PRESTRESSED CONCRETE STRUCTURES

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Module - 4: Design of Members

Lecture - 17: Design of Members for Axial Tension

Welcome back to prestressed concrete structures. This is the first lecture on design of members.

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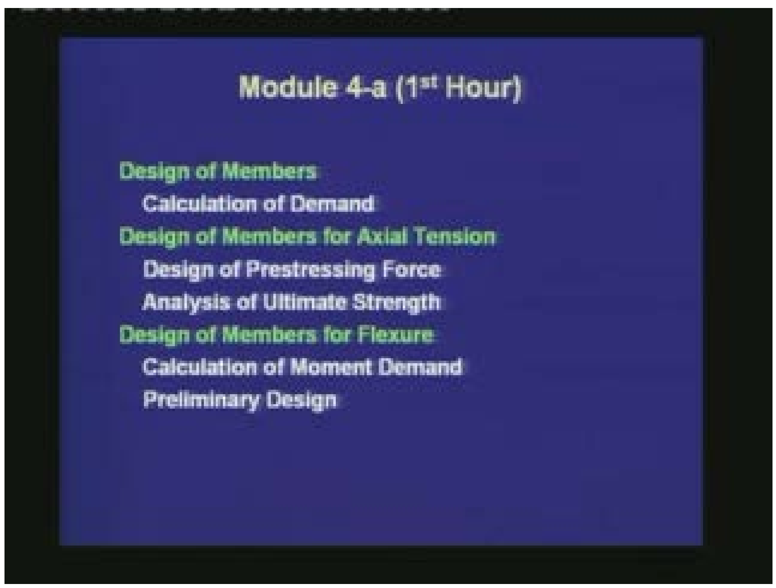

In this lecture, first we shall study the calculation of demand in a member. Next, we shall move on to design of members for axial tension. Under that, we shall study the design of the prestressing force and then, the analysis of ultimate strength. Next, we shall move on to design of members for flexure. Under that, first, we shall study about the calculation of moment demand and then, today we shall wrap up with the preliminary design.

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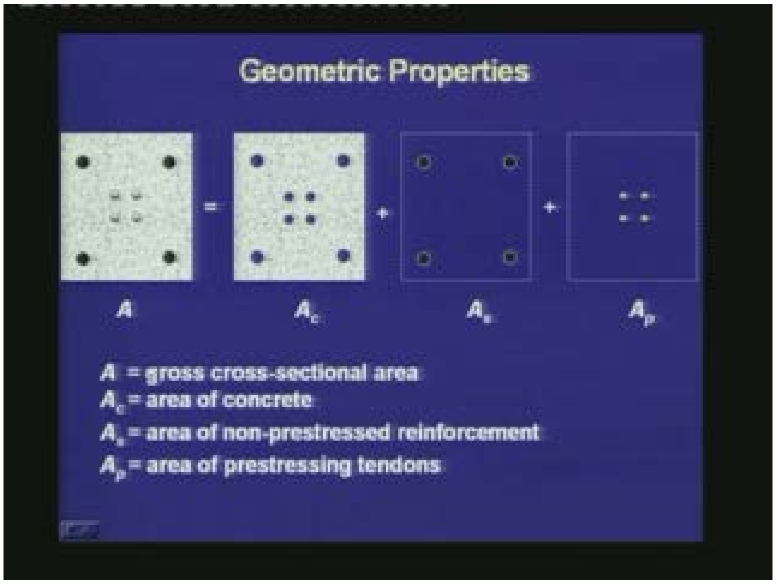

We shall be using some geometric properties in the analysis and design of members for axial tension. On the left side, we see the cross-section of a typical member prestressed for axial forces. The total section is represented by A. This section is broken up into three components: the net area of the section with concrete is represented by A_c; the area of the reinforcing steel, which is non-prestressed, is represented by A_s and the area of prestressing steel is represented by A_p. Thus, $A = A_c + A_s + A_p$.

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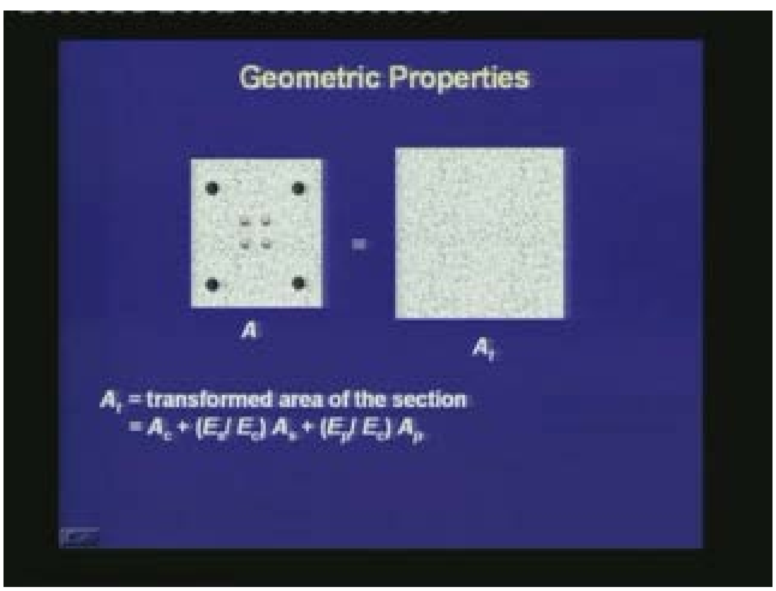

We shall use another definition, which is the transformed section. The transformed section means it is an equivalent section of concrete and it is larger than the original cross-section A. It is calculated as $A_t = A_c$ + (the ratio of the moduli of the steel and the concrete times A_s) + (the ratio of the moduli of the prestressing steel and the concrete times A_p). Thus, we calculate the transformed area for an elastic analysis of a section, where the material is same throughout, which is concrete.

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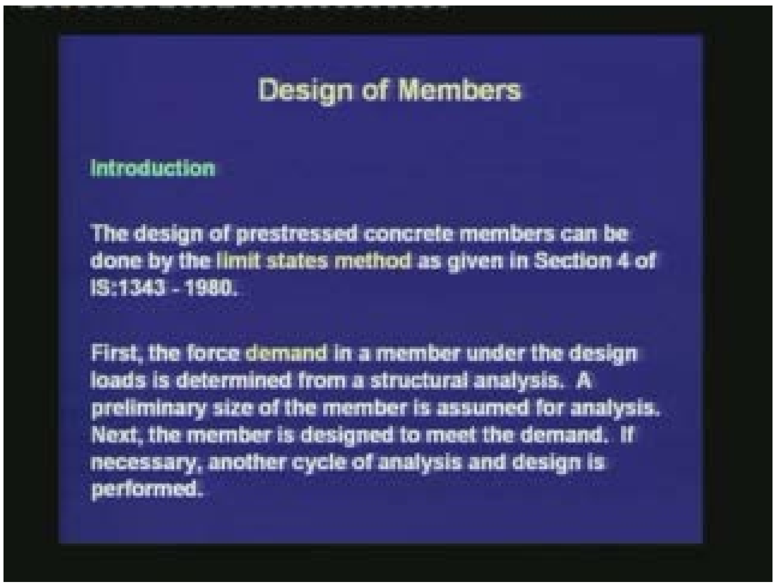

First, we shall study the design of members in general. For design of prestressed concrete members, we follow the limit states method as given in Section 4 of IS: 1343-1980. First, the force demand in a member under the design loads is determined from a structural analysis. A preliminary size of the member is assumed for analysis. Next, the member is designed to meet the demand. If necessary, another cycle of analysis and design is performed.

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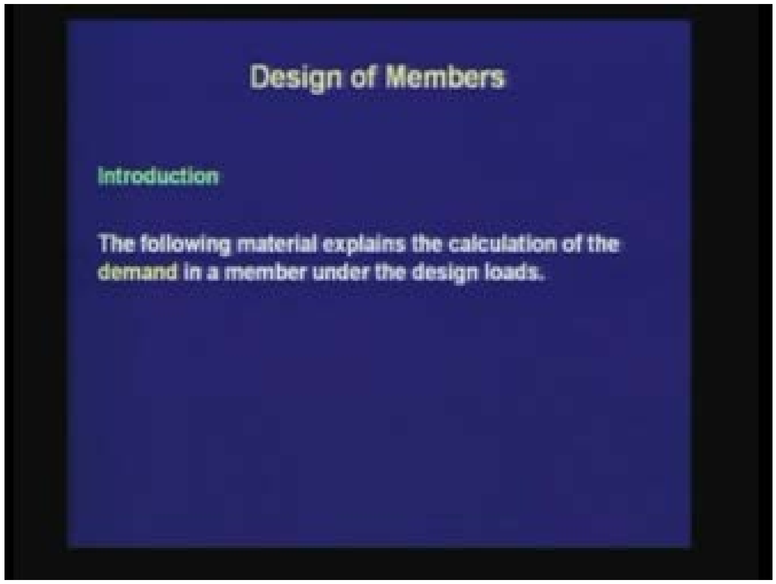

The first step even before we start the design, is analysis. In the analysis of the structure, we get the demand in each of the members. The following sections will help us to understand how to calculate the demand in a member under the design loads.

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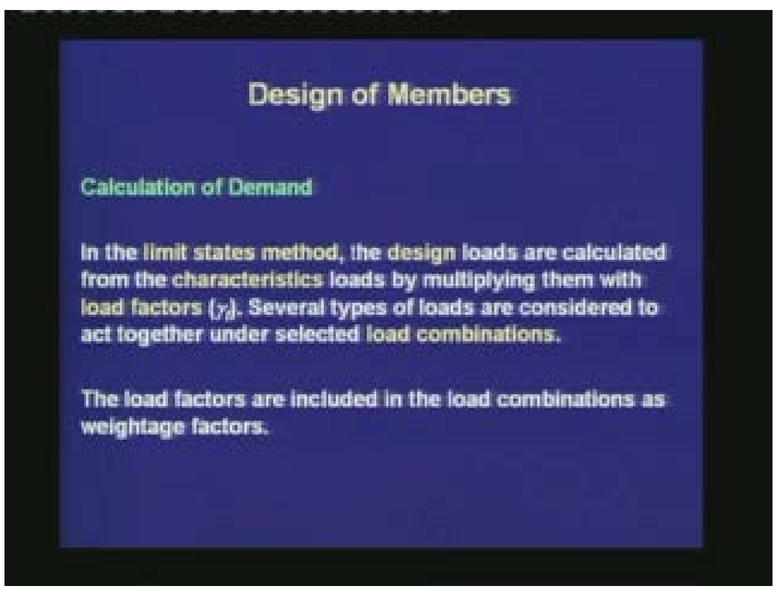

In the limit states method, the design loads are calculated from the characteristic loads by multiplying them with load factors, which are represented as γ_f. Several types of loads are considered to act together under selected load combinations. The load factors are included in the load combinations as weightage factors.

