Retrofitting and Rehabilitation of Civil Infrastructure
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Lecture 32
Design Considerations

Hello friends. Welcome to the NPTEL online certification course on Retrofitting and Rehabilitation of a Civil Infrastructure. Today we will discuss module E. The topic for module E is Retrofitting using Fiber Reinforced Polymer Composites.

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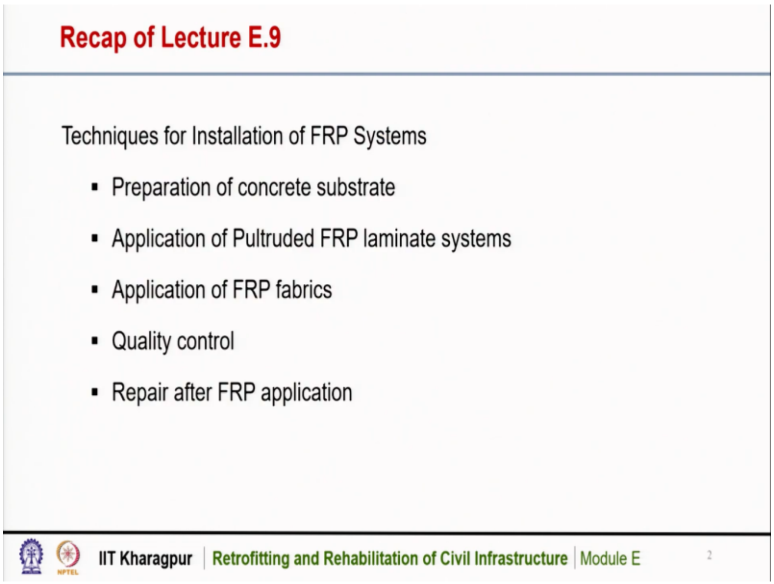

In the previous lecture, we have discussed the techniques for installation of FRP systems on existing concrete structures. We have discussed the several steps for installation. The preparation of concrete substrate before application of the FRP. Then the application of pultruded FRP laminate systems. The application of FRP fabrics. And also, the quality control during installation and repair after FRP application, if any damage is found during or after the FRP placement.

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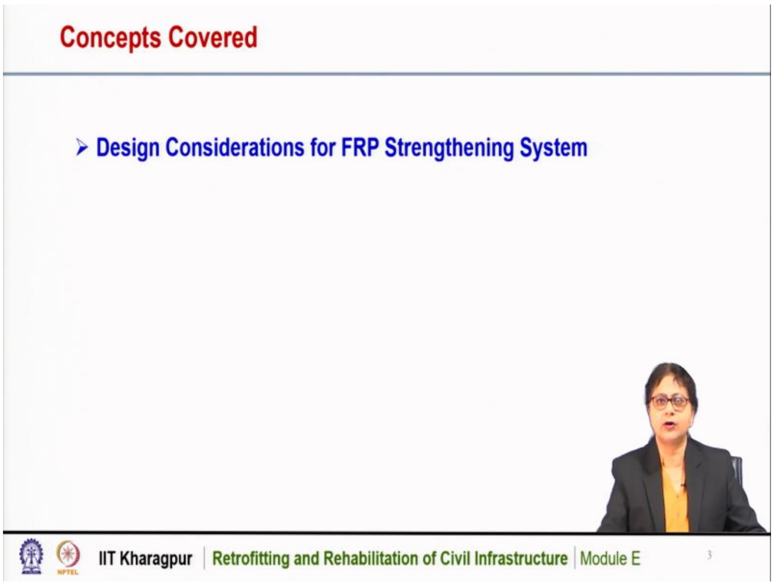

Today we will discuss design considerations for FRP strengthening system.

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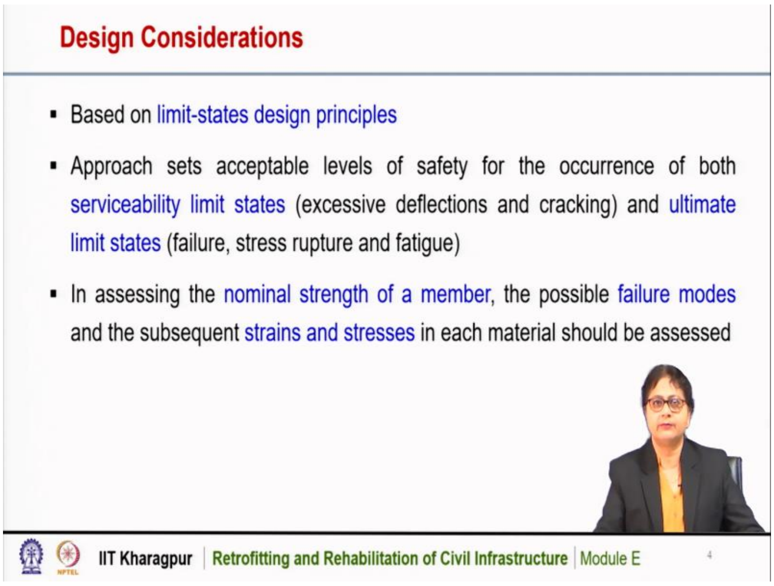

Fiber reinforced polymer composite has excellent properties like high tensile strength, high tensile modulus and because of this it has a potential to use as an external reinforcement for existing structures. It is used to improve the flexural capacity, shear capacity or axial capacity of structural members.

