PRESTRESSED CONCRETE STRUCTURES

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Module – 01: Introduction, Prestressing Systems and Material Properties

Lecture – 7: Prestressing Steel

Welcome back to Prestressed Concrete Structures. This is the seventh lecture in Module 1 on Introduction, Prestressing Systems and Material Properties.

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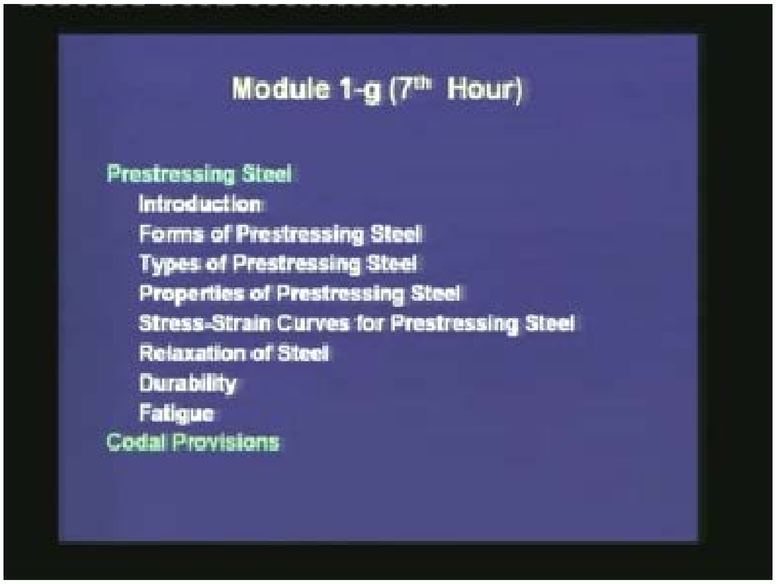

In this lecture, we shall study about prestressing steel. We shall learn the forms of prestressing steel, the types of the steel, the properties of prestressing steel, the stress-strain curves, relaxation of steel, durability and fatigue. At the end, we shall summarise the codal provisions related with the prestressing steel.

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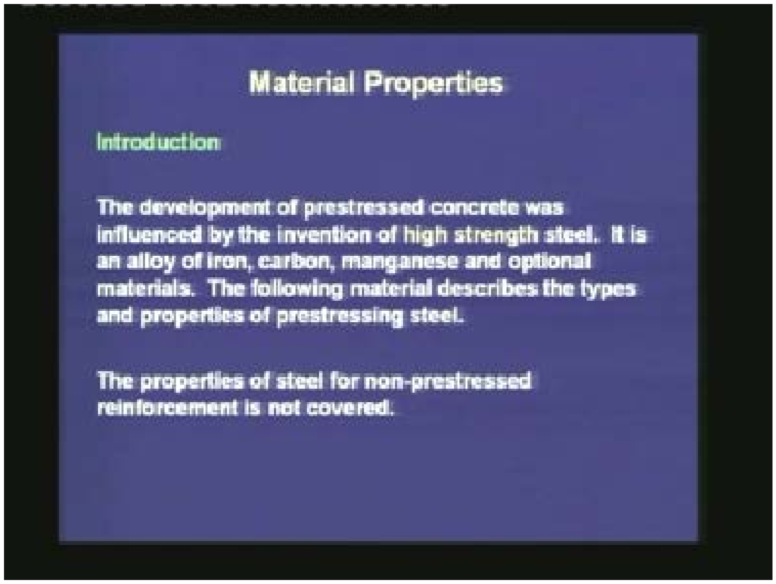

The development of prestressed concrete was influenced by the invention of high strength steel. It is an alloy of iron, carbon, manganese and optional materials. We learnt earlier, that during the early stages of prestressing concrete, it was noticed that the effective prestress reduced with time, and the reason was the creep and shrinkage of concrete. In order to overcome this problem, high strength steel was developed. restressing of concrete became successful only after the development of the high strength steel. In this particular module, we shall discuss about the properties of the prestressing steel. We are not covering the properties of conventional non-prestressed reinforcement because it is expected that the students of this course are familiar with those properties.

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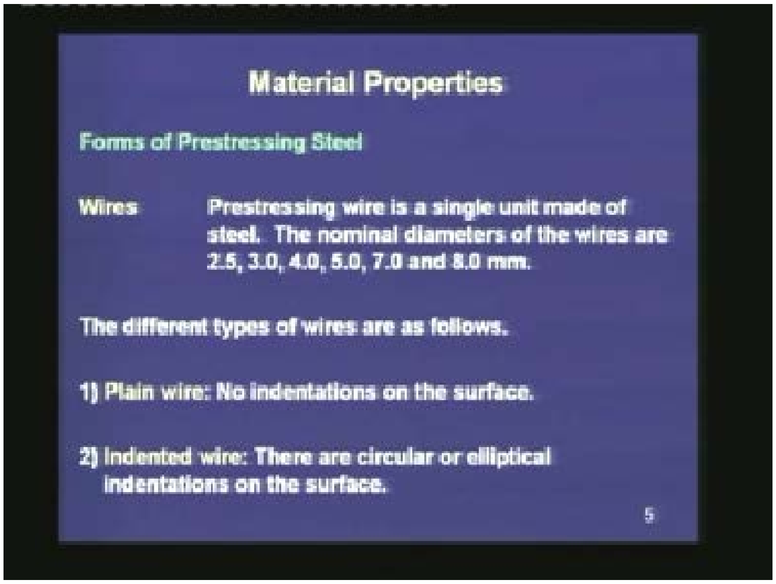

Forms of Prestressing Steel:

The prestressing steel comes in different forms. The first one is the wires. A prestressing wire is a single unit made up of steel. The nominal diameters of the wires can be 2.5, 3.0, 4.0, 5.0, 7.0 or 8.0 mm. The wire is the smallest single prestressing steel. There can be two types of wires: one is the plain wire, where there is no indentation on the surface; indentation refers to the depressions on the surface. The other type of wires can be indented, i.e. there can be circular or elliptical indentations on the surface. These indentations help in the bond between the prestressing steel and the grout.

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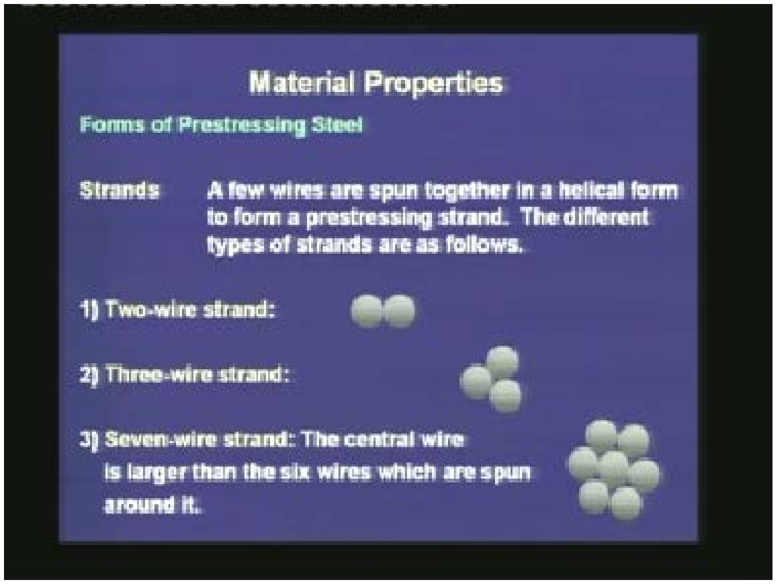

The next form of the prestressing steel is the strands. Here, a few wires are spun together in a helical form to form a prestressing strand. There can be different types of strands. The first one is a two-wire strand: here, two wires are spun together to form a helix after the spinning process. The second type is a three-wire strand, where the strand consists of three wires spun together. The third wire is a seven-wire strand, where the central wire is slightly larger than the other six wires, and these six wires are spun around the central wire in this type of strand.

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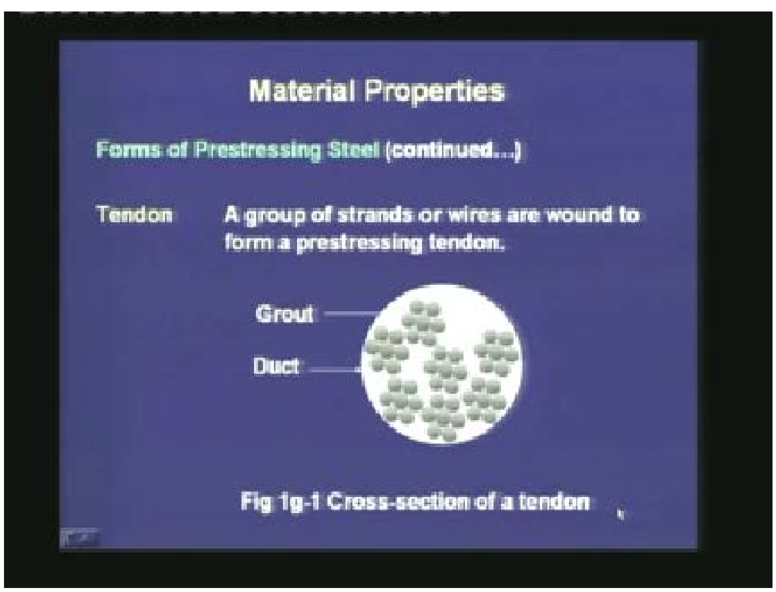

We can also have the prestressing steel in the form of a tendon. A group of strands or wires are wound to form a prestressing tendon. In the sketch of the cross-section of a tendon, we see that several strands have been inserted within a duct, and the duct has been filled up with grout. This whole assembly or this whole unit is called a tendon.

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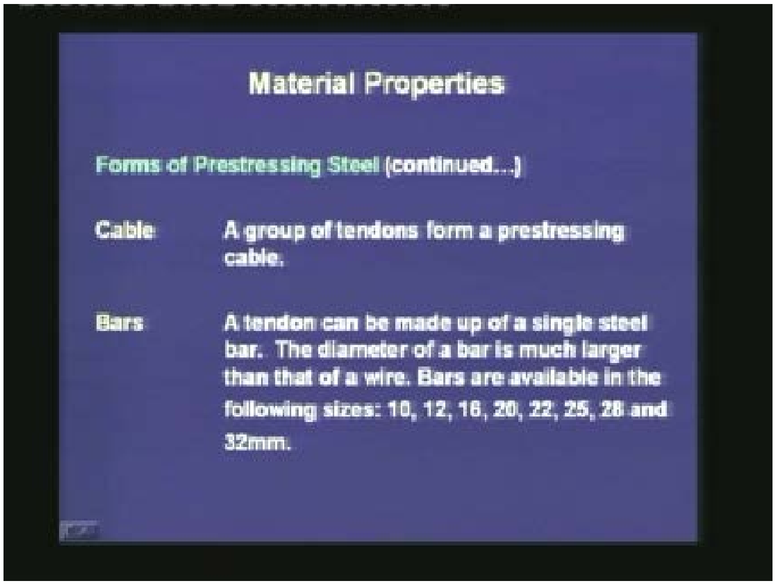

A cable is a group of tendons. There can be different groups of tendons to form a cable. Finally, we come to the bars. A tendon can be made up of a single steel bar where the diameter of a bar is much larger than that of a wire. The bars are available in the sizes of 10, 12, 16, 20, 22, 25, 28 and 32 mm.