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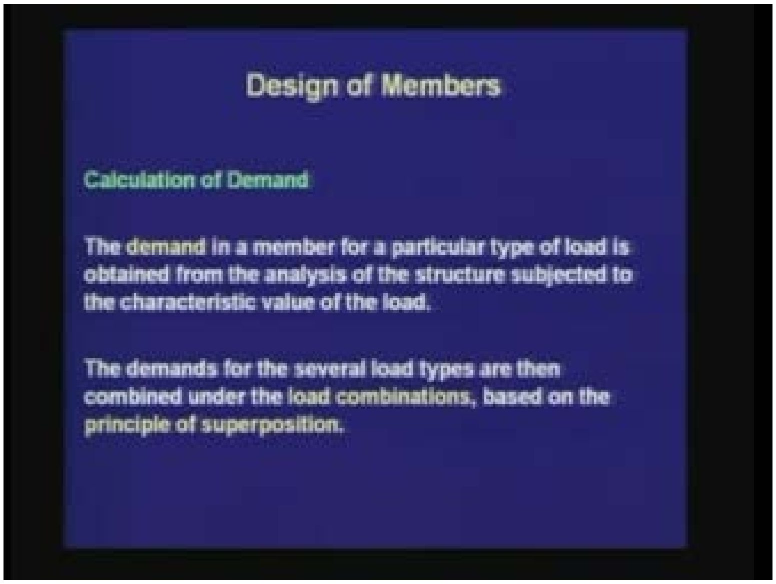

The demand in a member for a particular type of load is obtained from the analysis of the structure subjected to the characteristic value of the load. The demands for the several load types are then combined under the load combinations, based on the principle of superposition. Thus, when we say that several types of loads are acting on a member, we first consider the principle of superposition, which is based on a linear analysis for each type of the load. To calculate the total demand in a member, we first analyze the structure for each type of the load, and then combine the forces within the member by the load combinations. These load combinations have the appropriate load factors as weightage factors. Once we combine the forces under the load combinations, we get the total force demand in a particular member.

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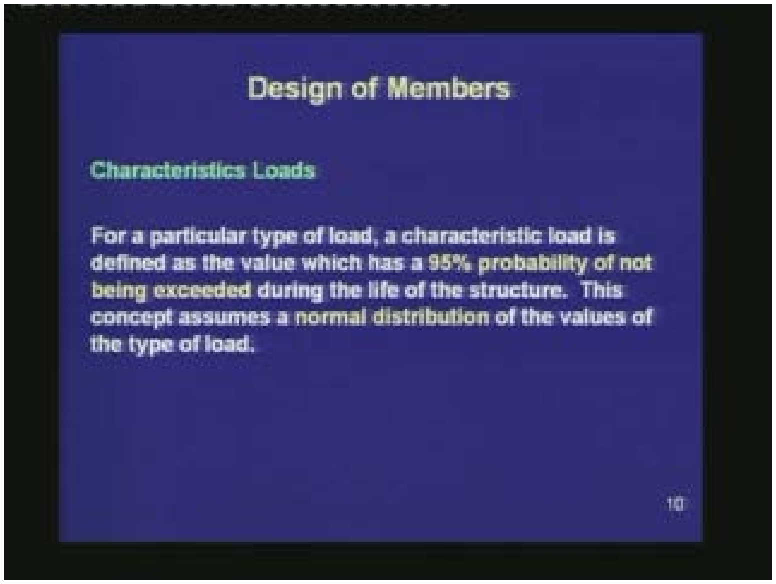

Next, let us study that for a particular type of load, a characteristic load is defined as a value which has 95% probability of not being exceeded during the life of the structure. This concept assumes a normal distribution of the values of the type of load.

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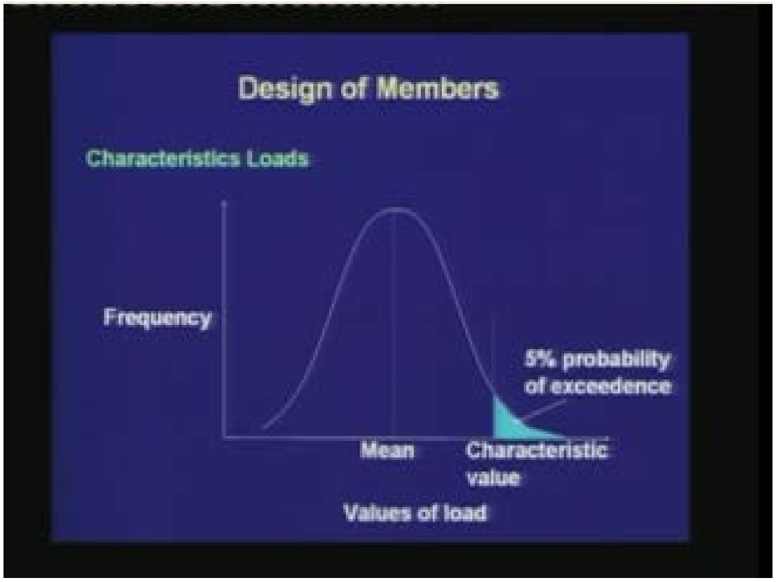

When we start the analysis, we pick up the characteristic value for a particular type of load. The characteristic value is defined as the value, which has only 5% probability of exceedence. That means, 95% of the time the load will not be exceeded. In the sketch, in the x-axis we are plotting the values of the load, and in the y-axis we are plotting the frequency. In a normal distribution, we can find out the mean and also the value of the load which has just 5% probability of exceedence. This value of the load is called the characteristic value.

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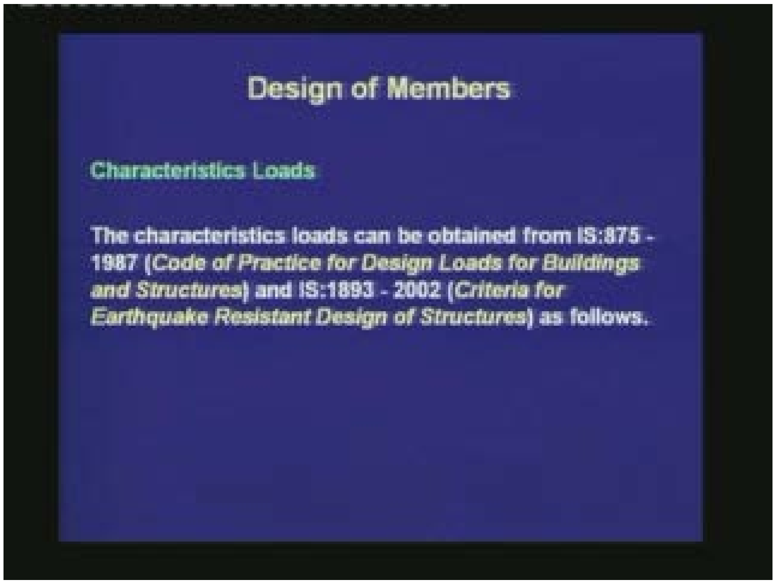

The characteristic loads can be obtained from IS: 875-1987 (which is the *Code of Practice for Design Loads for Buildings and Structures*) and IS: 1893-2002 (which is the *Criteria for Earthquake Resistant Design of Structures*) as follows.

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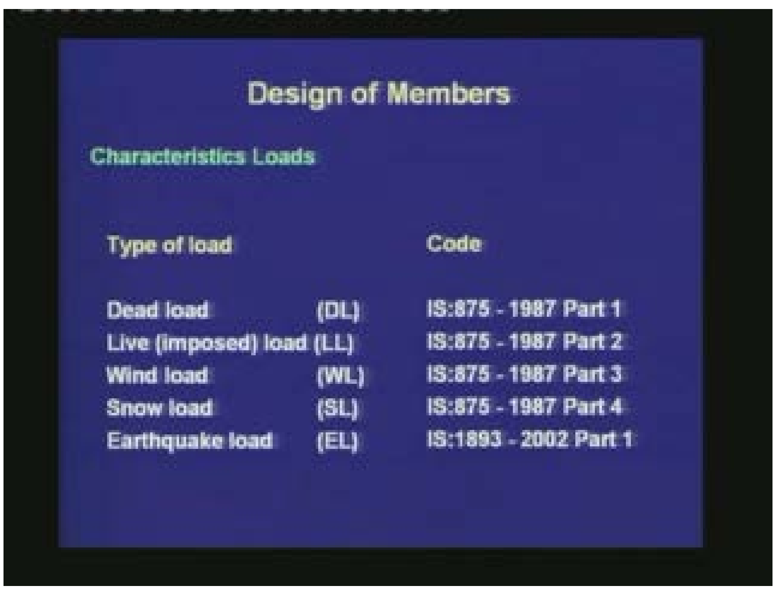

The several types of loads given in these codes are as follows: the dead load which is represented as DL is given in IS: 875 in Part 1. The live load which is also sometimes referred to as imposed load, is given in IS: 875 Part 2. There is a subtle difference between live load and imposed load. If a part of dead load does not act throughout the life of the member, if it acts only at certain periods, then that part of the dead load can also be included as imposed load. It is up to the discretion of the analyst to consider whether a fraction of dead load is imposed or not. Next, we calculate the wind load, which is represented as WL from IS: 875 Part 3. We calculate snow load, which is represented as SL from IS: 875 Part 4. The earthquake load, which is represented as EL, is obtained from a separate code which is IS: 1893 Part 1.

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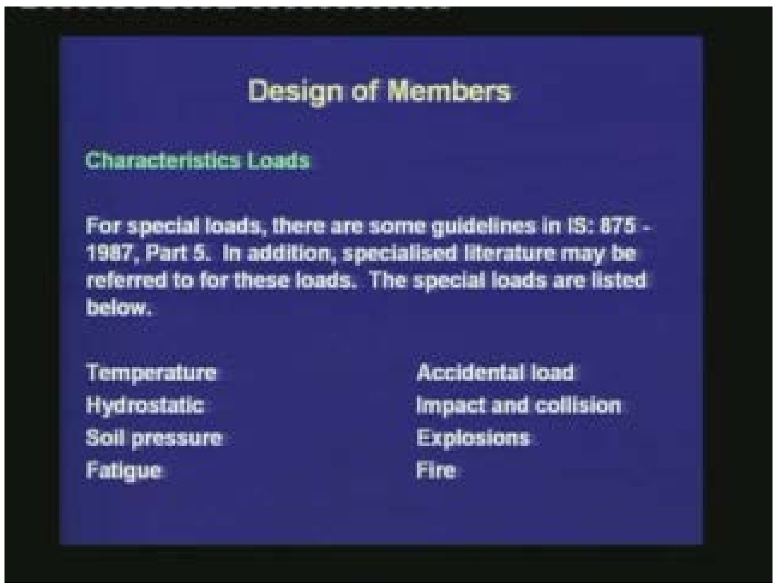

For special loads, there are some guidelines in IS: 875-1987 Part 5. In addition, specialized literature may be referred to for these loads. The special loads are listed below: Temperature, hydrostatic, soil pressure, fatigue, accidental load, impact and collision, explosions and fire. Thus, we see that for the special loads, IS: 875 Part 5 gives us some basic guidelines, but we may need specialized literature or international codes to get more detailed values for these special loads.

