PRESTRESSED CONCRETE STRUCTURES

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Module – 1: Introduction, Prestressing Systems and Material Properties

Lecture – 4: Prestressing Systems and Devices (Post-Tensioning)

Welcome back to Prestressed Concrete Structures. This is the fourth lecture of the module on Introduction, Prestressing Systems and Material Properties.

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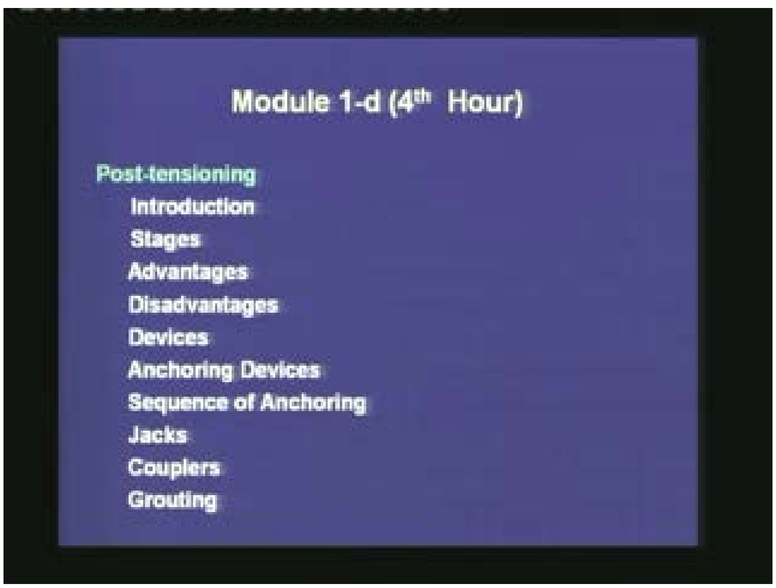

In this lecture, we shall cover post-tensioning and under it, we shall cover the introduction, the stages of post-tensioning, advantages and disadvantages of post-tensioning and the devices used. Then we shall focus on the anchoring devices, the sequence of anchoring, jacks, couplers and grouting.

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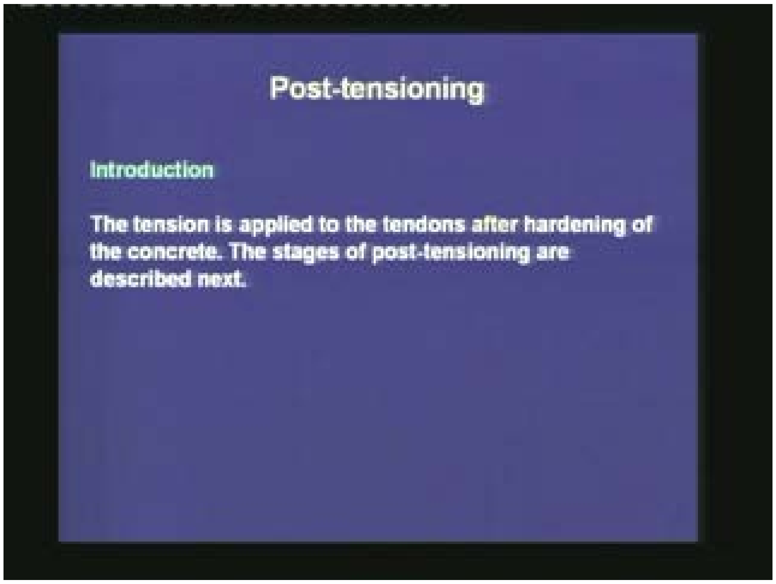

As we have mentioned earlier, prestressing can be broadly classified into two types: one is pre-tensioning and the other is post-tensioning. Post-tensioning is the one where the tension is applied to the tendons after hardening of the concrete. This is different from pre-tensioning. In pre-tensioning, the tension is applied first and then the concrete is cast. In our last lecture, we covered pre-tensioning in details. In this lecture, we shall cover post-tensioning and its devices.