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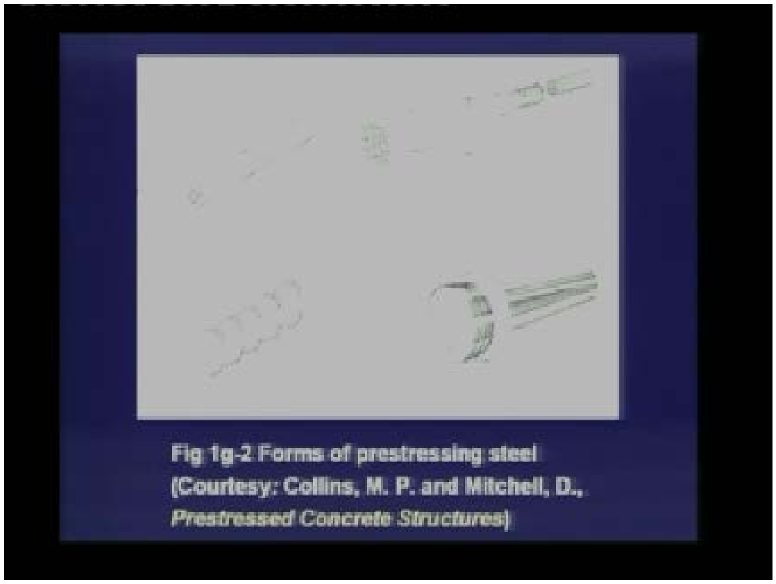

In these figures, we can understand the difference. In the top left, we have a 7-wire strand which can itself be a tendon. The bottom left is a single bar tendon, where it is just one unit which forms the tendon. On the bottom right is a multi-wire tendon, where several wires form the tendon. At the top right, we can see how the tendons are attached in a post-tensioned member through the help of the anchorage system.

Next, we are moving on to the types of the prestressing steel.

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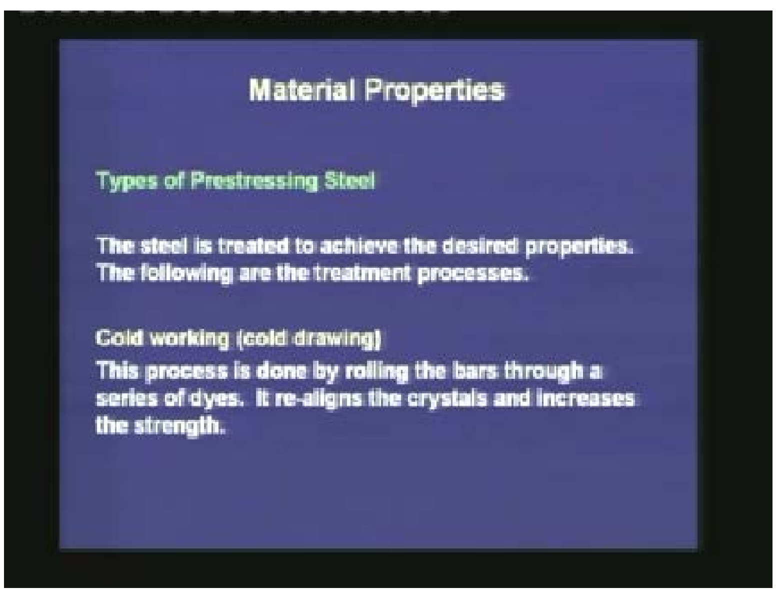

The prestressing steel is treated to achieve the desired property. If there is no other special treatment then the steel is called as-drawn or untreated steel. But the following are some special treatments which enhances the properties of the prestressing steel. The first treatment process is cold working or cold drawing. This process is done by rolling the bars through a series of dyes. It re-aligns the crystals and increases the strength. That is, the cold working of a bar is done to increase the strength of the wire which was earlier having less strength.

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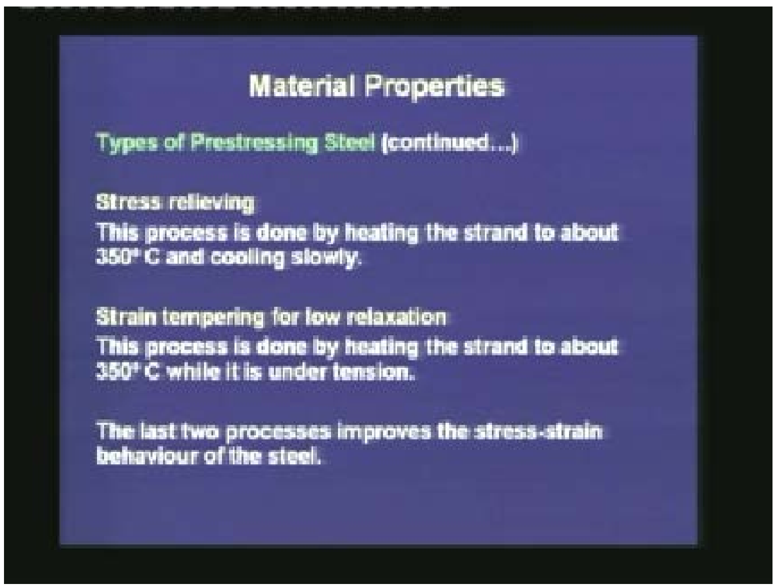

The second treatment process is stress relieving. In this process, the strands are heated to about 350°C, and then they are cooled slowly. This enhances the stress-strain curve of the steel, and we shall see this enhancement in a later slide. The third type of treatment is the strain tampering for low relaxation. In this process, the heating of the strand to about 350°C is done under tension. The resultant stress-strain curve is better, and also the relaxation observed in this type of steel is lower than the steel which is untreated.

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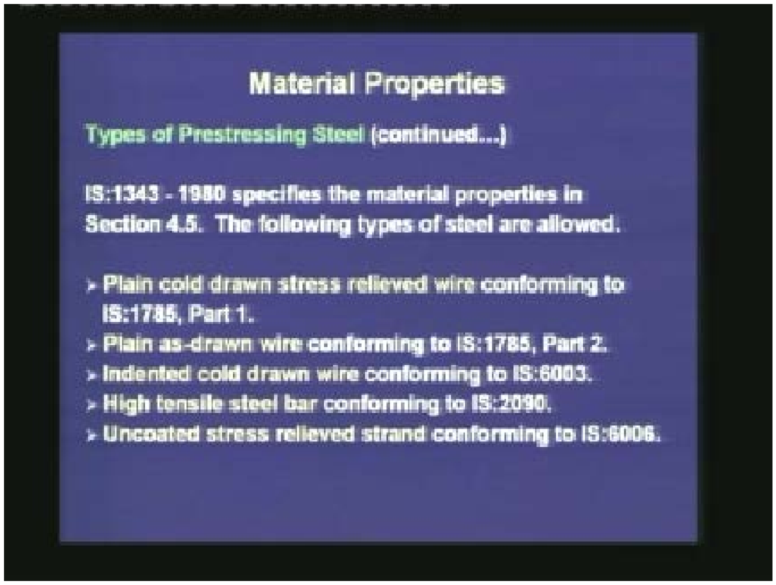

IS: 1343 specifies the material properties of the prestressing steel in Section 4.5. The following types of steel are allowed. The first type is the plain cold drawn stress relieved wire conforming to IS: 1785, Part 1. The second is the plain as-drawn wire without any treatment, conforming to IS: 1785, Part 2. The third is the indented cold drawn wire conforming to IS: 6003. The fourth is the high tensile steel bar conforming to IS: 2090. The fifth is the uncoated stress relieved strand conforming to IS: 6006.

All these codes specify the properties of the different types of strands. They also specify the testing procedure, the sampling procedure and the nomenclature used in the different types of steel. We are not going into the details of these individual codes, but we shall refer to the main properties from these codes.

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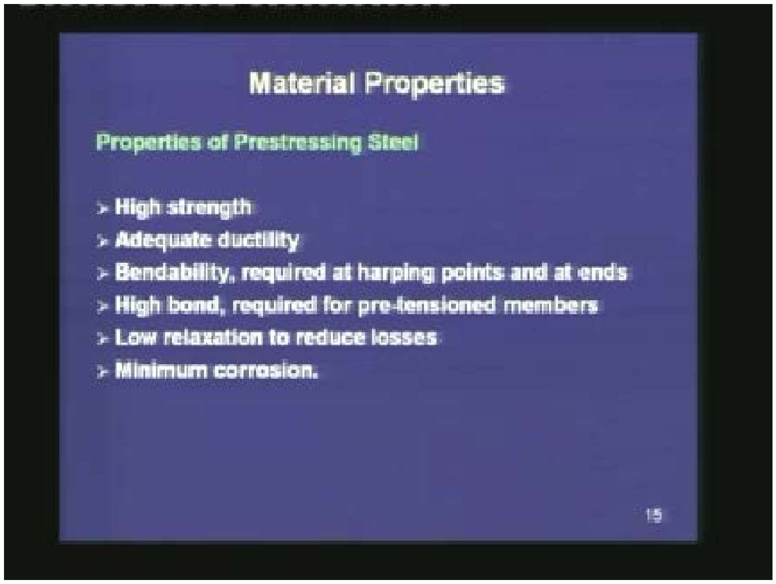

Properties of prestressing steel:

As I mentioned before, that the prestressing steel is different from a conventional non-prestressed enforcement by several factors. The first one is that the prestressing steel has to be of high strength. Unless, we have high strength, the initial prestressing strain will not be large and in that case, there will be substantial loss over time due to the creep and shrinkage of concrete. Hence, the high strength is a primary requirement of the prestressing steel.

The second is adequate ductility; in case of vibrating loads, this property becomes essential. The third is bendability, required at harping points and at ends. The prestressing steel needs to be bent around the harping points or the hold-on points, and also they are bent close to the ends because, they change in direction at the anchorage blocks. Hence, bendability is a requirement for the prestressing tendons.

Fourth is high bond, which is required for pre-tensioned members. In our lecture on pre-tensioned member, I had mentioned that the transfer of stress from the prestressing steel to the concrete takes through bond. Hence, the bond is a very important requirement for the tendons used in pre-tensioned members. In post-tensioned members also, if there is good bond between the prestressing steel and the grout, then the stress transfer is better along the length.

