PRESTRESSED CONCRETE STRUCTURES

Amlan K. Sengupta, PhD PE

Department of Civil Engineering,

Indian Institute of Technology Madras

Module – 3: Analysis of Members

Lecture – 11: Analysis of Members under Axial Load

Welcome back to prestressed concrete structures. Today is the first lecture of Module 3 on analysis of members.

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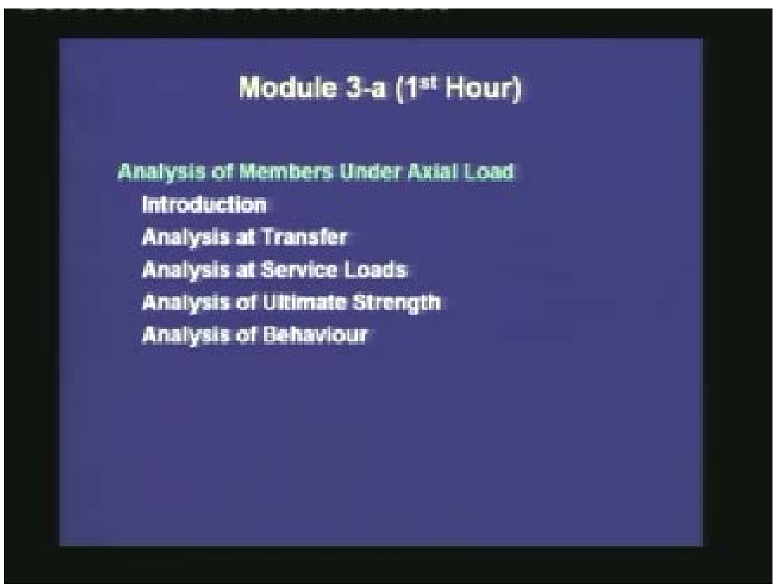

Till now, we have studied the material properties, the prestressing systems and devices and the losses of prestress. Today, we are moving on to the analysis of prestressed concrete members. First, we shall study the analysis of members under axial load and under that, we shall study the analysis at transfer, analysis at service loads, analysis of ultimate strength and finally, we shall study the analysis of behavior.

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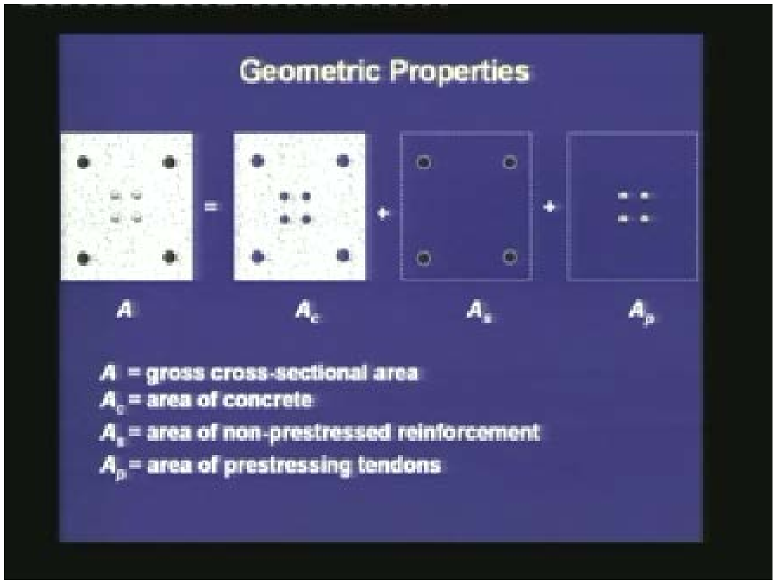

The geometric properties that we shall use are shown schematically in this figure. On the left, we can see a typical axially loaded member, where we may have both prestressing tendons and non-prestressed reinforcement. A is the gross cross-sectional area of the member. The prestressed member consists of the area of concrete which is represented as A_c. Then, it consists of the area of the non-prestressed reinforcement, which is represented as A_s and it also consists of the area of the prestressed tendons, which is represented by A_p. Thus, $A = A_c + A_s + A_p$.

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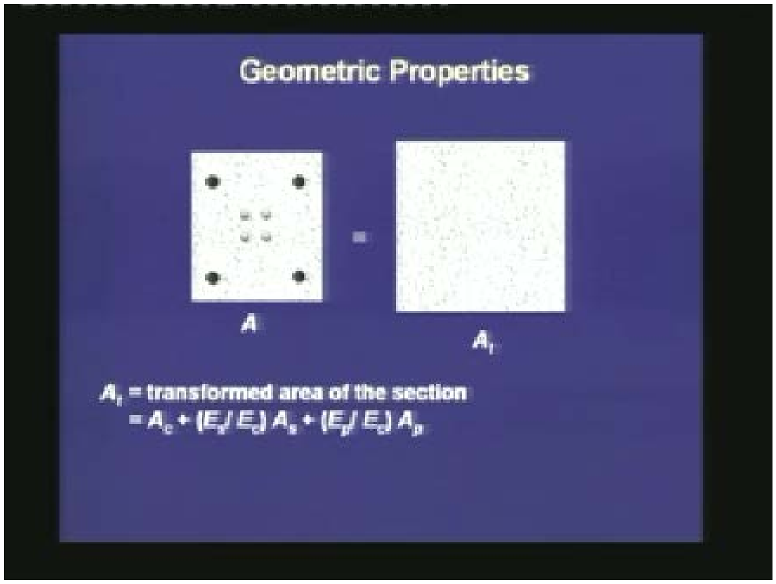

Another geometric property that we shall use is the transformed section. When the reinforcement and the prestressed tendons are transformed to equivalent areas of concrete and we add that to the remaining part of the concrete, the total transformed area is termed as the transformed area of the section. It is represented as A_t. A_t is equal to A_c plus the modular ratio times A_s plus the modular ratio of the prestressing tendons times A_p. The modular ratio for either of the reinforcement of the prestressed tendons is given as the ratio of the elastic modulus of the steel divided by the elastic modulus of the concrete. The transformation is done when we study the stresses under elastic analysis.

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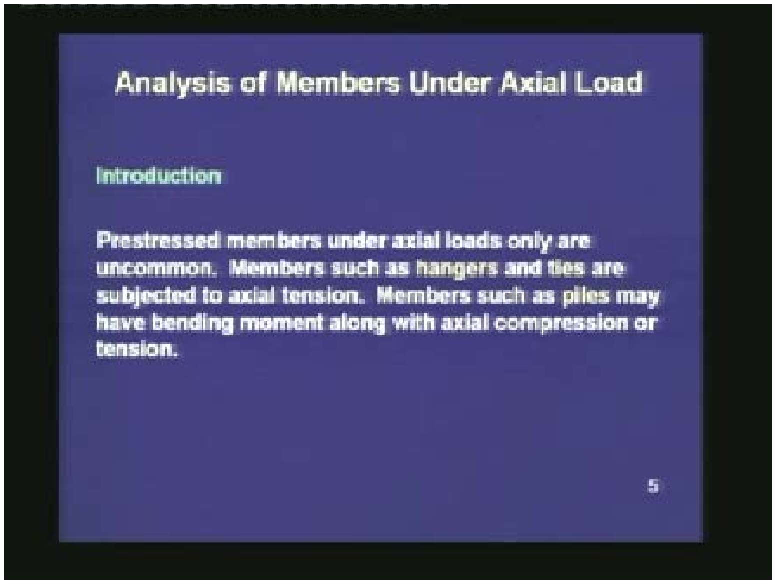

Prestressed concrete members only under axial loads, are uncommon. Members such as hangers and ties are subjected to axial tension. Members such as piles may have bending moment along with axial compression or tension.

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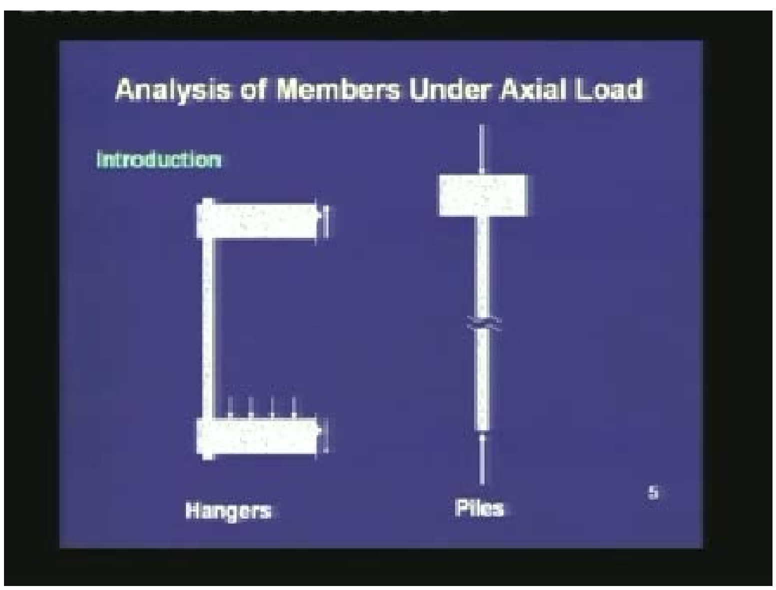

In this figure, we see that on the left hand side, the floor at the bottom has been suspended from the floor at the top by hangers. This hanger is subjected to axial tension and it needs to be prestressed to have area of the member within the certain architectural limit. On the right hand side, we see a pile, which is subjected to axial compression. But piles can go to axial tension also, when there will be uplift under high lateral force on the building. Also, the piles are subjected to shear and it can be subjected to bending moments. In these sketches, we have shown only the vertical forces. The ties are horizontal members subjected to tension.