By applying the FRP on existing members, the strength of the members is improved, significantly. Not only the strength, the ductility of the members is also improved, significantly. Therefore, the FRP composites are used in recent years, for retrofitting of several existing structures. It is important to properly design the FRP system, so that we can get an improved structural system with FRP composites.

The design of FRP retrofitted members is based on limit state design principles. American Concrete Institute or British standard or Australian standards have developed some design guidelines for the FRP retrofitted structural members to improve the flexural capacity, shear capacity or axial capacity of members. The approach sets an acceptable level of safety for the occurrence of both serviceability limit state and ultimate limit stage.

We have seen in the previous lectures that there is significant improvement in the strength of the members, when it is retrofitted with FRP composites. And by knowing their failure modes, we can understand that the behaviour of the FRP system. The failure modes may be due to rupture of fibers or due to debonding of the FRP from the concrete substrate or due to concrete crushing or steel yielding.

So, by knowing these failure modes, there are acceptable limits that has been developed in these guidelines for the design of FRP retrofitted members. For the serviceability limit states, we consider the excessive deflections or cracking. And for the ultimate limit state, the failure and the stress rupture and fatigue have been considered. So, in assessing the nominal strength of a member, the possible failure modes and the subsequent strains and stresses in each material should be assessed.

So, while designing the FRP retrofitted member, the nominal strength is to be estimated and that is based on the possible failure modes of the member and considering the material properties, what are the strains developed or what are the stresses developed on the member. And based on that the design guidelines have been developed.

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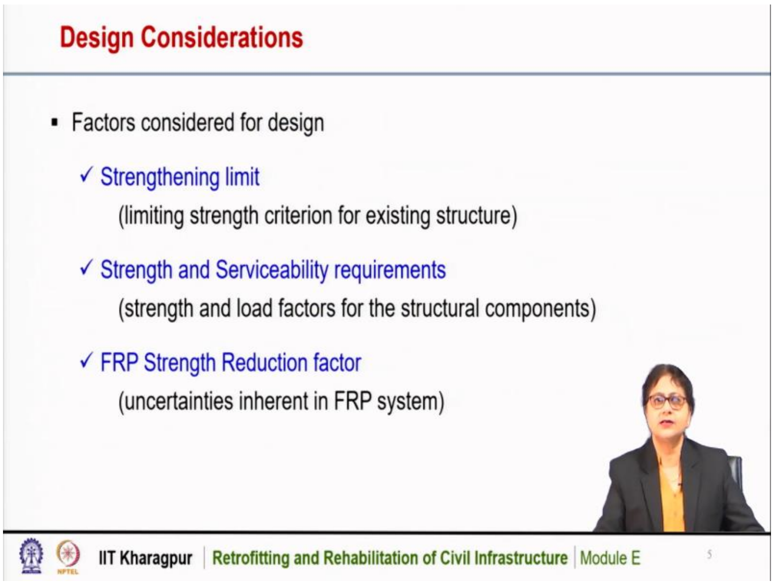

There are several factors that are to be considered for the design of FRP retrofitted members. One is strengthening limit, that is the limiting strength criteria for existing structure. Strength and serviceability requirements, these are the strength and load factors for the structural components and FRP strength reduction factor that is the uncertainties inherent in FRP system has been considered here. This we will discuss now.

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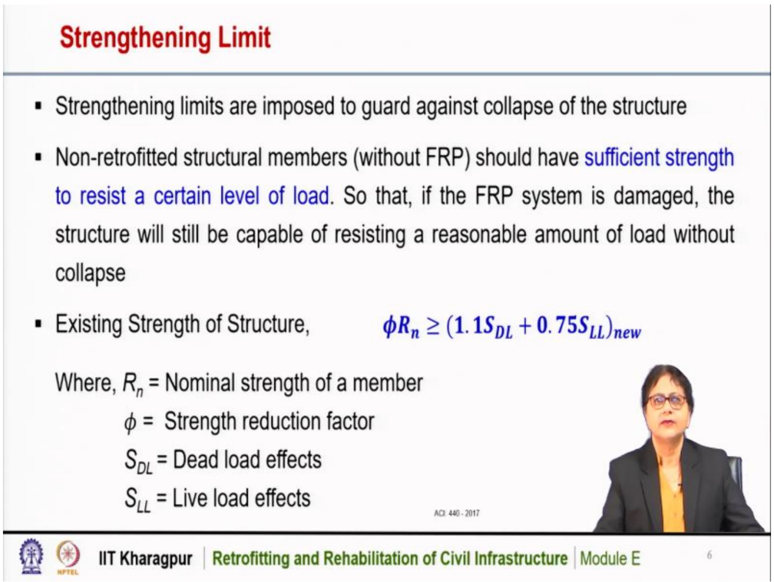

The strengthening limit on existing structure that is imposed to guard against the collapse of the structure. So, there is a strengthening limit for the existing structure and that is imposed to guard against the collapse of the structure. Non-retrofitted structural members without FRP should have sufficient strength to resist a certain level of load, so that if the FRP system is damaged or failed for any reason, the structure will still be capable of resisting a reasonable amount of load without collapse.