The fifth important property is low relaxation to reduce loss. We shall cover the concept of relaxation later in this lecture. It is desired that the prestressing steel should have low relaxation. Hence, sometimes the steel is heated under tension to have this desirable property.

Finally, the steel should have minimum corrosion. Although there is an alkaline environment around the steel, it is always preferred to have steel which is less susceptible to corrosion.

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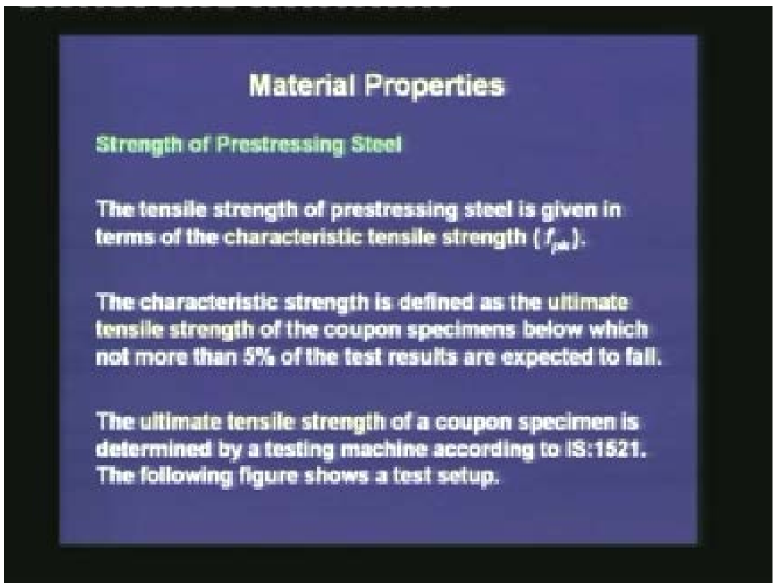

We are coming to the first and the foremost important property of prestressing steel, that is the strength of prestressing steel. The tensile strength of prestressing steel is given in terms of the characteristic tensile strength, which is denoted by the term f_{pk}. The characteristic strength is defined as the ultimate tensile strength of coupon specimens below which not more than 5 percent of the test results are expected to fall. In the lecture on material properties of concrete, we learnt that the definition of characteristic strength is based on a probability distribution of the test results of several numbers of specimens. A normal distribution is assumed and the characteristic strength is defined as the value below which not more than 5 percent of the test results are expected to fall. The ultimate tensile strength of a coupon specimen is determined by a testing machine as per the code IS: 1521. The following figure shows a test setup.

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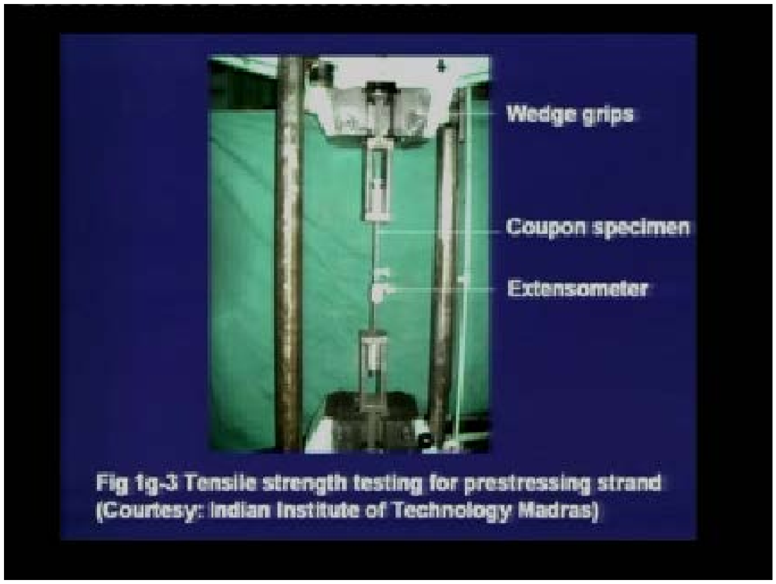

Fig 1g-3 Tensile strength testing for prestressing strand
(Courtesy: Indian Institute of Technology Madras)

In this figure, a coupon specimen has been gripped at the two ends. This gripping has been possible by the wedge action at the top and at the bottom. The testing machine applies the load on the wedges, which is then transferred to the coupon specimen. The elongation of the coupon specimen is measured by the extensometer. When we plot the load versus extension, from there we can get the stress versus strain curve of the prestressing strand. The strength is calculated from the failure load, at which the first wire in the strand snaps. The deformation can also be measured by linear variable differential transducers or in short LVDTs.

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Fig 1g-4 Failure of a prestressing strand
(Courtesy: Indian Institute of Technology Madras)

After the testing of the specimen, we can see how the specimen has ruptured. The individual wires in the strands have come separated, and this is the failure state of the coupon specimen.

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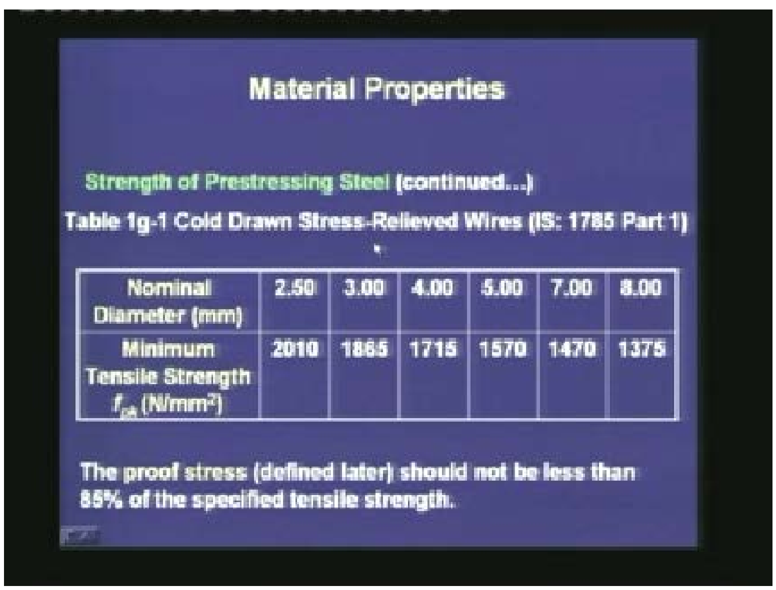

Nominal Diameter (mm)	2.50	3.00	4.00	5.00	7.00	8.00
Minimum Tensile Strength f_{pk} (N/mm^2)	2010	1865	1715	1570	1470	1375

The IS codes for the individual types of wires and strands specifies some minimum tensile strength for each type of wire. First, in IS: 1785 Part 1 for the cold drawn stress relieved wires, we see that for wires of diameter 2.5 mm, the minimum tensile strength is 2010 N/mm^2. For 3 mm diameter wires, it is 1865 N/mm2; like that for wires of 8 mm diameter, the strength is 1375 N/mm^2. All these values are much higher than those for the conventional steel that is used in reinforced concrete. In reinforced concrete, the tensile yield stress is around 250 or 415 or 500 N/mm^2. Compared to that, we can observe that the tensile strength in the prestressing wires is much higher. The proof stress which we shall define later, should not be less than 85 percent of the specified tensile strength.

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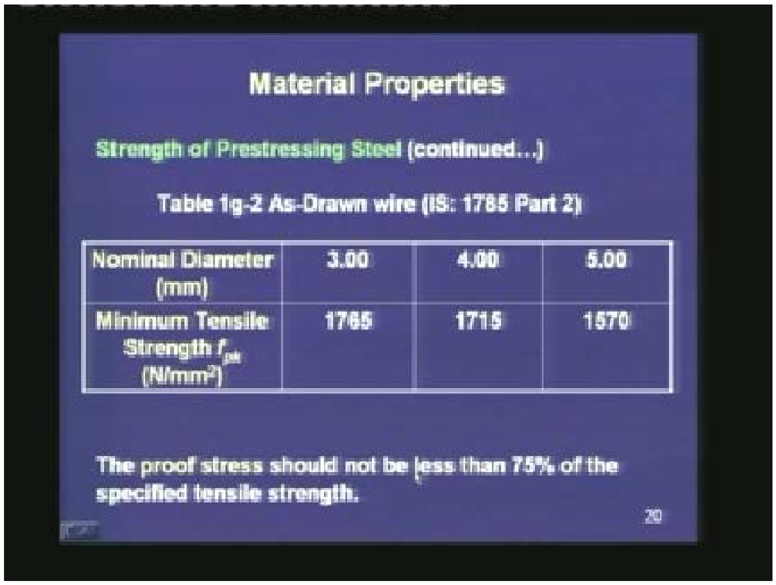

The second table is from IS: 1785 Part 2. This table is for as-drawn wires. For wires of diameter 3 mm, the tensile strength is 1765 N/mm^2. It can be noted that this value is less than the previous value for a corresponding cold drawn wire; that means, a cold drawn process increases the tensile strength of the wires. Similarly, values are specified for the 4 and 5 mm diameter wires. The proof stress should not be less than 75% of the specified tensile strength. We can observe that the specification for proof stress is lower for as-drawn wires as compared to the cold drawn wires.

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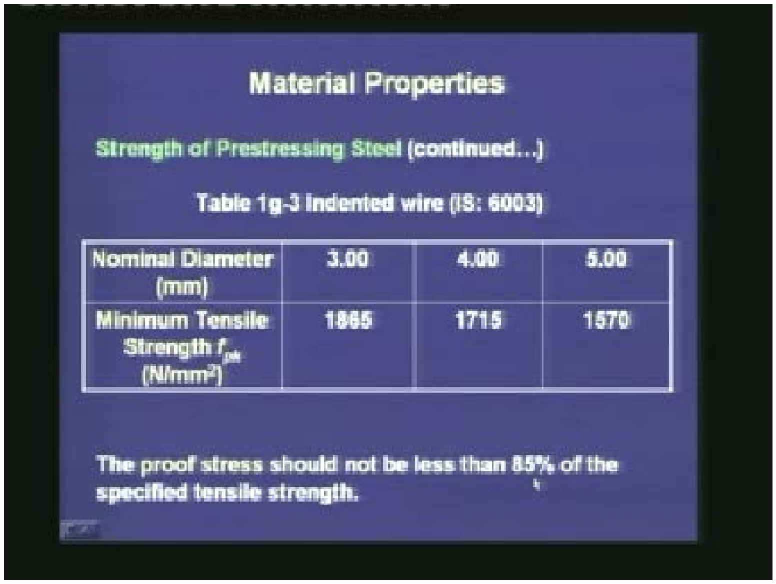

The third table is for indented wires. According to IS: 6003, the tensile strength for a 3 mm diameter wire is 1865 N/mm^2. Similar values are given for wires of diameters 4 and 5 mm. The proof stress should not be less than 85% of the specified tensile strength. These values are similar to the cold drawn wires that we have seen in the first table.

