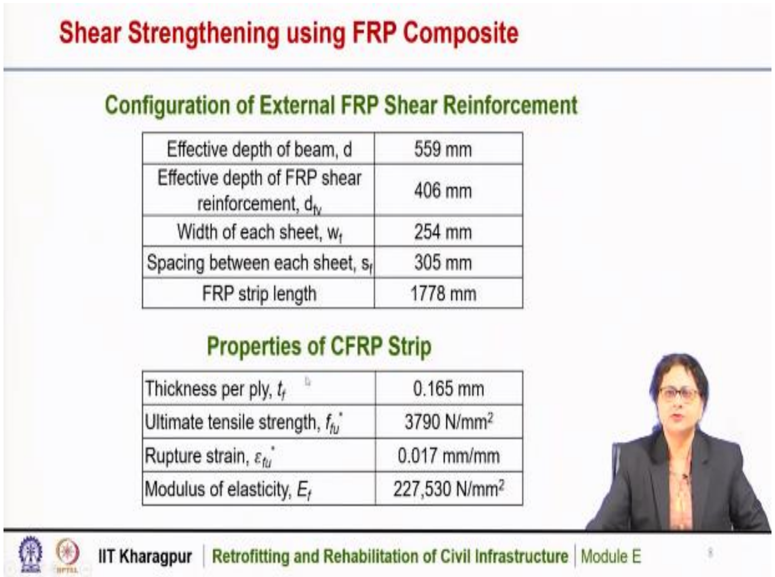

This is the configuration of the external FRP shear reinforcement, we have used CFRP the effective depth of beam is given here as 559 millimeter, the effective depth of FRP shear reinforcement is 406 millimeter, the width of each strip is 254 millimeter as shown in the diagram and the spacing between each strip that is the center to center distance between the strips is maintained as 305 millimeter and that FRP strip is to be provided where the additional shear strength is required and that is up to 1.778 meter.

The properties of the CFRP which has been given by the manufacturers are written here, the thickness of the CFRP strip per ply is 0.165 millimeter, the ultimate strength is 3790 Newton per millimeter square, the ruptured strain or ultimate strain is also given that is 0.017 and the modulus of elasticity of the FRP is 227,530 Newton per millimeter square.

So, these are the properties generally provided by the manufacturer and we will use this CFRP for the shear strengthening and let us see whether this scheme and this pattern of the CFRP can be able to take up that additional shear strength on the beam.

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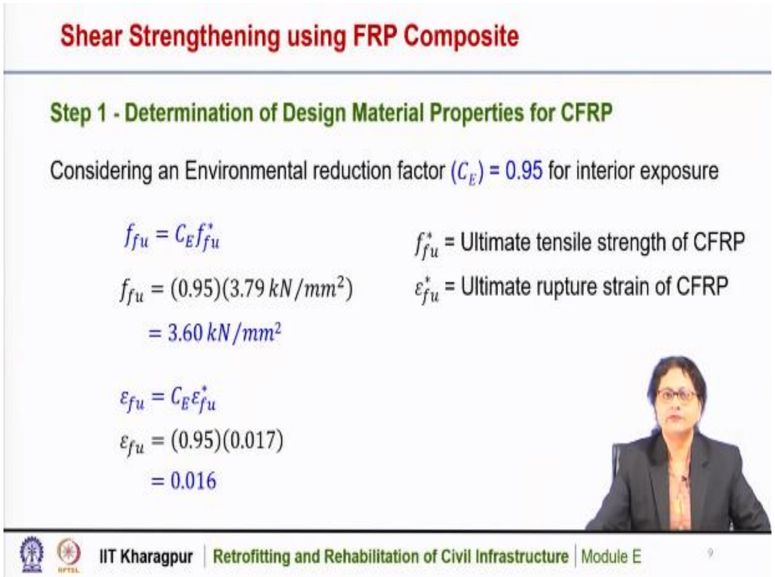

So, we will follow certain steps for the design and that we have discussed in the previous lecture. So, the first step is the determination of the design material properties for the CFRP composite, the beam is situated inside of a building, so the exposure condition is interior. So, we have to consider the environmental reduction factor as 0.95 considering the type of FRP, here it is CFRP and the exposure condition is interior.