So, a limiting strength of the existing structure has been considered. And if the strength of the existing structure is below this limit, then we should not go for retrofitting. It is better to demolish the structure. So, that limit has been imposed, so that there should not be any sudden collapse, if somehow the FRP system is damaged or failed. So, this strengthening limit has been considered based on the dead load and live load effects on the structure.

So, this equation has been developed by the American Concrete Institute that the strength of the existing structure should be more than ($1.1\ S_{DL} + 0.75\ S_{LL}$) of the new structure. That means the existing strength of the structure should be more than 1.1 times the dead load effects plus the 0.75 times the life load effects of the new structure. So, these are shown here. This is the nominal strength and S_{DL} is the dead load effect and S_{LL} is the live load effect.

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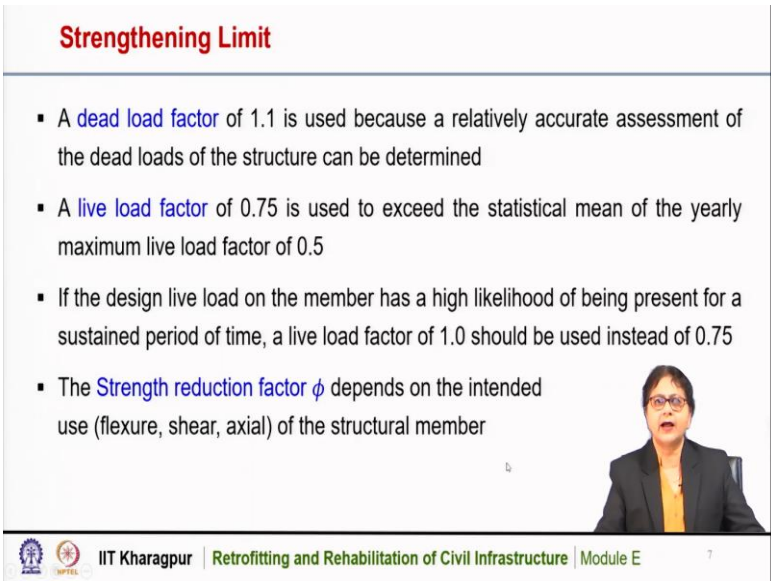

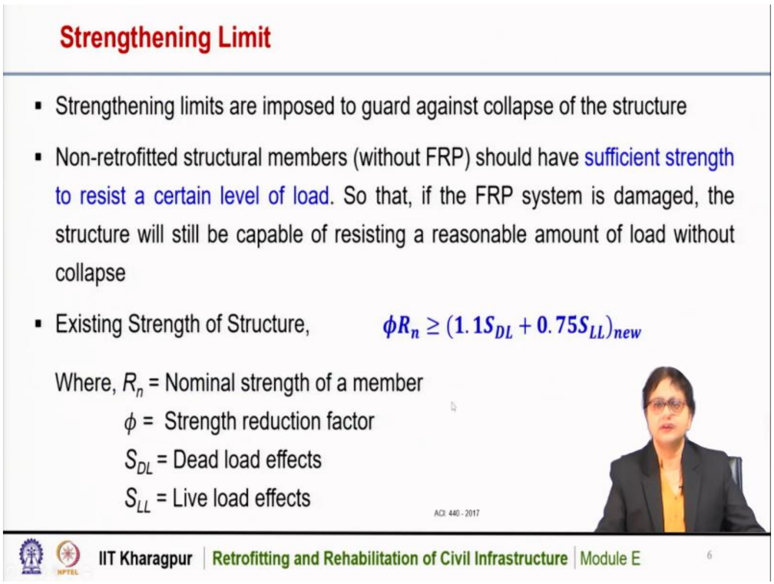

A dead load factor of 1.1 is used here because a relatively accurate assessment of dead load is possible for the structure. A live load factor of 0.75 has been considered, here, in this equation, and this has been considered to exceed the statistical mean of the yearly maximum life load factor of 0.5. So, a factor of 0.75 has been used here. If the design life load on the member has a high likelihood of being present, for a sustained period of time, a live load factor of 1 should be used instead of 0.75.

So, higher live load can be considered, if the live load is for a sustained period of time. The strength reduction factor depends on the intended use of the structural member, whether it is flexural, shear or axial member depending on that a strength reduction factor has been used. So, an existing structure should have sufficient strength, so that it can go for retrofitting. So, this limiting strength is given by this equation.

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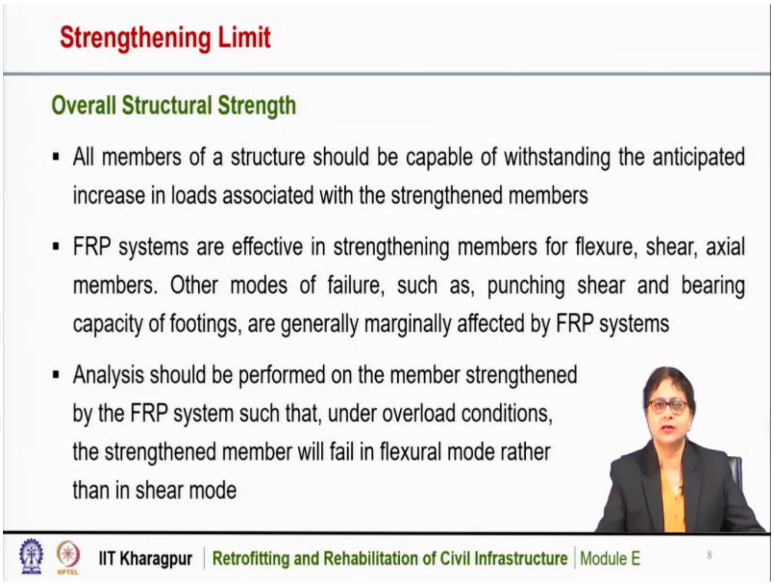

