PRESTRESSED CONCRETE STRUCTURES

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Module – 1: Introduction, Prestressing Systems and Material Properties

Lecture – 1: Introduction

Welcome to Prestressed Concrete Structures. In this course, you will be introduced to prestressed concrete and the different applications. In the first module, we shall cover introduction, prestressing systems and material properties.

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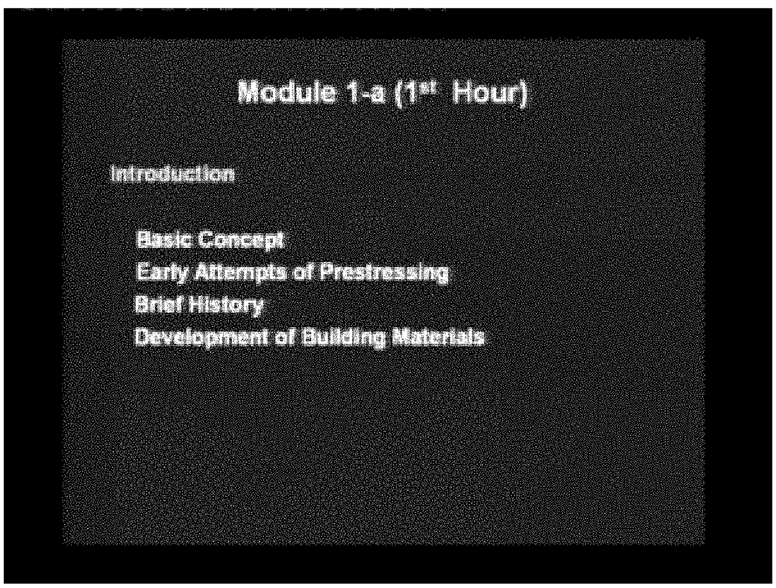

In this module, first we shall learn about the basic concepts of prestressing. From there, we shall move on to early attempts of prestressing. We shall then go through the brief history of the development of prestressed concrete. Finally, we shall look into the development of building materials - that also comes under the brief history in a different perspective.

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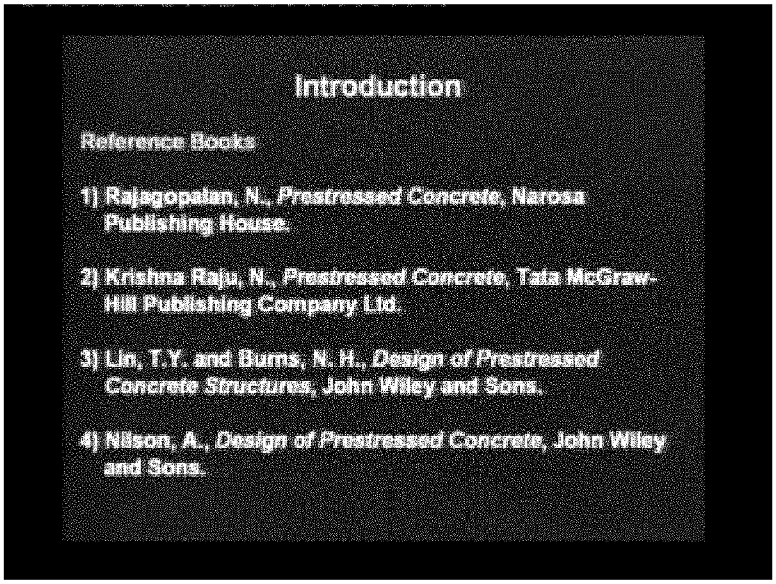

The reference books that we shall follow in this course are: the first one is by Professor N. Rajagopalan; the title of the book is *Prestressed Concrete* and the publisher is Narosa Publishing House. The second book is by Professor N. Krishna Raju and the title is *Prestressed Concrete*; the publisher is Tata McGraw-Hill Publishing Company limited. The third one is an international book; it is written by Professors T. Y. Lin and N. H. Burns and the title of the book is *Design of Prestressed Concrete Structures*; the publisher is John Wiley and Sons. The fourth one is also an international book; it is written by Professor A. Nilson and the title is *Design of Prestressed Concrete*; the publisher is John Wiley and Sons.

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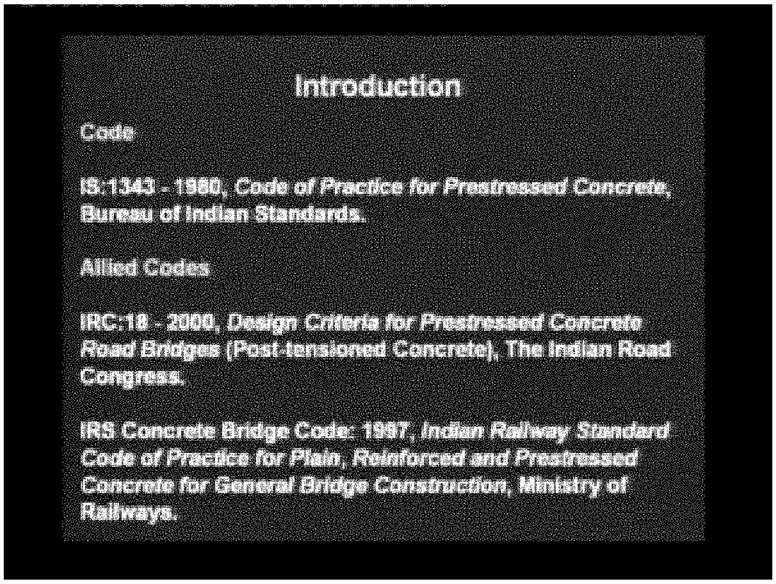

The main code that we shall follow in this course is IS: 1343 – 1980. The title is *Code of Practice for Prestressed Concrete*. It is published by the Bureau of Indian Standards. Remember, that you are expected to know IS: 456 - 2000 which is the Code of Practice for Structural Concrete. Some of the provisions of IS: 456 are also applicable for Prestressed Concrete.

There are some allied codes which are used for prestressed concrete structures in various applications. The first one is IRC: 18 – 2000. It is *Design Criteria for Prestressed Concrete Road Bridges*, specifically for post-tensioned concrete. It is published by The Indian Road Congress. This code is also in conjunction with the other codes published by The Indian Road Congress for bridge design. Another code is IRS Concrete Bridge Code: 1997. The title is *Indian Railway Standard Code of Practice for Plain, Reinforced and Prestressed Concrete for General Bridge Construction*. This is published by the Ministry of Railways. This code is also in conjunction with the other codes for bridge design for the Indian railways.

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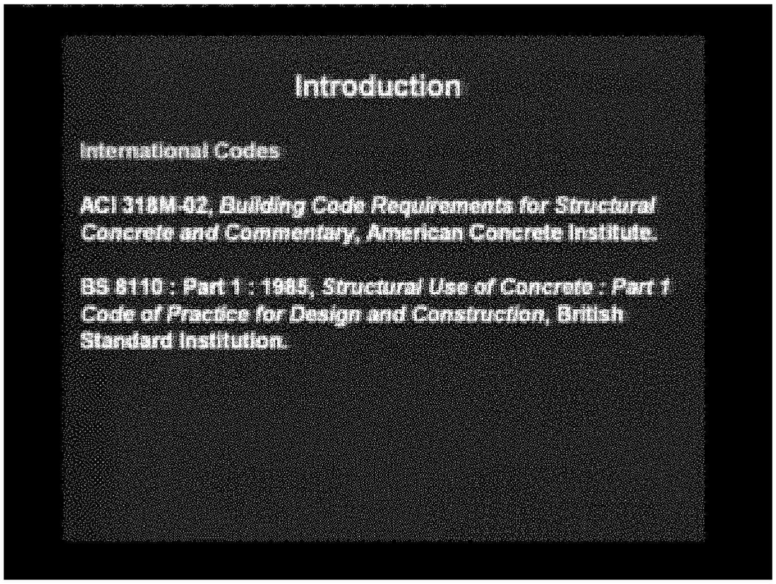

Time-to-time, we may refer to some international codes. The two codes which we shall restrict to ourselves are: the first one is ACI 318M-02, the *Building Code Requirements for Structural Concrete and Commentary*. It is published by the American Concrete Institute. This code covers structural concrete, including prestressed concrete. The second international code is the BS 8110: Part 1: 1985; the title is *Structural Use of Concrete: Part 1 Code of Practice for Design and Construction*. This is published by the British Standard Institution and this code also covers structural concrete.

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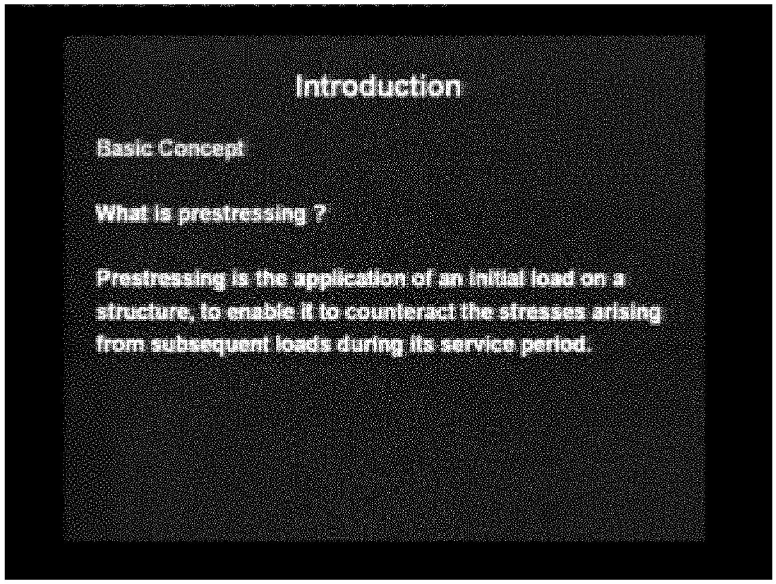

Next, we are moving on to the basic concept of prestressing. The question that arises in our mind is what is meant by prestressing? To define it: Prestressing is the application of an initial load on a structure, to enable it to counteract the stresses arising from subsequent loads during its service period. That means the structure initially is loaded before any external load is applied. Next, when the external load is applied, the previous stresses counteract the stresses due to the external loads.