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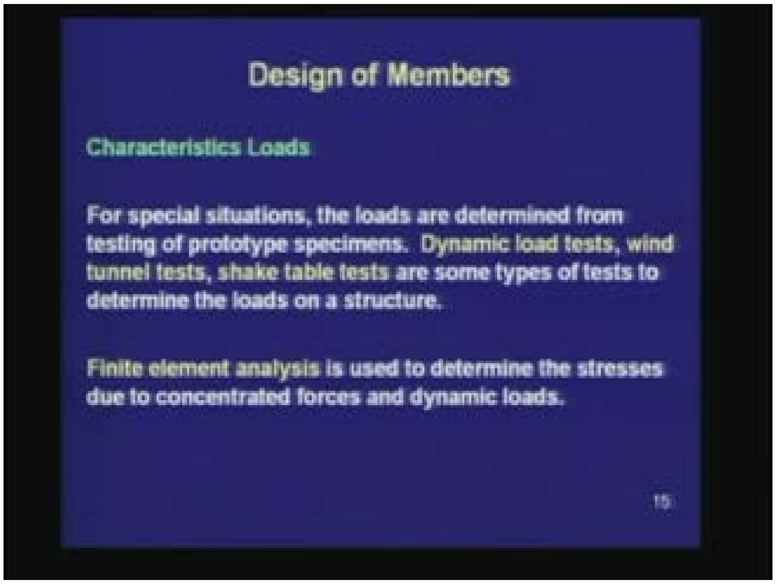

For special situations, the loads are determined from testing of prototype specimens like dynamic load tests, wind tunnel tests, shake table tests or some type of tests to determine the loads on a structure. Finite element analysis is used to determine the stresses due to concentrated forces and dynamic loads.

If we are looking for specialized structures like nuclear containment structures, then the loads given in the codes may not be adequate. We undertake specialized study or experiments to calculate the characteristic loads or the design loads for the particular type of structure. Hence, we understand that for generic purpose, we have the codes. But, if we are analyzing some special structures for special situations, we may have to do special studies or experiments to get the loads acting on the structures.

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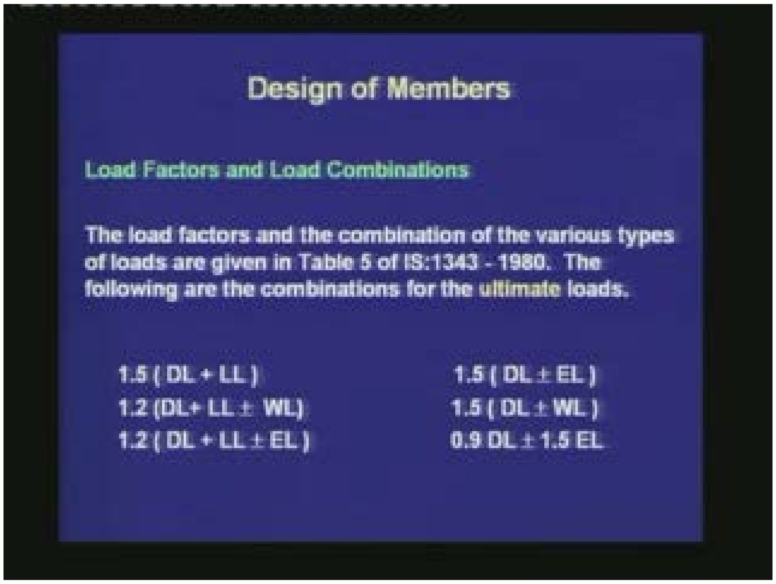

Next, the load factors and the combination of the various types of loads are given in Table 5 of IS: 1343-1980. The following are the load combinations for the ultimate loads:

1.5 (DL + LL)

1.2 (DL + LL ± WL)

1.2 (DL + LL ± EL)

1.5 (DL ± EL)

1.5 (DL ± WL)

0.9 DL ± 1.5 EL.

Since both wind load and earthquake load can act in either direction, we use a ± sign in the load combinations. Thus, we have two groups of loads: one is the gravity load, which is the dead load, live load or snow load, and we have the lateral loads, which are the wind load and earthquake load. There are special types of loads like hydrostatic or soil pressure, which are also lateral loads.

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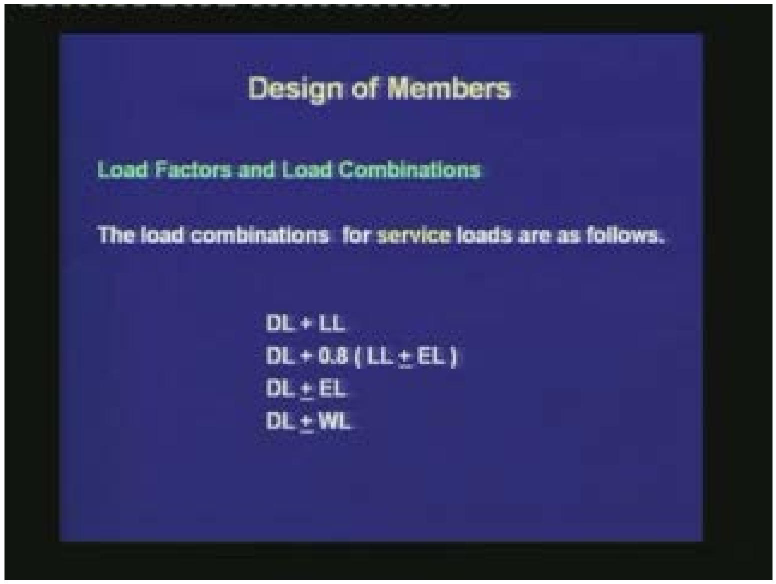

The load combinations for service loads are as follows:

DL + LL

DL + 0.8 (LL ± EL)

DL ± EL

DL ± WL

Thus, we have two sets of load combinations. The first set is for ultimate loads with higher load factors. The second set is for service loads, which have load factors equal to 1.0 for most of the cases.

In some cases, the load factors are less than 1.0. When the dead load helps in the stability of the structure, a reduced load factor is used for the dead load even in the load combination for ultimate loads. A load factor of 0.9 is used for the dead load in the combination meant for stability. When the chance of live load and earthquake load acting at their characteristic values simultaneously is less, the load factor is 0.8 in the combination for service loads.

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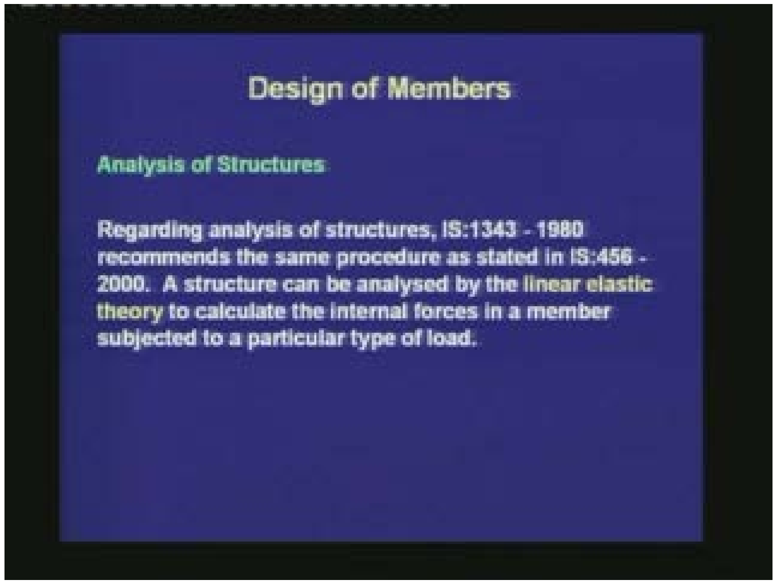

Regarding analysis of structures, IS: 1343-1980 recommends the same procedure as stated in IS: 456-2000. A structure can be analyzed by the linear elastic theory to calculate the internal forces in a member subjected to a particular type of load. Thus, the code allows us to use the linear elastic theory for the analysis, even if we do the design based on the limit states method.

For design of a member, there can be more than one way to proceed. In design, the number of unknown quantities is larger than the number of available equations. Hence, some quantities need to be assumed at the beginning. These quantities are subsequently checked. If they are not appropriate, then we need to do the design cycle once again.

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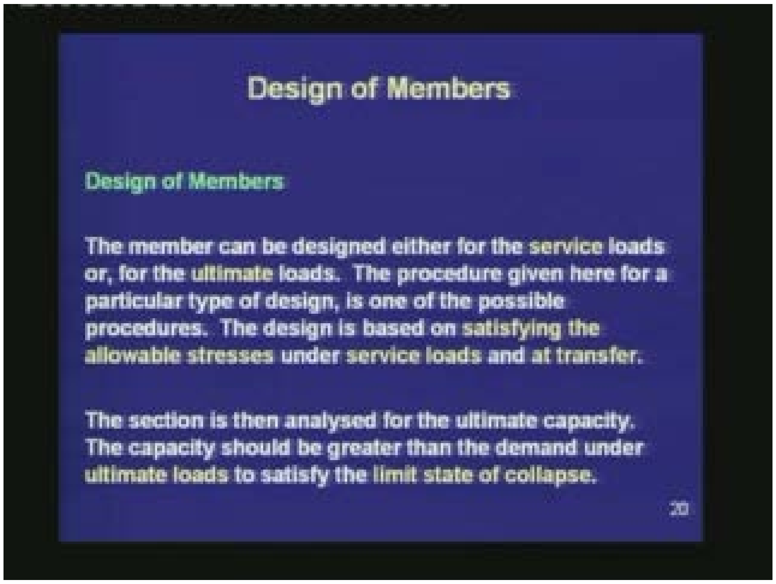

The member can be designed either for the service loads or for the ultimate loads. The procedure given here for a particular type of design, is one of the possible procedures. The design is based on satisfying the allowable stresses under service loads and at transfer. The section is then analyzed for the ultimate capacity. The capacity should be greater than the demand under ultimate loads to satisfy the limit state of collapse. This procedure is different from what we have studied for reinforced concrete.

For reinforced concrete, the design is based on the ultimate strength being greater than the demand under ultimate loads. But for prestressed concrete, we are adopting a different approach. First, we do the design based on the service loads. Next, we do an analysis for the ultimate strength, and compare the strength with the demand under ultimate loads.

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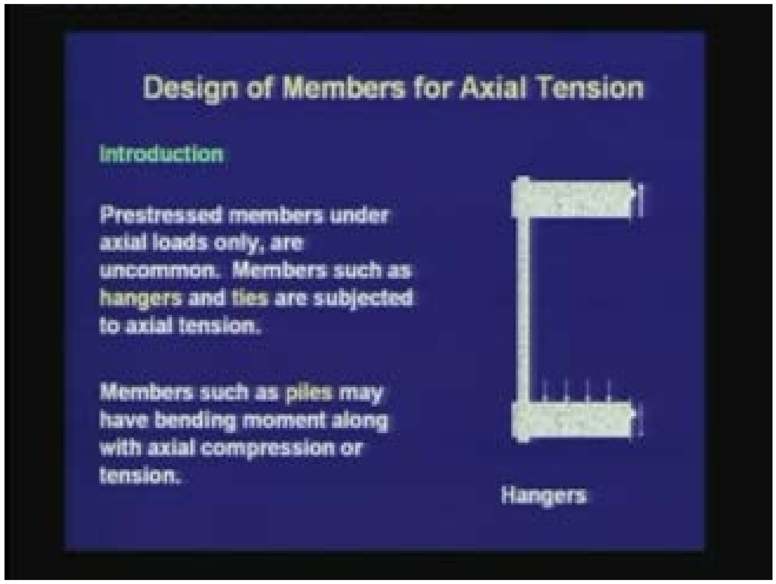

Next, we move on to design of members for axial tension. Prestressed members under axial tension only, are uncommon. Members such as hangers and ties are subjected to axial tension. Members such as piles may have bending moment along with axial compression or tension. In this figure, we see a hanger, where only the forces in the vertical direction have been shown. This hanger can be prestressed to have no tension in the concrete under the service loads.