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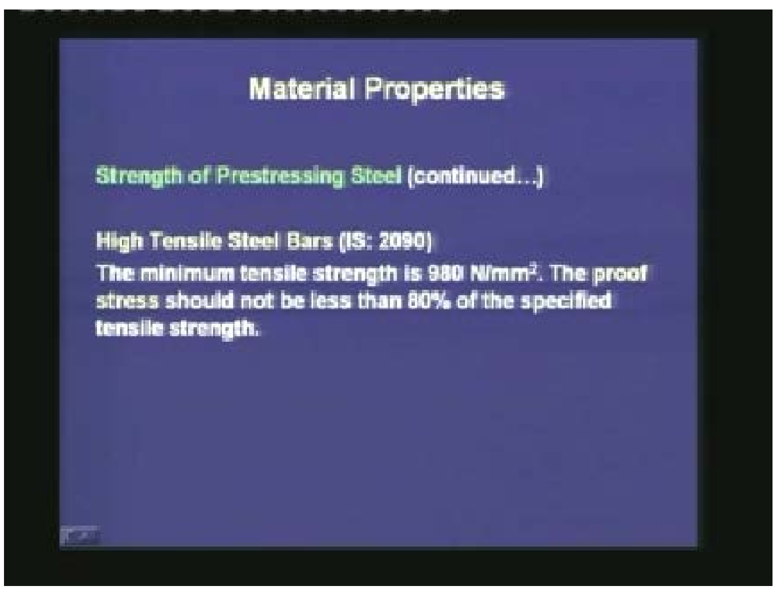

For high tensile steel bars as per code IS: 2090, the minimum tensile strength is 980 N/mm^2. We can observe that this value is much lower than the individual wires, which are shown in the previous three tables. If we use a steel bar as a prestressing tendon, its tensile strength is much less. But the benefit we get is that the anchorage becomes simpler, where we have to deal with one bar instead of a group of wires or strands. The proof stress for a bar should not be less than 80 percent of the specified tensile strength.

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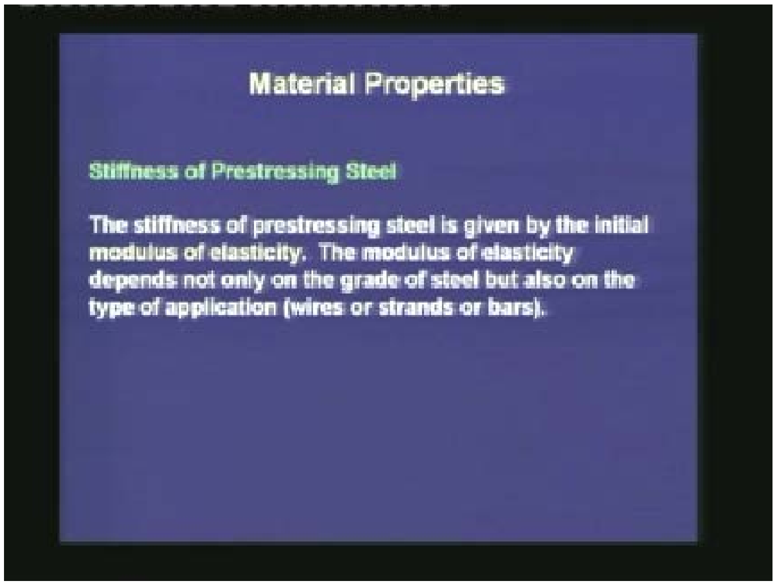

Next, we move on to the stiffness of prestressing steel. The stiffness of prestressing steel is given by the initial modulus of elasticity. The modulus of elasticity depends on the type of application like wires or strands or bars. Remember that in strands, there is not just a single wire; it is a cluster of wires which is spun together. When we are testing this strand, the modulus can be different from the modulus of the individual wires.

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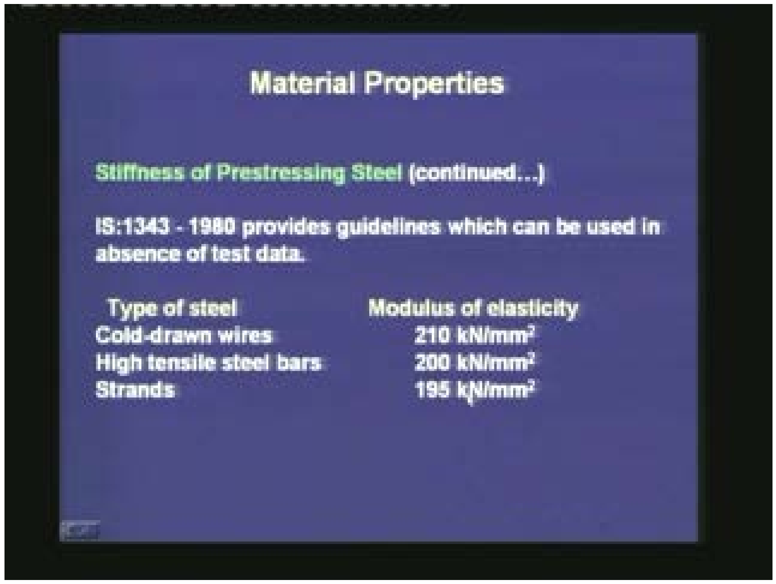

IS: 1343-1980 provides some guidelines, which can be used in absence of test data. For cold drawn wires, the modulus of elasticity is 210 kN/mm^2. For high tensile steel bars, it can be taken as 200 kN/mm^2 and for strands 195 kN/mm^2. We can observe that for the strands, the modulus is lower as compared to the wires because a strand is formed of several wires. Hence if we test a strand, due to unwinding, the modulus is found to be less than that for an individual wire.

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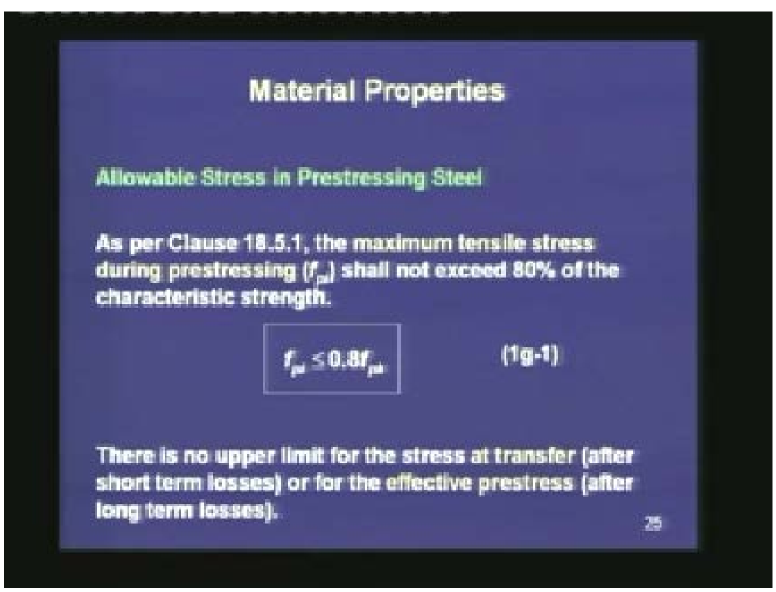

Based on the strength of the steel, allowable stresses have been specified in the code, which should be maintained during the prestressing process. As per Clause 18.5.1, the maximum tensile stress during prestressing which we are denoting as f_{pi}, shall not exceed 80% of the characteristic strength. During the prestressing process, we have to make sure that the tensile stress that we are applying on the tendons is limited within 80% of the characteristic tensile strength. I had told earlier, that the prestressing process is a difficult process, and we have to take adequate safety measures during the prestressing operation. The limit is a safety measure, so that the wire does not snap during the prestressing process. The code IS 1343 does not specify any upper limit for the stress at transfer which is after the short-term losses, or for the effective prestress which is after the long-term losses. But in some international codes, there are specifications for these two stresses.

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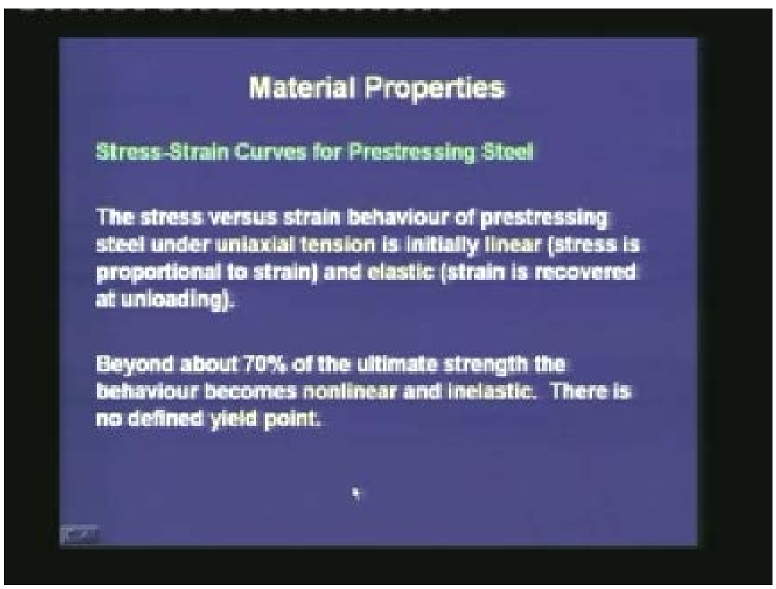

Next we move on to the stress-strain curve of prestressing steel. We need the stress-strain curves of prestressing steel to study the behavior of a prestressing member. The stress versus strain curve under uniaxial tension is initially linear. That means, the stress is proportional to strain, we can apply the Hooke's law. The behaviour is also elastic, that is, the strain is recovered at unloading. But beyond about 70% of the ultimate strength, the behaviour becomes nonlinear and inelastic. If we stretch the bar beyond 70% of the ultimate strength, then the stress-strain curve is no more linear, that is, stress is not proportional to strain any more. Also, we see some elastic or plastic deformation in the steel. For prestressing steel, unlike conventional mild steel reinforcement, there is no specific yield point. That means, we do not have any plateau in the stress-strain curve of the prestressing steel. Then how do we define the yield point for our design purpose?