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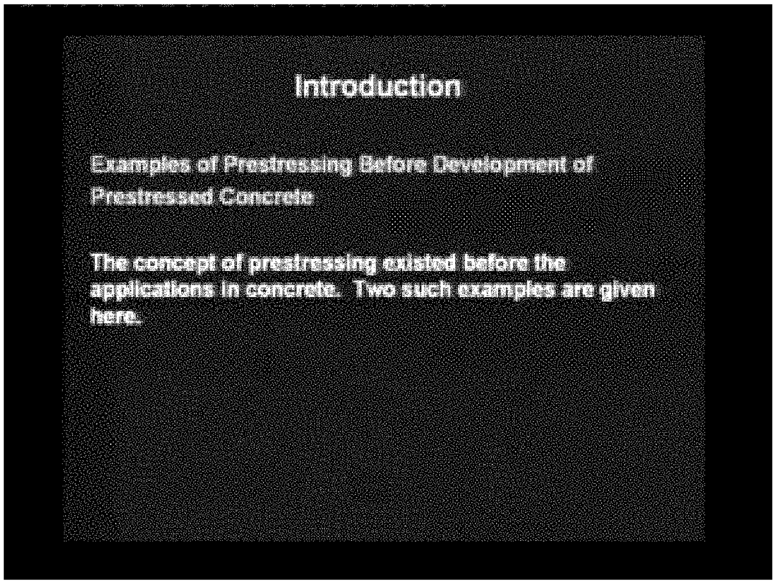

There are examples of prestressing even before the development of prestressed concrete. The concept of prestressing existed before applications in concrete. Two such examples will be explained in this module.

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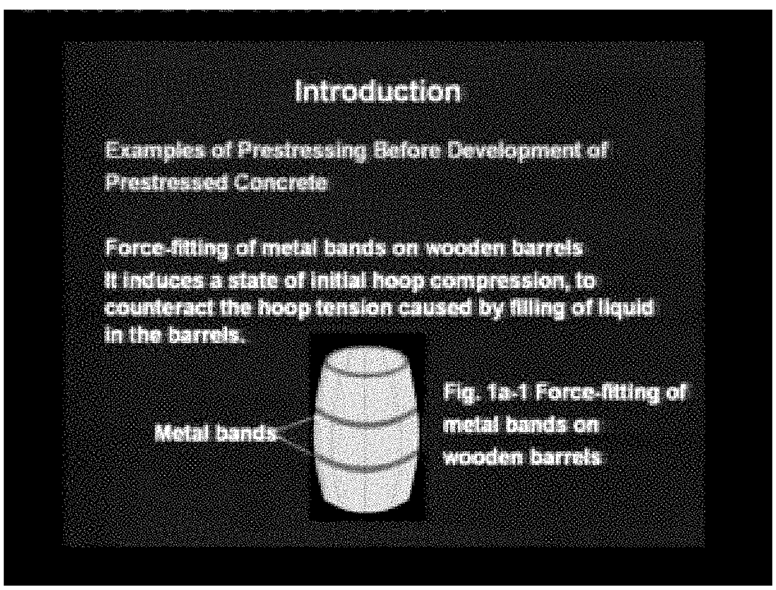

The first one is the force-fitting of metal bands on wooden barrels. These types of barrels were used to transport liquid and oil, and types of grains. Now, what the prestressing does is that, the metal bands create a hoop compression around the barrel. When this barrel is filled with liquid, the liquid tries to push out; it creates a hoop tension. The hoop compression created by the metal band counteracts the hoop tension that is created by the liquid while filling the barrel.

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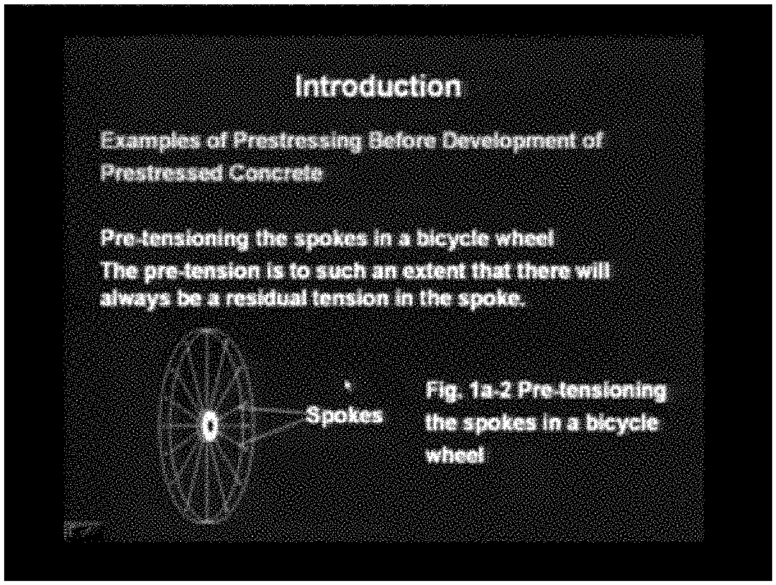

The second example is the pre-tensioning of the spokes in a bicycle wheel. Here you can see that in a bicycle wheel, each one of these spokes is pulled and tightened. This pre-tension is to such an extent that there will always be a residual tension in the spoke. Let me explain these two examples on the black board.

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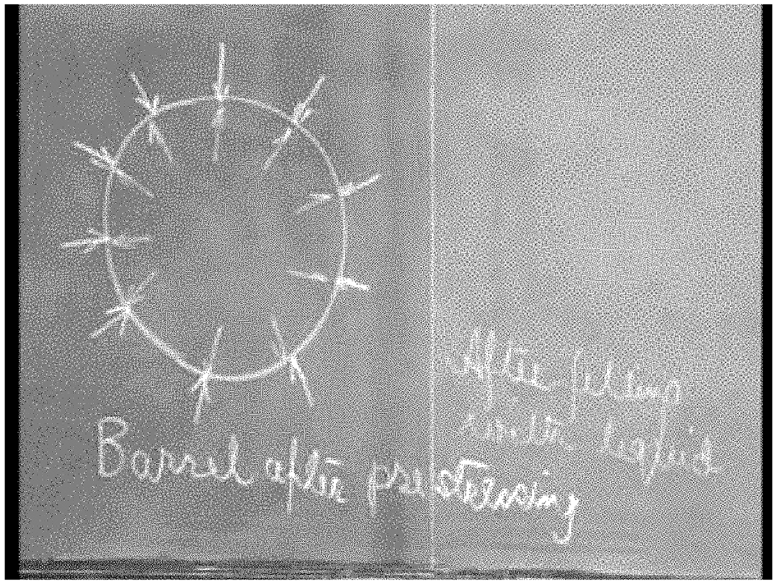

When the barrel is first prestressed, the prestressing causes a hoop compression throughout the barrel. Next, we are filling this barrel with liquid; this liquid creates a hoop tension. The hoop tension that is created by the liquid is counteracted by the hoop compression that is generated due to the prestressing.

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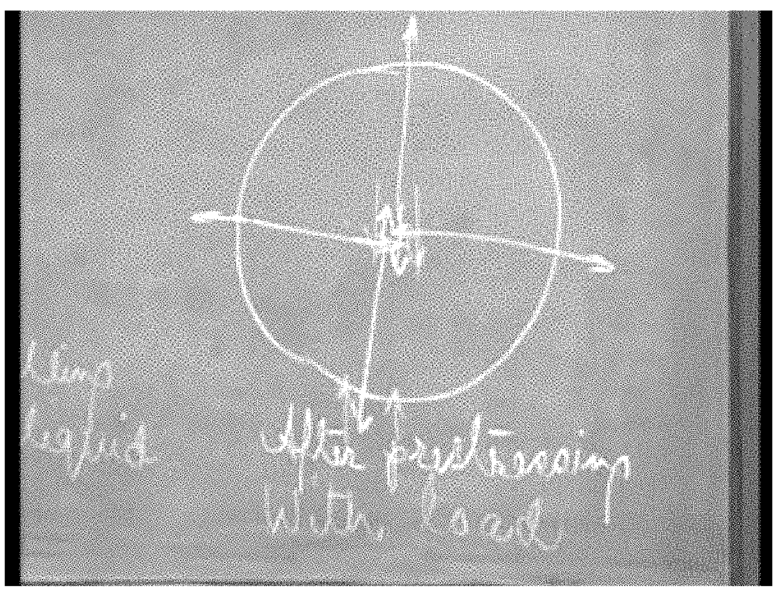

The second example is the cycle spokes. Due to the tensioning of the spokes, each of the spokes is under tension. When the rider rides on the cycle, the weight creates some compression in the spoke; but since there was an original tension and this tension is higher than the compression that generates, in each one of the spokes there is a residual tension. This concept of prestressing is applied in concrete and the definition of prestressed concrete is also similar.

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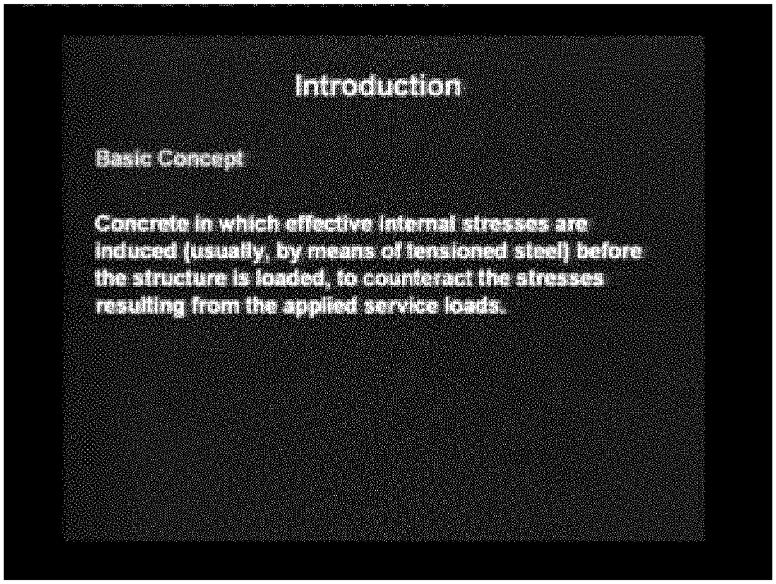

Concrete in which effective internal stresses are induced (usually, by means of tensioned steel) before the structure is loaded, to counteract the stresses resulting from the applied service loads. Here also the concept is similar. That is, after prestressing when the structure is subjected to the external loads, the stresses due to prestressing counteracts the stresses due to the external loads.

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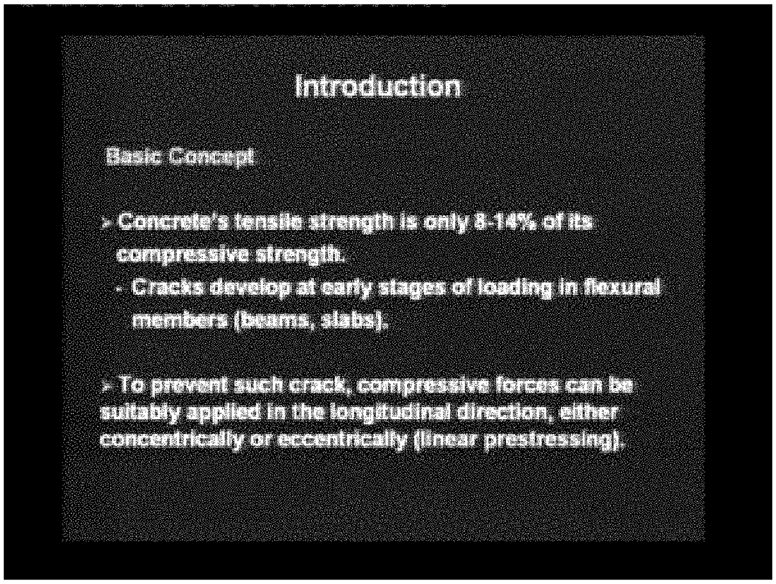

Why do we need prestressing for concrete? The main reason is the concrete's tensile strength is only 8 to 14 percent of its compressive strength; this is the weak point of concrete. For flexural members, cracks develop at early stages of loading. Examples of flexural members are beams and slabs. If we gradually load the structure, we shall observe that cracks are being generated in the flexural members.