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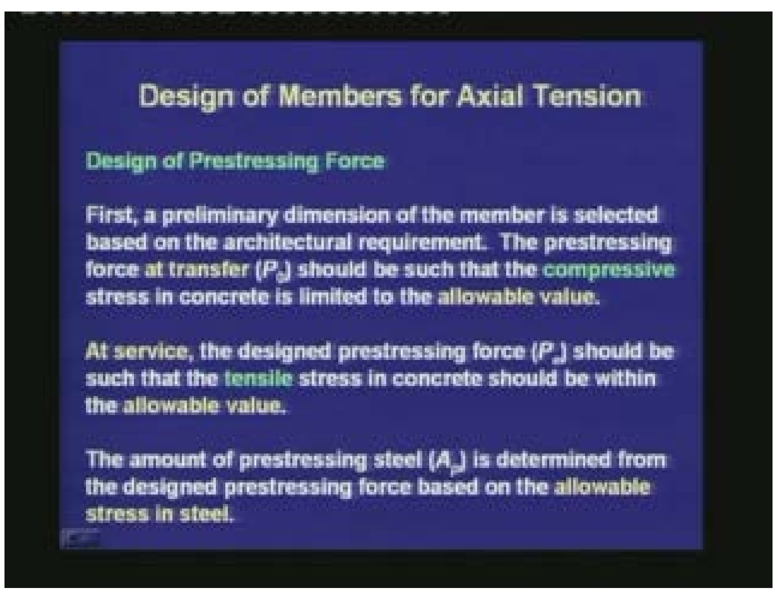

First, a preliminary dimension of the member is selected based on the architectural requirement. The prestressing force at transfer, which is represented as $P_{0,}$ should be such that the compressive stress in concrete is limited to the allowable value. At service, the designed prestressing force, which is represented as P_e, should be such that the tensile stress in concrete should be within the allowable value. The amount of prestressing steel A_p is determined from the designed prestressing force based on the allowable stress in steel.

What are the equations that help us to calculate the stresses in the member at transfer and at service?

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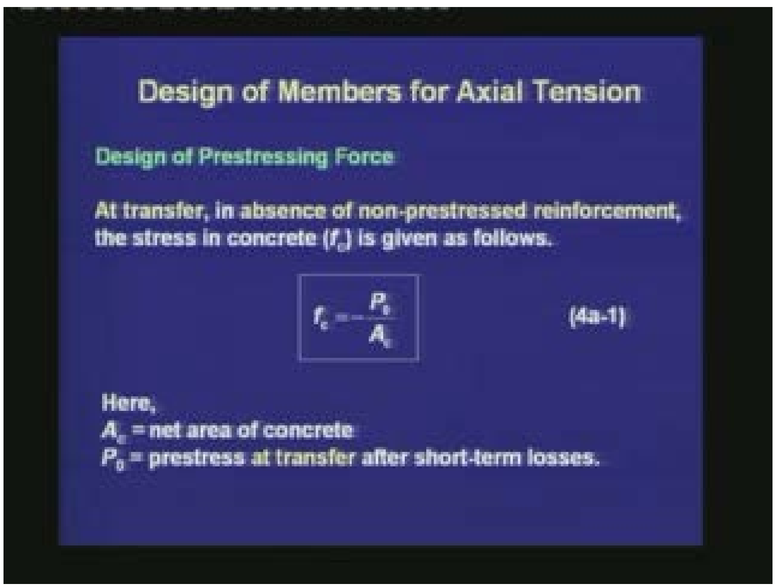

At transfer, in the absence of non-prestressed reinforcement, the stress in concrete, which is denoted as f_c is given as follows: $f_c = – P_0 / A_c$. Here, A_c is the net area of the concrete that we have studied earlier, and P_0 is the prestress at transfer after short-term losses. We are denoting the negative stress for compression.

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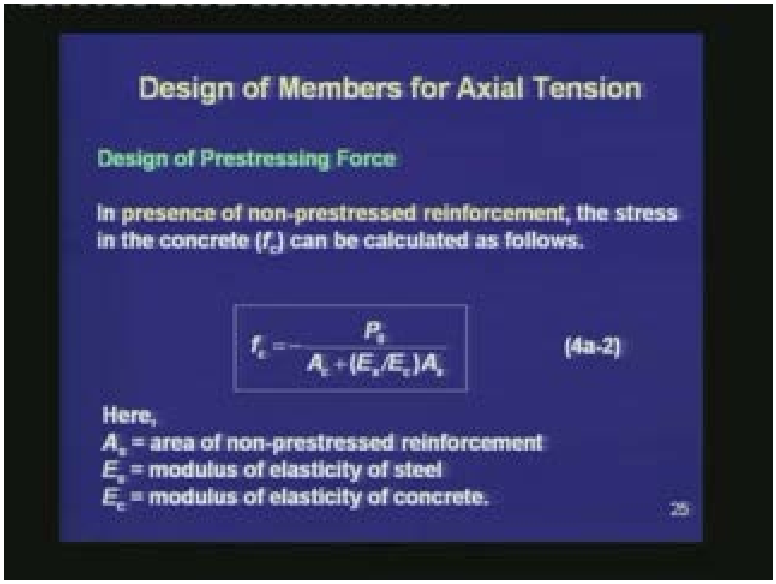

If we have non-prestressed reinforcement in addition to prestressing tendon, the stress in the concrete can be calculated as follows: $f_c = -P_0 / (A_c + (E_s/E_c)A_s)$. A_s is the area of non-prestressed reinforcement, E_s is the modulus of elasticity of steel, and E_c is the modulus of elasticity of concrete.

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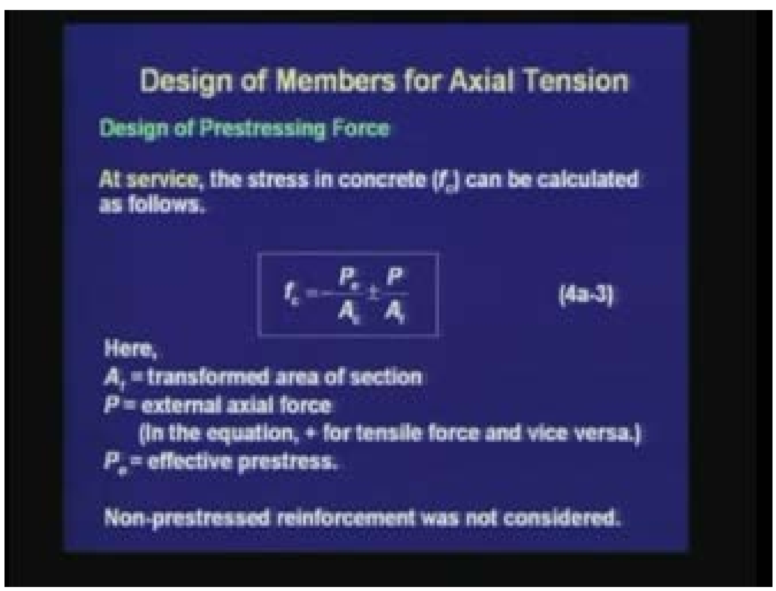

Next, we are moving on to the analysis of stresses for service loads. At service, the stress in concrete can be calculated as follows: $f_c = -P_e/A_c \pm P/A_t$. Here, A_t is the transformed area of the section, P is the external axial force (in the equation, + is used for tensile force and – is used for compressive force) and P_e is the effective prestress after long term losses. In this expression, we did not consider the non-prestressed reinforcement.

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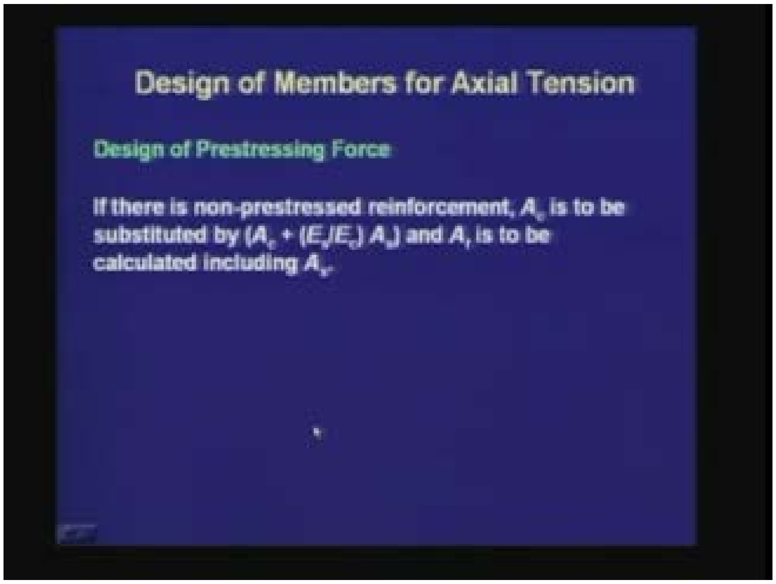

If there is non-prestressed reinforcement, A_c is to be substituted by $(A_c + (E_s / E_c) A_s)$ and A_t is to be calculated including A_s, as we have learnt during the definition of geometric properties. Thus, we find the resultant stress at service loads as a combination of the stress due to the prestressing force and the stress due to the external axial force. Once we have designed the member for the stresses at service loads and satisfying the allowable stresses at transfer, next we move to the analysis for the ultimate strength.

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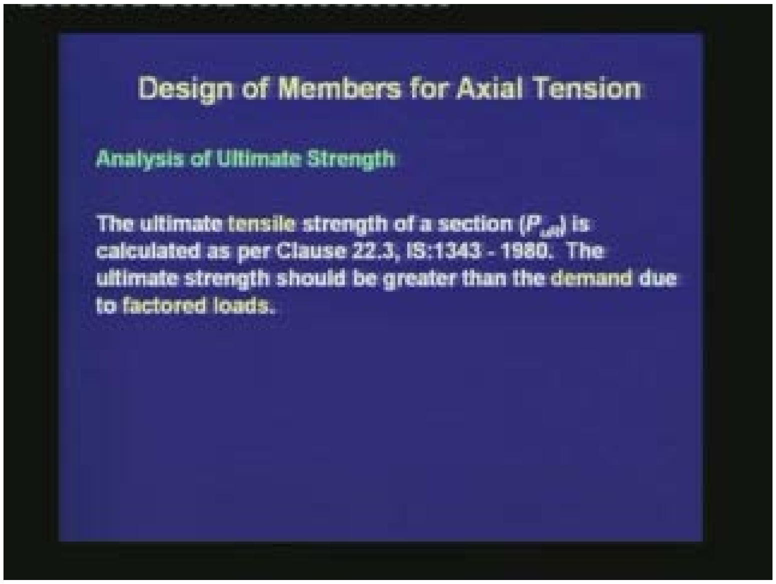

The ultimate tensile strength of a section, which is represented as P_{uR}, is calculated as per Clause 22.3 of IS: 1343-1980. The ultimate strength should be greater than the demand due to factored loads.