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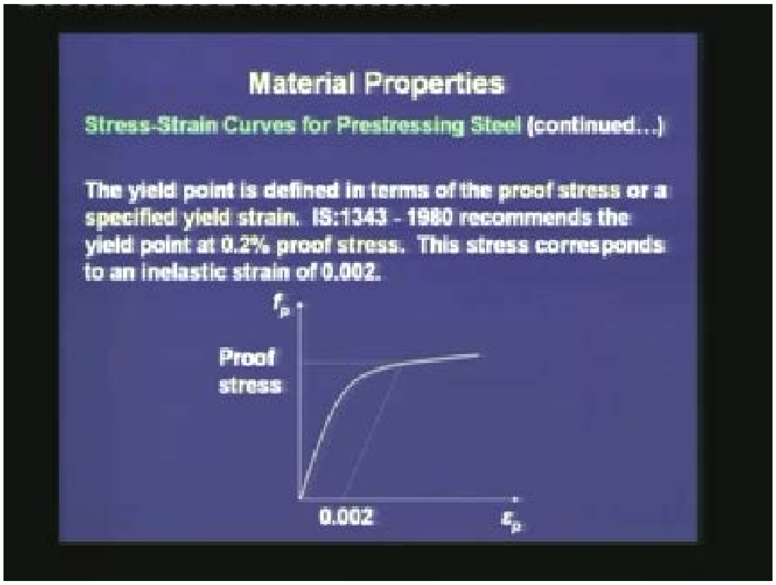

The yield point is defined in terms of the proof stress or a specified yield strain. IS: 1343 recommends the yield point at 0.2% proof stress. Thus, the 0.2% proof stress is defined as the stress corresponding to an inelastic strain of 0.002. From this graph, we can understand that initially the stress versus strain is linear, and then it becomes nonlinear with the increase in stress.

The proof stress is that particular value of the stress which corresponds to a plastic deformation of 0.002. In order to get the proof stress, we draw a line which is parallel to the initial part of the curve; wherever this line intercepts the stress-strain curve, we pick up that point, and the stress corresponding to that point is the proof stress. The purpose of drawing a line parallel to the initial slope is that we are considering a point which is having a plastic deformation of 0.002. In some other international codes, the yield point is defined corresponding to a specified yield strain.

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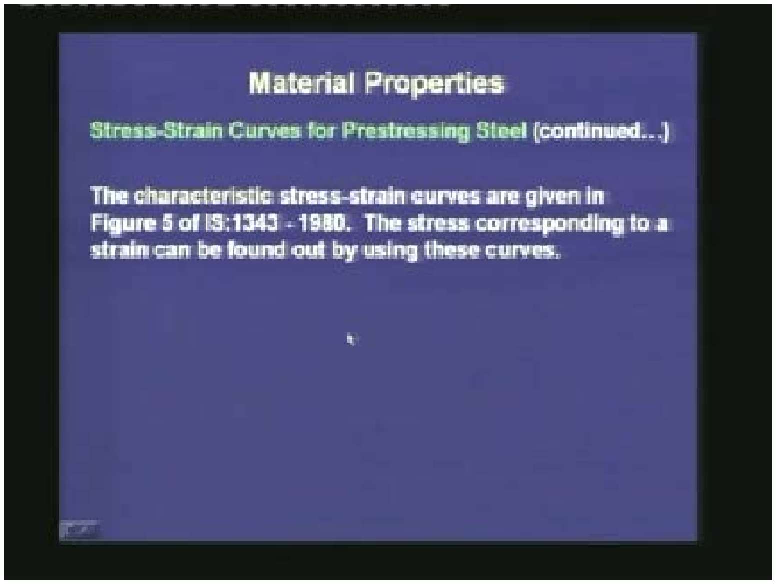

The stress-strain curve for different types of prestressing steel are given in Figure 5 of IS: 1343. In case, if we need the stress corresponding to a strain in our calculations we can use these curves.

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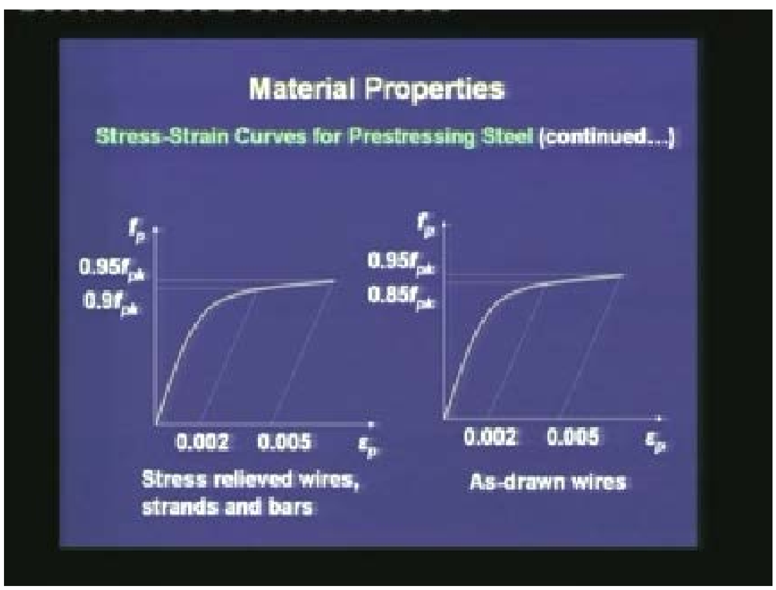

On the left side, the curve is for stress relieved wires, strands and bars. Here, the curve is specified in terms of stresses corresponding to different amounts of plastic strain. For the particular curve on the left, the value of the stress for a plastic strain of 0.002 is 90% of the characteristic strength. The stress corresponding to a plastic strain of 0.005 is 95% of the characteristic strength. On the right hand side, the curve is for an as-drawn wire. Here, we can see that the stress corresponding to a plastic strain of 0.002 is lower and it is given as 85% of the characteristic strength, whereas the plastic strain of 0.005 has a stress which is almost same as that of the other curve. Thus, the main difference between the as-drawn and the stress relieved wires is the variation of the stress-strain curve near the yielding region.

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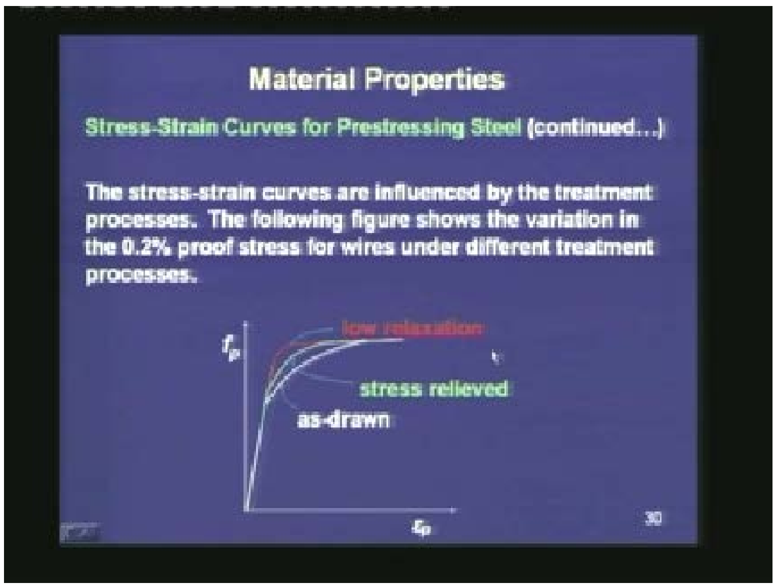

Let us now try to understand the effect of the different treatment processes that we have learnt earlier. In this figure, we see that the main variation comes in the particular region where the bar starts yielding. If we have an as-drawn wire or an untreated wire, then the variation from the elastic to the plastic region is quite gradual. If we treat this wire to a stress relieved wire, then we see that this variation is relatively sharper. At the transition, for a given strain, the stress relieved wires have higher stress compared to the as-drawn wires. Finally, if we do a low relaxation treatment process then we have a further sharper peak. Here also we find that for a given strain, the stress is higher as compared to those in as-drawn and stress relieved wires. After the treatment process, we gain in a higher elastic behavior, and then the yielding occurs relatively sharply. By this, we achieve a better behaviour of the stress-strain curve for low relaxation or stress relieved wires, as compared to as-drawn wires.

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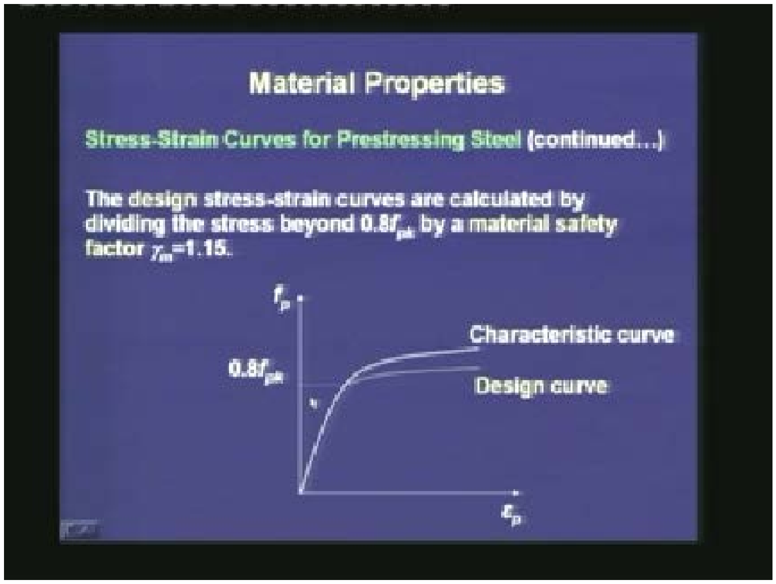

From the characteristic curve, we can define the design stress-strain curve. The design stress-strain curve is calculated by dividing the stress beyond 0.8 f_{pk} by a material safety factor of γ_m = 1.15. If we compare the design stress-strain curve of concrete with respect to its characteristic curve, vis-a-vis the design curve of steel with respect to the corresponding characteristic curve, we can see that the material safety factor in steel is applied only after a certain amount of stress. The reason is that, it has been observed that the variation of the modulus of the steel does not change much for the different grades of steel. Hence, any variability in the strength is not reflected in the modulus of the steel. That is why the material safety factor is incorporated only in the strength, and it has not been incorporated in the initial modulus.

For concrete, the variation of strength also shows a variation in the initial modulus and hence, the partial safety factor is used throughout the stress-strain curve. A curve of lower strength will also have a lower elastic modulus. Another difference is that the value of the material safety factor for concrete is 1.5, because the variability is high; whereas for the prestressing steel the value of the material safety factor is 1.15 which is lower than that for concrete.