The overall structural strength. All members of a structure should be capable of withstanding the anticipated increase in loads associated with the strengthened members. We can strengthen one particular member or a number of members. However, all members of the structure should be capable of withstanding the anticipated load coming on it associated with the strengthened members.

The FRP systems are effective in strengthening members for flexure, shear, axial members. Other modes of failure such as punching shear and bearing capacity of footings are generally marginally affected by FRP system. Analysis should be performed on the members, strengthened by the FRP system such that under overloading condition, if any the strengthened member will fail in the flexure mode rather than in the shear Mode.

So, this has been considered and it is desirable that if by any chance, due to overloading or so, the structure fails and that failure will be in the flexure mode rather than in shear mode. Because, when the structural member fails in shear, the failure is more abrupt. So, it is desirable to have a failure mode, which is a flexural failure mode as compared to a shear mode of failure.

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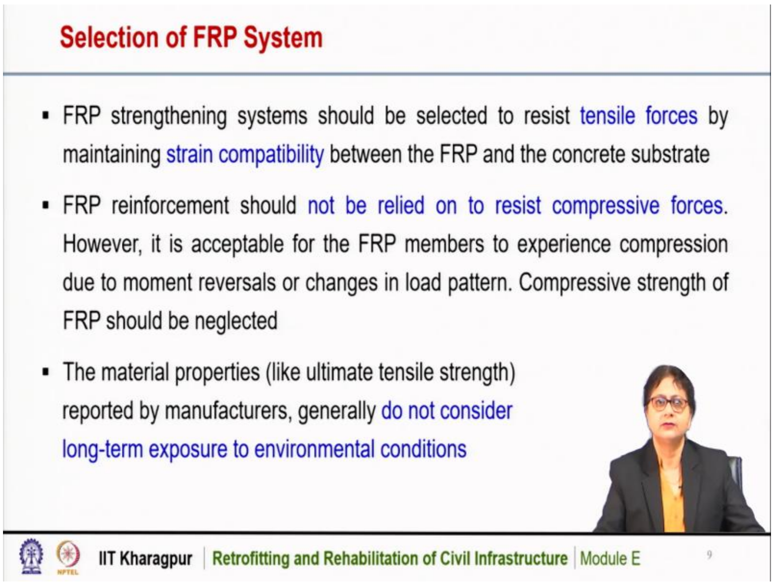

Now, we have to select an FRP system considering the load coming on it. The increase in load is there on the structure, so because of that, it has to carry a higher load and that is why it is to be strengthened. The FRP strengthening system should be selected to resist tensile forces by maintaining strain compatibility between the FRP and the concrete substrate. FRP has excellent tensile strength and tensile modulus therefore, it is used to resist tensile forces only.

And here we consider that their strain compatibility between the FRP and the concrete substrate that is the strain in the FRP and the strain in the concrete is the same. FRP is attached to the existing concrete member either as an external reinforcement at the soffit of the beam members, to improve its flexural capacity or at its sides may be two sided or three sided or all around, to improve its shear capacity or it could be wrapped on a concrete column around its section. So, for these cases, there should be proper bond between the FRP and the concrete.

And we assume that the strain in the concrete and the strain in the FRP is the same. FRP reinforcement should not be reliant on to resist compressive forces. Because it has high strength in tension and it should not be therefore relied on to resist compressive stresses. However, it is acceptable for the FRP members to experience compression due to moment reversals or changes in the load pattern.

Compressive strength of FRP, however should be neglected. So, we should not consider the compressive strength of FRP while designing. It is only the tensile strength of the FRP that is to be considered. The material properties like the ultimate tensile strength is reported by the manufacturers. Generally, when we use the FRP and purchase from a manufacturer, the manufacturer provides the material properties like what is the tensile strength or tensile modulus or maximum strain at failure. These are reported.

However, it is always desirable to test the FRP properties in the laboratory before application. Because in most of the cases, it has been seen that the properties which are reported by the manufacturers are higher as compared to the actual strength. So, it is desirable to test the material before its use. And generally, the properties which are mentioned by the manufacturers, do not consider the long-term exposure to environmental conditions.

FRPs are not that susceptible to environment like steel because steel is undergoing corrosion and that is one of the major problems of steel. FRP being non-metallic, there is no corrosion, but there may be some degradation due to the environmental effect. And the properties which are generally mentioned by the manufacturers do not consider these environmental effects.