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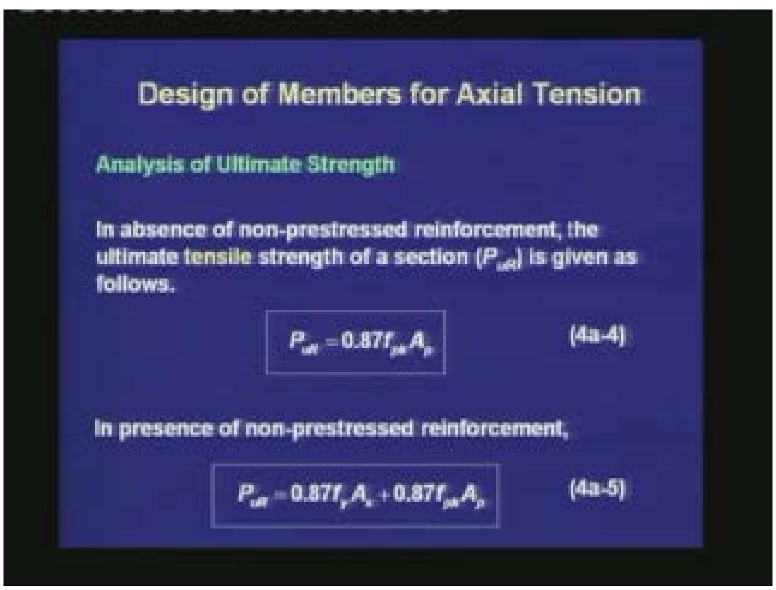

In the absence of non-prestressed reinforcement, the ultimate tensile strength of a section is given as $P_{uR} = 0.87 f_{pk} A_p$. The code limits the maximum tensile stress in the prestressing tendon to 0.87 times the characteristic tensile strength. Any tensile capacity of the concrete is neglected at the ultimate limit state. If there is non-prestressed reinforcement along with prestressing tendons, then the expression of $P_{uR} = 0.87f_y A_s + 0.87f_{pk} A_p$.

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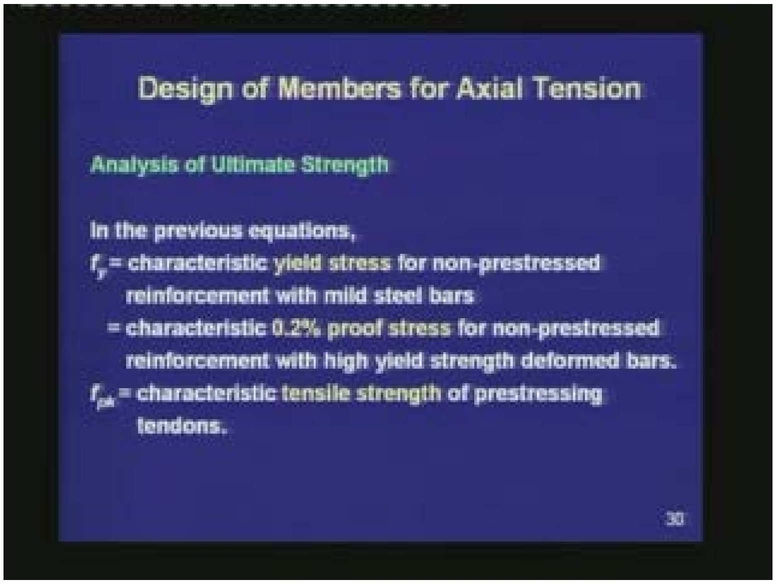

Here, f_y is the characteristic yield stress for non-prestressed reinforcement with mild steel bars, or it is the characteristic 0.2% proof stress for non-prestressed reinforcement with high yield strength deformed bars; f_{pk} is the characteristic tensile strength of prestressing tendons.

Let us now see this design method with an example.

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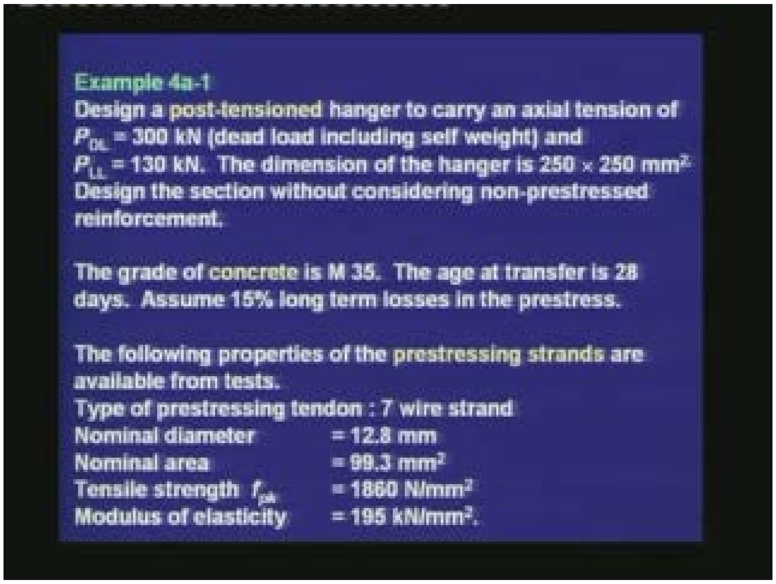

Design a post-tensioned hanger to carry an axial tension of P_{DL} = 300 kN (the dead load includes the self-weight) and P_{LL} = 130 kN. The dimension of the hanger is 250 × 250 mm^2. Design the section without considering non-prestressed reinforcement. The grade of concrete is M35, and the age at transfer is 28 days. Assume 15% long-term losses in the prestress.

The following properties of the prestressing strands are available from tests. The type of prestressing tendon is 7-wire strand, nominal diameter = 12.8 mm, nominal area = 99.3 mm^2, tensile strength f_{pk} = 1860 N/mm^2, and modulus of elasticity = 195 kN/mm^2.

From the structural analysis, the forces due to dead load and live load are given. The long-term loss in the prestressing tendon is estimated. Information on the material properties is given.

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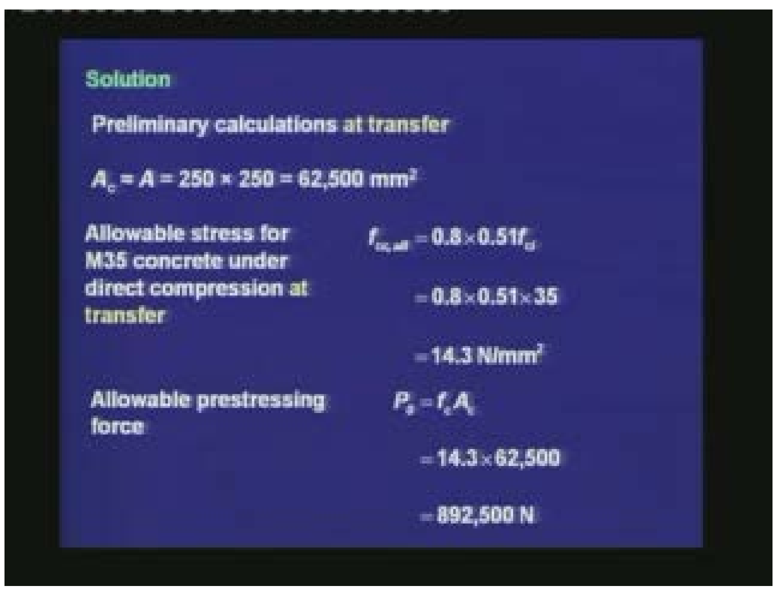

First, we are doing a preliminary calculation at transfer. We are assuming that the area of concrete is almost equal to the total area, which is equal to 250 × 250 = 62,500 mm^2. Next, we are calculating the allowable stress for M35 concrete under direct compression at transfer. As per the code, $f_{cc,all}$ = 0.8 times the allowable stress for compression under flexure. The allowable stress for compression under flexure is given as $0.51f_{ci}$, where f_{ci} is the instantaneous compressive strength. Substituting the value of f_{ci} = 35 N/mm^2 at 28 days, $f_{cc,all}$ = 14.3 N/mm^2.

The allowable prestressing force $P_0 = f_c A_c = 14.3 \times 62{,}500 = 892{,}500$ Newton. Thus, we have found the upper limit of the prestressing force that can be applied at transfer.

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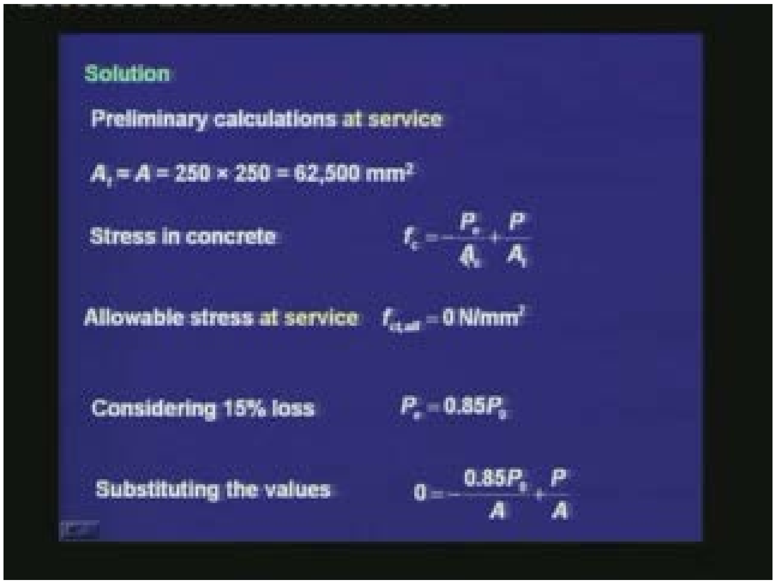

Next, we are doing the preliminary calculations at service. We are assuming $A_t = A = 62{,}500$ mm^2. The stress in concrete can be calculated by the expression which we learned in the modulus of analysis of members. $f_c = -P_e/A_c + P/A_t$. From the definition of the problem, allowable stress at service $f_{ct,all} = 0$ N/mm^2. That means, we are not allowing any tension under service loads. Considering 15% loss, $P_e = 0.85\ P_0$. Once we substitute the values of $f_{ct,all}$ and P_e in the above equation, we get an equation with 'A' as an approximate value for both A_c and A_t.

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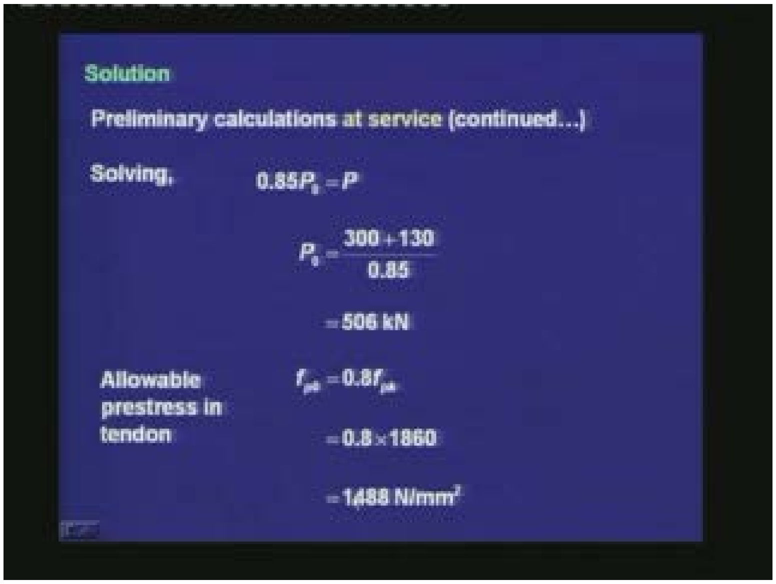

By solving the equation, we find 0.85 P_0 = P which is the external load. Thus $P_{0,}$ the required amount of prestressing force at transfer is equal to the external load divided by 0.85, which is equal to 506 kN. The allowable prestress in the tendon $f_{p0} = 0.8f_{pk} = 1488$ N/mm^2.