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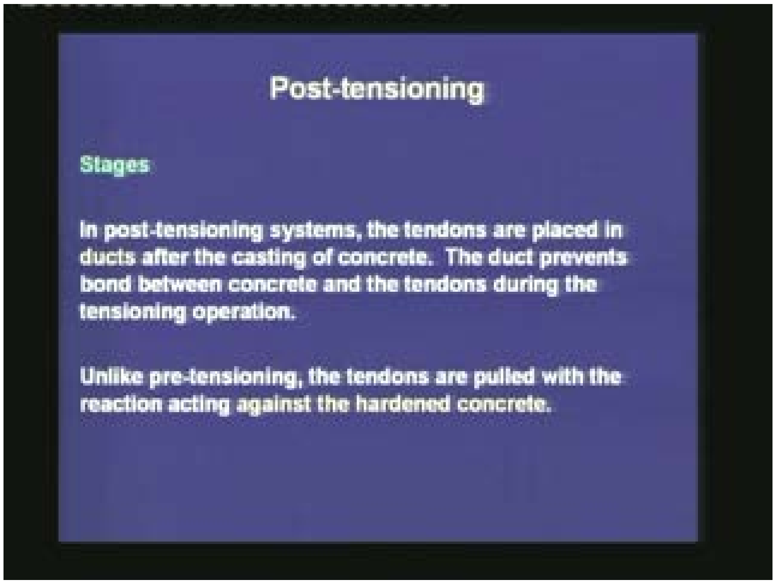

In post-tensioning systems, the tendons are placed in ducts after the casting of concrete. The duct prevents the bond between the concrete and the tendons during the tensioning operation. This is very essential because, when the tensioning operation is done if there is resistance, then the tension will not be applied properly. The duct ensures that there is no bond between the concrete and the steel during the tensioning process.

Unlike pre-tensioning, the tendons are pulled with the reaction acting against the hardened concrete. In the last lecture, we mentioned that in pre-tensioning, the jacks need an end abutment to get the reaction; but in post-tensioning, we do not need such an end abutment because, the jacks are placed against the concrete member itself from which it gets the reaction.

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After the tensioning operation, if the ducts are grouted then it is known as bonded post-tensioning. Grout is a neat cement paste or a sand cement mortar containing suitable admixtures. The grouting is done to prevent the steel tendons from corrosion. After the grouting, there is a contact between the concrete and the steel through the hardened grout. In unbonded post-tensioning, as the names suggests, the ducts are never grouted and the tendon is held in tension solely by the end anchorages. The purpose of unbonded post-tensioning is that it avoids the process of grouting. It is usually used for slabs where grouting may be difficult in the small duct holes. But in most of the cases where corrosion is a problem, the tendons are always grouted and hence it is a bonded tendon.

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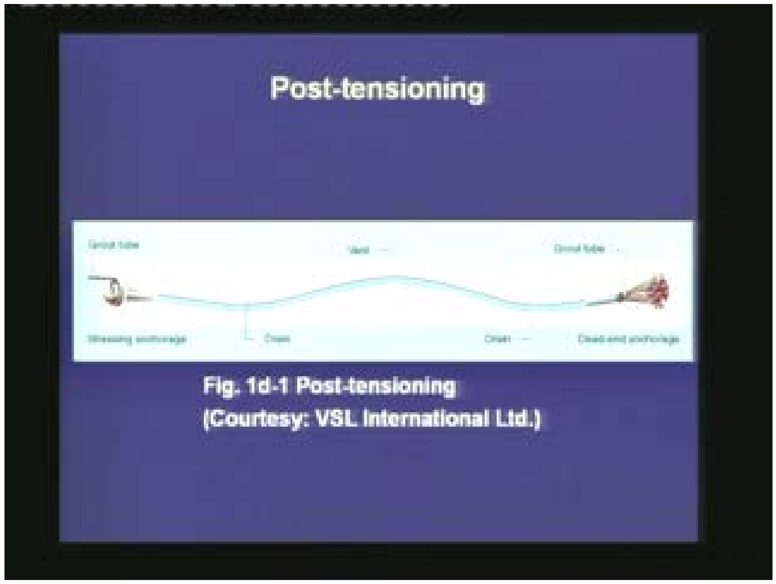

Fig. 1d-1 Post-tensioning
(Courtesy: VSL International Ltd.)

This sketch gives you a schematic idea of the post-tensioning operation. The duct can have a curved form, based on the design of the profile of the tendon. The tendons are attached in one end by some anchorage system and then on the other side, the tendons are pulled by the jacks. Once the tensioning operation is done, then the grout is pumped from one end and as the grout flows, it is made sure that it covers the full length of the duct, so that the excess amount of the grout oozes out from the other end. There are some bent tubes for the escape of the air and there are some drain tubes for the escape of the excess amount of water. The grouting process is a very important process for a bonded post-tensioning system, because if it is not grouted properly, then the assumptions in the analysis, that there will be a stress transfer in the interface of the concrete and the steel will not be valid.

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In this photograph, we can see that the ducts have been laid within the reinforcement cage. There can be several ducts depending on the size and the load carried by the member. These ducts are usually made of some plastic or PVC sheets, and the ducts need to be clean. The annular space within the duct has to be free of any debris so that, when the tendon is passed through the duct, there should not be any obstruction. In this photograph, we can see that the end portion of the post-tensioning system has been cast previously using a high strength concrete, because most of the stresses are concentrated in this end region. The end region is subjected to higher stresses as compared to any other portion of the beam. This is a box girder section of a bridge deck.