To prevent such cracks, compressive forces can be suitably applied in the longitudinal direction, either concentrically or eccentrically. Now, what this prestressing does is, it counteracts these tensile stresses and reduces the chances of formation of these cracks. The prestressing that is applied in a flexural member is called linear prestressing, because the axis of the prestressing is same as the axis of the flexural member.

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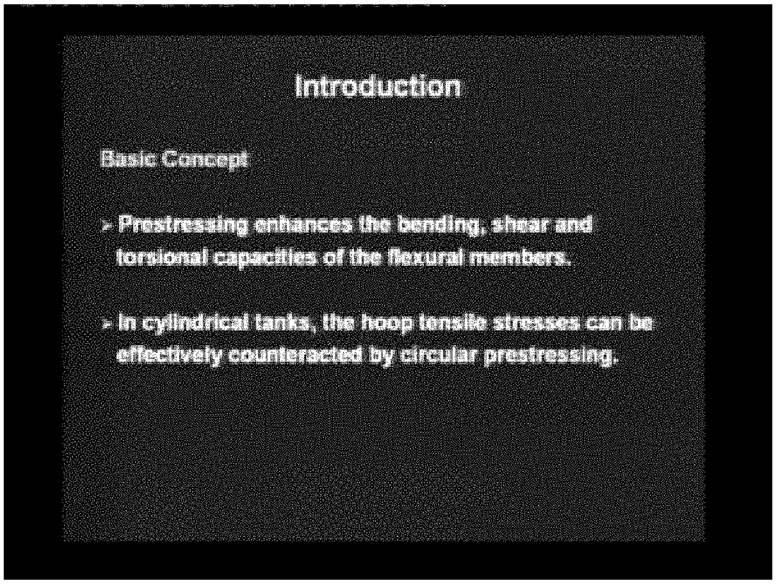

The prestressing enhances not only the bending capacity, but it also enhances the shear and the torsional capacities of the flexural members. In the subsequent modules of this course, we shall see that both the shear capacity and the torsional capacity are enhanced due to the pre-compression that is introduced by the prestressing.

There are other examples of prestressed concrete. In cylindrical tanks, the hoop tensile stress can be effectively counteracted by circular prestressing. This concept is similar to the barrels that we have seen before. Before the tank is loaded, the prestressing creates a compression in the tank and then when the tank is filled up with water, the water tries to expand the tank. The compression due to prestressing counteracts the expansion due to the hydrostatic force, and thus the chances of cracking get reduced.

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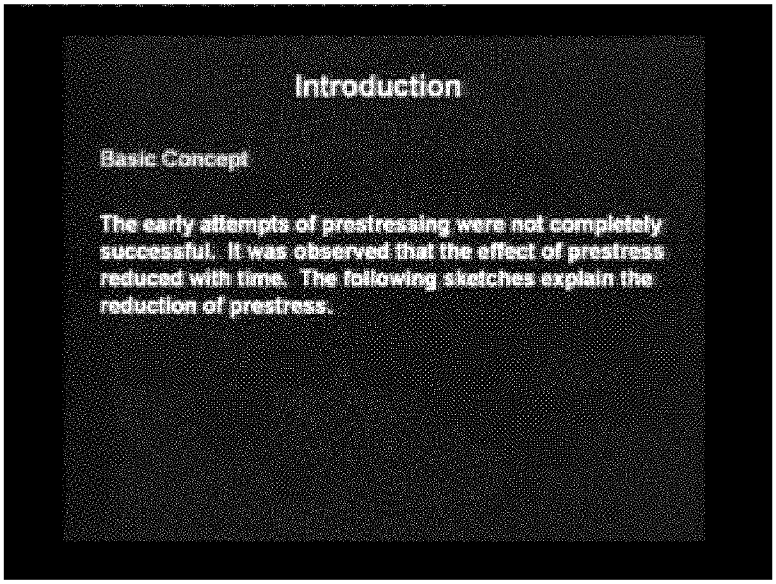

Although it appears to be quite mundane but the early attempts of prestressing were not completely successful. It was observed that the effect of prestressing reduced with time. The following sketches will explain why this prestressing force has to reduce.

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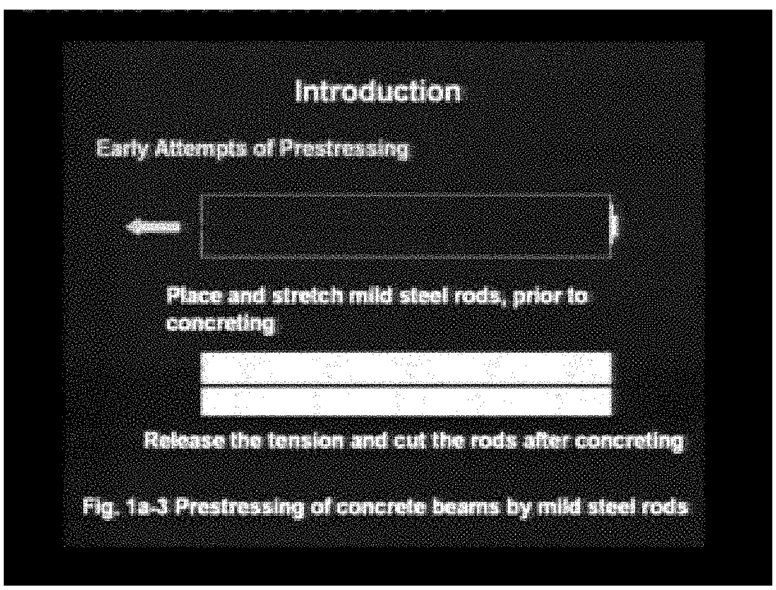

In the earlier days, the way the prestressing was done was that, initially a rod used to be pulled with an anchor at one end and then in the mould, the concrete used to be placed. Once the concrete has hardened, the tension used to be released in the tendon and then this tendon used to be cut. This is the early form of prestressed concrete by the mild steel rods.

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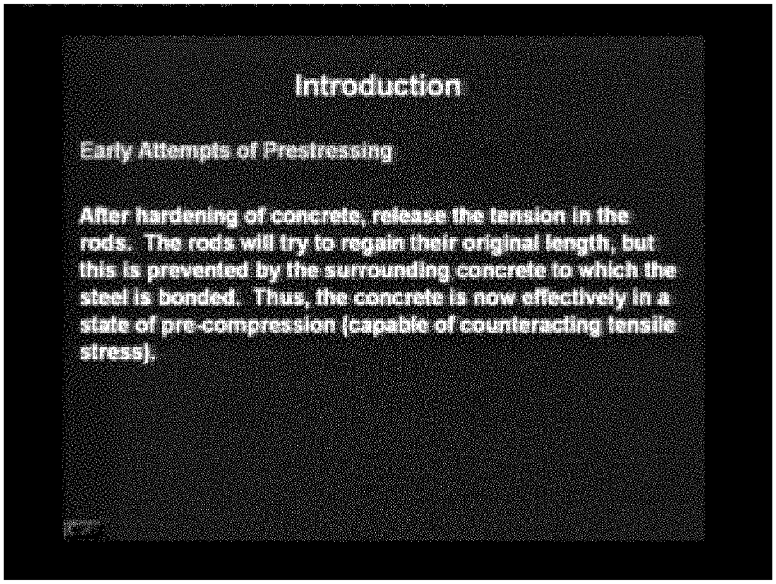

What happens is after the hardening of concrete and when the tension is released from the rods, the rods will try to regain their original length, but this is prevented by the surrounding concrete to which the steel is bonded. Thus, the concrete gets effectively under a state of pre-compression which is capable of counteracting the tensile stresses.

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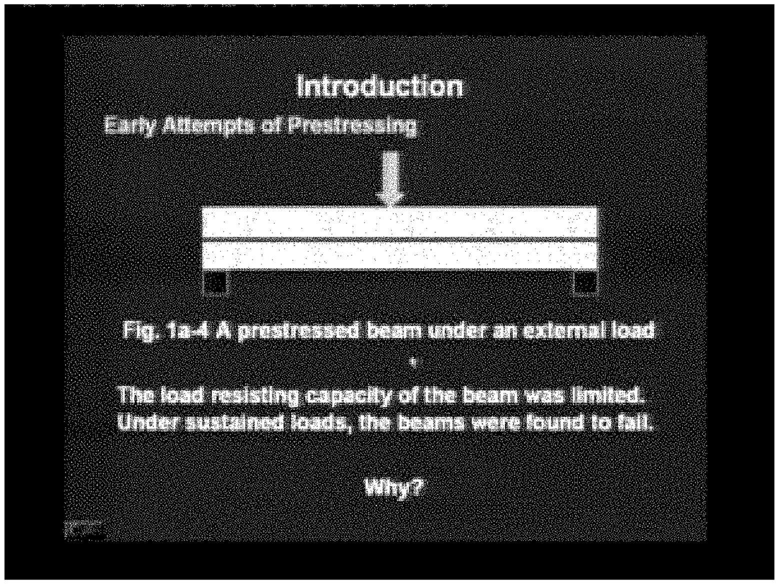

It was observed that, this type of simple beams which were prestressed initially may have a good flexural capacity. But with time, it was found that the flexural resisting capacity got limited and if the load is kept sustained, it was observed that sometimes the beams tend to fail. The question that comes to our mind is why does it happen so? Initially it is found to be effective, but with time it is found that the effect of prestressing is getting reduced. Why is this so?

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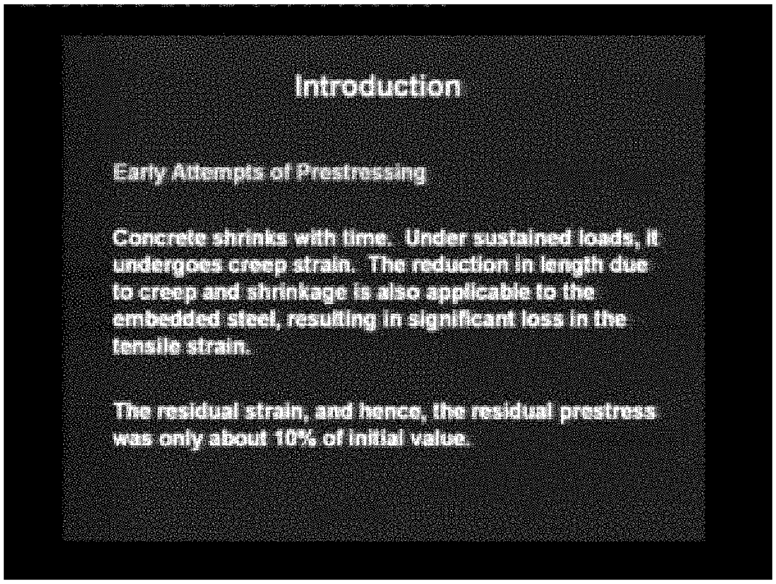

One very important phenomenon of concrete is that concrete during hydration shrinks with time. That means, it tends to reduce in volume and there is a reduction in length. Moreover, under sustained load, it undergoes a creep strain. Now, what is meant by creep? Creep is the strain under a sustained load. Since there is a pre-compression in the concrete, this concrete over the time tends to get reduced and this is called the effect of creep. The reduction in length due to creep and shrinkage is also applicable to the embedded steel. That means when the concrete is shrinking, along with that the embedded steel is also shrinking. When the length of the embedded steel reduces, it results in significant loss of the tensile strain; that is, originally it was under a substantial tensile strain, but with time the length is reducing and the tensile strain in the steel is getting reduced. After several years, the residual strain and hence, the residual prestress can be as low as 10 percent of the initial value or even lower than that.