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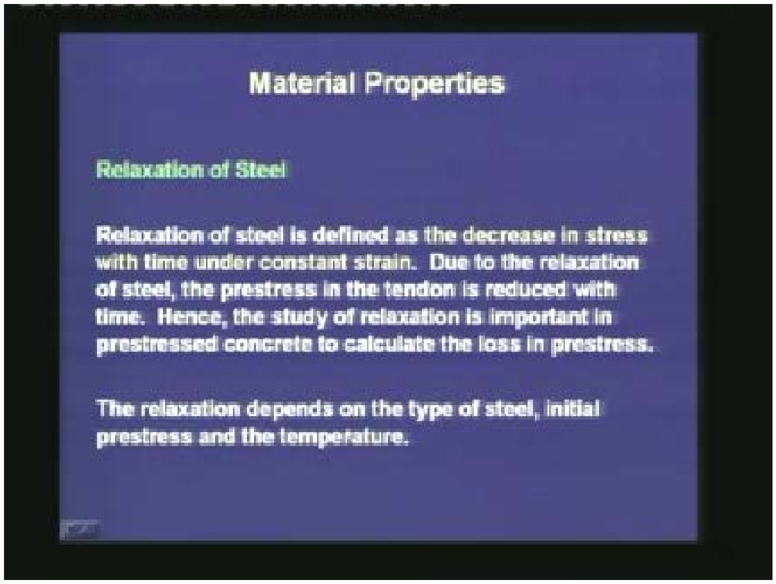

We are moving on to another important property of steel, i.e. relaxation of steel. The relaxation of steel is defined as the decrease in stress with time under constant strain. Due to the relaxation of steel, the prestress in the tendon is reduced with time. Hence, the study of relaxation is important in prestressed concrete to calculate the loss in prestress. Earlier in the study of the material properties of concrete, we had studied creep and shrinkage. We understood that these phenomenons are very important to be studied for prestressed concrete, because they lead to the loss of prestress over time. Similarly, the relaxation is also an important property which needs to be studied because it also has the same effect of the reduction of prestress over time. The relaxation of steel depends on the type of steel, the amount of initial prestress, and the temperature to which the steel is subjected.

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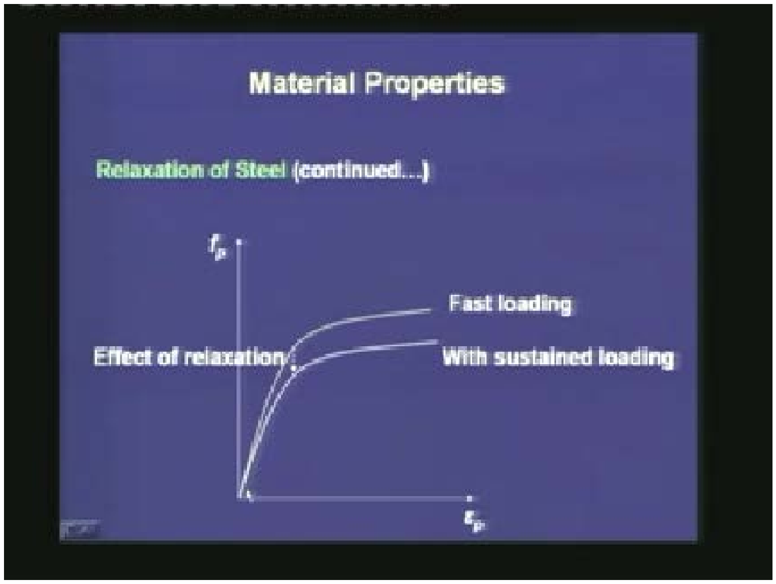

This curve shows the relaxation process. If we are testing a coupon specimen quickly, we shall achieve the top curve. But if we are stopping the load at a certain point and if we are maintaining the strain, what we shall observe is that the stress carried by the specimen gets reduced. The drop in stress with time for a constant strain, is defined as relaxation. That is, the shift of the curve along the stress axis under sustained strain, is defined as relaxation.

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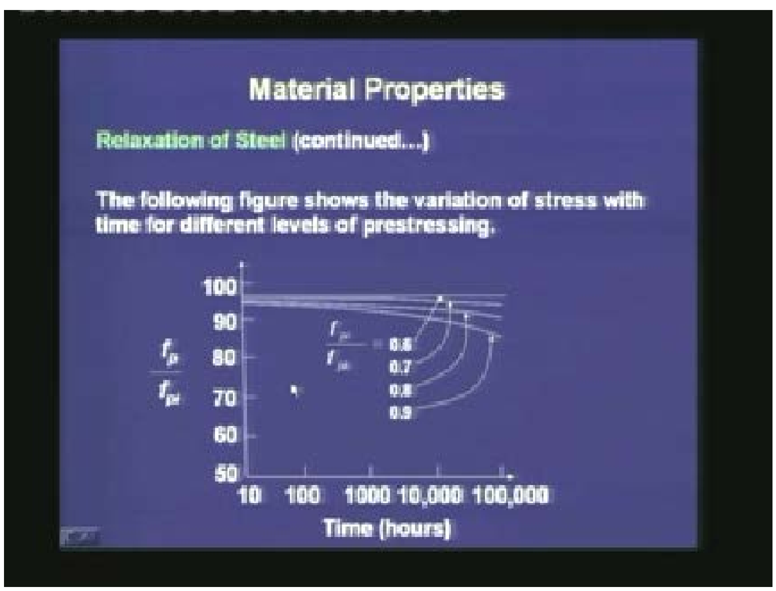

The above figure shows the variation of stress with time, for different levels of initial stressing. If the initial stressing is about 60% of the characteristic strength, then the drop of the prestress due to relaxation is much lower. But if we increase the initial stressing to say 70%, 80%, or 90% of the characteristic strength, then we see that the drop in prestress with time gets substantial. This is another reason why the code limits the value of the initial prestress to 80% of the characteristic strength, so that the relaxation loss is relatively limited. Note that, here the time axis is a logarithmic axis. Most of the relaxation tests are done for a period of 1000 hours, or if it is not possible to do for 1000 hours, then the tests are done for a period of 100 hours.

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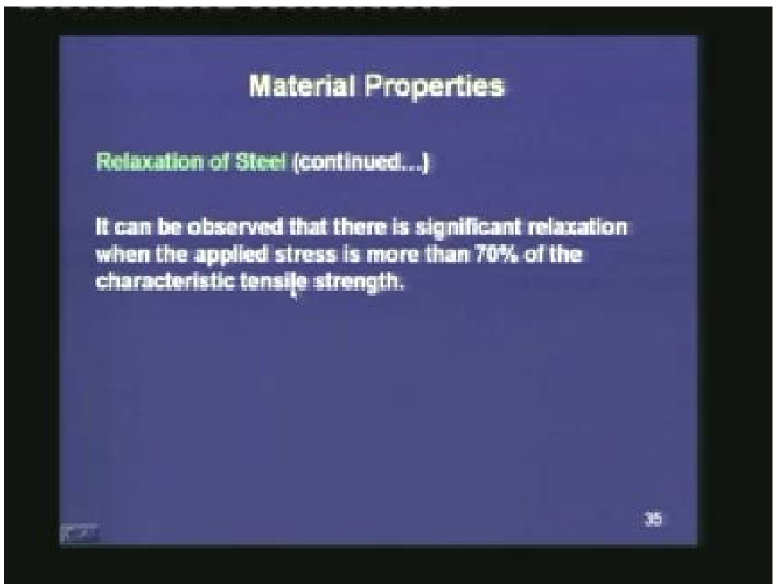

It can be observed that there is significant relaxation loss over a period, when the applied stress is more than 70% of the characteristic tensile strength. We have to be aware that if we are stretching the tendons beyond 70% of the characteristic strength, we shall see significant relaxation loss. Hence, we have to include that in our calculation of the effective prestress after several years.

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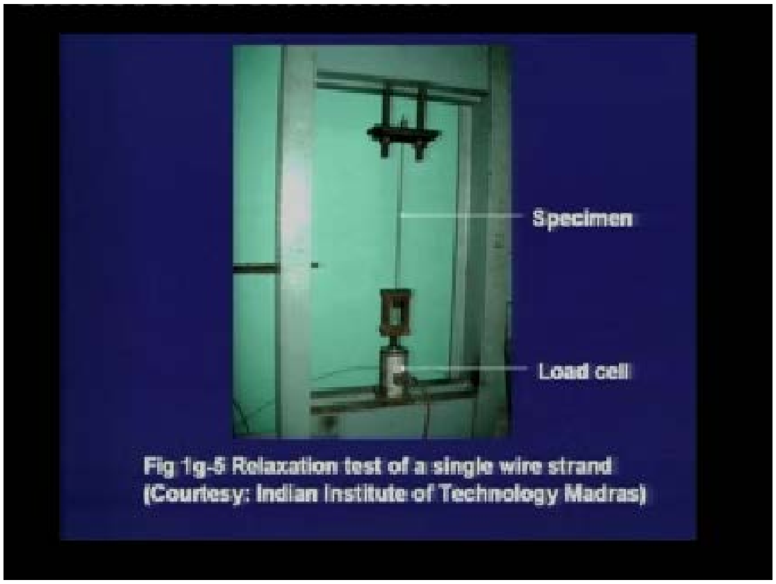

This photograph shows the determination of relaxation loss for a particular type of steel. Here, the coupon specimen has been held between two grips, and a certain amount of load has been applied on the specimen. Then the grips are maintained at a particular distance. That is, the strain in the specimen is maintained constant. The drop in the stress is recorded by the load cell. The whole assembly has been placed in a chamber with controlled temperature. As I said before that the relaxation loss depends on the initial prestress and the temperature. Hence, in a standard test, both these values are specified so that we are able to compare the relaxation loss for the different types of steel. In this particular photograph, a single wire is being tested for the relaxation loss.

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Fig 1g-6 Relaxation test of a seven-wire strand
(Courtesy: Indian Institute of Technology Madras)

In this sketch, it is a similar type of set up where a strand is being tested for the relaxation loss.

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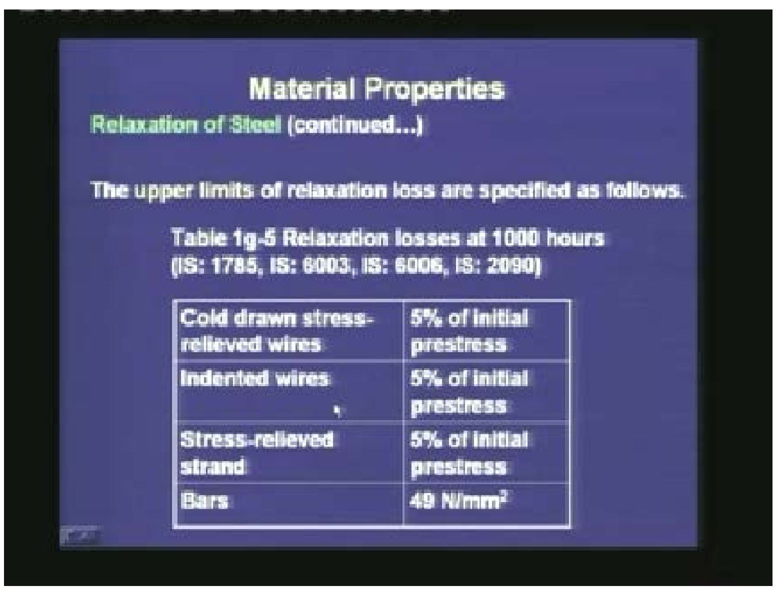

The code specifies some upper limits for the relaxation loss. For cold drawn stress relieved wire, for indented wires and for stress relieved strand, the maximum amount of relaxation loss after 1000 hours is 5% of the initial prestress. For bars, the relaxation loss after 1000 hours can be maximum up to 49 N/mm^2. As prestressed steel has to be of better quality as compared to conventional reinforcement, the steel before any construction should be subjected to the tests specified in the code, and the designer should check those test results before approving the construction of the structure. The material testing is a very important aspect of precast, prestressed concrete construction.