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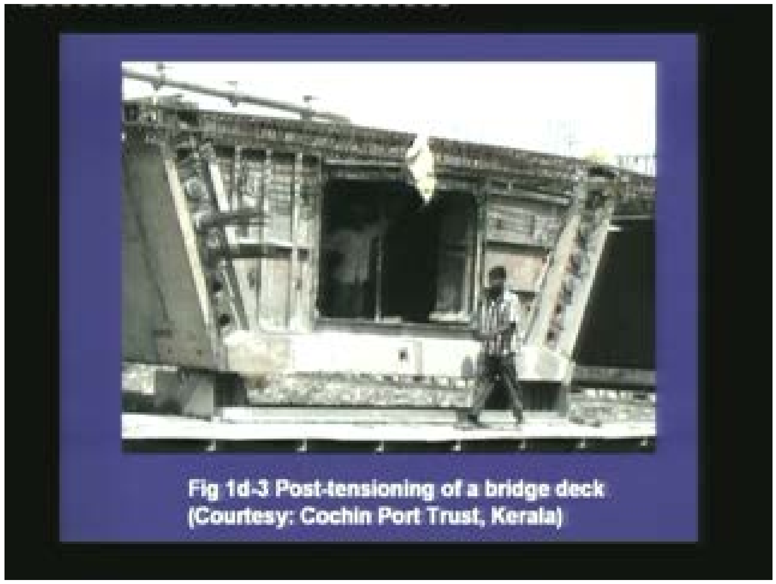

In a similar section after it has been post-tensioned, we can observe that the tendons are sticking out from the end blocks. Once the full post-tensioning operation is done in one duct, then the extra excess amount of the tendons is cut off, and the end anchorage block may be covered with grout so that it is not subjected to corrosion.

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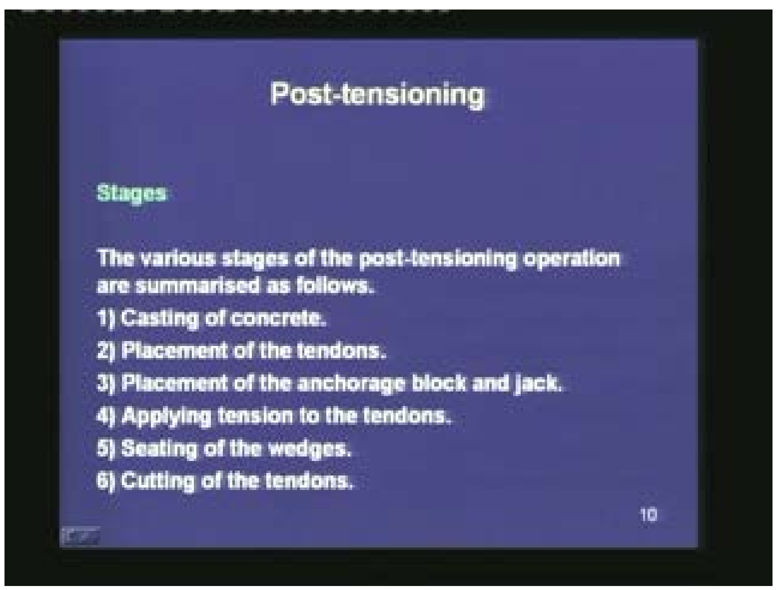

The various stages of the post-tensioning operation can be summarized as follows: first, the concrete is cast; it is allowed to cure and harden to achieve the desired strength before the tensioning operation is done. Next, the tendon is placed in the ducts which were located within the concrete and after that, the anchorage block and the jacks are placed at the ends of the members. Next, tension is applied to the tendons. The wedges in the anchorage blocks are allowed to sit so that the tensions do not slip from the anchorage blocks. Finally, the excess amount of the tendons is cut off from the ends.

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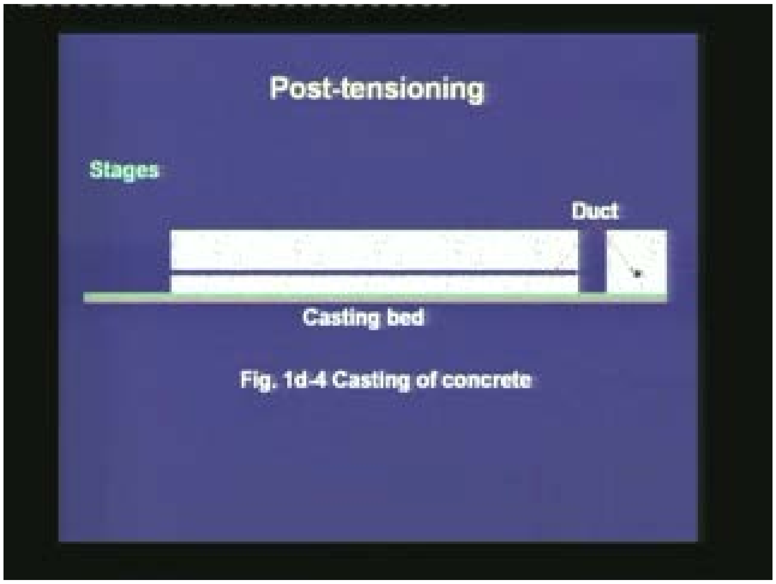