So, as we have discussed earlier, we have to take the environmental reduction factor and that factor is 0.95 here. So, this factor is to be multiplied with the ultimate strength and strain to get the design material properties for the CFRP.

So, the design strength that is f_{fu} for the CFRP is $(CE)f_{fu}{}^*$, $f_{fu}{}^*$ is the ultimate tensile strength of the CFRP and $\varepsilon_{fu}{}^*$ is the ultimate rupture strain of the CFRP that we are getting from the manufacturer's data. However, we have to use a value lesser than these values as our design strengths and strain.

So, the design tensile strength is 0.95×3.75 which is the ultimate tensile strength of the CFRP and that is coming out as 3.60 kilo Newton per millimeter square. So, similarly the design strain is the ultimate strain multiplied with the environmental reduction factor and we are getting the design strain for the CFRP is 0.016. So, these are the strength and strain values that are to be used in the design calculations.

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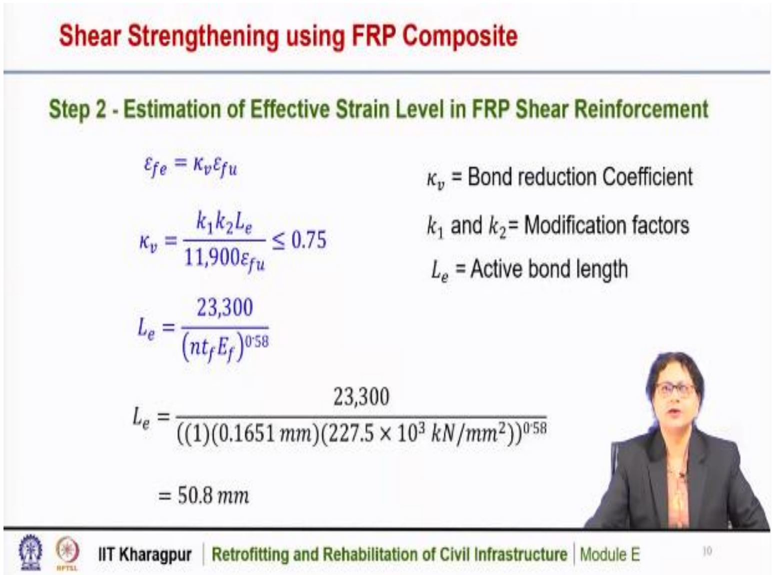

Now, the next step is the estimation of effective strain level in the FRP shear reinforcement and for that we have to use this equation $\varepsilon_{fe} = \kappa_v \varepsilon_{fu}$, ε_{fu} is the design strain and that we have just obtained by multiplying the ultimate strain into the environmental reduction factor and κ_v is the bond reduction coefficient.

We have discussed earlier that for the shear strengthening we can have different types of wrapping pattern and that could be completely wrapping or 3-sided wrapping or 2-sided wrapping.

Now, when it is completely wrapped majority of cases the failure is due to the rupture of the FRP. However, when it is 2 sided bonded or 3 sided bonded and present case it is 3 sided bonded, the failure is due to debonding of the FRP from the concrete substrate. So, we have to consider that and because of this type of debonding we have to estimate the effective strain in FRP and that we can do by multiplying with a bond reduction coefficient.

So, this κ_v is the bond reduction coefficient and that is to be multiplied with the ultimate or the design strain of the FRP. So, this is the effective strain level in FRP that is $\varepsilon_{fe} = \kappa_v \varepsilon_{fu}$.

Now, κ_v can be found out with this equation as we have discussed in the previous lecture and these equations have been developed based on a number of experiments on shear strengthening. We have discussed that there are different experiments carried out by researchers to understand the demanding type of distress or delamination and the behavior of the shear strengthened beam using FRP and based on that it has been seen that there is certain length which is responsible for that debonding and that is active bond length.