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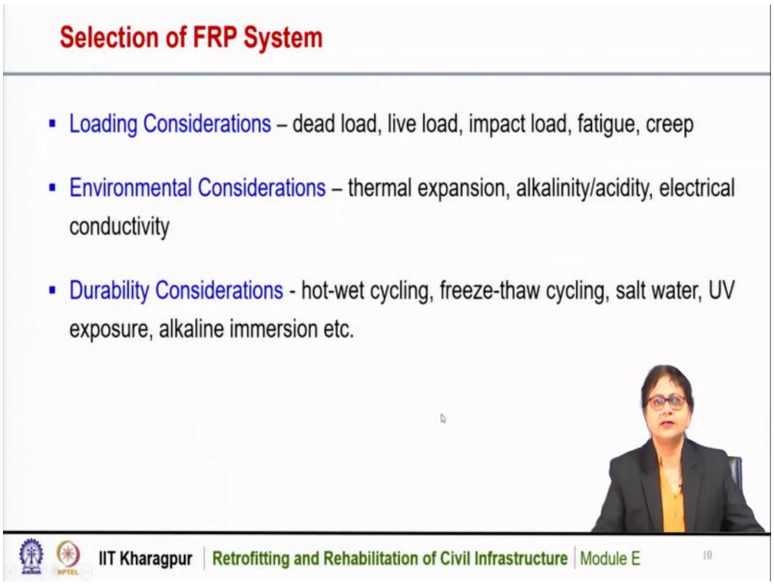

Now, while selecting the FRP system for an existing structure to its strengthening, we have to consider the loading. So, loading consideration should be there. Environmental considerations are also another thing we have to consider. And durability considerations. So, while selecting the FRP system, we have to consider the load coming on the structure, the environmental conditions and the durability conditions or the exposure conditions.

The loading conditions include the dead load, live load, impact load or fatigue that is repeated load or creep or sustained loading. We also have to consider the environmental conditions like thermal expansions, alkalinity or acidity, electrical conductivity, etcetera, depending on the type of structures and its use.

We also need to consider the durability or the effect of weathering actions like hot-wet cycling, freeze-thaw cycling, exposure to salt water, UV exposure, alkaline immersion, etcetera. So, while selecting an FRP system for an existing structure for strengthening, we have to consider the loading conditions, the environmental conditions and the durability conditions.

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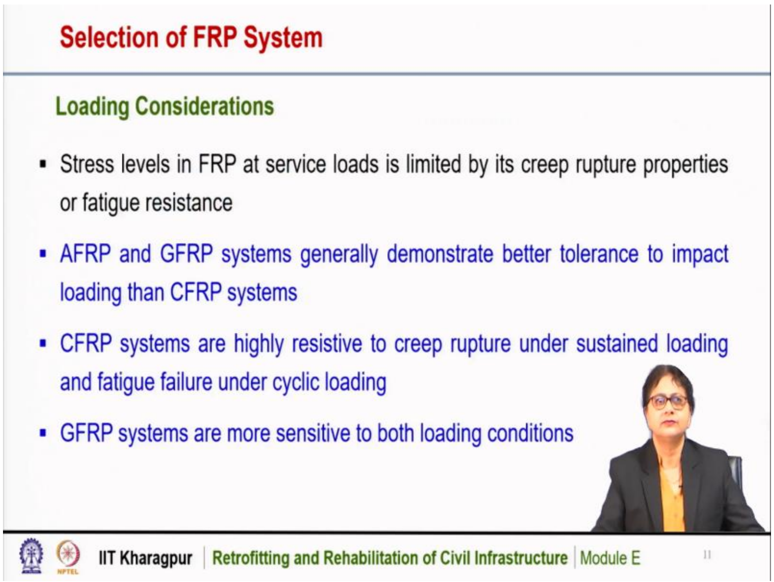

The loading conditions include, as we have mentioned dead load, life load or repeated load or sustained load, etcetera and the stress level in the FRP at service load is limited by its creep rupture properties or fatigue resistance. So, if the structure is such that it is undergoing repeated loading or sustained loading, then we have to select the FRP in such a way that it should take that type of loading. So, the stress level in FRP at service loads may be limited by its creep rupture properties or fatigue resistance.

It has been found from several experimental works that AFRP and GFRP systems generally demonstrate better tolerance to impact loading as compared to CFRP systems. So, if there is an impact-loading coming on the structure and the structure is subjected to that type of loading then AFRP or GFRP performs better as compared to CFRP system. CFRP systems are highly resistive to creep rupture under sustained loading and fatigue failure under cyclic loading.

So, in case the structure is subjected to cyclic loading or sustained loading then CFRP system performs better as compared to AFRP or GFRP systems. So, these things we have to consider while selecting an FRP system. GFRP systems are generally more sensitive to both these loading conditions like sustain loading or repeated loading. So, while selecting an FRP system for load considerations, we have to see that what type of loading the structure is subjected to. And based on that we have to select an appropriate FRP system.