In this first sketch, we can see when the concrete is cast, there is a hole or a duct inside the concrete. Again, this duct should be free from any debris or obstruction because later on we are going to pass the tendon through this duct.

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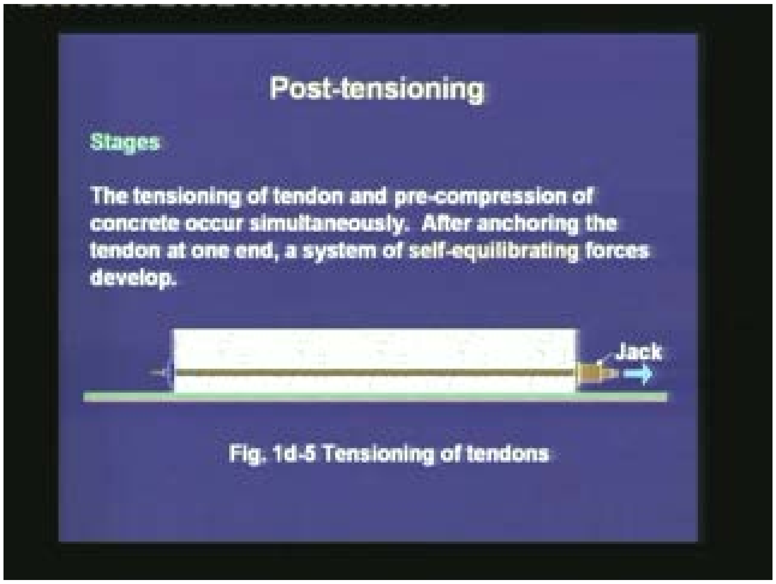

In the next stage, the tendon has been passed through the duct and it has been anchored in one end. A jack has been placed on the other end and the jack is applying tension to the tendon. As the tension is applied against the concrete, the concrete will undergo elastic shortening. This is different from the process of pre-tensioning. In pre-tensioning, since the jacks get the reaction from the end abutments, the elastic shortening does not occur during the tensioning period, because at that time the concrete is not there at all. The elastic shortening occurs when the tendons are cut and the prestress is transferred from the steel to the concrete. But in the post-tensioning operation, the elastic shortening occurs during the jacking operation itself. Hence, when the final jack force is recorded, by that time the elastic shortening has already occurred, and it may not be considered as a loss in prestressing force. We shall discuss this again in details when we study the losses of prestress in the second module.

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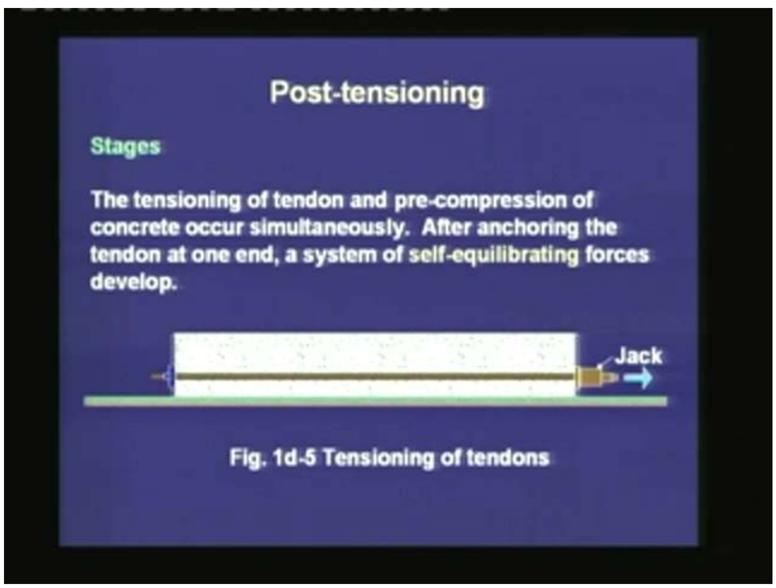

As I said before that in the pre-tensioning system, if we use a precasting bed and end abutments, it needs strong foundation. We can avoid strong foundation, if we use a stress bench which is a self-equilibrating system. In post-tensioning, the whole process itself is self-equilibrating, because the jack gets the reaction from the concrete member. Once the tendons are anchored at one end, the whole system, the prestressed member itself is a self-equilibrating system because the tension in the steel and the compression in the concrete balance each other. Thus in post-tensioning, we do not need any special foundation during the tensioning process.