So, here we are using this equation for estimating the active bond length that is L_e and κ_v that is the bond reduction coefficient is given by this equation and this equation depends also on the design strain of the FRP and that considers several other factors like k_1 and k_2, k_1 and k_2 are the modification factors one is due to the concrete strength k_1 and k_2 is depending on the wrapping scheme.

So, these are the factors that need to be considered to estimate the bond reduction coefficient. So, the effective strain level in the FRP should consider these factors and as we have considered our FRP system with one layer of U-wrap and that is the CFRP with the given properties. So, we can estimate the effective or active bond length using this equation and we can put these values and get the effective bond length or the active bond length as 50.8 millimeter using this equation. So, the active bond length what is needed is coming out as 50.8 millimeter.

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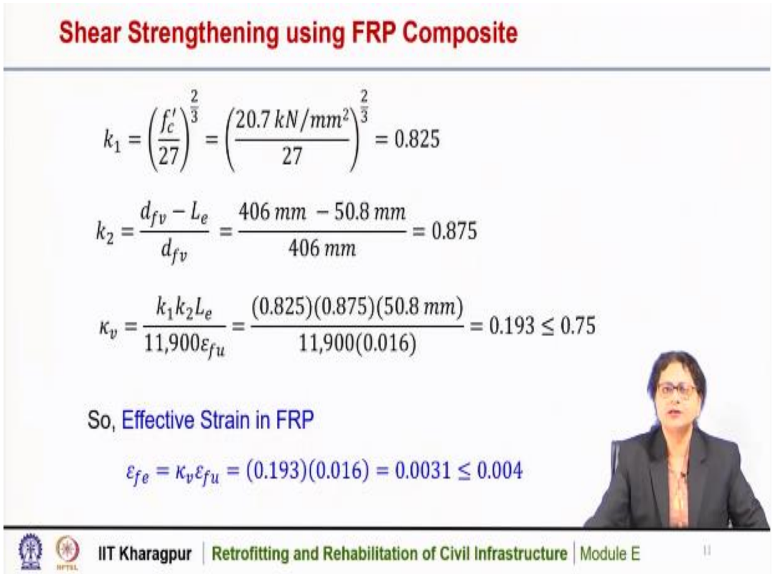

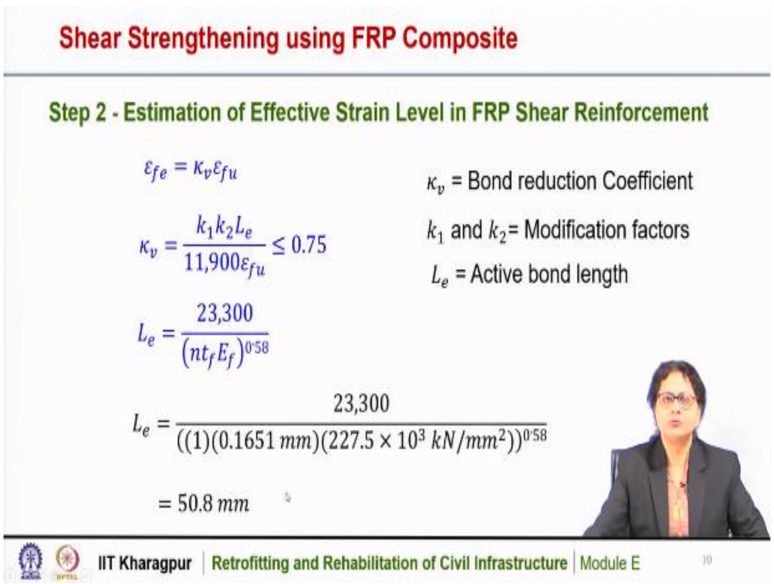

Now, we need to calculate those modification factors this k_1 is just mentioned that it is due to the concrete strength. So, this equation has been developed to determine this modification factors and these equations have been developed based on a number of experiments as we have discussed. So, k_1 is to be found out from this equation and by putting the values of f_c' that is the compressive strength of concrete we can find the value of k_1 as 0.825.