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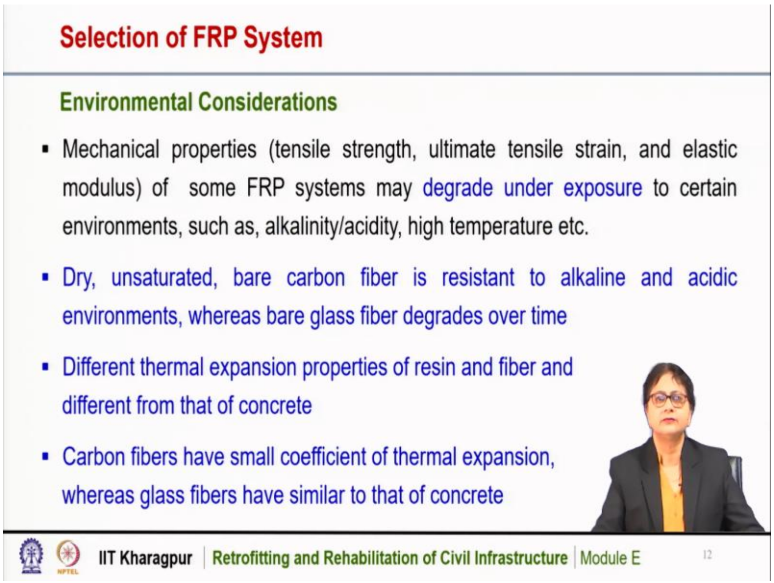

Then comes the environmental considerations. Mechanical properties of some FRP system may degrade under exposure to certain environments like alkalinity or acidity or high temperature, etcetera. FRPs generally have very high tensile strength, high ultimate tensile strain and elastic modulus.

But, due to certain environmental conditions like alkalinity or acidity exposure or high temperature, etcetera, the mechanical properties may degrade. So, we have to consider these things while selecting an appropriate FRP system. If the structure is subjected, so that it is exposed to alkaline atmosphere or acidic atmosphere or high temperature, etcetera, we have to select the FRP system such that it can resist this type of environments.

It has been seen that dry, unsaturated, bare carbon fiber is resistant to alkaline or acidic environments whereas bare glass fiber degrades over time. So, if the structure is situated in such a condition, where it is exposed to alkaline or acidic environments, then as compared to glass fiber, carbon fiber is more resistant.

Different thermal expansion properties of resin and fiber are there and they are different from that of concrete. So, if the structure is subjected to high temperature or so, we have to select the

FRP with the fiber and the resin part such that it can be resistant to these conditions. Because, the resin and the fibers have different thermal properties. Resin is very much susceptible to temperature.

So, we have to select the FRP system also, so that it can resist this type of high temperature. Carbon fibers have very small coefficient of thermal expansion whereas glass fibers have similar to that of concrete. So, carbon fibers are much more resistant to temperature as compared to glass fibers. It has very less coefficient of thermal expansion as compared to glass fiber and aramid fibers. So, these things we have to consider while selecting a proper FRP system. Based on different environmental conditions, we have to select a proper epoxy fiber system, so that it can resist these type of exposures.

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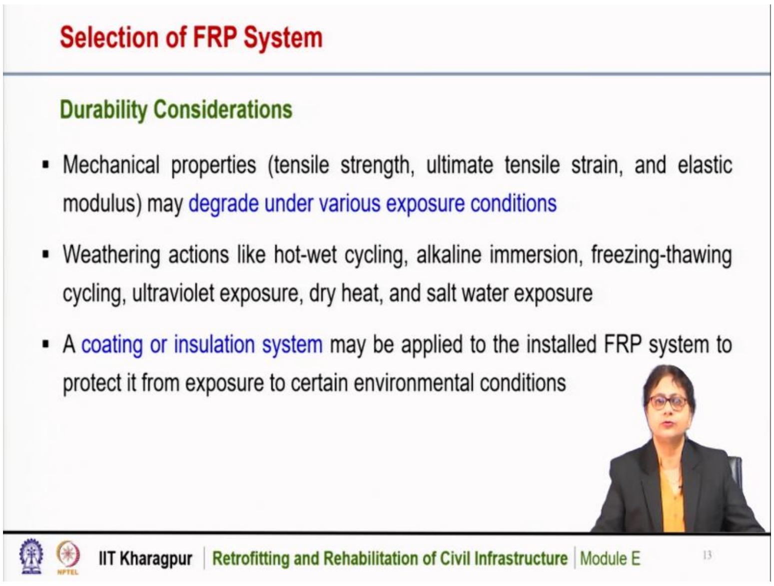

We also need to consider the durability and the weathering effects. The mechanical properties of several FRP system may degrade under various exposure conditions. We have seen that there may be different environmental conditions like high temperature or acidic or alkaline environment.

In addition to that there may be several weathering effects due to which the mechanical properties of FRP may degrade over time. So, the mechanical properties are tensile strength or tensile strain or elastic modulus and over a long period of time, due to the effect of these weathering actions, the mechanical properties may degrade.

The weather reactions are like hot-wet cycling or alkaline immersion, freezing and thawing type of distress, ultraviolet exposure, dry heat, salt-water exposure, etcetera. So, if these type of weathering actions are there and their extent is also significant then we have to select the FRP system such that it can resist this type of exposure conditions.

Sometimes a coating or insulation system may be applied to the installed FRP system to protect it from exposure to certain environmental conditions. And that type of coating or insulation system may be a plaster, which can resist some of these environmental conditions or this type of exposure conditions.