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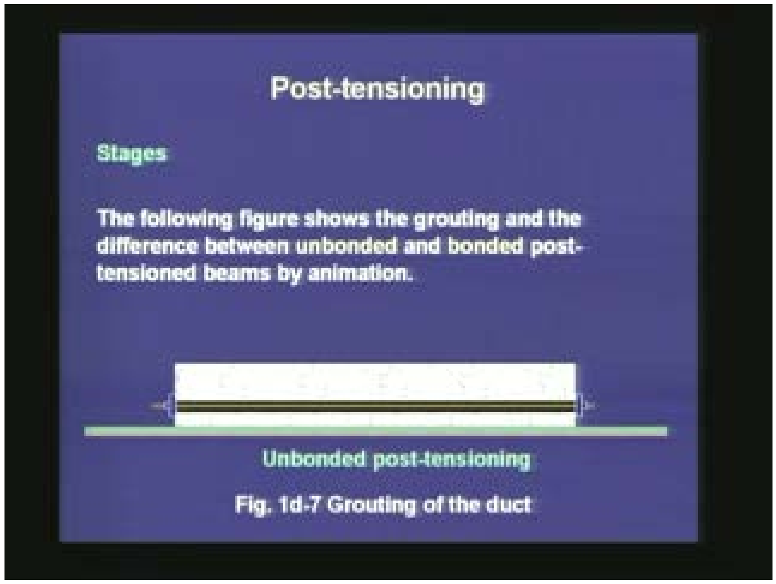

This figure will show the difference between a bonded tendon and unbonded tendon. In this sketch, you can see that the duct hole is free of any grout. We can see this black annular space which does not have any grout. If the beam is left just like this, then it is called an unbonded post-tensioned beam.

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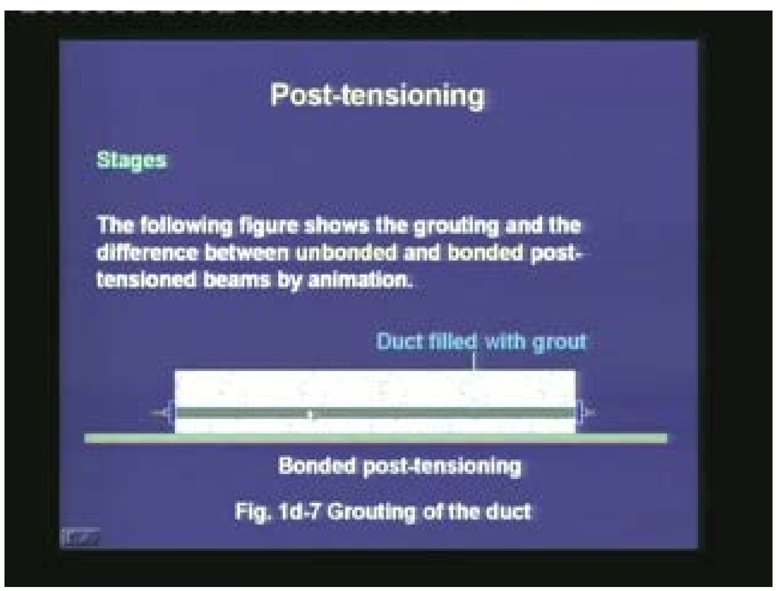

But if the annular space is filled up with grout then it is called a bonded post-tensioned beam.

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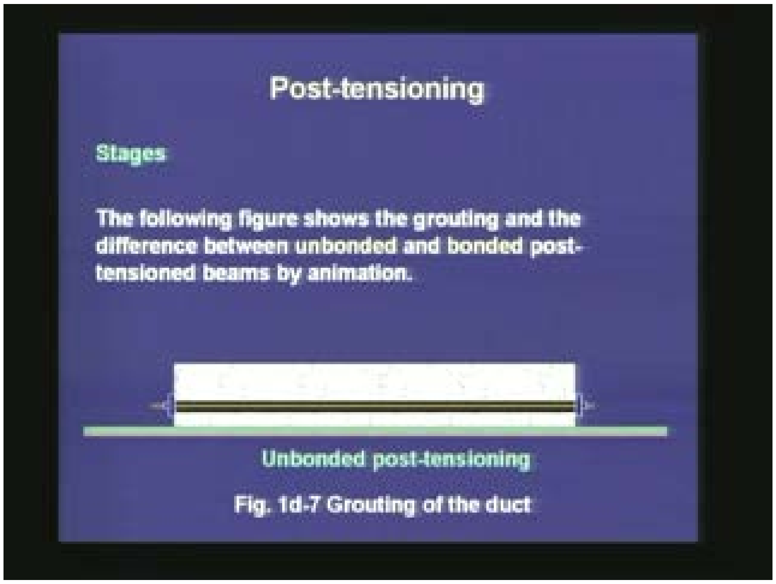