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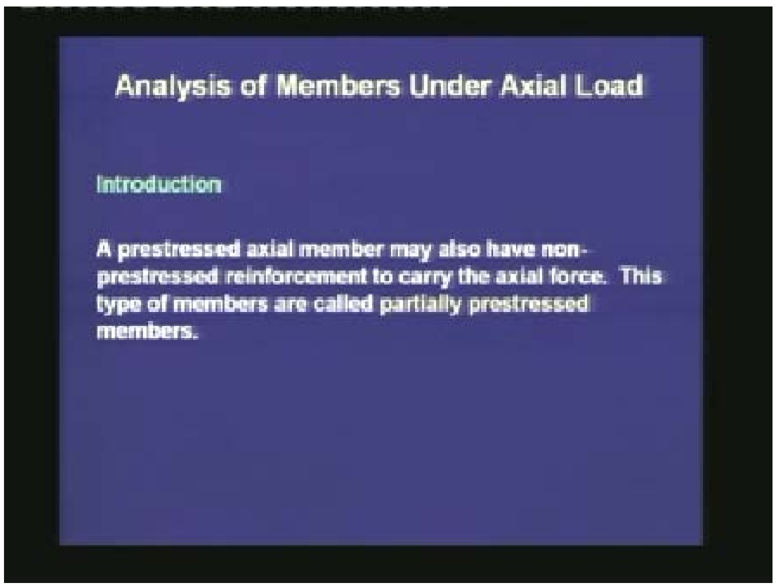

A prestressed axial member may also have non-prestressed reinforcement to carry the axial force. This type of members is called partially prestressed members. We shall also come back to partially prestressed members for flexure. This type of members is somewhere in between the reinforced concrete members and fully prestressed members. The partially prestressed members have both prestressing tendons and non-prestressed reinforcement to carry the forces.

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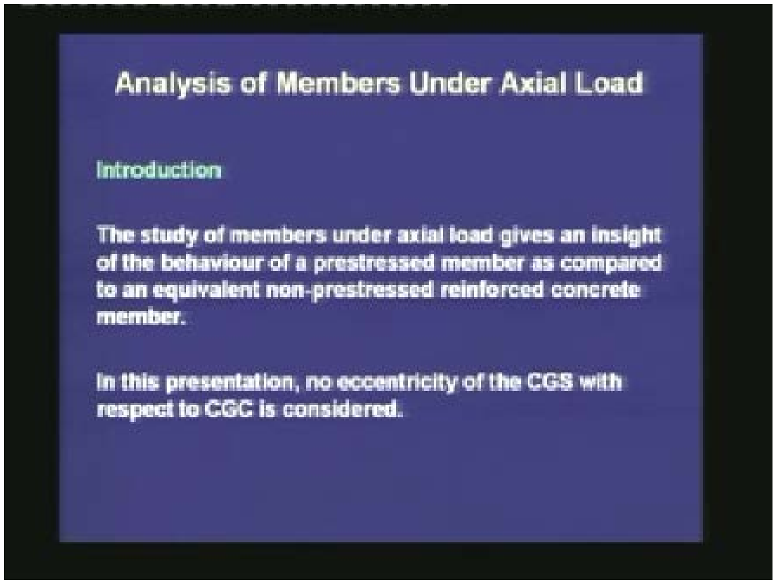

The study of members under axial load gives an insight of the behavior of a prestressed member as compared to an equivalent non-prestressed reinforced concrete member. Why at all, are we studying members under axial load, if such members are not common? The reason is that there are some basic differences between a reinforced concrete member and a prestressed concrete member, which is easy to understand, if we are studying the axially loaded members first. This gives an insight into the effect of prestressing on the behavior of reinforced concrete members. In the case of the members we are studying now, we will neglect any eccentricity of the prestressing tendons with respect to the CGC, which means we are considering that the CGS lies at the level of the CGC.

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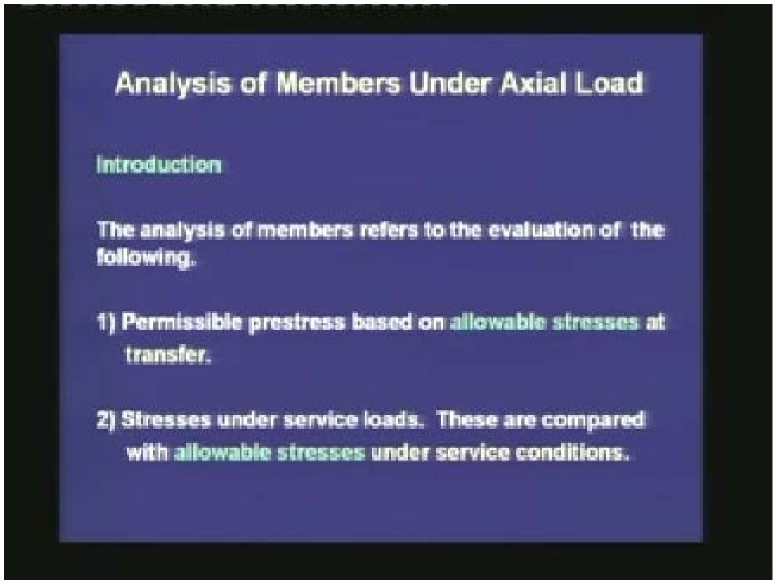

The analysis refers to the following.

First, we shall study the permissible prestress based on allowable stresses at transfer. Earlier we had known that the load stages in a prestressed concrete member can be divided into several stages; the first one is the stage at the transfer of prestress; second, is the stage during transportation of the prestressed member from its casting site to its permanent position; third, is the stage under service loads and finally, under some extreme event, it can be subjected to ultimate loads. For all these load stages, we need to study the stresses, or the strength. Here we are first studying the stresses at transfer and based on the allowable stresses at transfer, the maximum prestress is determined.

Second, we are studying the stresses under service loads. These stresses are compared with the allowable stresses under service conditions. Remember that the allowable stresses can be different at transfer and under service conditions. We have studied the allowable stresses under the module of “Material Properties”.

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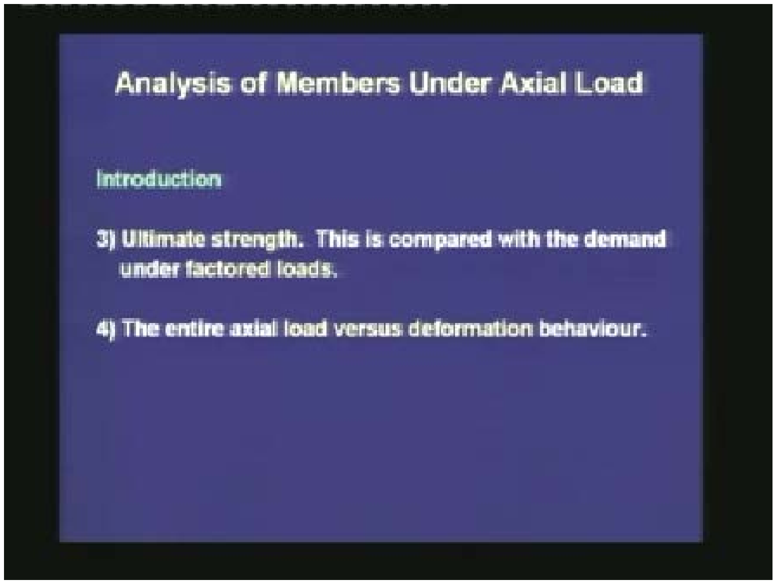

Third, we shall study the ultimate strength. This is compared with the demand under the factored loads. That means, in a limit state design, we compare the ultimate strength with the demand under ultimate loads, which are the load factors times the characteristic loads. Finally, we shall study the entire axial load versus deformation behavior to understand the full property of the prestressed concrete member. First, we are studying the analysis at transfer.

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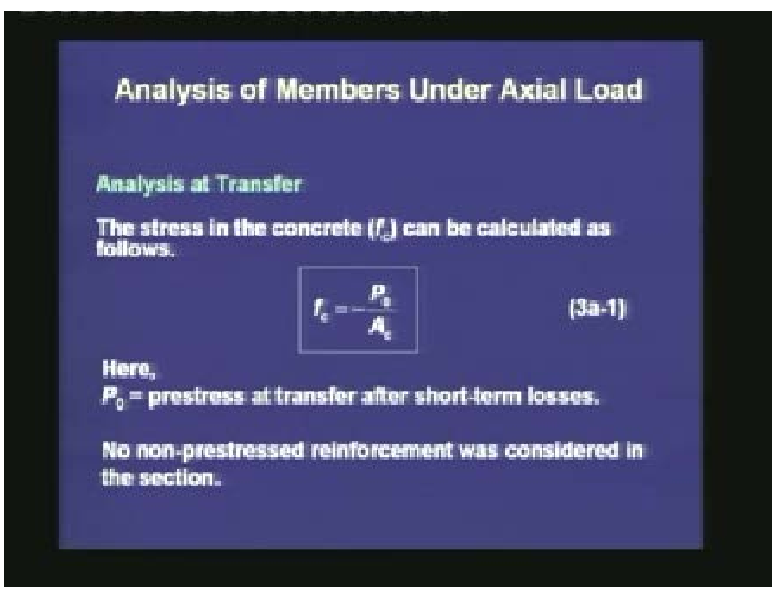

The stress in the concrete can be calculated as follows. The stress is given as the ratio of the prestress at transfer after short-term losses divided by the area of the concrete. In this expression, we have not considered any non-prestressed reinforcement. Just note that we are considering a negative sign for a compressive stress under the prestressing force.