Similarly, k_2 depends on the wrapping scheme, for 3 sided wrapping k_2 is given by this equation and that we have discussed in the previous lecture. So, by putting these values of d_{fv} that is the effective depth of FRP shear reinforcement and the active bond length we can find out the modification factor k_2 as 0.875. So, by knowing the k_1, k_2 and L_e we can now estimate the factor κ_v.

So, this is the bond reduction factor κ_v and that can be estimated now from this equation and we have obtained the values of k_1, k_2, L_e and also ε_{fu} that is the design strain of the FRP. So, by putting these values we are getting κ_v is equal to 0.193. So, the bond reduction coefficient is obtained as 0.193 and in the American Concrete Institute guideline it has been mentioned that it should be less than 0.75.

So, the effective strain in FRP can be found out as $\varepsilon_{fe} = \kappa_v \varepsilon_{fu}$ as we have just shown here. So, it is 0.193×0.016 that is the design strain for the FRP and which is coming out as 0.0031 and it should be less than 0.004. So, what we are getting is satisfying this condition that is it is less than 0.004.

So, here we can see that the effective strain level in the FRP when it is 3 sided bonded to the existing concrete beam the strain level in the FRP is coming as almost 20 percent of its design strain. So, the strain is what we are considering to avoid the debonding type of a failure. We are taking the strain level as much less than its ultimate strain or the design strain. So, the effective strain is much less than its design strain so that we can have restriction in debonding type of failure.

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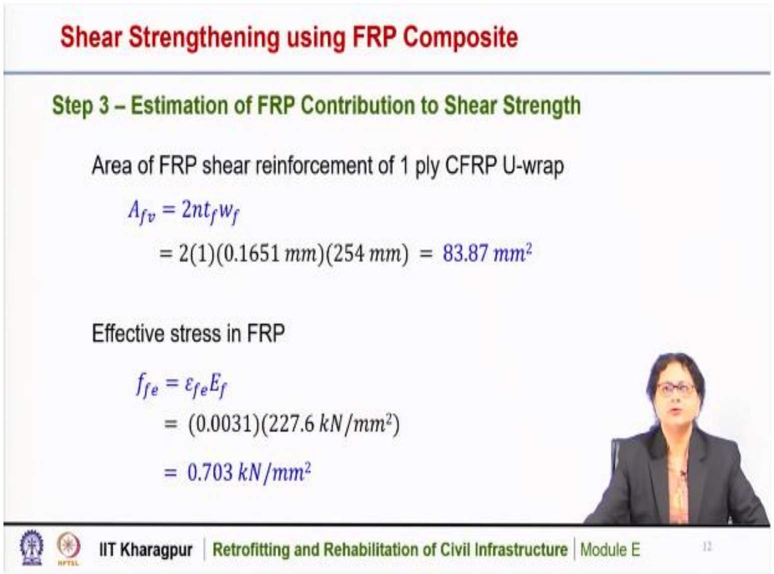

Now, the next step is the estimation of the FRP contribution to shear strength. So, for that we need to find out that what is the area of FRP shear reinforcement for 1 ply of CFRP U-wrapping, so A_{fv} that is the area of the CFRP is equal to $2nt_f w_f$ and this also have been discussed in the previous lecture, while discussing the design approach.

So, here n is the number of layers, here we have considered one layer, t_f is the thickness of each layer, w_f is the width of the strip. So, by putting these values we are getting 83.87 millimeter square that is the area of FRP shear reinforcement for the beam. So, by knowing the area of FRP shear reinforcement we can find out the effective stress in the FRP.

So, the stress is equal to the strain into the elastic modulus so the effective strain is 0.0031 that we have obtained in the previous step that needs to be multiplied with the elastic modulus of the FRP, which is 227.6 kilo Newton per millimeter square. So, this elastic modulus value need not be reduced with environmental reduction factor because it is the ratio of the stress by strain. So, there is no effect of environment on the elastic modulus of the FRP.

So, we can take this value of E_f and this is the effective strain level in the FRP. So, by multiplying these two we can get the effective stress level in the CFRP U-wrap that is coming out as 0.703 kilo Newton per millimeter square. So, this is the stress level in the FRP.