Let me show this once again. In this beam, the annular space between the tendon and the concrete is free of any grout and there is no direct stress transfer between the steel and the concrete along its length. The prestress is transferred only at the end anchorages.

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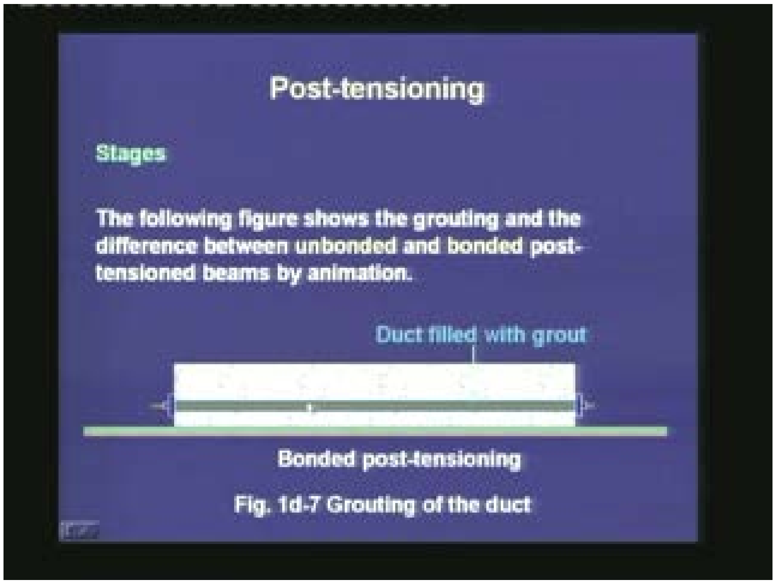

Next, if we fill the space with grout, after the grout hardens, then the steel and the concrete are bonded together, and then there can be stress transfer between the steel and the concrete. The prestress is transferred by the end anchors as well as along the length of the prestressing steel. For bonded tendons, there is a strain compatibility between the prestressing steel and the concrete. It means that the change in strain in the prestressing steel at a certain location is same as the strain in the concrete at that level. We shall be studying about this concept in the module of analysis of beams under flexure.

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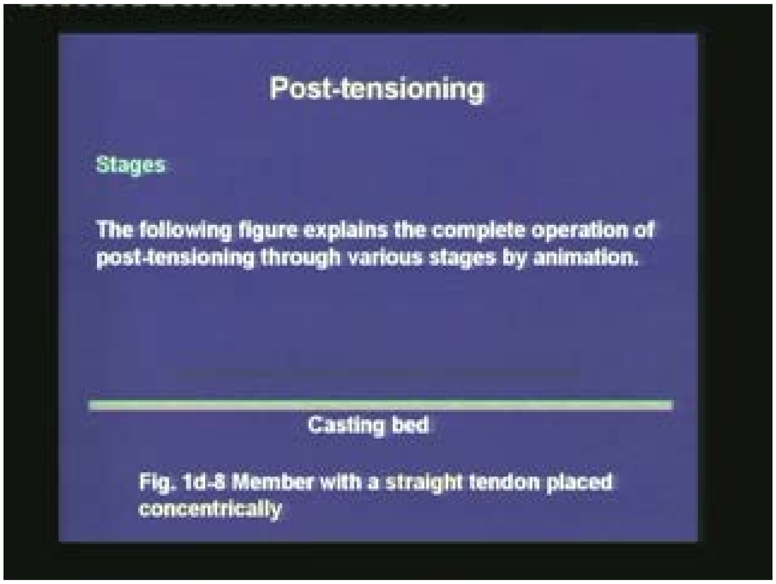

The stages of prestressing by the post-tensioning method are explained by this animation. First we need a casting bed where the concrete will be cast.