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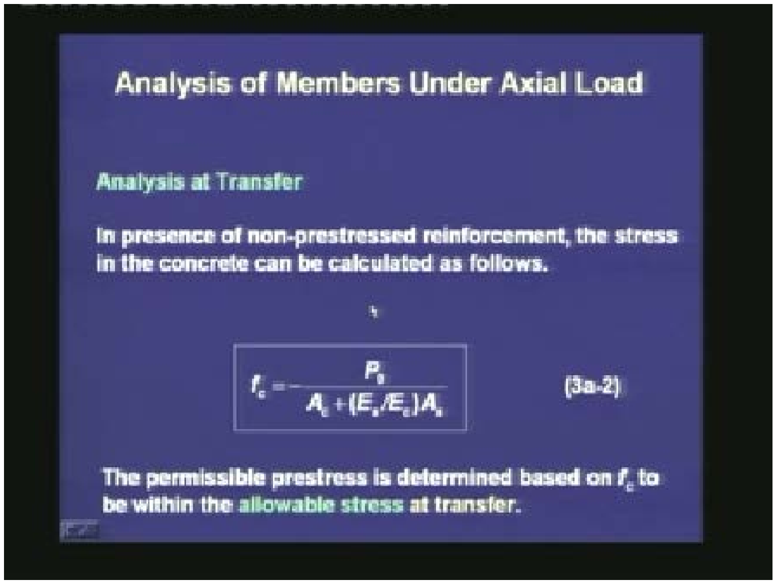

In presence of non-prestressed reinforcement, the stress in the concrete can be calculated as follows. The stress is given by the prestress at transfer divided by a transformed area, which is equal to the area of the concrete plus the modular ratio of the reinforcement steel times the area of the reinforcement steel. This denominator is higher than just the area of the concrete. The permissible prestress (P_0) is determined based on f_c to be within the allowable stress at transfer, which means, we can apply the prestress up to a certain level such that the stress under transfer is within the allowable value.

Next, we are studying the analysis at service loads.

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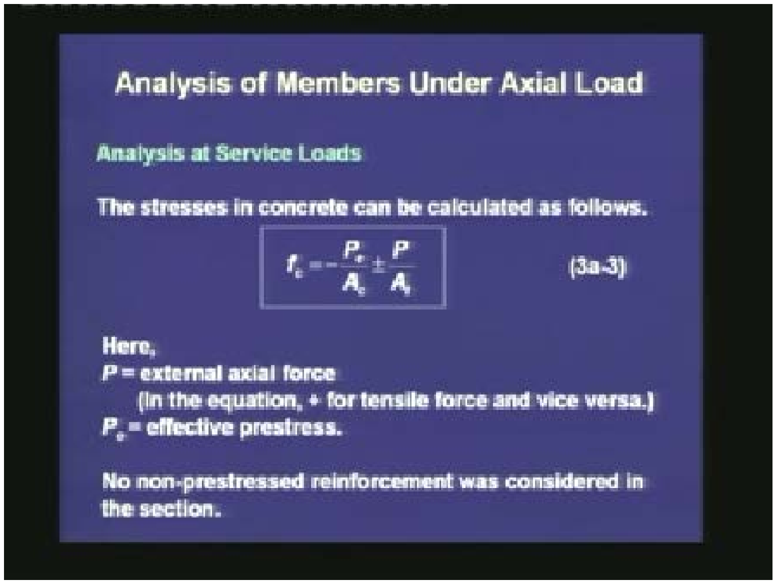

The stresses in concrete can be calculated by the following expression: $-P_e/A_c \pm P/A_t$, where P_e is the effective prestress after the long-term losses, A_c is the area of the concrete, P is the external force and A_t is the transformed area. If we have a tensile force, then we shall use the '+' sign and if we have a compressive external force, then we shall use the '–' sign. The stress in the concrete is equal to the compressive stress, which is generated by the effective prestress, plus or minus the stress that is generated by the axial load. In the expression, we have not considered any non-prestressed reinforcement.

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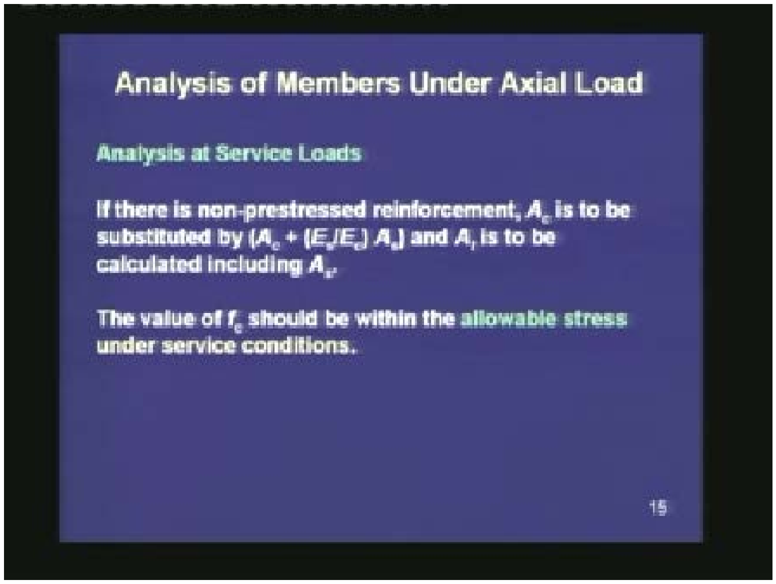

If there is non-prestressed reinforcement, then the area A_c is to be substituted by A_c plus the modular ratio times A_s, and the transformed area A_t is to be calculated including A_s. That is, the way we have included A_s in the previous expression, similarly, we shall include A_s in this expression as well.

The value of f_c should be within the allowable stress under service conditions. As I said before, the allowable stress under service conditions is different from the allowable stress at transfer. We need to make sure that the total stress that is generated by the effective prestress and the external load, should be within the allowable stress under service conditions.

Next, we are moving on to the analysis of ultimate strength.

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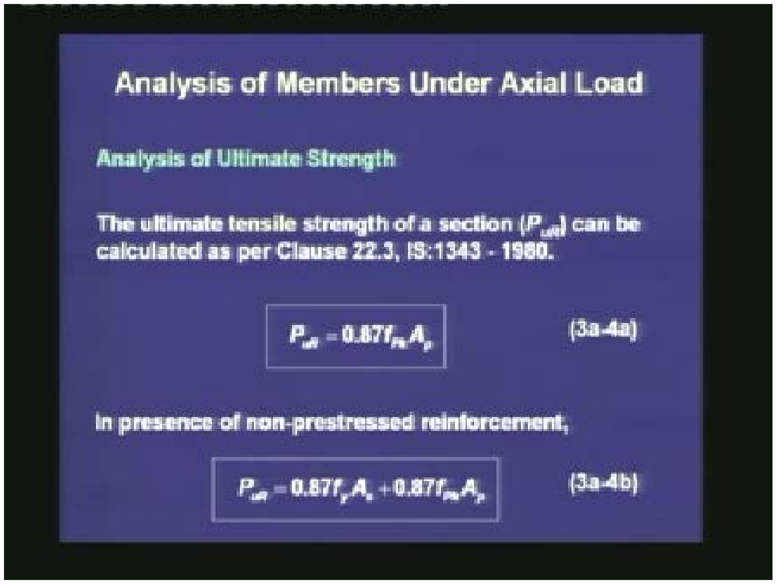

The ultimate tensile strength of a section (which is denoted as P_{uR}, the ultimate load of resistance) can be calculated as per Clause 22.3 of IS: 1343 – 1980. The ultimate load in absence of any non-prestressed reinforcement is given as $0.87f_{pk}A_p$, where the area of the prestressing tendon is A_p. If we have non-prestressed reinforcement, then the ultimate tensile strength is given as $0.87f_yA_s$, where A_s is the area of the non-prestressed reinforcement, plus $0.87f_{pk}A_p$. Here 0.87 is the inverse of 1.15, the material safety factor.

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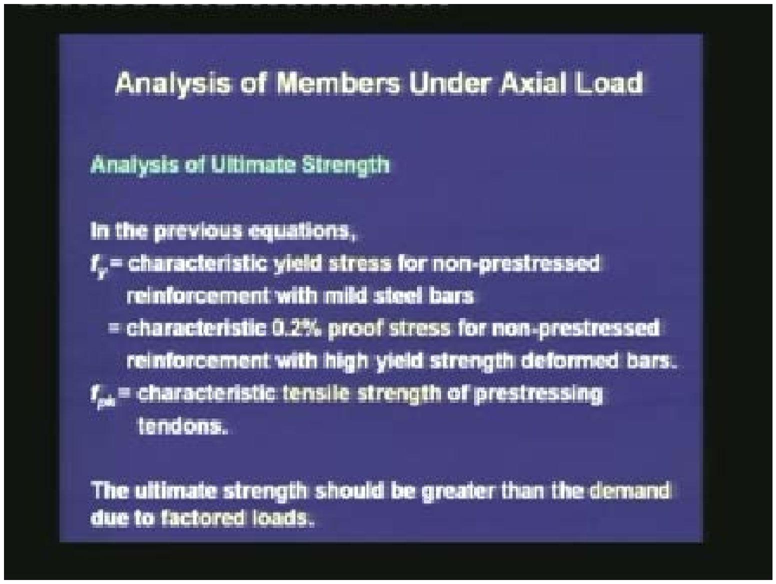

In this previous equation, f_y is the characteristic yield stress for non-prestressed reinforcement with mild steel bars, the bars which have a definite yield plateau. The stress corresponding to the yielding is denoted as f_y. For high strength deformed bars, f_y is equal to the characteristic 0.2 proof stress. We have learnt that the proof stress is the stress corresponding to a particular plastic strain. The 0.2 proof stress is obtained by drawing a line parallel to the initial modulus and it starts with a plastic strain of 0.002. Wherever this parallel line intercepts the stress-strain curve, the corresponding stress is termed as the 0.2 percent prestress. f_{pk} is the characteristic tensile strength of the prestressing tendons.