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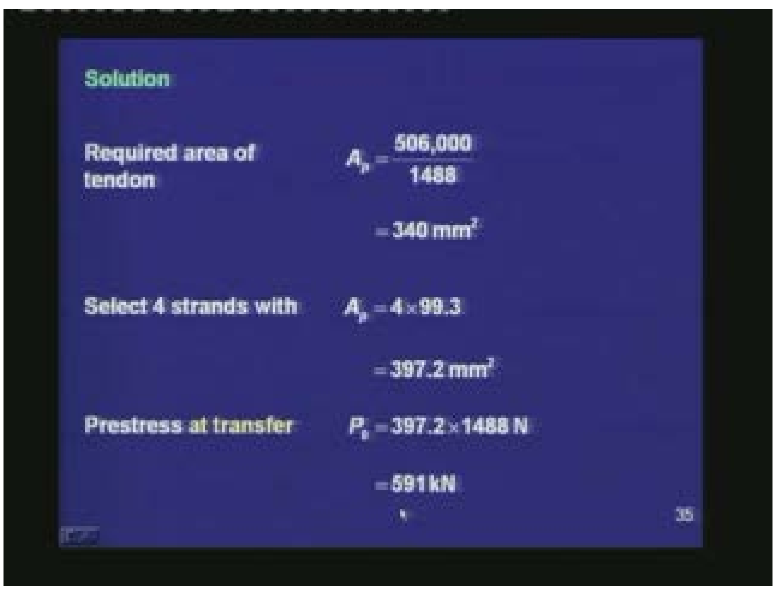

Thus, the required area of the tendon A_p = 506,000/1488 = 340 mm^2. Select four strands with $A_p = 4 \times 99.3 = 397.2$ mm^2. The prestressing force at transfer P_0 is equal to the area of the prestressing steel times the allowable stress, which gives P_0 = 591 kN. The required prestressing force was 506 kN, but we can apply a slightly higher prestressing force because we have used approximate values of A_c and A_t in our calculations.

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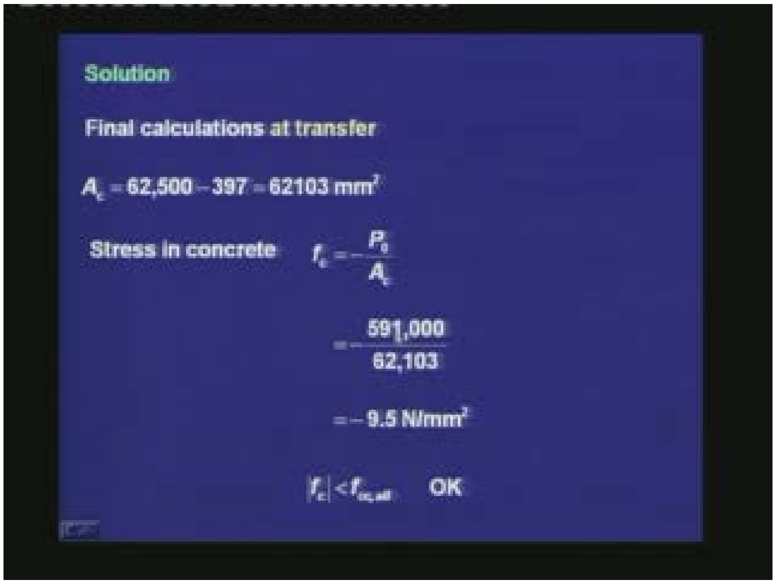

Next, we are doing the final round of calculations with the accurate values of A_c and A_t. The final calculations at transfer are as follows: A_c = 62,500 – 397 = 62,103 mm^2. The stress in concrete at transfer is equal to $-P_0/A_c = -9.5$ N/mm^2. We find that this value of f_c is less than the allowable compressive stress for M 35 concrete at transfer. Hence, we can say that the prestressing force is acceptable.

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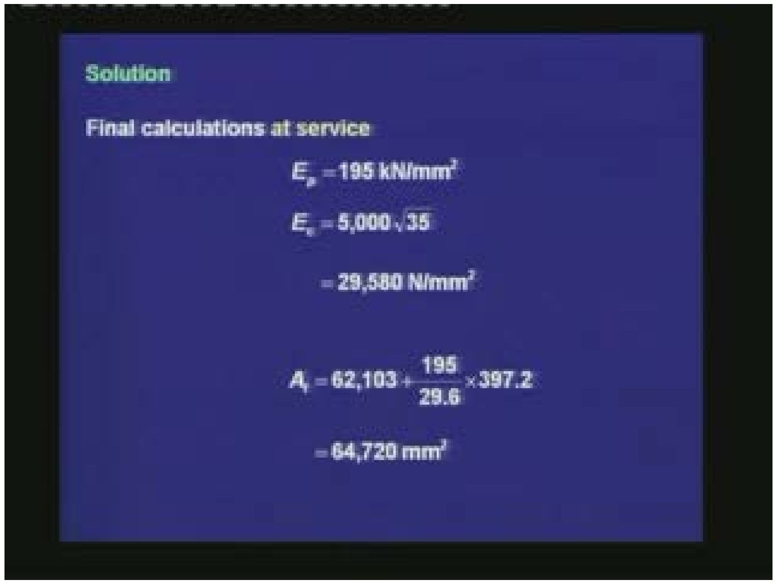

Next, we are doing the final calculations at service. E_p = 195 kN/mm^2, E_c = 5000 √35 = 29,580 N/mm^2. Thus, we can calculate the transformed area A_t is equal to the area of the concrete, which is 62,103 plus the ratio of the two moduli 195 divided by 29.6, times the area of the prestressing steel which is 397.2, which gives us A_t = 64,720 mm^2. Thus, we find that the A_t is larger than the total area A.

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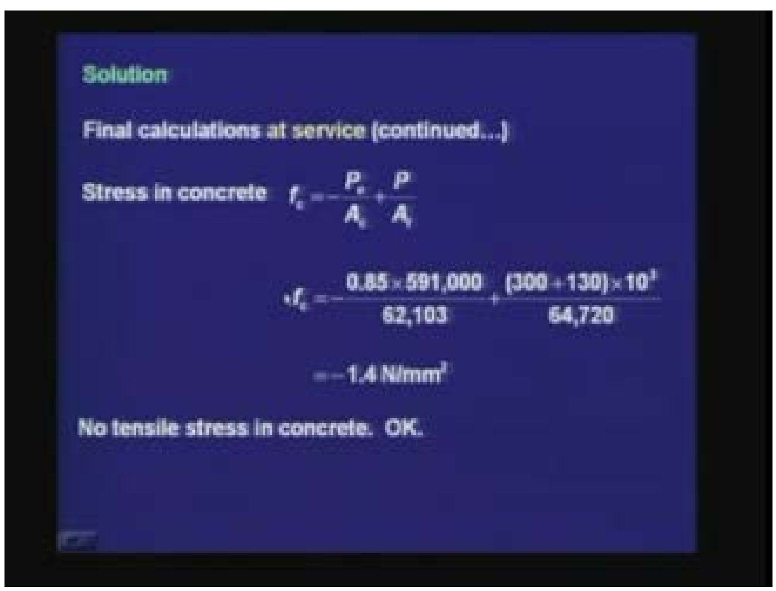

The stress in concrete due to service loads is given as $f_c = -P_e/A_c + P/A_t$. The value of P_e is equal to 85% of the prestress at transfer. The external force is 300 (the dead load) plus 130 (the live load). Substituting the accurate values of A_c and A_t, we find that the stress in the concrete is – 1.4 N/mm^2 at service. Thus, there is no tensile stress in concrete under service loads, and it satisfies the objective of the design.

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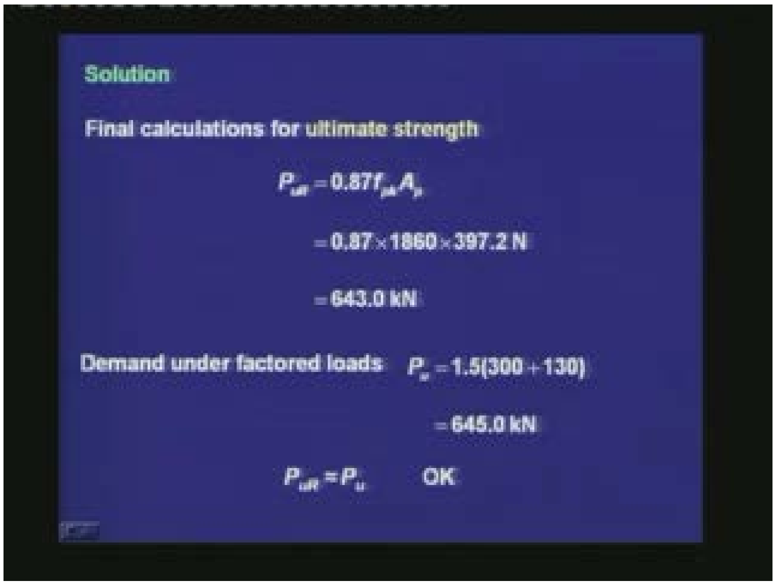

We are doing the final calculations for the ultimate strength. The ultimate strength is given as P_{uR} = 0.87 f_{pk} A_p = 0.87 × 1860 × 397.2 = 643 kN. The demand under the factored loads is equal to P_u = 1.5 (300 + 130) = 645 kN. We find that P_{uR} is almost the same as P_u, and the design can be considered to be adequate.

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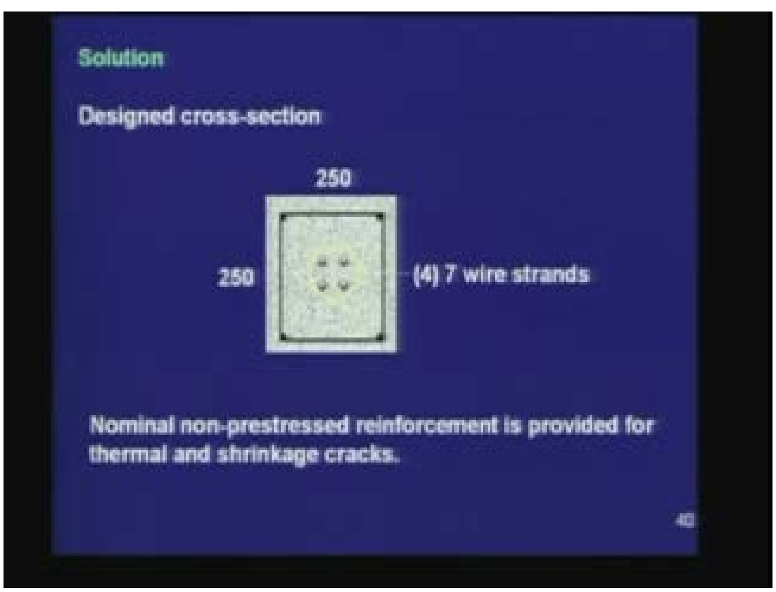

The above sketch shows the designed cross-section. The dimension of the section is 250 mm × 250 mm. There are four 7-wire strands, with a total prestressing force of 591 kN. Nominal, non-prestressed reinforcement is provided for thermal and shrinkage cracks.

Next, we are moving on to the design of sections for flexure.