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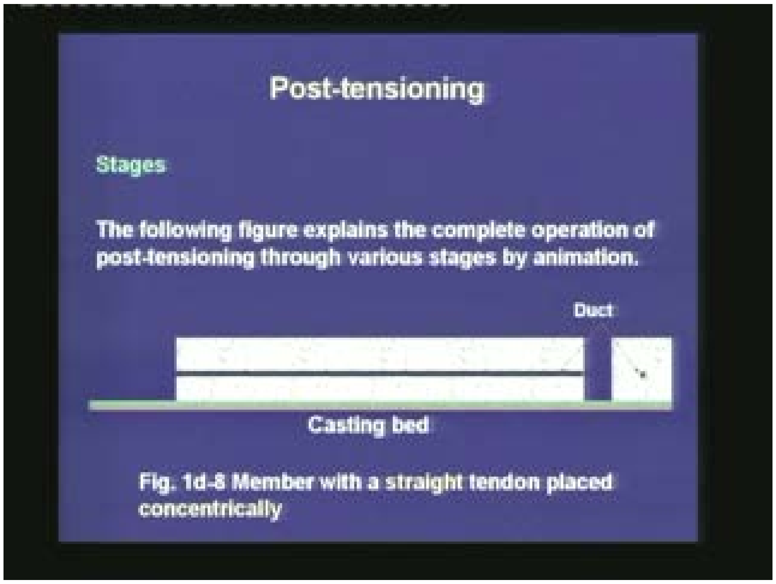

After placing the moulds, the concrete is cast with the duct inside it. The duct leaves a space within the concrete which should be free of any obstruction.

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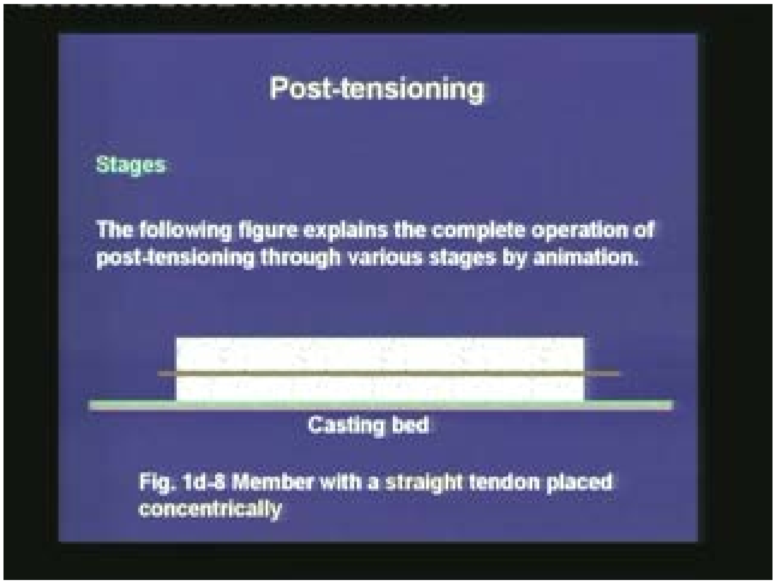

After the concrete cures and hardens, a tendon is placed through the duct.

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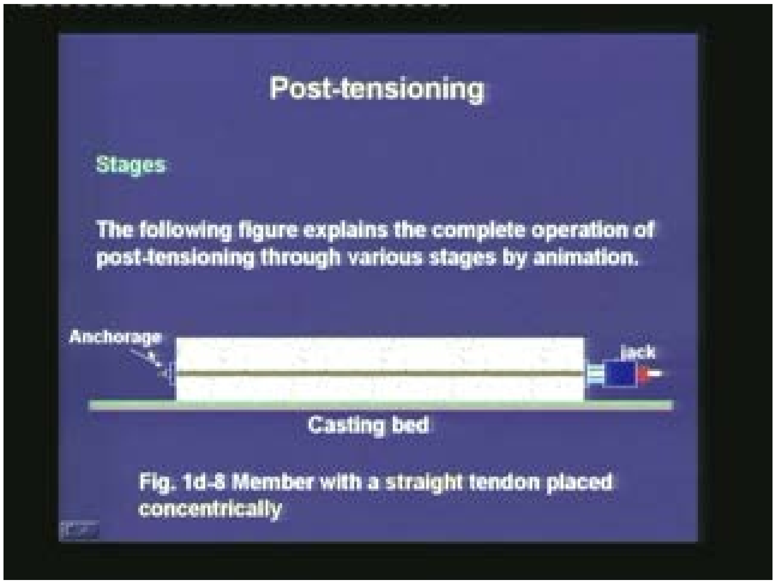

Then one end is anchored. Here, we can see that the left end has been anchored and in the right end, we have placed a jack, which gets the reaction from the hardened concrete itself.