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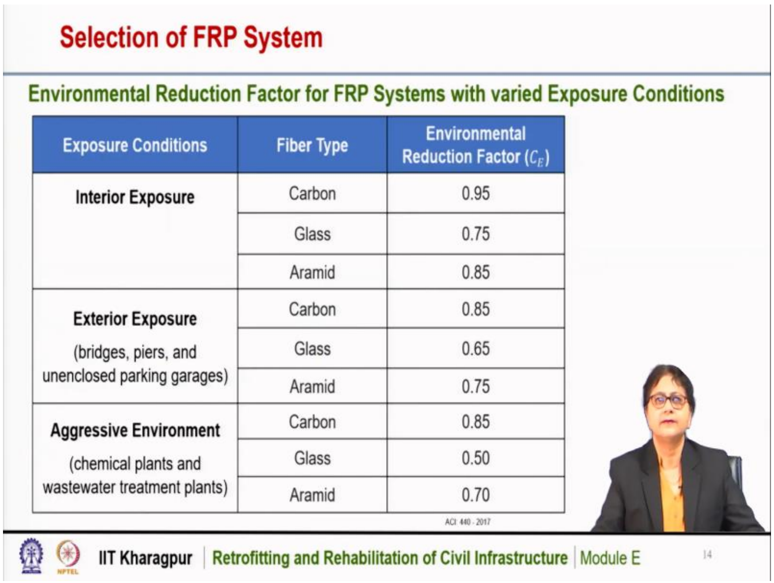

Exposure Conditions	Fiber Type	Environmental Reduction Factor (C_E)
Interior Exposure	Carbon	0.95
	Glass	0.75
	Aramid	0.85
Exterior Exposure (bridges, piers, and unenclosed parking garages)	Carbon	0.85
	Glass	0.65
	Aramid	0.75
Aggressive Environment (chemical plants and wastewater treatment plants)	Carbon	0.85
	Glass	0.50
	Aramid	0.70

These are the environmental reduction factor for FRP system with varied exposure conditions. We have seen that the mechanical properties of the FRPs may degrade due to the effect of several weathering conditions or exposure conditions. And several research works have been carried out to find out the effect of these exposure conditions on different types of FRP system.

Based on the type of exposure therefore environmental reduction factor has been developed. And this can be used in the design, so that the strength reduction is taken care of. So, these are the different environmental reduction factor for different types of FRP system and with different exposure conditions.

When the exposure condition is interior, that means the existing concrete member is situated inside of a structure then these are the environmental reduction factor for carbon fiber composites, glass fiber composite and aramid fiber composite. For the exterior exposure, that means the structure are exposed to environment like a bridge, the pier, the deck slab or unenclosed parking garages, etcetera, they are all exposed to environment.

And that is why the environmental correction factor is lower as compared to the interior exposure condition. Whereas, in some cases it may be due to aggressive environment, the structure may be situated in. And example is like a chemical plant or wastewater treatment plant where the environment is aggressive. So, lot of chemicals are there in the environment.

So, because of that we have another set of environmental reduction factor which are even less than the exterior exposure condition. So, here we can see that for all these cases the carbon fiber has the highest reduction factor. It is nearly one when there is no reduction, we can call it 1. However, when there is more degradation, we can have the environmental reduction factor less than 1.

So, glass fiber has the least environmental reduction factor that means the degradation of the glass fiber is maximum as compared to the carbon fiber or aramid fiber. So, the degradation of the carbon fiber is the least under the interior, exterior or aggressive environment as compared to aramid fiber and glass fiber. In case of aggressive environment, the reduction factor is the least.

Next is the exterior exposure condition and next is the interior exposure condition. If the structural member is placed in an environment which is of aggressive environment, then the strength reduction will be maximum. Then for the exterior condition and then for the interior exposure condition. So, these are the environmental reduction factor that is to be considered for the FRP system to find out the strength of the FRP system.

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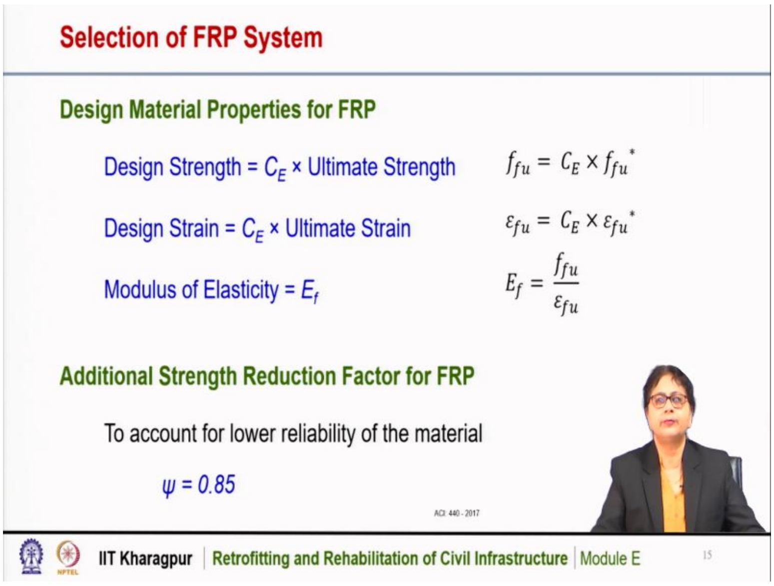

So, the design material properties for the FRP system, we can use these environmental correction factor to find out the design strengths. So, the design strength of the FRP system can be written as (CE that is the environmental correction factor × the ultimate strength of the FRP system). The design strain is equal to (CE that is the environmental correction factor considering the type of exposure × the ultimate strain). And the modulus of elasticity is the same as the original modulus of elasticity. So, we can write this thing that is $f_{fu} = CE \times f_{fu}^*$

This is the ultimate strength or the actual strength of the FRP system.