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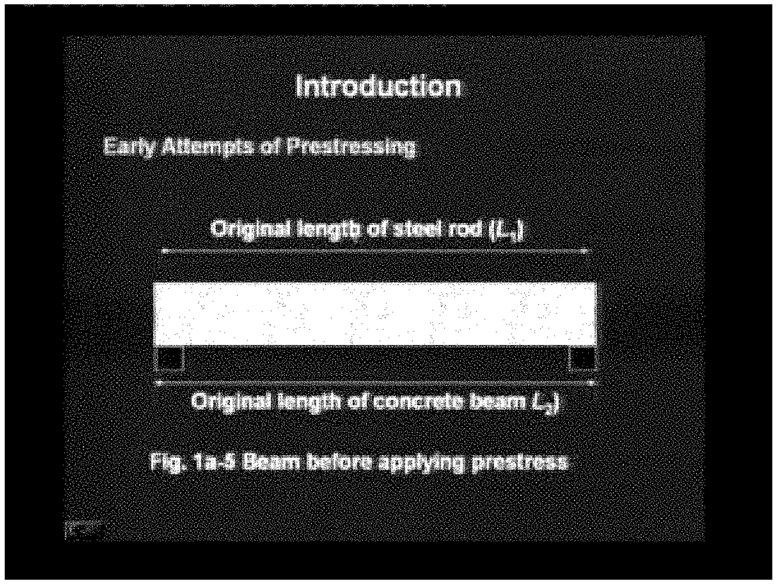

Let us try to understand this by a simple sketch. In this beam, the original length of the steel rod was L_1. It has been tensioned to a length which is equal to the original length of the concrete beam, that is L_2. This is the state of the beam before applying prestress.

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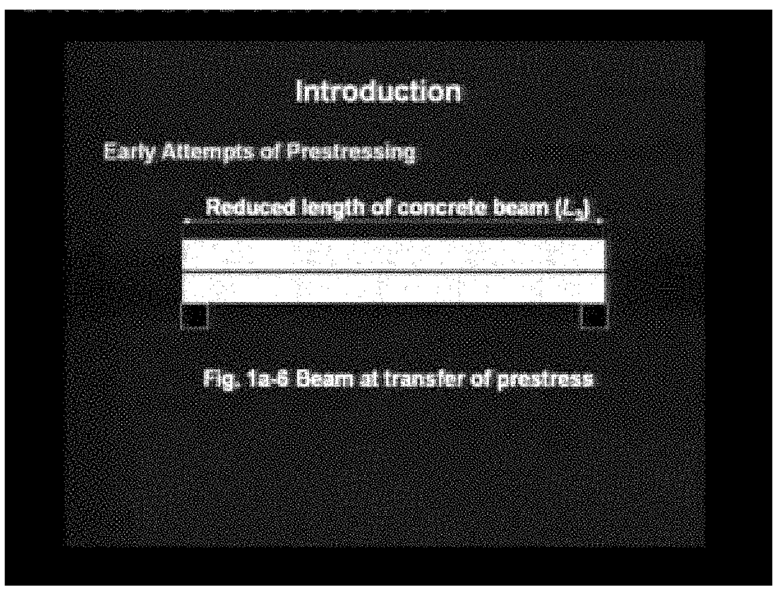

When the rod is cut, since the steel is applying compression in the concrete, the concrete will tend to compress; this is called the phenomenon of elastic shortening. After the elastic shortening, the length of the beam reduces to L_3 which is lower than the initial length of L_2; that means, at transfer of the prestress, the beam gets reduced due to elastic shortening.

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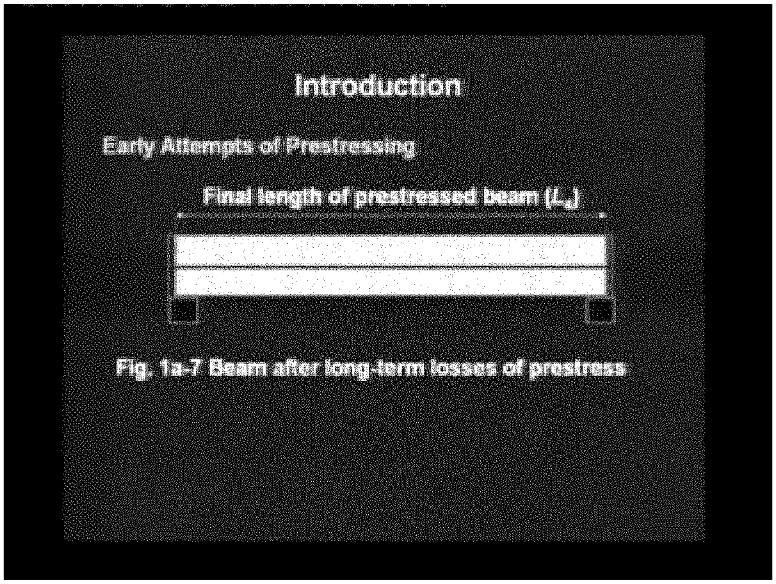

Then over a period, say a few years, there will be creep and shrinkage in the concrete and that will lead to further reduction in the length of the beam. Let this length be L_4; that means the length L_4 is after the long-term losses of prestress. The long-term losses are different from the short-term losses. The elastic shortening is the short-term loss which is happening right at the transfer of prestress, but the long-term losses is over a substantial period, over a few years, after the prestressing operation has been done.

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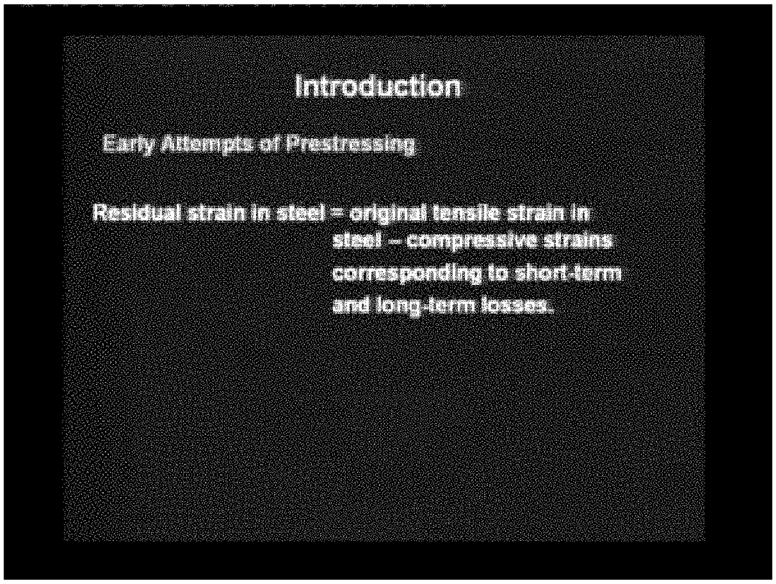

We have to calculate what the residual strain in the steel is, because it is the residual strain which will have the residual prestress. The residual strain can be calculated as the original tensile strain in steel minus the compressive strains corresponding to short-term and long-term losses. In this expression, we shall consider the tensile strain to be positive and the compressive strains to be negative; that is why we have placed a subtraction for the compressive strains.

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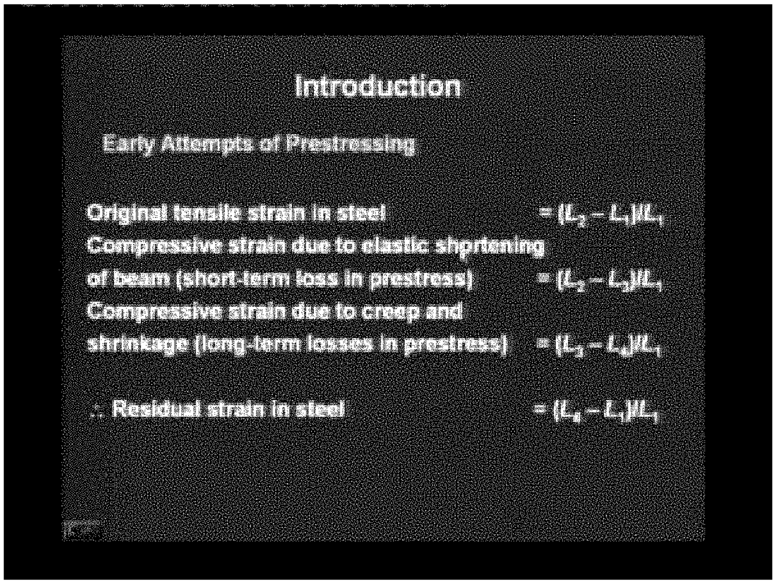

For the example that we have shown before, the original tensile deformation in the steel was L_2 minus L_1, where L_2 was the original length of the beam and L_1 was the original length of the steel rod. That means, when the rod was tensioned, the strain in the steel was given as L_2 minus L_1 divided by L_1.

Then, there was the elastic shortening which led to some compressive strain. The short-term loss in prestress can be calculated by the strain which is L_2 - that is the original length of the beam, minus L_3, which is the length of the beam after the elastic shortening divided by L_1, which is the original length of the steel rod. This expression L_2 minus L_3 divided by L_1 is the loss in the strain due to the elastic shortening of the beam. This can be called as the short-term loss in the prestress.

Over the time, there is a compressive strain in the beam due to creep and shrinkage. This strain can be calculated by the simple expression: L_3 minus L_4 divided by L_1. L_3 is the length after the short-term losses, that means the length after the transfer of prestress, and L_4 is the length after the long-term losses. The expression of L_3 minus L_4 divided by L_1 gives the compressive strain in the concrete and the loss in prestress due to creep and shrinkage. This loss can be termed as the long-term losses in prestress. If we subtract the second and the third term from the first term, then we arrive at the fourth expression, which is the residual strain in the steel. L_4 is the final length of the steel rod and L_1 was the original length. L_4 minus L_1 divided by the original length gives the final residual strain in the prestressing steel.