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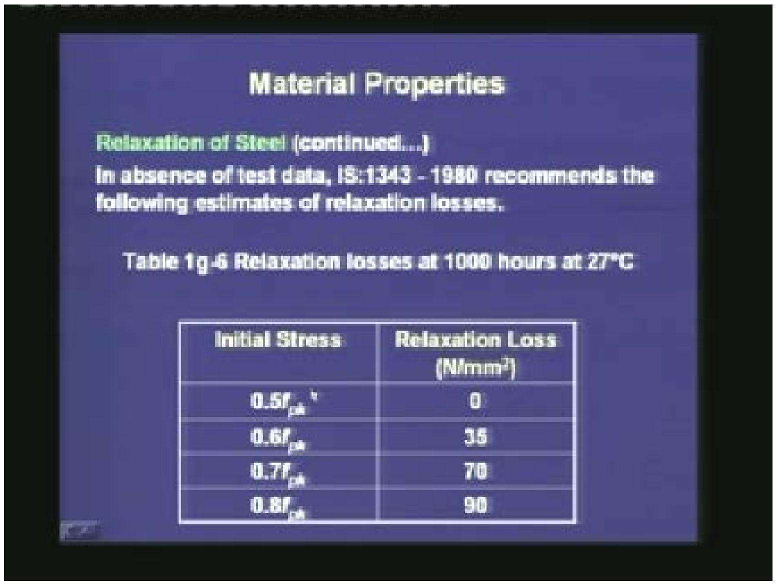

When we are doing some design calculations, if we do not have any test data, then the code allows us to use the above table to calculate the relaxation loss. Depending upon the initial stress, we can calculate the relaxation loss and these values are as follows. If the initial stress is about 50% of the characteristic strength, then we do not have to consider any relaxation loss. If the initial stress is 60%, the relaxation loss is 35 N/mm^2. Similarly, if the initial stresses are 70% or 80% of the characteristic strength, then the relaxation losses are 70 and 90 N/mm^2, respectively. We can observe that with the increase in the initial stress, the relaxation losses are also increasing.

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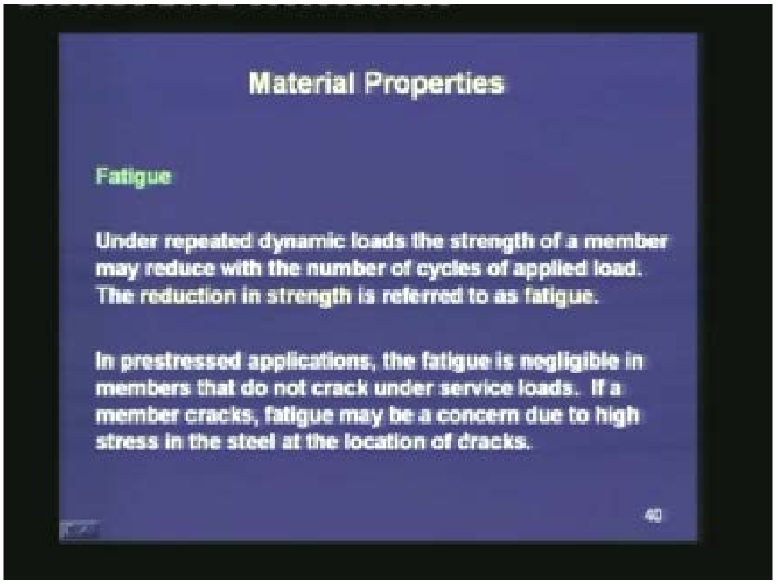

The next property that we shall study is the fatigue. Fatigue is a concern under repeated load or even reverse load. Under repeated dynamic loads, the strength of a member may reduce with the number of cycles of applied load. The reduction in strength is referred to as fatigue. Fatigue is a concern in structures like bridges or any other structural element which is subjected to vibration. In prestressed applications, the fatigue is negligible in members that do not crack under service loads. But if a member cracks, fatigue may be a concern due to high stress in the steel at the locations of the cracks. Earlier, we had said that we can design the prestressed members as one of the three types. For Type 1, no tensile stress is allowed in the prestressed member. For Type 2, tensile stress is allowed, but no cracking is allowed. For Type 3, tensile stress and cracking are allowed, but the cracking is limited only to a certain extent, i.e. the crack width is limited. Hence, the fatigue becomes a concern for Type 3 members. If we are designing a structure as Type 1 and Type 2 for the service loads, then we may not check for the fatigue.

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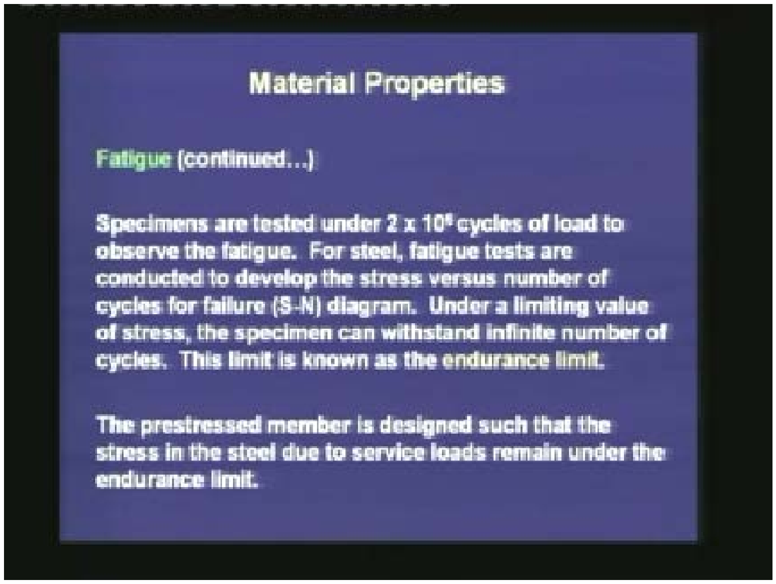

For fatigue testing, the specimens are tested under 2 million cycles of the load. For steel, the fatigue tests are conducted to develop the stress range versus number of cycles for failure (S-N) diagram. The S-N curve is an important characteristic behaviour to study the effect of fatigue. The S-N curve is a plot of the range of stress fluctuation versus the number of cycles which leads to failure. Under a limiting value of the stress range, the specimen can withstand infinite number of cycles, and this limit is known as the endurance limit. Let me explain the S-N diagram by a sketch.

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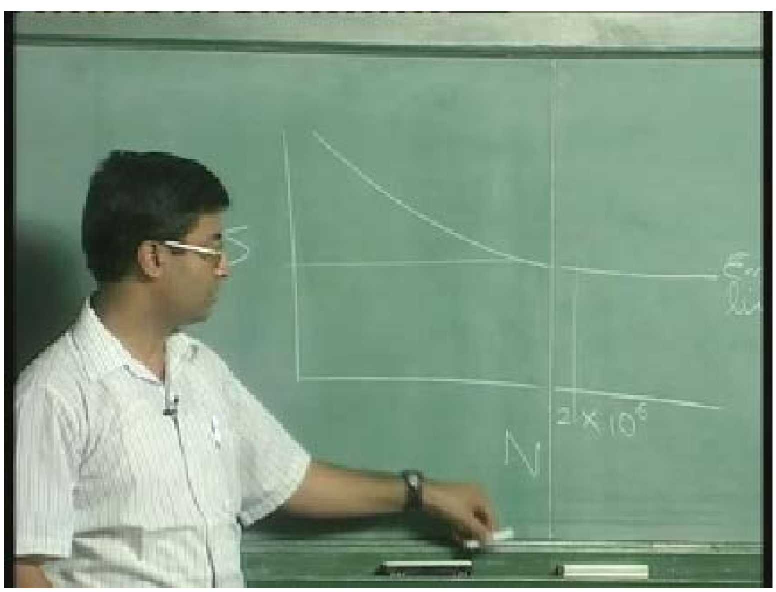

The S-N curve plots the stress range corresponding to the number of cycles for failure. What is observed is, as the number of cycles increases, the stress range reduces. But beyond a certain value, say a value of 2 million cycles, the stress range does not reduce. This value of stress range is called the endurance limit. Thus, if a structure is subjected to repeated loading and if we design the structure in such a way that the stress range is within the endurance limit, then we do not have a problem of fatigue. If the stress range exceeds the endurance limit, then we will have a problem of fatigue when the corresponding number of cycles is crossed.

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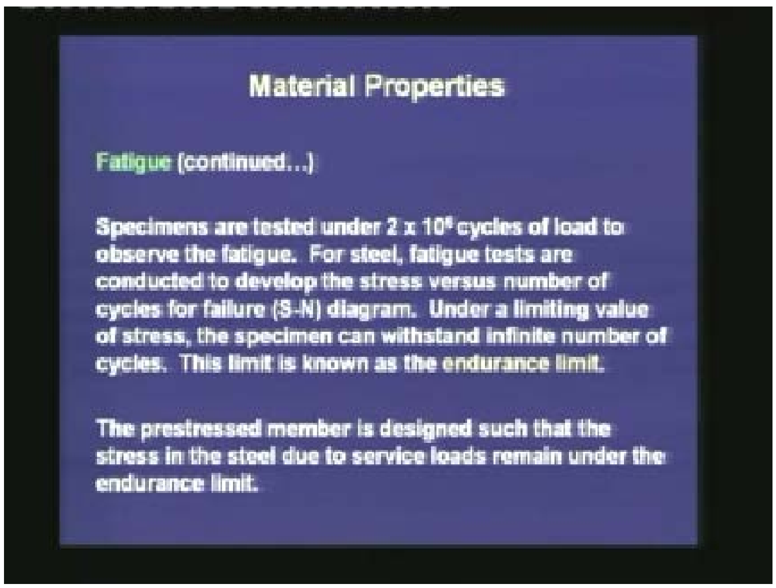

Usually the prestressed member is designed in such a way that the stress in the steel due to the service load remains under the endurance limit. That means the members are designed such that the stresses will not lead to a fatigue problem.