Once we know the material properties of both the types of steel, we can find out the ultimate tensile strength of a member. This ultimate strength should be greater than the demand due to factored loads. Here, there is a difference between the analysis at transfer and service loads with the analysis at ultimate strength. For transfer and service loads, we calculated the stresses and compared the stresses with the allowable value, whereas for the ultimate loads, we first computed the ultimate strength and then, we compared the ultimate strength with the demand under the ultimate loads or the factored loads. Hence, to summarize, the computation for the stage at transfer and that at service loads is based on stresses where we use an elastic analysis; whereas the computation for the ultimate strength is based on strength and not stresses, and there we use non-linear material properties of the steel.

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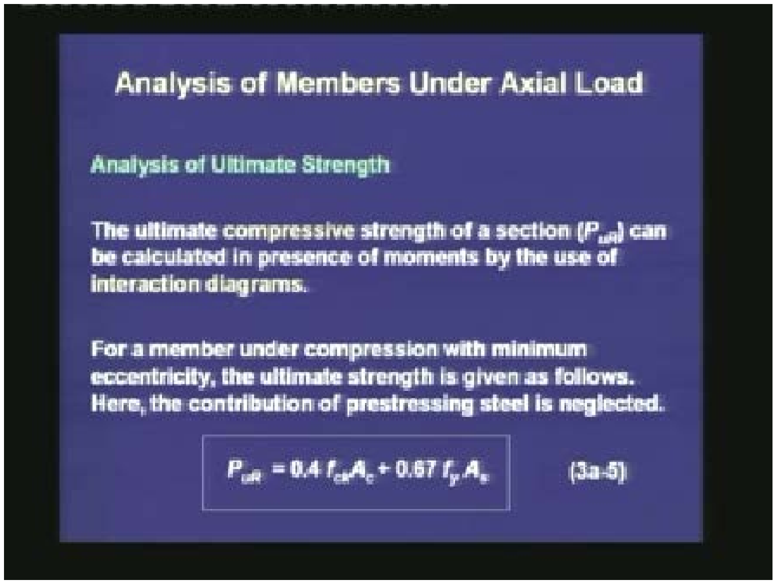

If we are calculating the ultimate compressive strength, then the expression in presence of moments, can be found out by the use of interaction diagrams. Usually, compression members are also subjected to moments, like columns. If we have to find out the ultimate compressive load in presence of moments then we have to use the interaction diagrams that we have learnt under reinforced concrete. The code IS: 1343 allows us the method given in IS: 456 to find out the ultimate compressive strength in presence of moments.

For a member under compression with minimum eccentricity, we can neglect the use of the interaction diagrams and then the ultimate strength is given by the following expression: $P_{uR} = 0.4\ f_{ck}\ A_c + 0.67\ f_y\ A_s$. In this expression, we have considered that both the materials have reached their ultimate capacities and also we have introduced a factor to consider the effect of minimum eccentricity. We find that the ultimate strength is a summation of the compressive strength of the concrete and the compressive strength of the reinforcement steel. In this expression, the contribution of prestressing steel has been neglected. Usually, the area of prestressing steel is very small and it need not be considered in considering the compressive strength of an axially loaded member.

Thus, till now what we have studied is: first, the analysis at transfer where we found out an expression of the stress. Since the stress has to be less than the allowable stress at transfer, we have to limit the maximum prestress that can be applied. We studied the analysis at service loads, where we found out the stresses due to the effective prestress after the losses and the external load that acts on the member. Then, we found out the ultimate strength, when both the materials, steel and concrete, are reaching their ultimate capacities. We are comparing this ultimate strength with the demand, which is coming under the factored loads. The ultimate strength has to be larger than the demand under the factored loads. Next, we are moving on to the study of an important aspect. It is the complete load versus deformation behavior of the axially loaded member.

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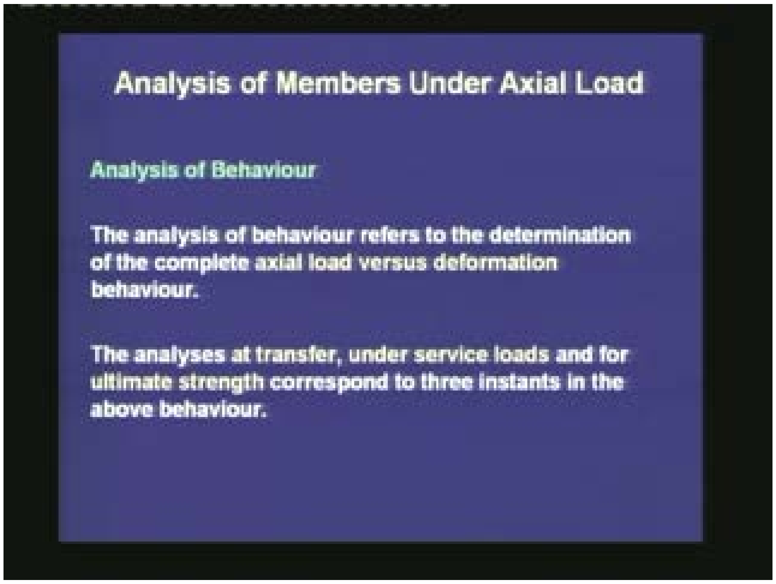

The analysis of behavior refers to the determination of the complete axial load versus deformation behavior. The analyses at transfer, under service loads and for ultimate strength correspond to three instants in the above behavior. Whatever we have studied till now are just three points in the complete load versus deformation behavior. The load versus deformation behavior is an entire curve, which shows how the member will behave, when we are gradually increasing the externally applied load.

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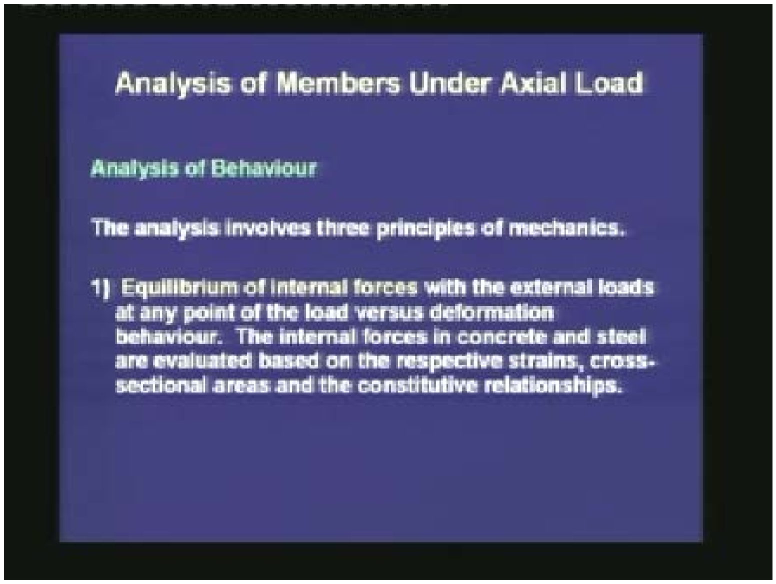

The analysis involves three principles of mechanics.

First is the equilibrium of internal forces. Here, the internal forces are in equilibrium with the external loads at any point of the load versus deformation behavior. This is a very important principle of mechanics that at any time, the structure is under static equilibrium. It means that the internal forces that are generated within the member and the external load are in equilibrium, and we can write the equations of statics at any point of this load versus deformation behavior. The internal forces in concrete and steel are evaluated based on their respective strains, cross-sectional areas and the constitutive relationships.

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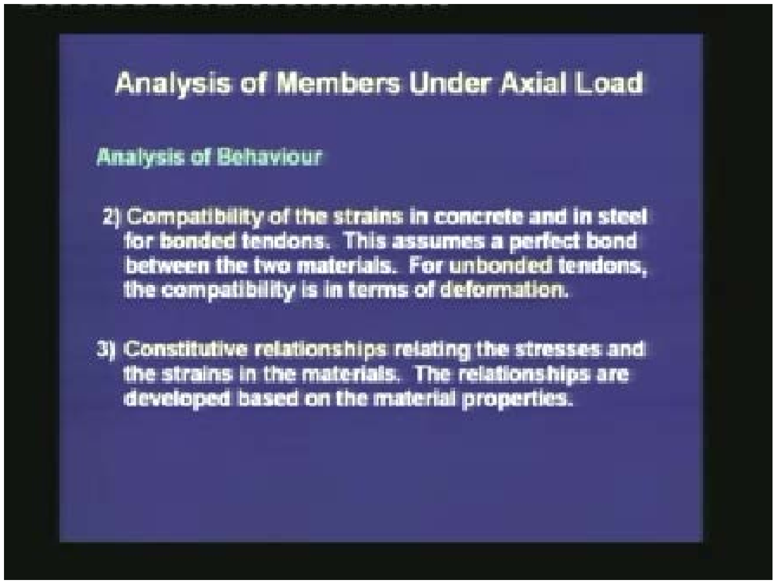

The second principle is the compatibility of the strains in concrete and in steel for bonded tendons. This assumes a perfect bond between the two materials. This is another important principle that the concrete and the prestressing tendon and any other non-prestressed reinforcement, if they are present, they deform together. The strain that the concrete undergoes at the level of the steel is same as the change in the strain in the prestressing tendon, and also it is equal to the strain in the corresponding level of the reinforcement.