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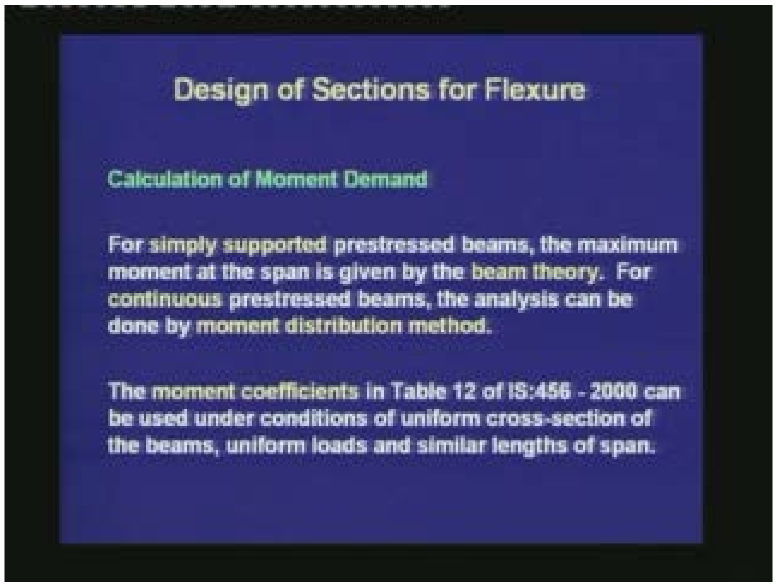

For flexure, how do we calculate the moment demand? For simply supported prestressed beams, the maximum moment at the span is given by the beam theory. For continuous prestressed beams, the analysis can be done by the moment distribution method. The moment coefficients in Table 12 of IS: 456-2000 can be used under conditions of uniform cross-section of the beams, uniform loads and similar lengths of span.

The design is done for the critical section, that is the section which has the highest positive moment or negative moment. For a simply supported beam, the critical section is at the mid-span when there is a uniform load throughout the beam.

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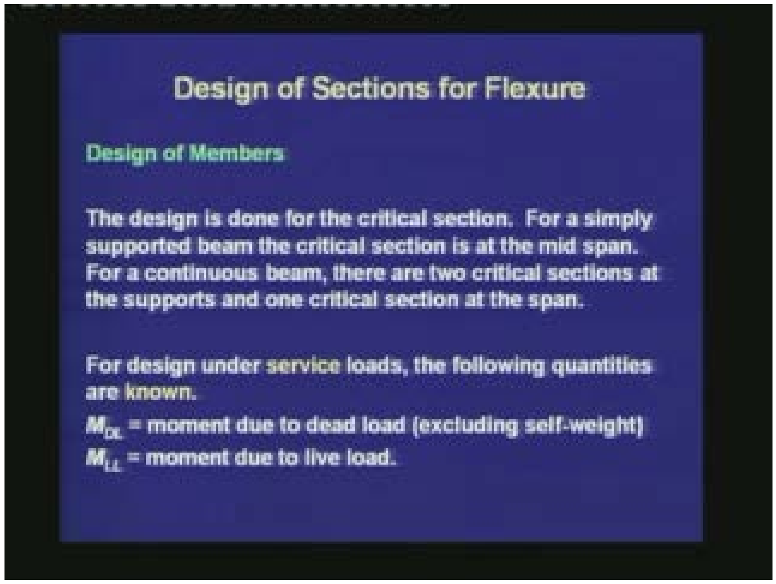

For a continuous beam, there are two critical sections at the faces of the supports and one critical section at the mid-span. Usually the higher of the two moments at the two supports is taken for the design of both the ends. For design under the service loads, the following quantities are known: M_{DL} is the moment due to dead load excluding the self-weight, and M_{LL} is the moment due to the live load. Thus, from the analysis, which is either by the moment distribution method or by using the moment coefficients, we find out the moment demands at the critical sections, one for the dead load which is represented as $M_{DL,}$ and another for the live load, which is represented as M_{LL}. We may not know the moment due to self-weight yet, because the section may not be available during the analysis.

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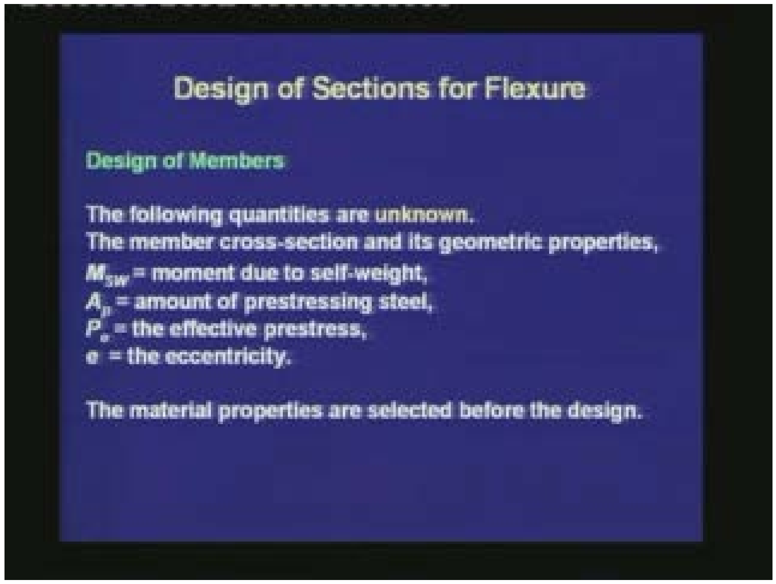

The following quantities are unknown: the member cross-section and its geometric properties. We do not know M_{SW}, the moment due to self-weight of the member. The other unknown quantities are: A_p the amount of prestressing steel, P_e the effective prestress, and e the eccentricity of the CGS at the critical section. Thus, the unknown quantities are in fact, more than the available set of equations.

The material properties are selected before the design, based on the availability and supply of the materials.

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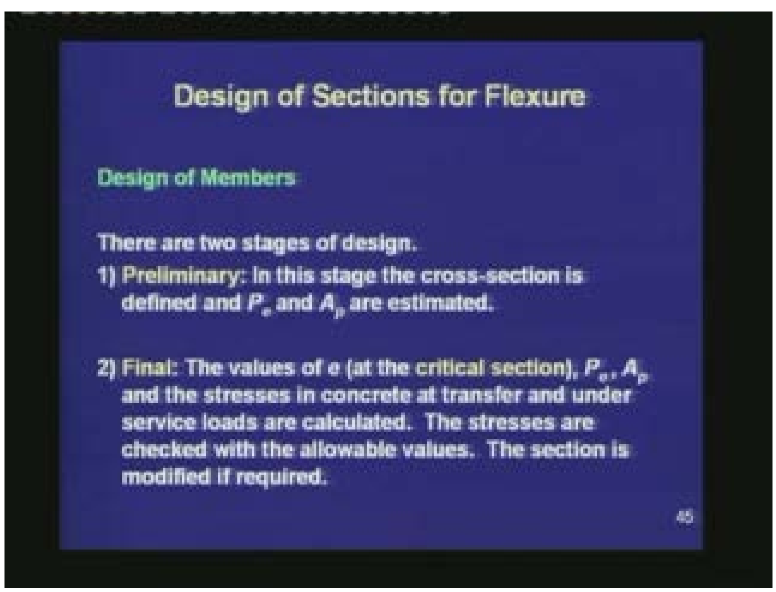

For the design of sections for flexure, there are two stages. The identification of these two stages is for an understanding of the design procedure. The design procedure that is presented here is not unique. It is one of the several possible ways. First, we are designing for the service loads making sure that the allowable stresses at transfer and at service are satisfied. Next, we are doing an analysis for the ultimate strength, and making sure that the strength is greater than the demand under ultimate loads.

The design steps are divided into two groups: one is the preliminary design and next is the final design. In the preliminary stage, the cross-section is defined, and the effective prestress (P_e) and the area of prestressing steel (A_p) are estimated. In the final design, the values of e, the eccentricity at the critical section, P_e and A_p are calculated. The stresses in concrete at transfer and under service loads are also calculated. The stresses are checked with the allowable values. If required, the section is modified to satisfy the allowable stresses. Then, the ultimate strength is checked.

Today, we shall cover only the preliminary design. In the next lecture, we shall move on to the final design.

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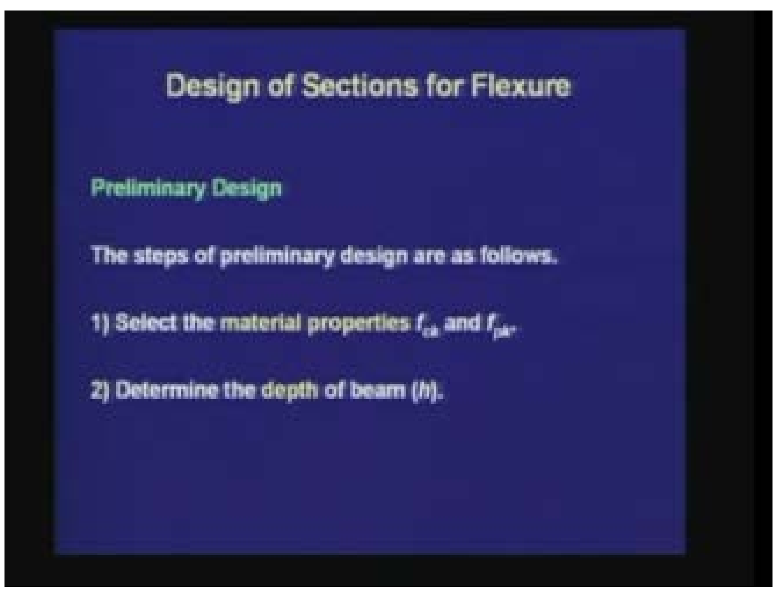

For a preliminary design, the steps are as follows.

1) Select the material properties f_{ck} and f_{pk}, which are the characteristic strengths for the concrete and the prestressing steel.

2) Determine the depth of a beam, which is represented as h.

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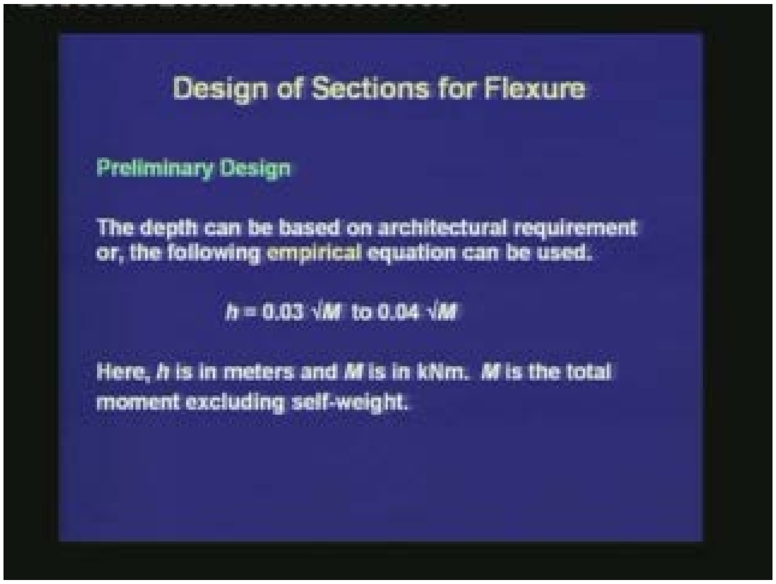

The selection of the depth of a beam usually is governed by the architectural requirement, depending on the required clearance beneath the beam. If the architectural requirement is not given, then a preliminary estimate of the depth can be based on the following empirical equation. $h = 0.03 \sqrt{M}$ to $0.04 \sqrt{M}$. Here, h is in meters and M is in kNm. M is the total moment excluding self-weight.