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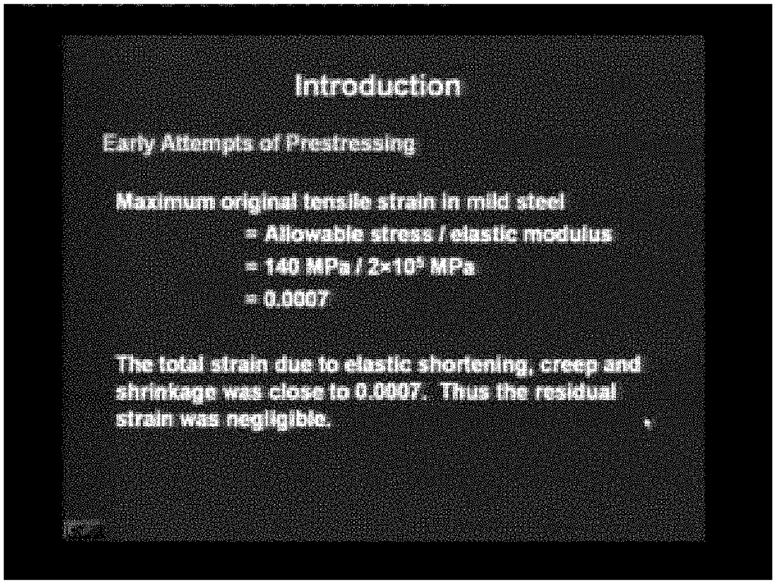

In the earlier days, when ordinary mild steel was used for prestressing, there was a limit of the tensile strain that could be applied to the steel. This limit was based on the allowable tensile stress. The maximum original tensile strain in mild steel can be calculated as the allowable stress divided by the elastic modulus of steel. The allowable stress can be around 140 MPa (Mega Pascal) and the elastic modulus is around 2×10^5 MPa. When we divide the allowable stress by the elastic modulus, the maximum original tensile strain is equal to 0.0007. If we observe, the total strain due to the strains of elastic shortening, creep and shrinkage was almost of the same value; it was almost equal to 0.0007. It means the loss in prestress gets almost equal to the original prestress, because the values of the corresponding two strains are close. Hence, the residual strain was negligible and finally, the effective prestress almost becomes nullified over a period of years.

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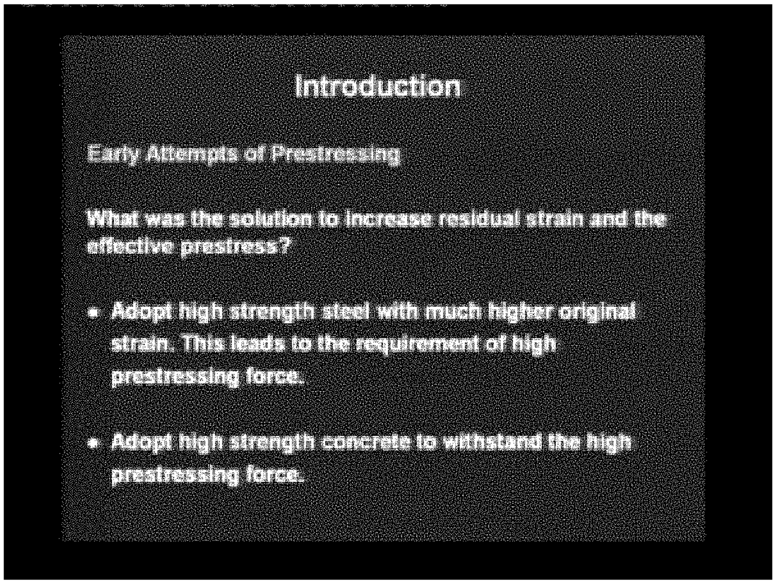

This problem had led to several research on the type of steel, the type of concrete and over the decades, this problem was resolved with the development of the material properties of both steel and the concrete. The question was: what was the solution to increase the residual strain and hence, the effective prestress? The first solution was to adopt high strength steel with much higher original strain. This leads to the requirement of high prestressing force. Compared to mild steel, if we use steel which has much higher tensile strength, then the allowable stress will also be much higher. The initial tensile force will also be much higher, if we are using a high strength tensile steel. With the development of the metallurgical process, high strength tensile steel was developed and that was applied in the prestressed concrete. But if we are applying high strength tensile steel, then we also need to have high prestressing force. We need to have adequate jacks to apply that high prestressing force.

The second development which helped the growth of prestressed concrete is the development of high strength concrete. A concrete of 15 to 20 MPa characteristic strength is not adequate for prestressed concrete. At least, it is recommended to have a concrete strength of 30 MPa or higher, so as to withstand the high prestressing force. As I said that with the adoption of high strength steel, the prestressing force became large and for that, the concrete had to be strong to withstand this high prestressing force. With this, the prestress concrete became successful in the different applications of structural elements.

Let me now move on to a brief history of the development of prestressed concrete.

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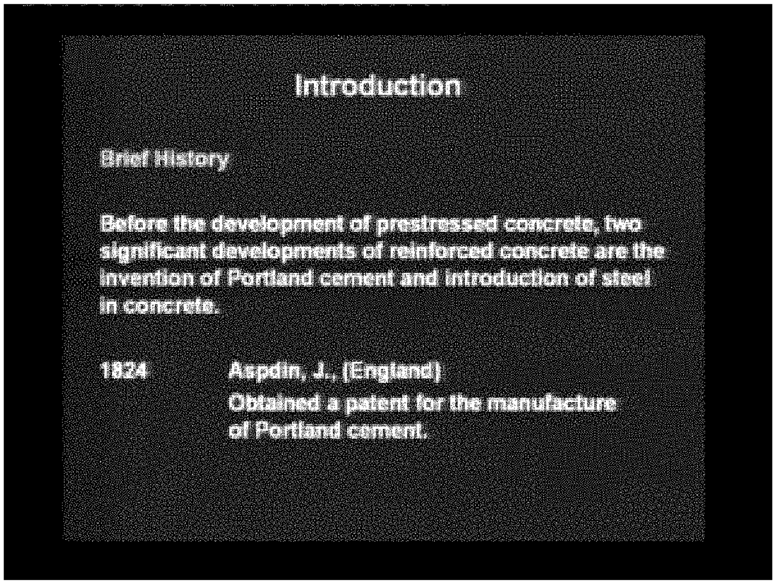

Before I start the development of prestressed concrete, let us know two significant developments of reinforced concrete itself. The two major breakthroughs in the development of reinforced concrete are: first, the invention of Portland cement and second is the introduction of steel in concrete; that means, the whole concept of reinforcing the concrete by steel was a very innovative concept at that time.

In 1824, Aspdin in England obtained a patent for the manufacture of Portland cement. In the earlier days, concrete was made by lime and other types of natural cementing materials. We can say with the development of Portland cement, an industrial product was developed which can give quite a lot of strength to the concrete. The development of Portland cement itself is a major breakthrough in the development of reinforced concrete.

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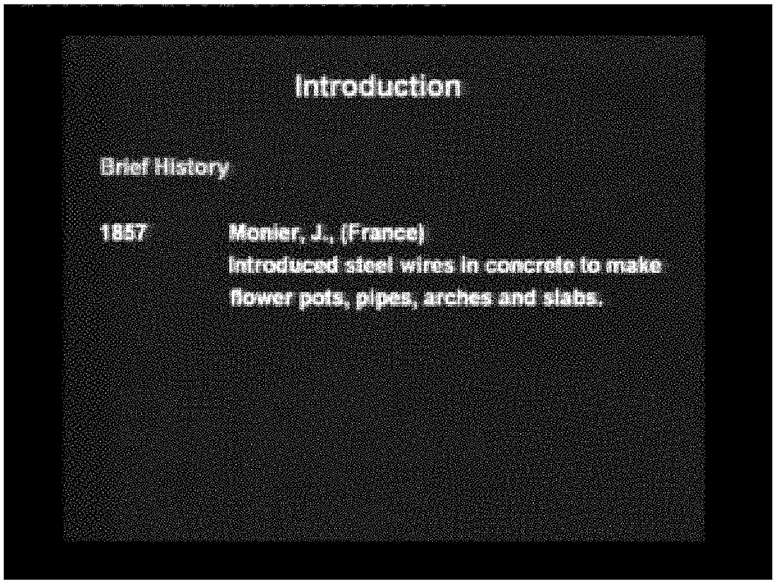

In 1857, Monier in France introduced steel wires in concrete to make flowerpots, pipes, arches and slabs. Here we can see that the concept of reinforced concrete has started to evolve. What Monier did was to place some steel wires to hold the cracked concrete and like that the application of reinforced concrete started to develop. Although, these applications of flowerpots, pipes and arches may appear to be mundane at present, during that time, it was quite a significant achievement in the development of the concept of reinforcing the concrete.

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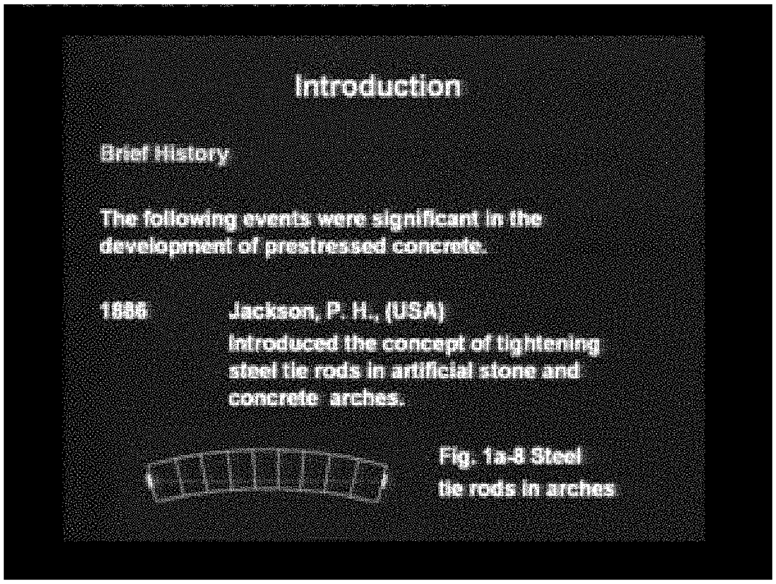

We are moving on to the major events of the development of prestressed concrete. In 1886, Jackson of USA introduced the concept of tightening steel rods in artificial stone and concrete arches. The arch form was a very popular structural form used in different types of structures - in buildings and in bridges. What Jackson did was that he introduced a steel rod within the arch, and increased its capacity by tightening the steel rod. The arch itself is under compression, but if we introduce a steel rod and tighten it, the compression is further increased and hence, the capacity of arch also increased.