The strain compatibility is true when we have a bonded tendon. In a pre-tensioned member, the tendons are bonded with the concrete. In a post-tensioned member, if we grout the member, then also the tendons are bonded with concrete and we can expect strain compatibility between the concrete and the steel. For unbonded tendons, the compatibility cannot be expressed in terms of strain, but it can be expressed in terms of overall deformation. In this lecture, we are not considering unbonded tendons. We are just studying bonded tendons, where we shall assume strain compatibility between the concrete and the steel.

The third principle of mechanics is the constitutive relationships. The constitutive relationships relate the stresses and the strains in the materials. These relationships are developed based on the material properties.

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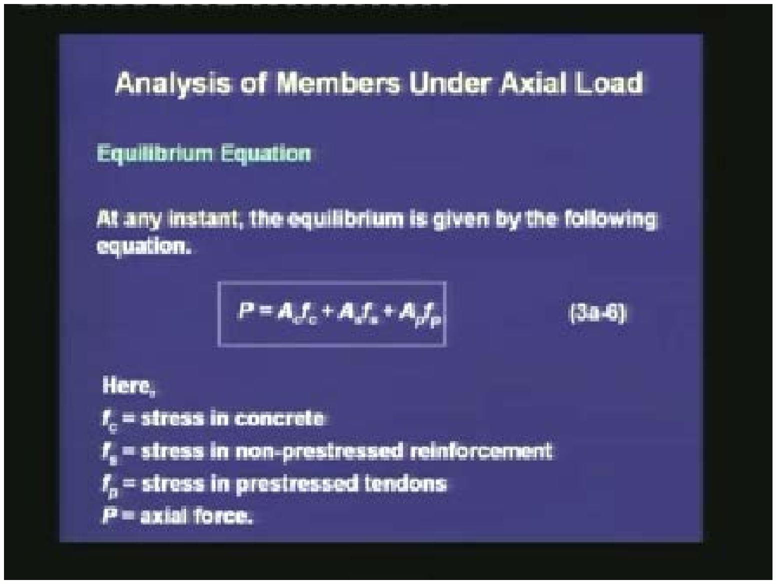

The first principle, that is equilibrium, can be expressed at any instant of the load versus deformation behavior by this following equation: The external load is equal to the internal force in the concrete plus the internal force in the non-prestressed reinforcement plus the internal force in the prestressing tendon. Here, f_c is the stress in the concrete, f_s is the stress in non-prestressed reinforcement and f_p is the stress in the prestressed tendons. The axial force which is externally applied is a summation of the internal forces that are generated within the concrete, steel and the prestressing tendon.

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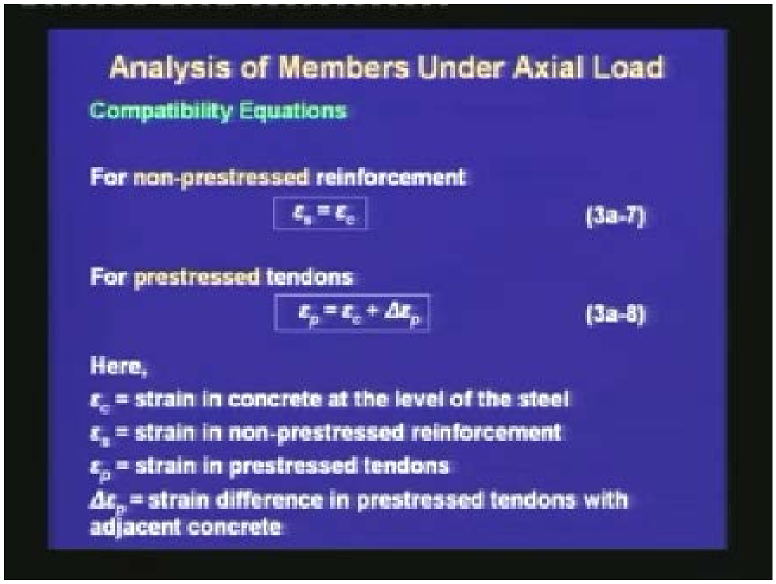

Next, we are writing the equations of compatibility. For non-prestressed reinforcement, ε_s which is the strain in the non-prestressed reinforcement is equal to ε_c which is the strain in the concrete at the level of the steel. We are trying to express that both the non-prestressed reinforcement and the concrete deform together. Hence, the strains of the concrete at the level of the non-prestressed reinforcement are same as that of the strain in the steel. For the prestressing tendon, the strain in the tendon is given as the strain in the concrete plus an additional term, which is called the strain in the prestressed tendon at the decompression of concrete.

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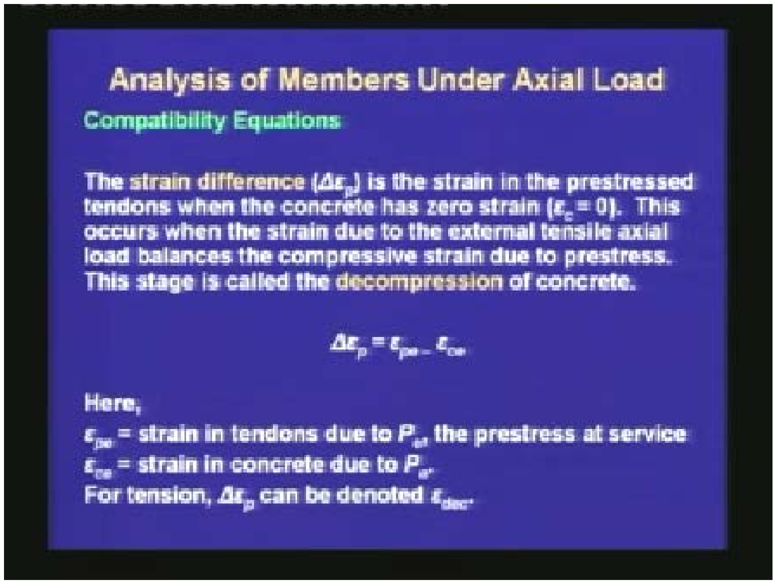

Let us try to understand this additional term in the strain compatibility equation of the prestressed tendons. The strain in the prestressed tendons at the decompression of concrete, which is denoted as ε_{dec} is the strain when the concrete has zero strain. How are we defining the strain at decompression of concrete? It is the strain in the prestressing tendon, when the strain in the concrete is zero. The concrete is no more under compression. It has been decompressed under the externally applied load. This occurs when the strain due to the external tensile axial load balances the compressive strain due to prestress. It means whatever strain the prestress is applying on the concrete member, the external load is applying an equal and opposite strain and hence, the strain in the concrete is finally equal to zero. For pre-tensioned and post-tensioned members, the values of ε_{dec} are different. The reason behind this difference is the different way of applying the prestressing force.

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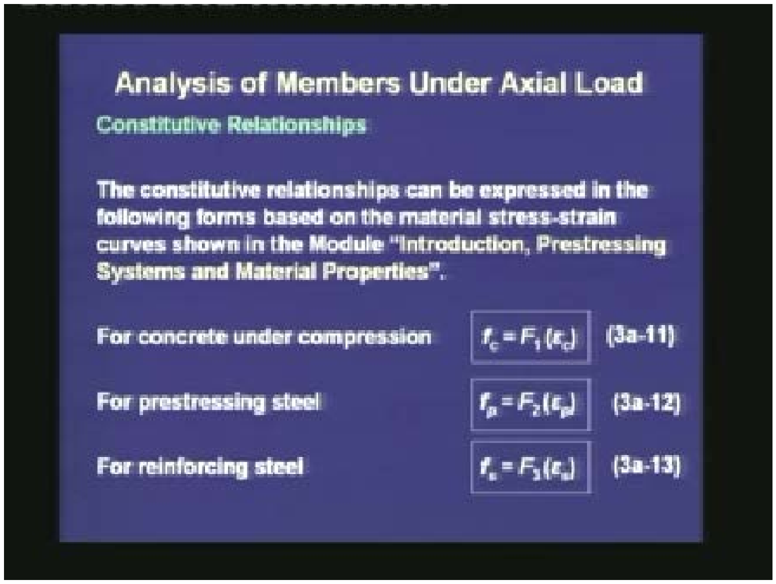

Next we move on to the third principle of mechanics which is the constitutive relationships. The constitutive relationships can be expressed in the following forms, based on the material stress-strain curves shown in the module of introduction, prestressing systems and material properties.

For concrete under compression, we have an expression which is f_c is equal to some function of ε_c. We are writing that function as $F_1(\varepsilon_c)$. For prestressing steel, the relationship can be written as f_p is equal to some function of ε_p and we are denoting this function as F_2. For reinforcing steel, the constitutive relationship can be written as f_s is equal to some function of ε_s and this function is denoted as F_3. Let us try to understand the constitutive relationship for each of the materials individually.