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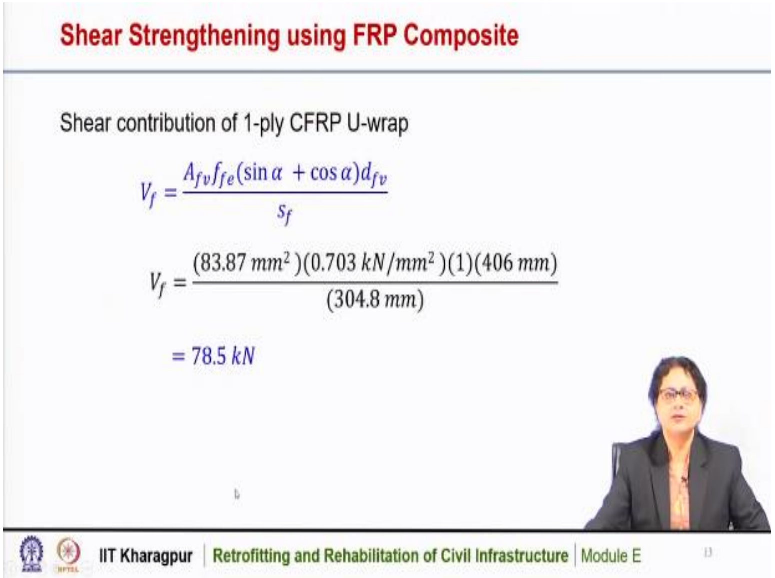

Now, we have to calculate the shear contribution of the CFRP U-wrap system. So, as you can remember that this is the equation that we need to use to find out the shear contribution of the CFRP. So, it is $V_f = [A_{fv} f_{fe}(\sin\alpha + \cos\alpha)\ d_{fv}]/s_f$, where A_{fv} is the area of the FRP shear reinforcement that we have just calculated, f_{fe} is the stress level in the FRP that also we have obtained in this step only and α is the angle by which we can place the CFRP.

So, here we are not putting it at any angle but it is at 90 degree to the length of the member, so α is 90 degree here, so this term sine alpha plus cos alpha becomes 1. So, this depends on the wrapping angle, so here we are using the FRP strips perpendicular to the length of the member and for that the alpha is 90 degree, so this term becomes 1.

We have used 305 millimeter, so we get the shear contribution of the CFRP is 78.5 kilo Newton. So, this is the shear contribution of the CFRP U-wrap what we have suggested with certain spacing and the width of the CFRP strip as well.

So, considering the effective strain level, the effective stress level on the FRP we can calculate the shear contribution of the CFRP U-wrap for this existing beam. Now, we have to calculate the total shear capacity of the CFRP strengthen system.

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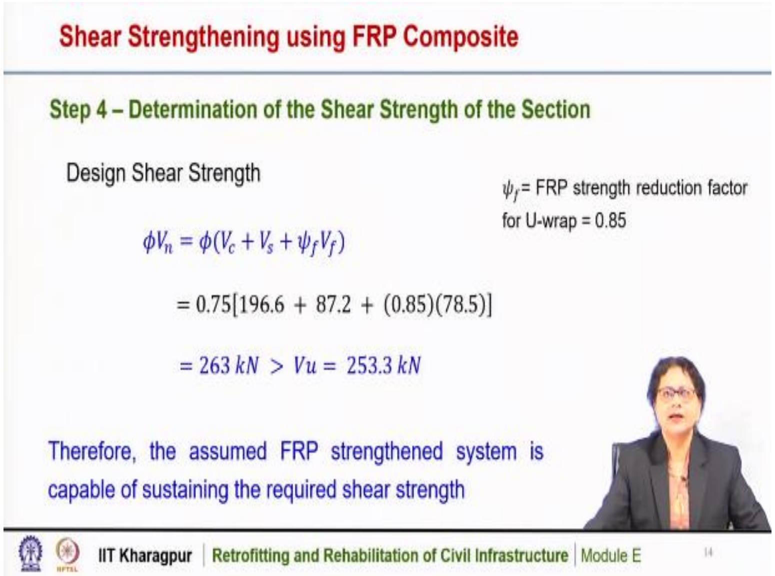

So, the next step is the determination of the shear strength of the section. So, the design shear strength is $\phi V_n = \phi(V_c+V_s+\psi_f V_f)$. So, this is the equation for the design shear strength, V_c is the shear contribution by the concrete, V_s is the shear contribution of the steel and V_f is the shear contribution of the FRP.