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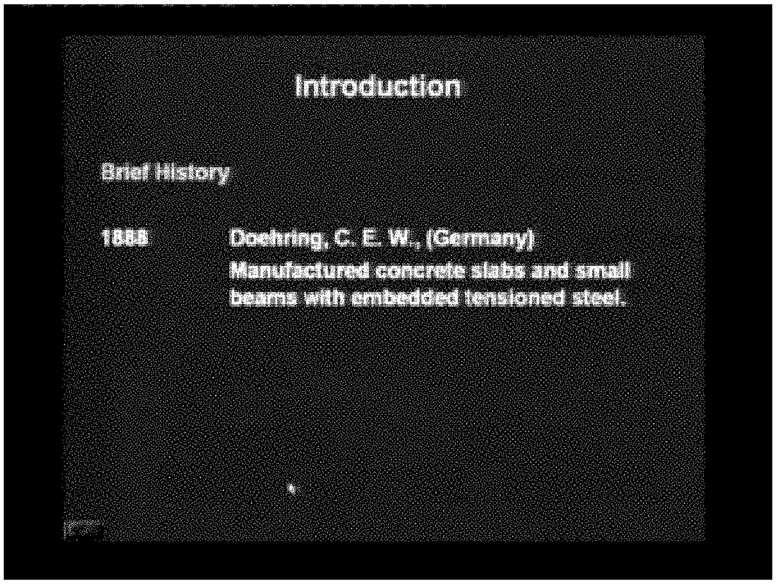

In 1888, Doehring of Germany manufactured concrete slabs and small beams with embedded tensioned steel. We can see that in reinforced concrete, the steel was just introduced, but now the inventors were tightening the steel rods in order to increase the capacity.

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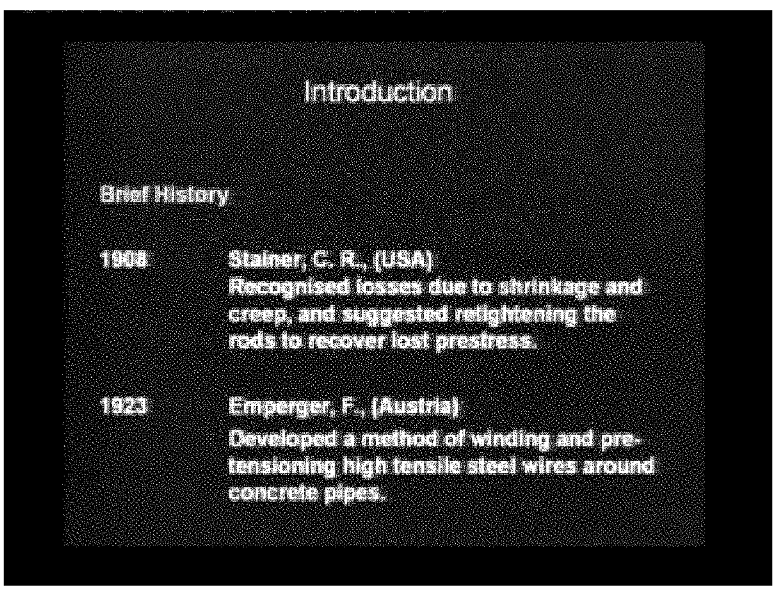

In 1908, Stainer of USA recognized the losses due to shrinkage and creep. This was a major breakthrough to understand the problem of reduction of the effective prestress with time. The phenomenon of creep and shrinkage was identified, and Stainer suggested retightening the rods to recover the loss of prestress after a certain time.

In 1923, Emperger of Austria developed a method of winding and pre-tensioning high tensile steel wires around concrete pipes. During the industrial development of the 20th century, concrete became a very popular construction material. Different types of innovative techniques were being developed to increase their capacity. The winding of steel wires around concrete pipes and tensioning the steel wires to check their cracking was actually an instance of prestressing the concrete pipes with the tensioned steel wires.

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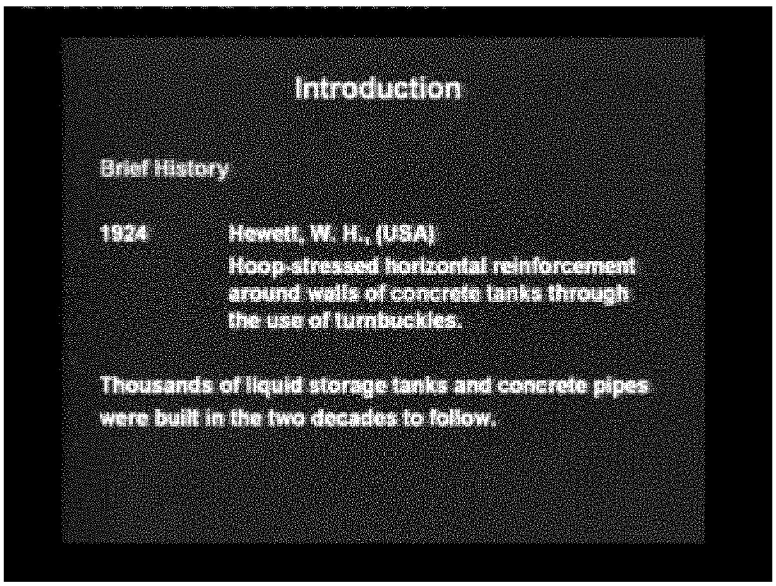

In 1924, Hewett of USA hoop-stressed horizontal reinforcement around walls of concrete tanks through the use of turnbuckles. We mentioned at the beginning, the concept of prestressing a barrel. Here we can see that the concrete tanks were being developed with prestressing them by some device called turnbuckles. These turnbuckles are a device to tighten the reinforcement around the concrete tanks. Over the period, thousands of liquid storage tanks and concrete pipes were built in the decades to follow. As the industrial production of concrete is increasing, we observe that the application of prestressing is also increasing with the time.

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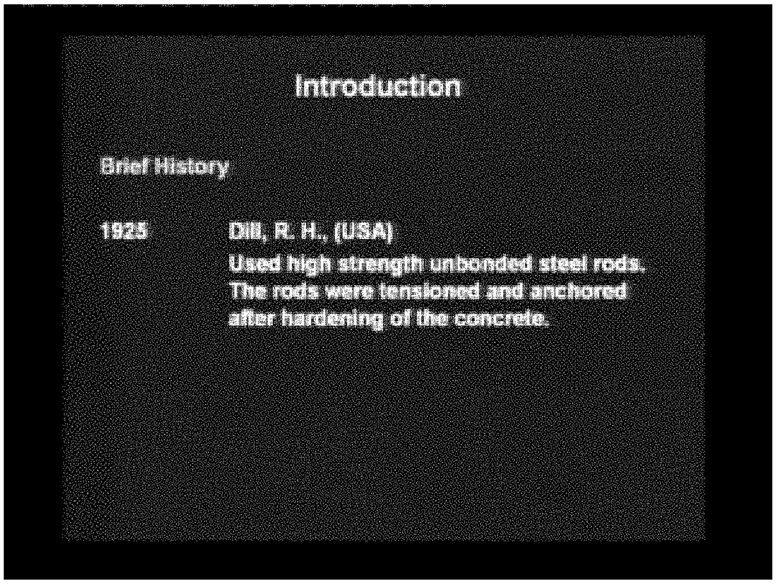

In 1925, Dill of USA used high strength unbonded steel rods. The concept of unbonded means, that there was no bond or, there was no physical stress transfer between the steel and the concrete at the interface. The transfer of stress was only at the ends. The reason of using an unbonded steel rod was that the rods could be tensioned and anchored after hardening of the concrete, and they could be again tightened so as to counteract the drop in the prestress.

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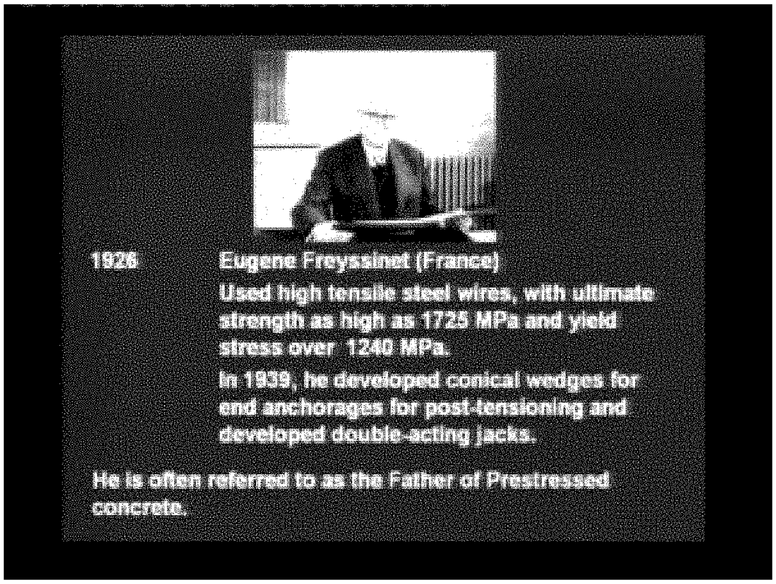

In 1926, Eugene Freyssinet of France used high tensile steel wires. We can see that he used steel which had an ultimate strength as high as 1725 MPa. This is a much higher value than the reinforcement that is used in conventional concrete. The yield stress of this type of high tensile strength rods was more than 1200 MPa. From your knowledge of reinforced concrete, you can understand that this is substantially high yield stress, and with this type of high strength tensile steel, the development of prestressed concrete was possible.

In 1939, he developed conical wedges for end anchorages of post-tensioning and developed double-acting jacks. The prestressed concrete is actually an industrial product. It needs more equipments and devices to apply the prestressing force, and to transfer the prestressing force from the steel to the concrete. Freyssinet developed and patented devices like the jacks and the anchorages, which are used in applying prestressing on the concrete members. Freyssinet is often referred to as the Father of prestressed concrete.

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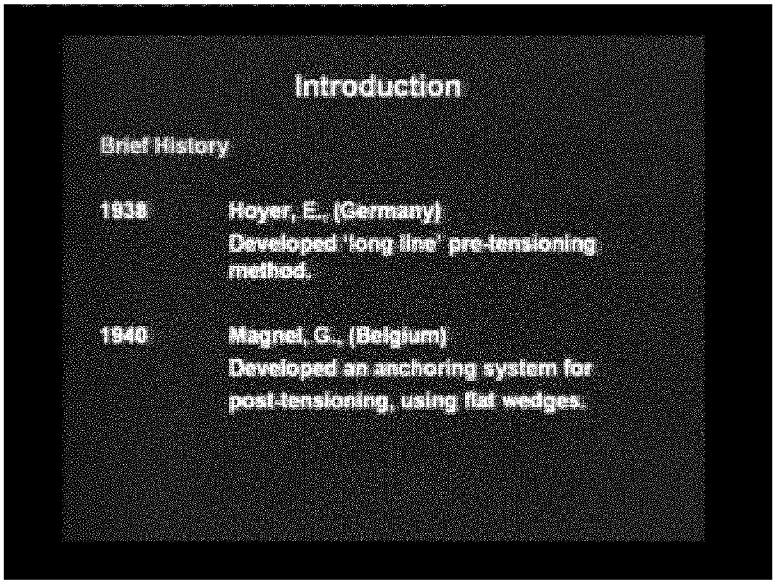

In 1938, Hoyer of Germany developed the long-line pre-tensioning method. This method can be compared with the assembly line method in the manufacture of cars. That is, under one industrial shed and in just one line, several prestressed members were being produced. This technique was used to produce pre-tensioned transmission poles for electric lines.