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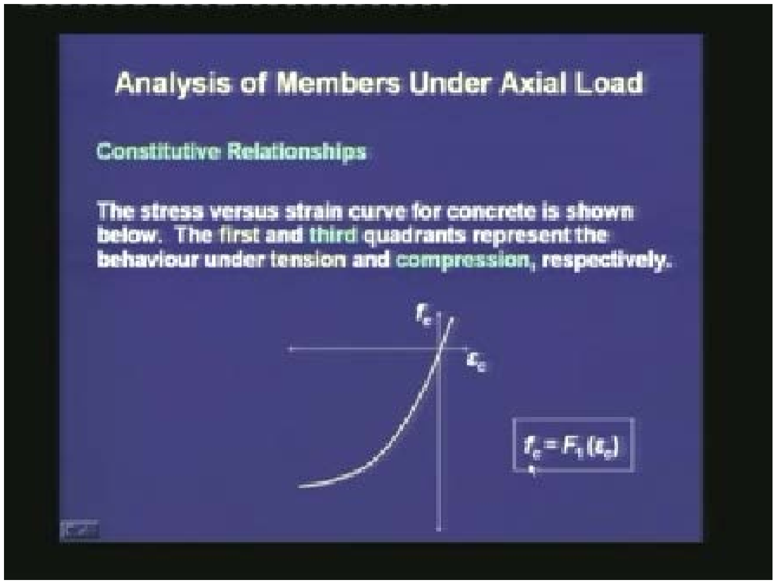

The stress versus strain curve for concrete is shown in this figure. Here, the first quadrant or the quadrant at the top right represents the behavior under tension. Once the concrete cracks, we are not considering any stress in the concrete. The curve in the first quadrant can be considered to be linear elastic, where f_c is equal to $E_c\varepsilon_c$. The third quadrant, which is the lower left quadrant, represents the behavior under compression, where the behavior is a parabolic form and we have seen the expression of Hognestad's equation for normal strength concrete, and the expression by Thorenfeldt, Tomaszewicz and Jensen for high strength concrete. We can use the expressions to get the functional form relating f_c and ε_c. Thus, for positive values of ε_c, we are using the linear elastic relationship. For a negative value of ε_c, we are using the relationship for concrete under compression.

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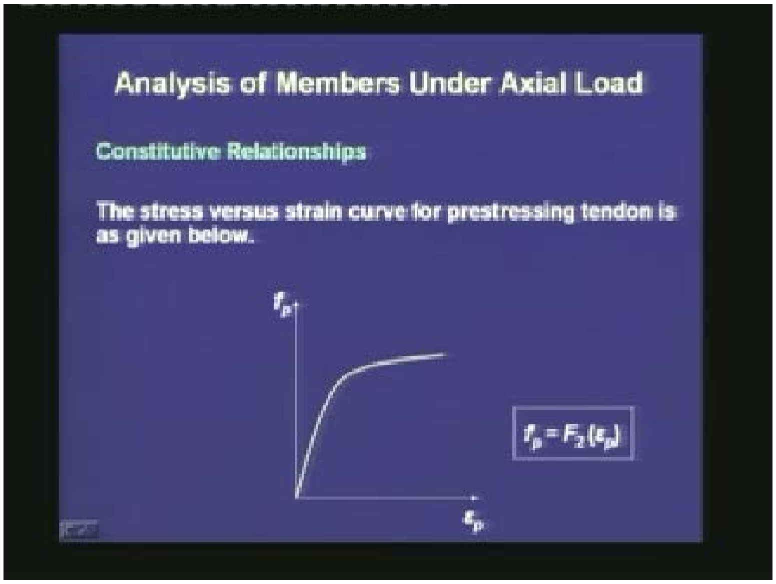

The second constitutive relationship is for the prestressing tendons. We are considering only the relationship for tension. Here we see that initially, the prestressing force is almost linear and then we have a curved behavior till it gains its ultimate strength. The variation of f_p with respect to ε_p can be given in the form of a curve in a graphical paper, or it can be given in the form of a table, or we can try to fit some equation. Once we have either one of these forms, we say that we are able to express the stress f_p in terms of ε_p in this functional form, which is denoted by $f_p = F_2(\varepsilon_p)$.

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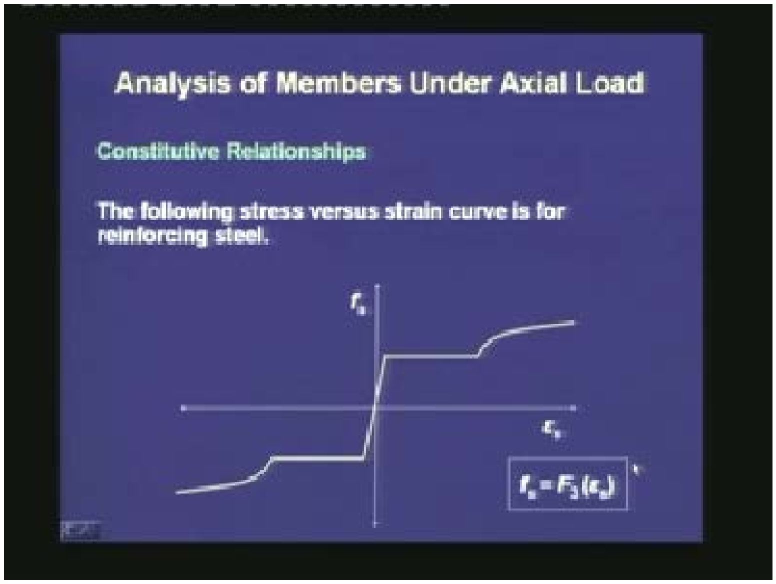

The third constitutive relationship is for the stress-strain curve for reinforcing steel. Here we have shown the behavior, both for the tension quadrant at the top right and for the compression quadrant, which is for the bottom left. We see that for either of the quadrants, the behaviour initially is elastic. For mild steel, we have a definite yield plateau and then we have a strain hardening region till it reaches its ultimate strength. If we do not have mild steel then we will not be seeing this yield plateau. But we will have a curve, which again will be given in either a graphical form or in a tabular form. This relationship between f_s and ε_s is expressed in terms of the equation $f_s = F_3(\varepsilon_s)$. This functional representation of the constitutive relationship implies that given a strain in the material, we are able to calculate the stress.

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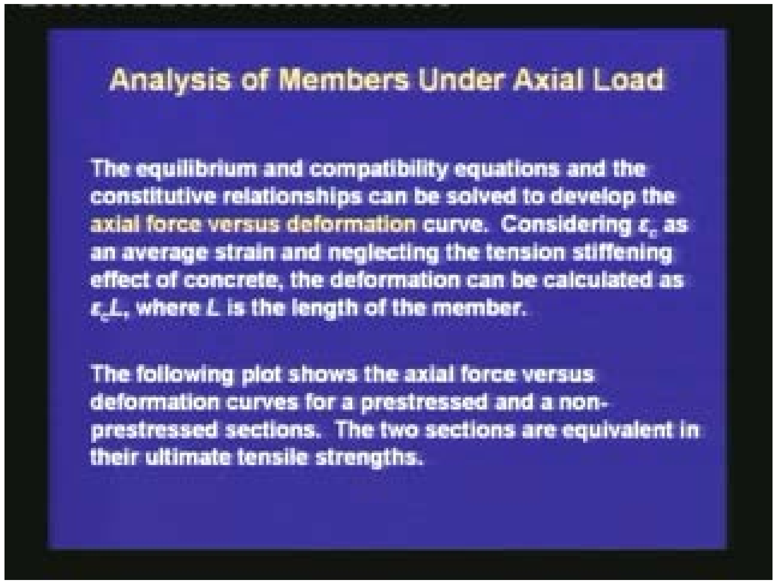

The equilibrium and compatibility equations, and the constitutive relationships can be solved to develop the axial force versus deformation curve. Here, we have seen a set of equations. First, we have seen an equilibrium equation, where the external load is equal to the summation of the internal forces. Next, we saw a set of compatibility equations, where for the reinforcement steel, we saw $\varepsilon_s = \varepsilon_c$. For the prestressing tendons, we have seen $\varepsilon_p = \varepsilon_c + \varepsilon_{dec}$. Then, we had three equational forms for the constitutive relationships: f_s is a function of ε_s, f_c is a function of ε_c, and f_p is a function of ε_p.

Once we have the set of equations, these equations can be solved simultaneously. Say, for a particular value of ε_c, we can calculate ε_s and ε_p. From these values of strains, we can calculate f_c, f_s, and f_p respectively, plug them in the equilibrium equation and get the axial force P. The axial deformation is given as $\varepsilon_c L$, where L is the length of the member. It means for any value of ε_c, we can determine a value of P and a value of the axial deformation.

The following plot shows the axial force versus deformation curves for members with prestressed and non-prestressed sections. Here, the two sections are considered to be equivalent, in terms that their tensile strengths are same.