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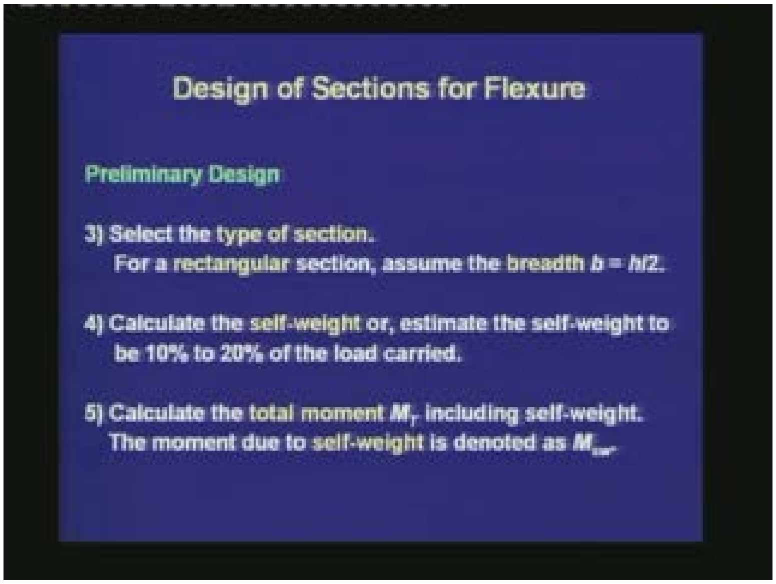

The third step in the preliminary design is to select the type of section. There can be several types of sections depending on the applications. We shall learn more about them in our subsequent lecture. For a rectangular section, which is the simplest type of section, we can assume the breadth b is equal to half of the total depth.

Next, calculate the self-weight or estimate the self-weight to be 10% to 20% of the load carried. Calculate the total moment M_T including the self-weight, $M_T = M_{DL} + M_{sw} + M_{LL}$. Here, the moment due to self-weight is denoted as M_{sw}.

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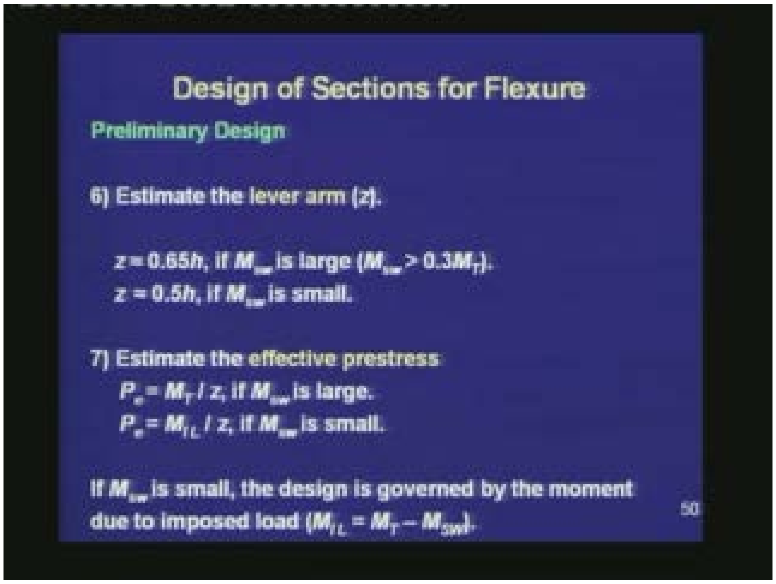

We are estimating the lever arm for the preliminary design. The lever arm z is roughly equal to 0.65 times h, if M_{sw} is large (M_{sw} greater than 30% of the total moment). If M_{sw} is small, then the lever arm can be taken as half of the total depth.

Once the lever arm is estimated, we can estimate the effective prestress that is needed to carry the total moment. Remember that when the moment is applied on a prestressed concrete beam, the compressive force shifts up from the CGS by a distance of z. The prestressing force does not change much within the service loads, and we assume that the prestressing force is staying constant. Hence, the moment applied is equal to the prestressing force times the lever arm by which the compression shifts from the CGS.

From this concept, we can calculate the effective prestress (P_e), which is equal to the moment divided by the lever arm. If the self-weight moment is large, then the total moment governs the effective prestress, and we express $P_e = M_T/z$. If the self-weight moment is small, then the moment due to imposed loads governs the design, and we estimate $P_e = M_{IL}/z$. M_{IL} is the moment due to imposed load, which is equal to the total moment minus the moment due to self-weight.

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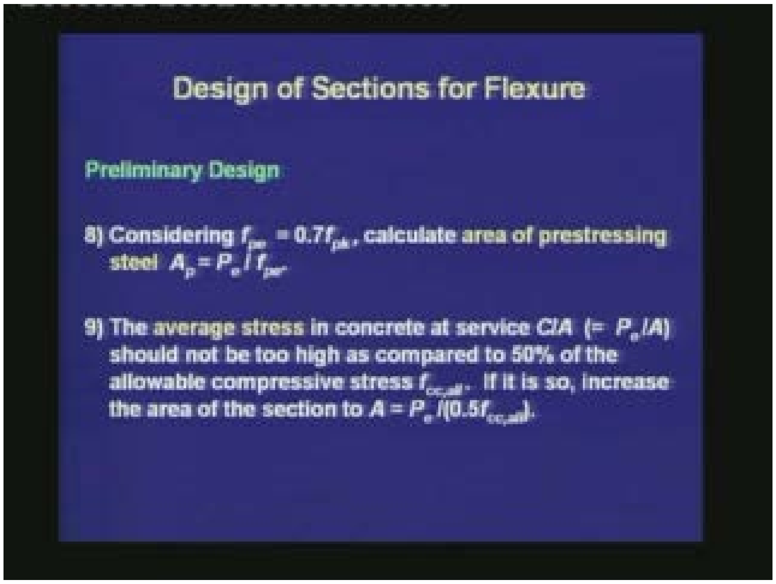

The eighth step is, considering the effective prestress (f_{pe}) is equal to 70% of the characteristic tensile strength of the prestressing steel, calculate area of prestressing steel $A_p = P_e/f_{pe}$. At this stage, we are estimating the area of the prestressing steel based on the estimate of the prestressing force and the effective prestress.

Next, we are checking the size of the section. The average stress in concrete at service, which is the stress that occurs at the CGC, is given as C/A, which is equal to P_e/A. This average stress should not be too high as compared to 50% of the allowable compressive stress, $f_{cc,all}$. This is because if $f_{cc,all}$ occurs at one extreme edge of the member, the average stress which occurs at about half the depth, should not be higher than 50% of $f_{cc,all}$. If it is so, then increase the area of the section to $A = P_e/(0.5f_{cc,all})$. Since we know P_e, we can just increase the area of the section to make sure that the average stress is within 50% of the allowable value at service.

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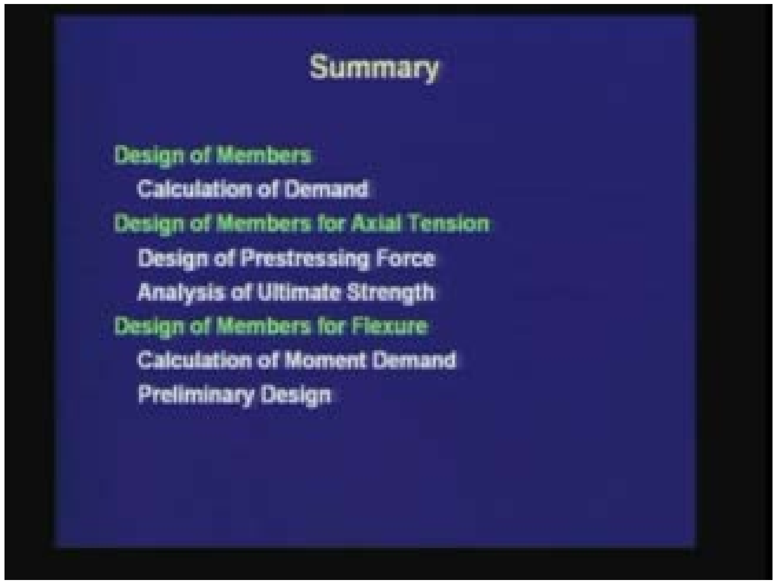

In this lecture, we started to learn about the design of members. First, we studied how to calculate the demand in the member. We need to have the characteristic values of the loads to start with. The characteristic values for dead load, live load, wind load and snow load are available from IS: 875. The earthquake load is available from IS: 1893 Part 1.

For special load situations like hydrostatic, soil pressure, fatigue, accidental loads, explosion, there are some basic guidelines in IS: 875, but we may need special literature to get the values of these loads. In special situations, we may have to do tests to get the loads acting on the structure. The tests can be load tests, wind tunnel tests, or shake table tests. Once we have got the loads, we analyze the structure by a linear elastic method and we calculate the force demand due to a particular type of load.

We combine the force demands for various loads, by the load combinations, which have the load factors as the weightage factor for each type of load. We studied the two sets of load combinations as per the code. For the ultimate loads, the load factors are usually greater than 1.0, and for the service loads, the load factors are usually equal to 1.0. Once we have combined the forces based on the load combinations, we get the total force demand in a member either for the service loads or for the ultimate loads.

The design of a member can be pursued in several ways. One way, is to first satisfy the allowable stresses at transfer and at service. That means the design is primarily based on the service loads. Then, the ultimate strength is checked to be greater than the demand under the ultimate loads. This design procedure is different from the design procedure of reinforced concrete, where we directly design for the ultimate strength to be greater than the ultimate load demand.

Next, we studied the analysis and design of members for axial tension. First, we saw how to design the prestressing force. We calculate the maximum possible prestressing force at transfer based on the allowable stress in concrete at transfer. Next, we calculate the designed prestressing force at service based on the allowable tensile stress at service. We need to make sure that the designed prestressing force is such that the prestress at transfer is less than the value calculated based on the allowable stresses at transfer. Finally, we calculate the ultimate tensile strength of the member, and this should be greater than the ultimate load demand. We solved a problem for the design of an axial member under tension.

Finally, we moved on to the design of members for flexure. We first learnt about how to calculate the moment demand. For simply supported beams, we pick up the expressions of the moment demand at the span for a uniformly distributed load or a point load. If it is a continuous beam, then we may use the moment coefficients provided in IS: 456. The applicability of the coefficients is based on certain conditions, which are uniform cross-section of the beam, similarity of the span lengths and uniform loads. If these conditions are not satisfied, then we have to go for a more rigorous analysis, such as based on the moment distribution method. Once we have done the analysis, we find the demand at the critical sections. For a continuous beam, the critical sections are at mid-span and also at the face of the supports.

Once we have the demand, then, we proceed for the design of the member. The design of the member under flexure is more involved. We have identified two stages of design: first, the preliminary stage and next, the final stage.

In today's lecture, we covered the preliminary stage, where we estimated the effective prestress, the amount of prestressing steel and also the area of cross-section. In our next class, we shall move on to the final design, where we shall recalculate all these values and make sure that the stresses at transfer and service are within the allowable values, and also the ultimate strength is greater the demand under ultimate loads.

Thank you.