In 1940, Magnel of Belgium developed an anchoring system for post-tensioning using flat wedges. As I mentioned before that the prestressed concrete needs more equipments and devices. The development of the anchoring system which helps in transferring the prestress from the steel to the concrete was a major breakthrough in the development of prestressed concrete, because it is the successful behaviour of the anchors which can lead to the transfer of the prestress to the concrete.

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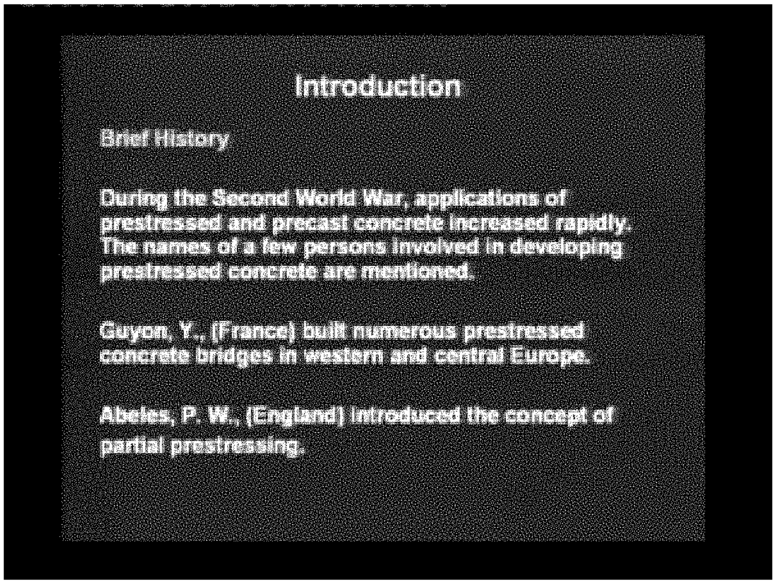

During the Second World War, the applications of prestressed and precast concrete increased rapidly. What happened is that with mass production of concrete, the concrete became an industrial product. The concept of precasting concrete, that means casting the concrete not at the place where it will exist, but at a different place under a much better control of quality. Precast concrete became popular, and along with that the prestressing of these precast members also became popular.

In this lecture, the names of the few persons who were involved in developing prestressed concrete will be mentioned. Guyon of France built numerous prestressed concrete bridges in western and central Europe. The application of prestressed concrete in bridge decks is a wonderful application. The bridge decks became slender, their spans increased and the aesthetics of the bridge profile became better. In Europe, the application of prestressing the concrete bridges became popular during the 1940s and 1950s.

Abeles in England introduced the concept of partial prestressing. Originally, the idea was that the prestressing force should be such that there will not be any tension in the prestressed concrete member. But it was found that with this objective, the amount of prestressing force is also substantially high; due to that, the creep effect was also large. Sometimes, the camber, that means the upward deflection of the prestressed members, became too high and the sections were not turning out to be economical. That is why a new concept was introduced, where some tension was allowed in the concrete which is not detrimental to the concrete. When some tension is allowed in the concrete, this is called partial prestressing. We see a gradual move from the more conservative concept of fully prestressing the concrete member to partially prestressing the member such that when the member is under severe loads, there are chances of even cracking; but those cracks will not be detrimental in the long run because under service loads, those cracks may not open up at all.

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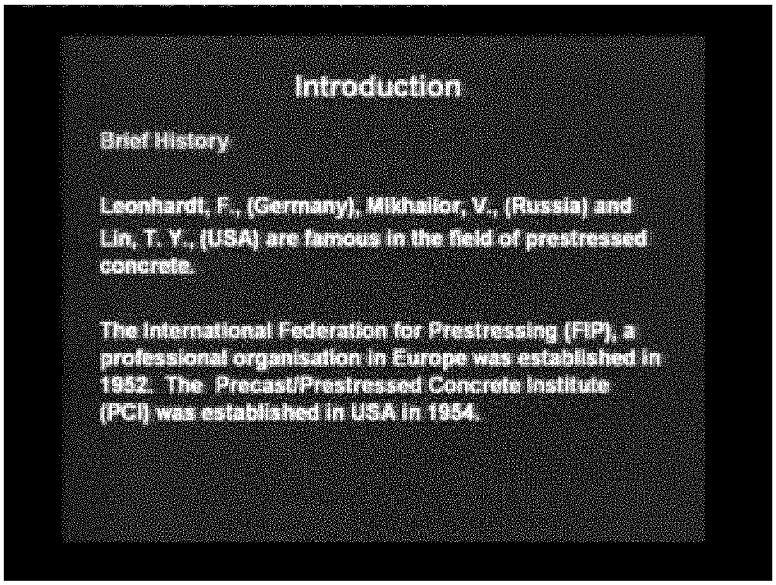

Leonhardt in Germany, Mikhailor in Russia and Lin in USA are very famous in the field of prestressed concrete. Each one of them contributed to significant developments of the application of prestressed concrete, whether it is the bridge decks, or the anchoring systems, or the shell construction, or different types of the applications of prestressed concrete.

We find that the professionals who were involved in the prestressed concrete, they formed the professional organisations. These professional organisations became a forum for the exchange of ideas and knowledge.

The International Federation for Prestressing, in short FIP, is a professional organization in Europe which was established in 1952. The Precast/Prestressed Concrete Institute, in short PCI, was established in USA in 1954. Both these organizations are very well known in the development and transfer of knowledge of prestressed concrete.

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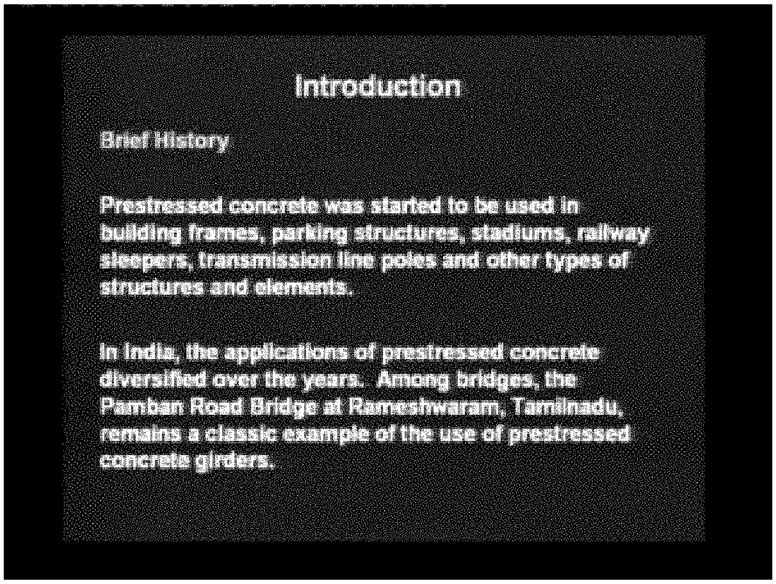

Prestressed concrete was being applied in various types of structures like building frames, parking structures, stadiums, railway sleepers, transmission line poles, water tanks and several other types of elements. In India also, the application of prestressed concrete diversified over the years. One of the classic examples is the Pamban Road Bridge at Rameshwaram, Tamilnadu, which is a classic example of the use of prestressed concrete girders.

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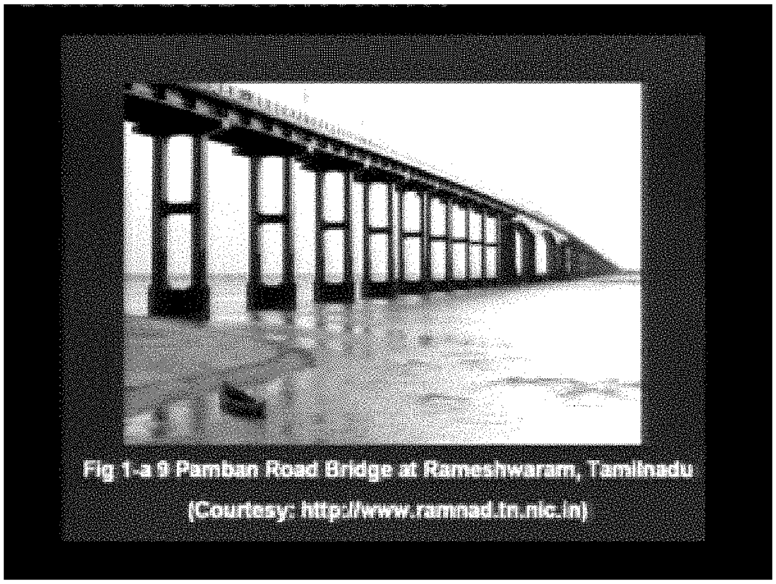

This is the picture of the Pamban bridge, and here you can see that in the central span, the deck profile is so nice and this was possible because of the prestressing. The span was long and also you can see that there is a substantial navigational clearance, because of the reduced depth of the prestressed beam. As I mentioned before, that a bridge is a wonderful application of prestressed concrete. Later on, time-to-time, we shall mention some of these applications and we shall show some of the photographs of these applications of prestressed concrete. Even in India, there were major steps to change the railway sleepers from the original timber sleepers to prestressed concrete sleepers. Water tanks, transmission line poles and other types of applications have become very popular in India.

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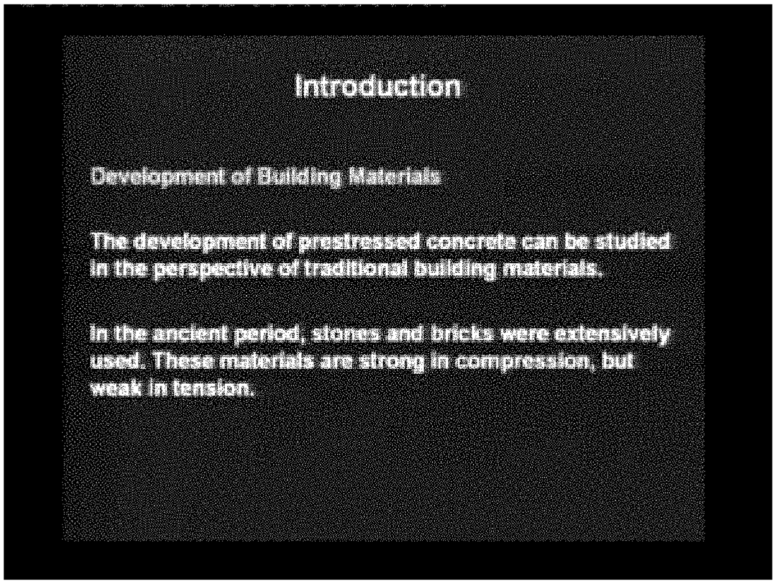

Next, let me explain the history of the prestressed concrete in terms of the development of the building materials. In the ancient period, the buildings were mostly made of stone and bricks. These materials were very strong in compression. Depending on the type of stone and depending on the quality of bricks, massive structures have been made by these two materials because of their inherent capacity to carry compression. But the disadvantage of these two materials was that they were weak in tension. Their reduced capacity in tension, led to the limited range of spans that we see in the ancient structures.