So, that has to be multiplied with this environmental reduction factor. So, the strength is reduced and that strength should be considered for design of the FRP retrofitted member. Similarly, the ultimate strain is also reduced depending on the type of exposure. We have to multiply the ultimate strain with the environmental reduction factor and then we are getting a lesser strain value as the design strain.

Now, the modulus of elasticity for the design is the ratio of the stress versus strain. So, this we are getting as $E_f = f_{fu} / \varepsilon_{fu}$. That means the environmental reduction factor does not have any influence on it. It cancels out. So, the elastic modulus is the same as the original elastic modulus. So, while designing an FRP retrofitted member, we have to consider the exposure conditions and based on the exposure conditions and the type of FRP system, we are selecting, we have to find out our design strength, design strain and the modulus of elasticity. For the FRP system, we also have to use an additional strength reduction factor to account for the lower reliability of the material.

And this additional strength reduction factor is denoted by ψ, which is equal to 0.85 as given in the American Concrete Institute guidelines. So, these are the reduction factors and the environmental reduction factors have also been considered by the American Concrete Institute and we have to consider those factors while considering the design values. So, while selecting the FRP system, we have to estimate the design strength, design strain and the modulus of elasticity, considering the exposure condition and that is considering the environmental reduction factor.

Along with that, an additional strength reduction factor for FRP has to be considered to be on the safer side, to account for the lower reliability of the material, because of the manufacturing process, it may be hand layup or so and for that there may be some local unevenness or there may be non-uniformity of the property. So, to take care of all these issues, we can take an additional strength reduction factor for the FRP system and which is equal to 0.85 as per the ACI guidelines.

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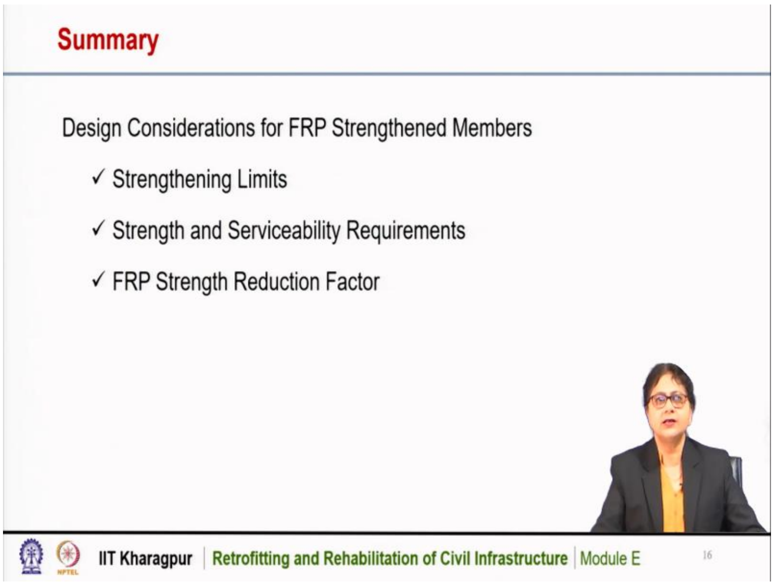

So, to summarize we have discussed today the design considerations for FRP strengthened members. We have discussed the strengthening limits for existing structures; the strength and serviceability requirements for the design of FRP retrofitted members and the FRP strength reduction factors.

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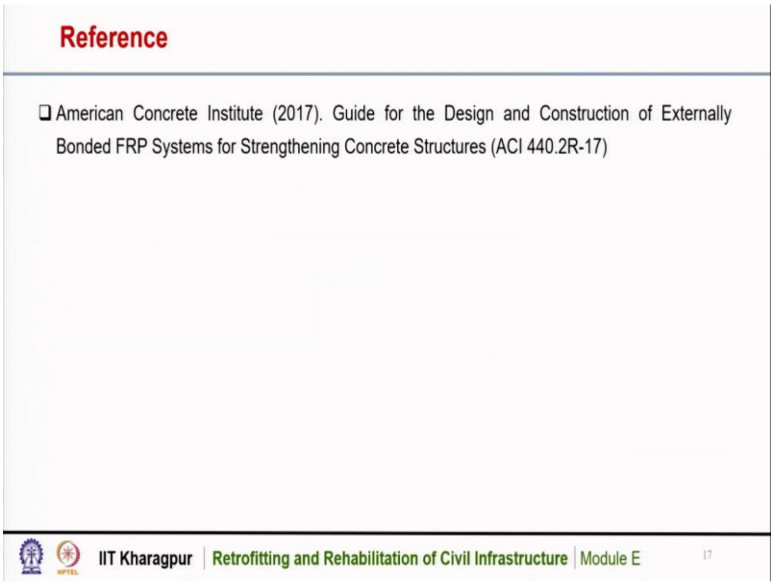

This is the reference for today's lecture. Thank you.