So, these values are given V_c is given as 196 kilo Newton, V_s is given as 87 kilo Newton and we have determined the V_f value. So, that is coming out as 78.5 kilo Newton and we have to use another factor FRP strength reduction factor and this factor also depends on the wrapping scheme.

So, for the U-wrap system that is with 3 sided wrapping, this ψ_f is to be taken as 0.85 and then by putting these values, also putting this value of phi that is the strength reduction factor as 0.75 we can get the design shear strength as 263 kilo Newton. So, the design shear strength of the beam with 1 layer of CFRP as U-wrap up to the length of 1.78 meter with that the shear capacity is 263 kilo Newton and it is found that it is more than the required shear strength, which is 253.3 as given in the problem.

So, we can see that our suggested CFRP system is capable of taking the required shear strength. So, the assumed FRP strengthening system with the scheme, FRP pattern and the scheme with U-wrapping with the given spacing and strips width, the system is capable of sustaining the required shear strength.

Now, if this value is coming as less than the required shear strength we can do another trial, we can use different ways to strengthen the existing beam, we can use one more layer of CFRP or we can reduce the spacing or we can use a different material which may have higher strength and strain values. So, in either way we can give another trial, so that the design shear strength of the strengthened beam is more than the required shear strength.

So, we can do that, those trials by either increasing the strip width or by reducing its spacing or you can use a different material or you can use more number of plies, say we have used one layer, so if it is not satisfying you can use two layers. So, a different way you can increase the total FRP reinforcement as external shear reinforcement to the existing beam, so that the design shear strength is more than the required shear strength.

So, here in this case we have seen that for our suggested CFRP system with 1 layer of CFRP U-wrap and with the given strips, width and spacing it is satisfying, that means it is more than the required shear strength. So, the assumed FRP strengthening system is capable of sustaining the required shear strength and the design can be considered as safe.

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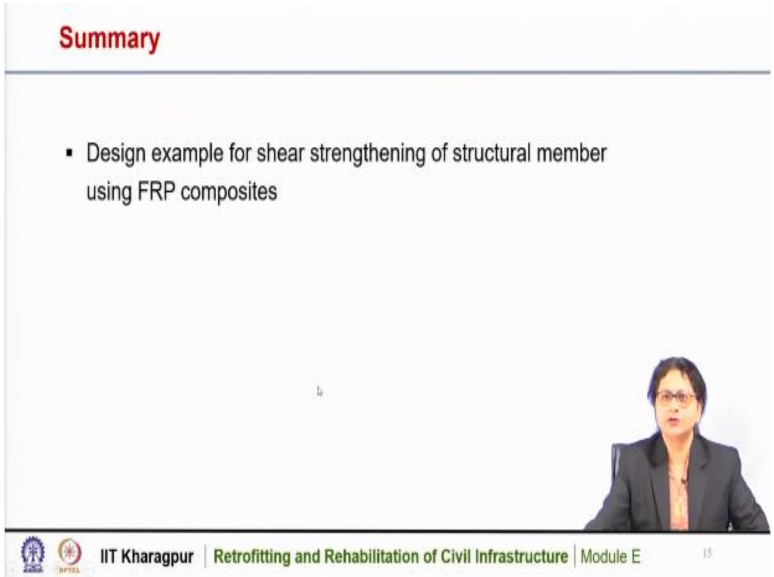

So, to summarize we have discussed a design example for shear strengthening of structural member using FRP composites, the design approaches have been discussed in the previous lecture and based on that design approach we have discussed the design example of FRP strengthening of concrete beam using FPR composites. Thank you.