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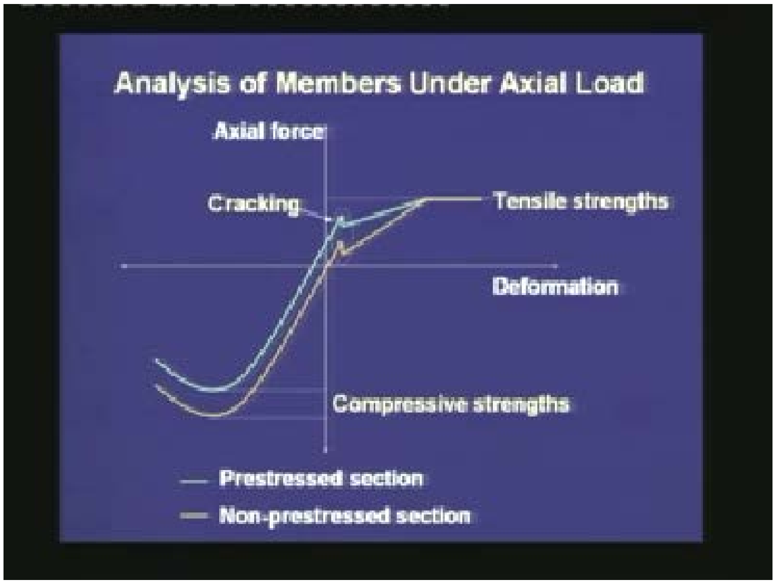

The orange curve is the axial force versus deformation curve for a section without any prestressing. It is just reinforced with conventional steel. We see in the tension quadrant, that the axial force increases linearly with deformation till the member cracks. In this region, the elastic analysis is applicable. After cracking, there is a drop in the axial force till the system comes under equilibrium, and again the axial force increases with deformation. But this time, it increases with a lower stiffness. The rate of increase of the axial force with deformation is low as compared to the pre-cracking behavior. Finally, when it reaches the yield stress of the steel, there is no increase in the axial force (neglecting the strain hardening of steel) and the member is considered to achieve its ultimate tensile strength.

On the other hand, if we look into the behavior in the compressive quadrant, then we see that initially the behavior can be almost linear elastic. But then, we see non-linearity due to the non-linear behavior of concrete. These curves are a schematic representation of the axial load versus deformation behavior. The exact curve depends on the equations that we are using and the type of steel that we have.

Compared to a non-prestressed section, which is represented by an orange line, let us observe what happens to a prestressed section which is represented by the blue line. The first thing we see is that the curve for the prestressed section is at an offset from the origin. It means that at zero external force, we have some negative deformation. That is, under prestressing, we have an axial compression in that member.

Next, as we are increasing the axial tension, we are achieving a zero deformation for a certain value of the axial load. It means that we need to have some external tensile load to have zero deformation in the member, and that instant is called the decompression of the concrete. The deformation increases with the axial force till the member cracks. What we observe is that this cracking level is much higher compared to the cracking level for a non-prestressed section. That is, the beauty of a prestressed member is that the cracking level is much higher than the non-prestressed member. Once it cracks, the behavior is similar to the reinforced concrete member. That is, there will be an increase in the required axial force with deformation, but with much reduced stiffness. The increase in axial force is till the section achieves an ultimate strength, beyond which it may stay constant depending on the type of steel.

On the other side, if we are applying compressive load then we see that the behaviour is similar to reinforced concrete. However, it does not achieve the same compressive strength as that of the reinforced concrete. Here the concrete is under a pre-compression and hence, it reaches its ultimate strength at a lower external load. These two curves give the essential difference between a reinforced concrete member and a prestressed concrete member.

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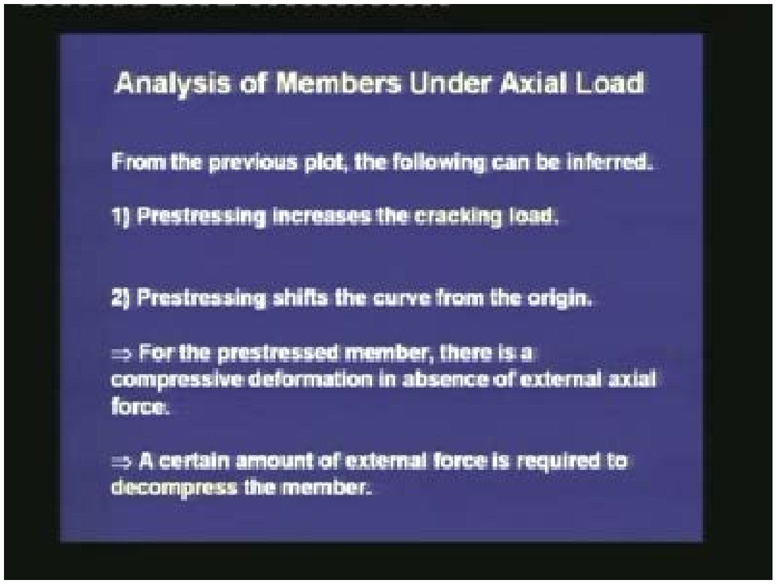

Let us try to understand them with some logical statements.

The first one is that prestressing increases the cracking load. In the first lecture, I had said why is concrete prestressed at all. The basic reason is that concrete is weak in tension as compared to compression, and to check the cracking of concrete, to make up for the weakness of concrete under tensile load, prestressing is done. Once we prestress a member, the cracking load is increased

The next inference we have is that prestressing shifts the curve from the origin. The two analogous statements are: first, for the prestressed member, there is a compressive deformation in absence of external axial force. We can see that even if there is no external force in the prestressed member, there is a compressive deformation in the axially loaded member, because that comes due to the effect of prestressing. The second corollary statement is that a certain amount of external tensile load is required to decompress the member. We need some external load to have zero strain in the concrete. These two aspects are unlike reinforced concrete. In reinforced concrete, if there is no external load, then there is no strain in the member, and also we do not need any external load to have zero strain in the concrete.

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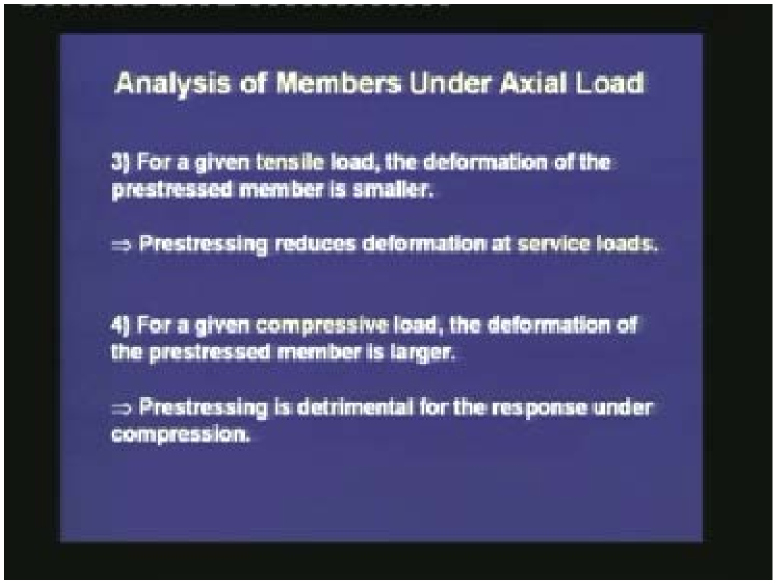

The third statement is, for a given tensile load, the deformation of the prestressed concrete member is smaller.

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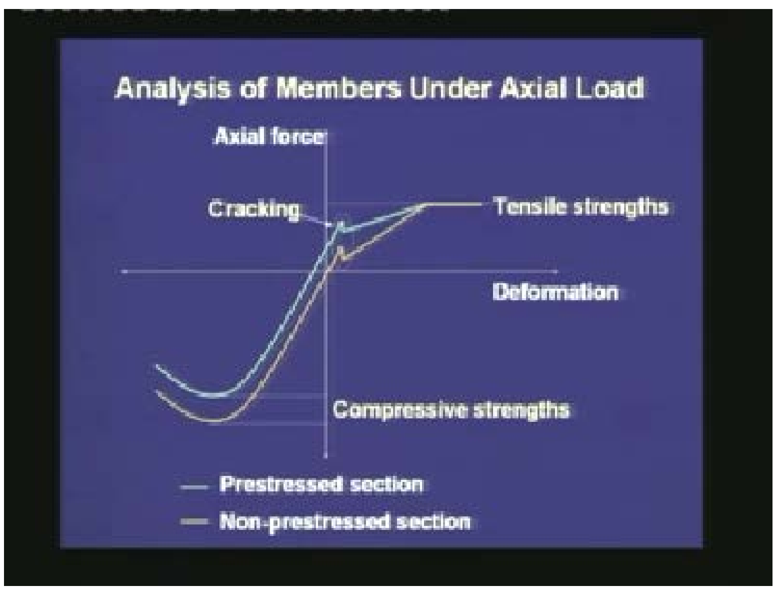

If we go back to the previous figure and if we pick up any axial tension, we see corresponding to the force, the orange line is much shifted from the blue line along the deformation axis. What it means is that the deformation of the reinforced concrete member is much higher as compared to a prestressed concrete member for a given level of the axial force. Thus, prestressing reduces deformation at service loads. This is an important benefit of prestressed concrete members, that is, if we prestress a member then we will have less deformation under service loads.

The fourth inference is that for a given compressive load, the deformation of a prestressed concrete member is larger. From the two curves, we observe that for a given axial force, the blue line is shifted from the orange line on the left hand side; that means, the deformation of a prestressed concrete member under compression is more than the deformation of a corresponding reinforced concrete member.

We can conclude that prestressing is detrimental for the response under compression.