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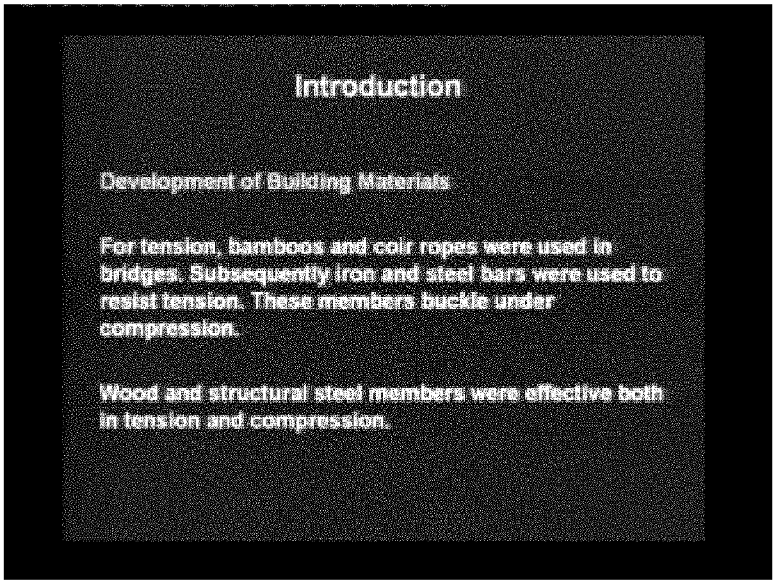

If tension was needed, then bamboos and coir ropes were used. For example, in the suspension bridges of the earlier days, coir ropes were used as suspenders to hang the deck from the main suspension cable. Subsequently, iron and steel bars were used to resist tension. But there is a problem with these members also. These members cannot carry high compression because they tend to buckle under compression. In one group, we have stones and bricks which are strong in compression. In the other group, we have bamboo, coir, steel and iron bars which are strong in tension. If the steel was moulded into a form of the structural member like an I-section, then that type of structural steel and wood were used both in tension and in compression. The wood that we see in the older buildings and the I-sections, were only the members that were able to carry both tension and compression under flexure.

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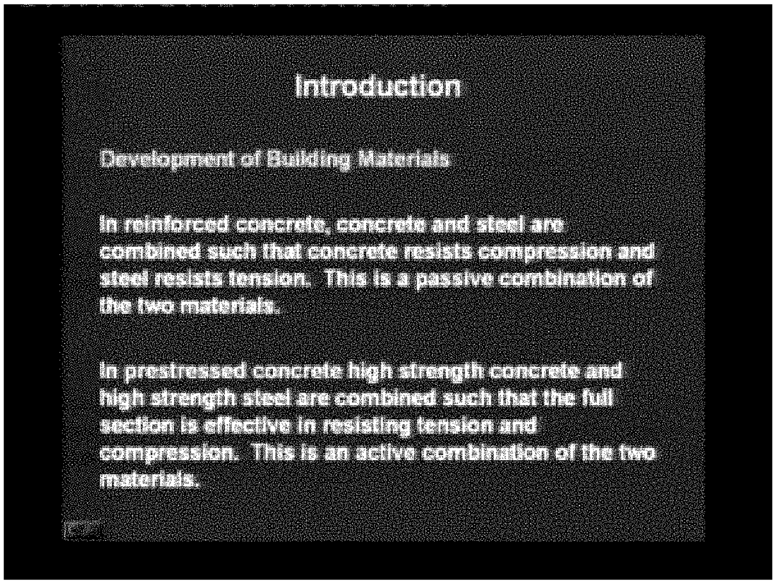

In reinforced concrete, concrete which is strong in compression and steel which is strong in tension, are judiciously placed to counteract the stresses that come due to the external loads. The concrete resists compression and the steel resists tension. This is a passive combination of the two materials. Why are we saying passive is that none of these materials are stressed before the load is applied. The stress in these elements come only after there is some external load, may be just the self-weight. When the self-weight starts acting and whenever there is an external load, then only these materials get stressed. That is why we term reinforced concrete as the passive combination of concrete and steel.

Whereas, in prestressed concrete, we see that there is a combination of high strength concrete and high strength steel to resist the tension and compression effectively, but this combination is an active combination. What we mean by an active combination is that even before the external loads start to apply, both these materials are stressed. The steel is under tension and the concrete is under compression after the prestressing operation. These stresses are there even before some external loads come on to the member.

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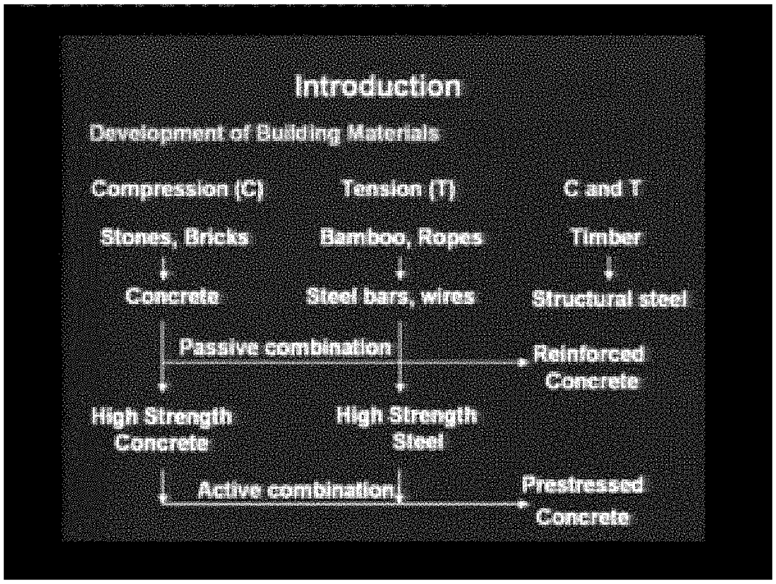

Now, this figure summarizes the development of building materials in a nutshell. As we said before that in the original structures in the olden days, the compression used to be carried by stones and bricks. They were strong in compression and weak in tension. The development of concrete, which was originally a lime concrete and then it moved on to the cement concrete, was termed as the artificial stone. The beauty of the concrete was that it could be moulded in any shape for the use for which it is meant.

The tension can be carried by bamboos and ropes which were the original materials for carrying tension. Gradually they led to the development of the steel. Initially, it was wrought iron, and then subsequently it became steel. The steel bars and wires are also very good in carrying tension, but they were weak in carrying compression because they tend to buckle.

There were some materials which were equally capable of carrying flexural compression and tension simultaneously, such as the timber or wood and the structural steel, which was an industrial product. These two materials were shaped in such a way that they were able to carry both compression and tension. In reinforced concrete, we see a passive combination of the concrete and the steel. Why is it passive? Because, there is no stress in either material before the external loads start to apply.

With the development of both concrete and steel, high strength concrete was developed whose strength can be as high as 100 MPa, and high strength steel whose yield strength and ultimate strength can be as high as 1200 and 1700 MPa, respectively. These two materials were combined to develop the prestressed concrete. The prestressed concrete is called an active combination. The reason is that both these materials are stressed before the application of the service load. The concrete is compressed so that the tensile stresses may not generate under service loads, chances of cracking get reduced, the members can have a longer span and the deterioration of the steel is much reduced. That is why prestressed concrete has some additional advantages over the reinforced concrete.

SUMMARY

In today's lecture, what we have covered is: first, we covered the basic concept – what is the definition of prestressed concrete? We have found that prestressed concrete is the concrete where some initial stresses are induced in the concrete to counteract the stresses that come due to the service loads.

Why do we need prestressed concrete? Concrete is weak in tension, so to counteract this deficiency of concrete, the prestressing is done. From the basic concept, we also found that the concept of prestressing was not just limited to concrete. The concept was there even before the application of concrete. We have seen the example of the barrels and the example of the spokes in the cycle wheels. Next, we moved to the early attempts of prestressed concrete and we found that the early attempts were not successful. The reason was that concrete has a special behavior. It is the change in length or volume over the time. The first is the shrinkage, which is a reduction in volume due to the hydration of the cement and evaporation of water and the second one is the creep, which is the reduction in length under the sustained load.

In the early attempts of prestressed concrete, both these phenomenon led to the reduction of the prestressing force. The original tensile strain got reduced because of the compressive strain that concrete was undergoing. That is why the residual stress was subsequently much lower than the original prestress, and the early attempts of prestressing were not successful because of these long-term effects.

With time, this problem was identified and concepts of retightening the rods to overcome the loss in prestress were introduced. Then we find that the development of the high strength materials, both the concrete and the steel, led to the better development of the prestressed concrete. Due to the high strength steel, a much higher original tensile strain was possible. Even after losses, there will be substantial residual tensile strain in the steel. Since we were using high tensile steel, the prestressing force also became much larger. It was only high strength concrete which was able to sustain this high load, and proper combination of high strength concrete and the high strength steel led to more economical and effective prestressed members.

We also went through the names of several pioneers in the development of prestressed concrete. We found that initially the prestressed concrete started as some tightening of the arches; and then we find its applications in pipes, tanks and other liquid retaining structures. The applications in bridges were marvelous because the bridge decks became longer, sleeker and aesthetically more appealing.

The development of the industrial products like jacks, the turnbuckles and the anchorage system also helped in the development of the prestressed concrete. With the industrial production of concrete, the precast and the prestressed structural members were becoming popular over the time. During the mid 20th century, there was an exponential growth of prestressed concrete. In India also, we find that prestressed concrete became very popular over the years. Whether it is in bridges or in railway sleepers or in transmission line poles or in liquid storage tanks, we find applications in India.

Finally, we discussed the development of the prestressed concrete in terms of the building materials. We found that in one part, we had materials like stone and bricks, which were strong in compression and weak in tension. On the other group, we had ropes and steel bars, which were strong in tension, but weak in compression. Only wood and structural steel were able to combine them both.

In reinforced concrete, we find a judicious combination of the artificial stone which is the concrete, and steel. But reinforced concrete is a passive combination, where there is no stress in either of the two materials. But in prestressed concrete, we find that the high strength concrete and the high strength steel are judiciously combined to have a member which is more effective in carrying the load. The prestressed concrete is called an active combination because both the materials are stressed even before the self-weight of the member or the external loads are acting.

The concrete is in compression to counteract the tensile stresses and the steel is in tension. Due to this, the prestressed concrete is much more advantageous than the reinforced concrete.

In our next class, we shall move on to the advantages of prestressed concrete as compared to reinforced concrete. We shall learn about the different terms that are used in prestressed concrete structures, and the different types of prestressing. We shall also learn the prestressing systems and devices that are available at present, with nice illustrations and sketches.

Thank you.