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This photograph shows a fatigue testing of prestressing steel and an anchorage block. Here, the pulsating load is applied by two jacks. There is a beam at the bottom, and there is a reaction beam at the top. As the pistons are moving down, the bottom beam is moving down, and it is applying tension to the steel. This load is being varied over several cycles to study the fatigue behavior of the prestressing steel and the anchorage block. As I said, usually these tests are done for 2 million cycles to check that the prestressing steel and the anchorage block are satisfactory to sustain the repeated loading.

Next, we move on to the durability of prestressing steel.

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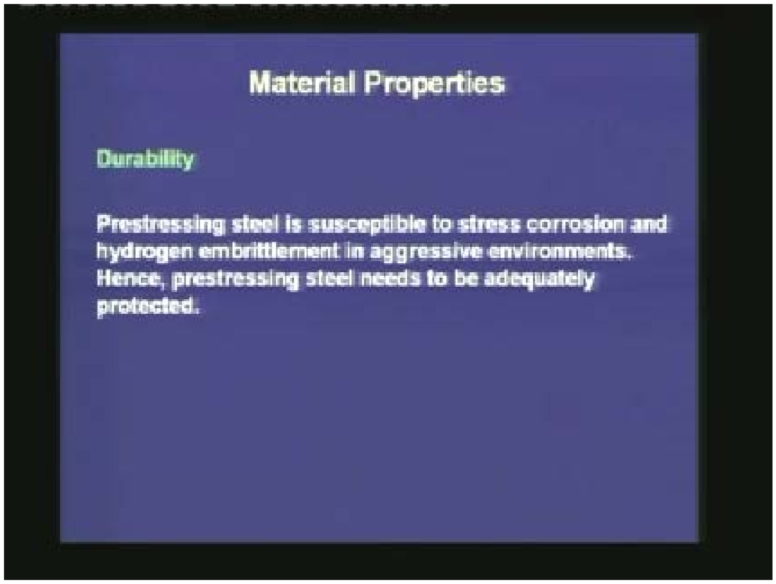

The prestressing steel is susceptible to stress corrosion and hydrogen embrittlement in aggressive environments. Hence, the prestressing steel needs to be adequately protected. Compared to conventional reinforcement, prestressing steel is subjected to much higher stress. This leads to some durability problems, which are termed as stress corrosion and hydrogen embrittlement. These two types of durability problems are more possible in aggressive environments. Hence, we need to check any corrosion problem of the prestressing steel. As I mentioned earlier, the amount of prestressing steel is usually much lower than the amount of conventional reinforcement. Hence, any corrosion of the prestressing steel is more dangerous as compared to the reinforcement steel. The reduction of diameter of a prestressing tendon will lead to more problem, because the proportional reduction in area is higher as compared to the same amount of reduction for reinforcement steel.

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For bonded tendons, the alkaline environment of the grout provides adequate protection. In pre-tensioned members, or in post-tensioned members where the grouting has been done properly, the grout itself provides an alkaline environment around the prestressing steel, which protects the steel from corrosion. But, if we are using unbonded prestressing tendons in post-tensioned members, then we have to be careful about the corrosion problem. Several corrosion protection measures are taken. They can be one of the following.

We can coat the prestressing tendons with epoxy; but this type of tendons has reduced bond. Hence, if we are using epoxy coated steel for pre-tensioned members, then we have to be careful that the stress transfer over a certain length will be reduced. The second protection measure is by wrapping the prestressing steel by some mastic tapes. These mastic tapes are grease impregnated tapes which protect the steel from any corrosion coming from acidic environment. We can use galvanised bars as prestressing tendons, but the cost of galvanised bars is substantially higher than conventional prestressing steel. Else, we can also use some tubes to encase the unbonded tendons within the duct itself.

Thus, when the ducts are not grouted, prestressing steel is susceptible to corrosion. To avoid corrosion, we are either using some epoxy coating, or we are covering it by some mastic wrap, or we are encasing them in tubes, or we may use galvanized bars to check the corrosion.

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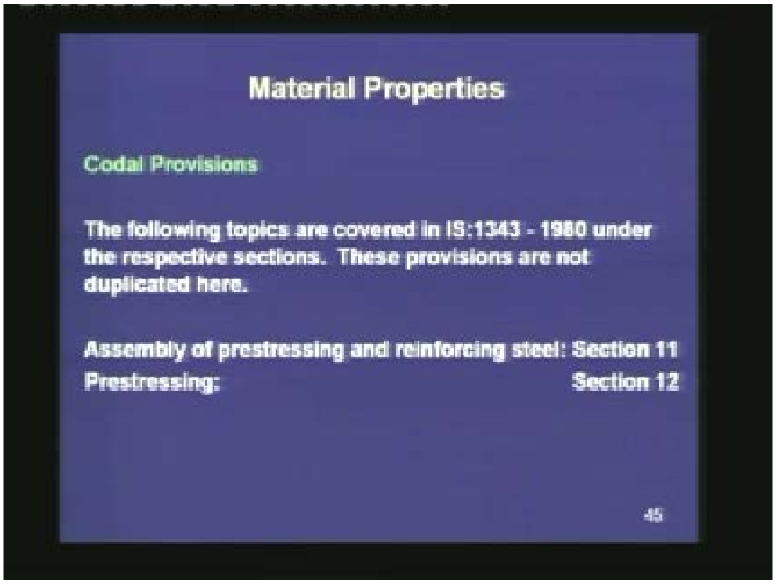

There are several other provisions in IS: 1343 regarding the handling of prestressing steel. These provisions are not being reproduced here because they are self-explanatory, and it is expected that you get familiar with those provisions. The assembly of prestressing and reinforced steel is explained in Section 11. Since the prestressing operation is a difficult operation, it needs skilled personnel to perform this operation and hence, the code specifies some provisions for the prestressing process. The specifications for prestressing are covered under Section 12 of the code.

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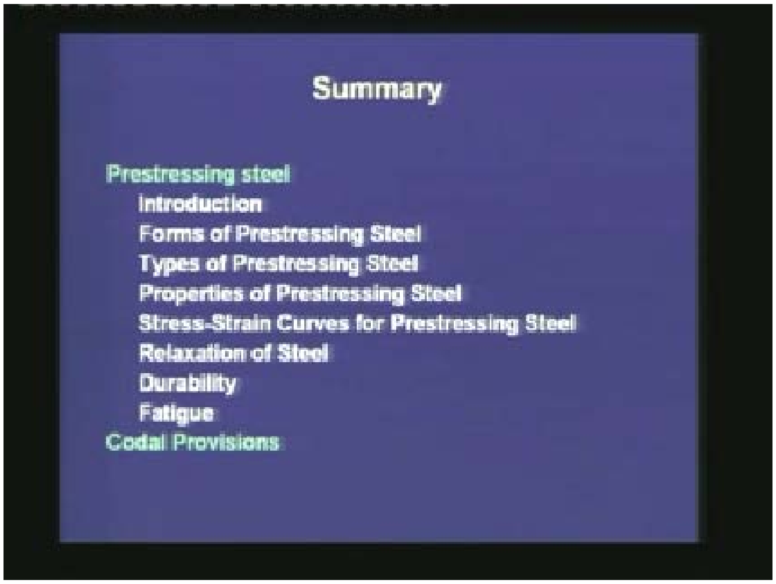

Today, we covered the material properties of prestressing steel. As I said, the prestressed concrete became successful only after the invention of high strength steel. Because, if we use conventional steel, then the loss of prestress will be substantially high as compared to the initial prestress that can be allowed. Hence, the effective prestress will be almost negligible. If we are having high strength steel, then the initial strain and the initial prestress are substantially high. Then, even after the losses, the effective prestress will be substantial. Hence, the prestressed concrete member will be successful to carry the service loads.

First, we discussed the different forms of prestressing steel. The prestressing steel can be in the form of a wire, which is an individual unit. The different wire diameters are specified in the code. The wires can be plain wires or indented wires. The indented wires have some depressions on the surface.

Next, we moved on to the strands. The strands are made up of several wires spun together in a helical form. It can be a two-wire strand, or three-wire strand, or a seven-wire strand. Several strands can be grouped together to form a tendon. The strands are placed in a duct and the duct is grouted in a post-tensioned member to form a tendon. Several tendons can be grouped together to form a prestressing cable. Sometimes the tendons are made up of individual bars, and these individual bars are of much larger diameter. The bars are used because it is easy to anchor them in the concrete.

Next, we moved on to the different types of prestressing steel. We learnt that, if the prestressing steel is untreated or as-drawn, then the stress-strain behavior may not be satisfactory. Hence, some treatment processes are undertaken to enhance the strength or the stress-strain behaviour. In cold working, the strength is increased. In the stress relieving process or in the low relaxation steel, the stress-strain behaviour is enhanced where the curve at the yield region is higher than the curve corresponding to an as-drawn wire.

Next, we moved on to the properties of prestressing steel. The first property that we studied was the strength, because that is the most important property of the prestressing steel. Thus, minimum strength requirements for the different types of prestressing steel are given in the different codes. For the wires, we have found that the characteristic strengths are much higher compared to the characteristic strengths of conventional reinforcing bars. For a single bar prestressing tendon, the tensile strength is lower than that of the wires, but still that is much higher compared to that of conventional reinforcement.

The tensile strength can be obtained by tests performed in testing machines, wherein the coupon specimen is held between two grips and the deformation is measured by extensometers or LVDTs. The tensile strength is calculated from the load at failure. We also learnt about the stiffness of prestressing steel which is measured by the elastic modulus. We have seen that the elastic modulus of strand is lower than that of the individual wires, because the wires in the strand are spun together. The code gives us some guidelines for the elastic modulus, which can be used in absence of test data.

We moved on to the stress-strain curve of prestressing steel. We had found that unlike conventional reinforcement of mild steel, the prestressing steel does not have any yield plateau. The code gives us some characteristic curves, from which we can calculate the stress corresponding to a strain. We learnt the definition of proof stress, i.e. a 0.2 percent proof stress is the stress corresponding to a plastic deformation of 0.002. The code specified minimum proof stress for the different types of steel.

Next, we moved on to an important property of steel, which is the relaxation. The study of relaxation is important because it helps us to calculate the loss of prestress over time. The relaxation of steel depends on the initial prestress. It depends on the type of steel, and also on the temperature. What we have found is that if the initial prestress is substantially high, say beyond 70% of the characteristic strength, then the relaxation loss can be substantial. The code limits the initial prestress to 80% of the characteristic strength. First, for the safety reason and second that the relaxation loss should be limited. The code specifies the maximum amounts of relaxation loss for different types of steel. In our design calculations, if we need the relaxation loss then the code gives us some lump sum values, which are independent of time. If we need more detailed calculations, then we have to look into special literature.

We also looked into the durability and fatigue of the prestressing steel. Both of these can be important under specific situations. Hence, depending on the case, we have to investigate them in detail. In our next class, we shall move on to the calculation of losses for prestressed concrete.

Thank you.