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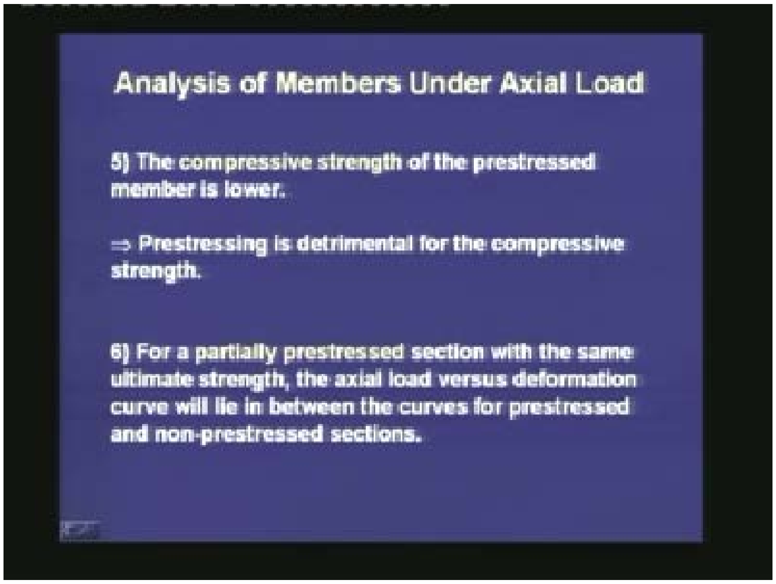

The fifth inference is that the compressive strength of the prestressed member is lower. We have taken two sections, which have equivalent tensile strength. What we find is that, if we prestress then the compressive strength of the prestressing member is lower. Hence, we can see that prestressing is actually detrimental for the compressive strength.

The sixth inference is that for a partially prestressed section with the same ultimate strength, the axial load versus deformation curve will lie in between the curves for prestressed and non-prestressed sections.

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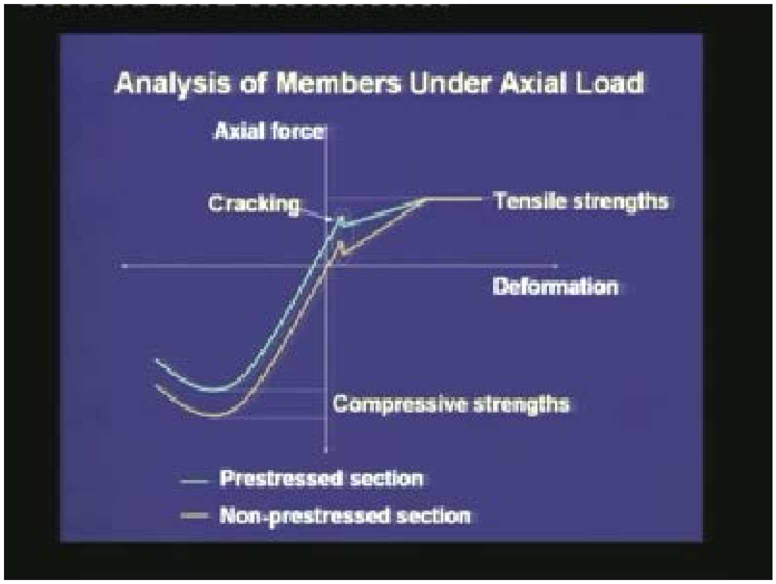

The orange line represents the curve for a reinforced section. The blue line represents the curve for a prestressed section, both of which have equivalent tensile strength. If we pick up a partially prestressed section which has both prestressing tendons as well as conventional reinforcement, and if it is also of the same tensile strength, then its axial load versus deformation curve will lie somewhere in between the orange and the blue lines.

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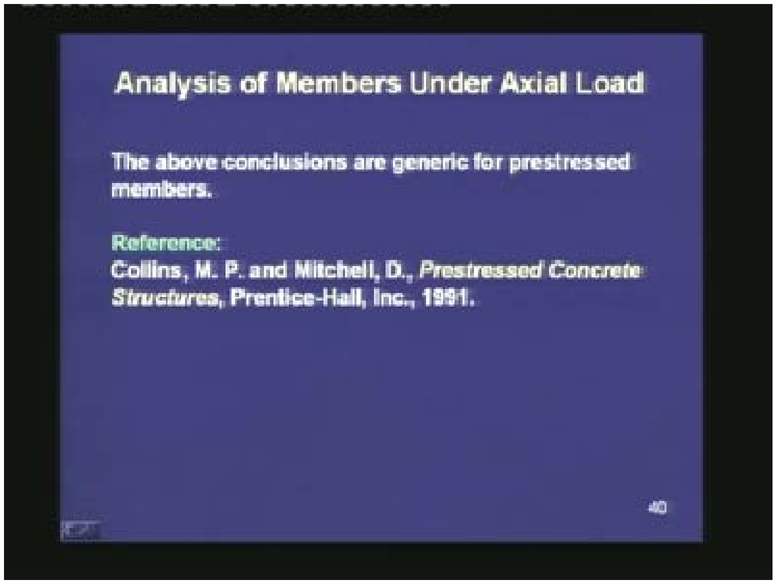

The above conclusions are generic for prestressed members. The purpose of studying this behavior under axial load was to understand the essence of prestressing compared to reinforced concrete members. The observations are similar for any other prestressed members, such as members under flexure. This material has been taken from the book *Prestressed Concrete Structures*, written by Collins and Mitchell.

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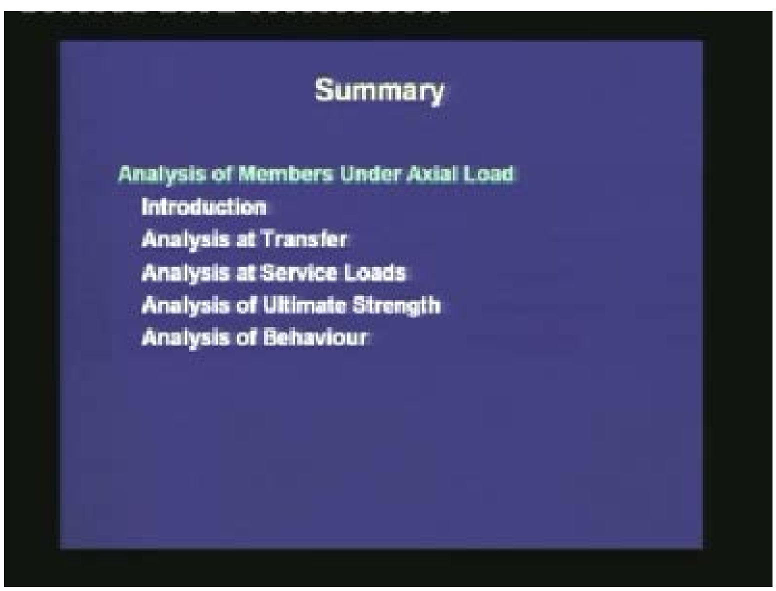

Today we studied the analysis of members under axial load. Such members can be very few and far between, because we do not have members which are purely under axial load very frequently. We may have some hangers or ties which are under axial tension. We may have piles which may be under axial compression or axial tension but usually, piles are also subjected to moments and shear. But, the whole purpose of studying the behavior of members under axial load is to understand the difference of the prestressed members and the reinforced concrete members. It gives us a foundation to understand the analysis procedure for members under flexure.

First, we studied the analysis at transfer where we have found that based on the allowable stresses at transfer, we can determine the maximum amount of prestressing force that we can apply. Next, we studied the analysis at service loads where we determined the stresses using elastic analysis, from the effective prestressing force (after the long-term losses) and the external characteristic loads. The stresses under this effective prestressing force and external loads should be within the allowable stresses under service. A member can be either fully prestressed, where we do not take account of any non-prestressed reinforcement for the strength, or a member can be partially prestressed, where we take advantage of non-prestressed reinforcement also.

We studied the analysis of ultimate strength, where we found out the maximum capacity of an axially loaded member. It can be either the tensile strength or it can be the compressive strength. This strength has to be larger than the demand that comes from the external factored loads. Next, we moved on to the analysis of behavior where we studied the complete load versus deformation curve of an axially loaded member and we have seen that this needs three principles of mechanics. The first is the equilibrium of forces, which means that the external load is equal to the internal forces that generates in the concrete in the reinforcement steel and the prestressing tendon. The second is the compatibility relationship, where we have seen that the strain in the steel is related with the strain in the concrete. For the non-prestressed reinforcement, the strain $\varepsilon_s = \varepsilon_c$ of the concrete at the level of the steel. For the prestressed reinforcement, $\varepsilon_p = \varepsilon_c + \varepsilon_{dec}$, where ε_{dec} is the strain at decompression of concrete. The strain at decompression means it is the strain in the prestressing tendon, when the concrete has zero strain. The expressions of ε_{dec} are different for the pre-tensioned and post-tensioned members.

For the pre-tensioned members, ε_{dec} is equal to $\varepsilon_{pi,}$ which is the strain right before the cutting of the tendons. For the post-tensioned members, ε_{dec} is equal to ε_{p0} after transfer plus the corresponding strain in the concrete.

The third principle is the constitutive relationships. When we solve the simultaneous equations, we get the complete load versus deformation curve. We have seen for a prestressed member, that the curve shifts from the origin. The cracking load is higher. The deformation under service load is lower compared to a reinforced concrete member. Prestressing is not beneficial for compression. The difference in the behaviour between the reinforced concrete and prestressed concrete members are quite generic, and it will help us to understand the behavior of members under flexure. In our next lecture, we shall move on to the analysis of members under flexure.

Thank you.