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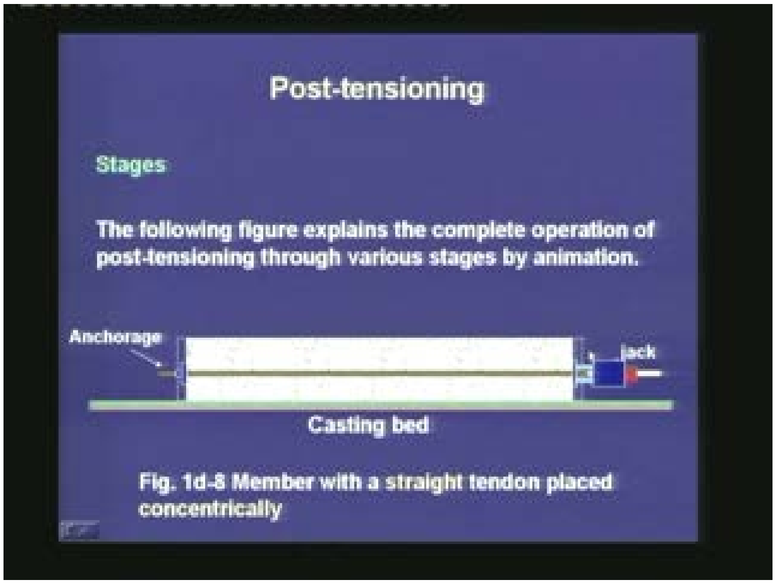

Once these are placed in position, the tension is applied by the jack and we can see as the jack applies tension, the concrete undergoes the elastic shortening. Before I go to the next one, let me show the previous animation once again.

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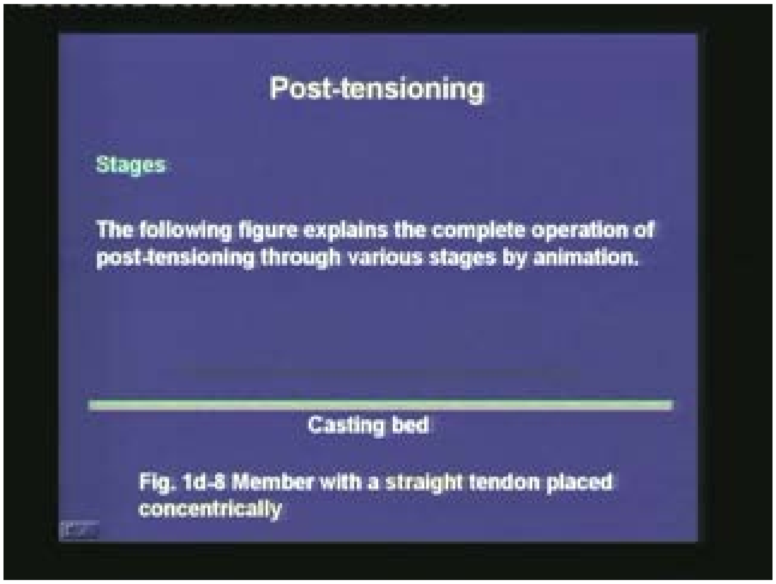

So, as I said in the post-tensioning, the casting bed need not be like a prestressing bed in the pre-tensioning system. The casting bed is just like any other ordinary casting yard.

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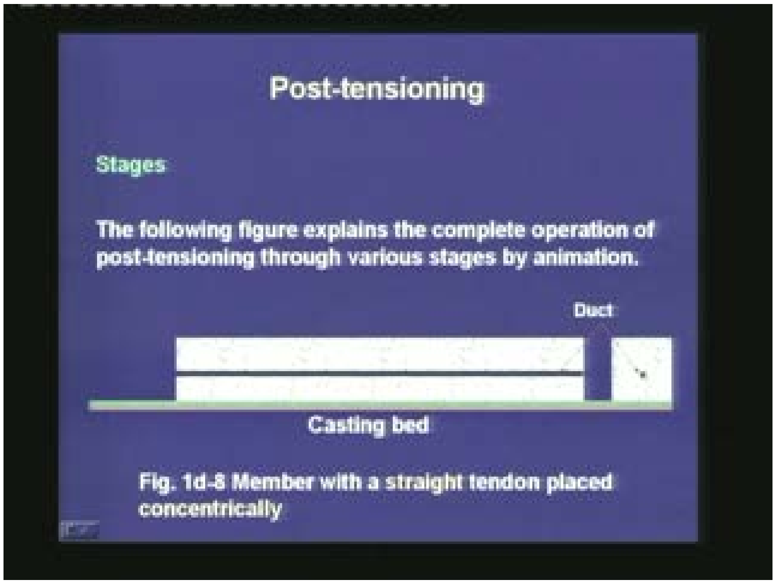

After the mould is placed, the concrete is cast with an annular space inside. This space is provided by placing a duct inside the concrete. After the casting of the concrete, when it has cured and hardened, a tendon is placed within the duct.

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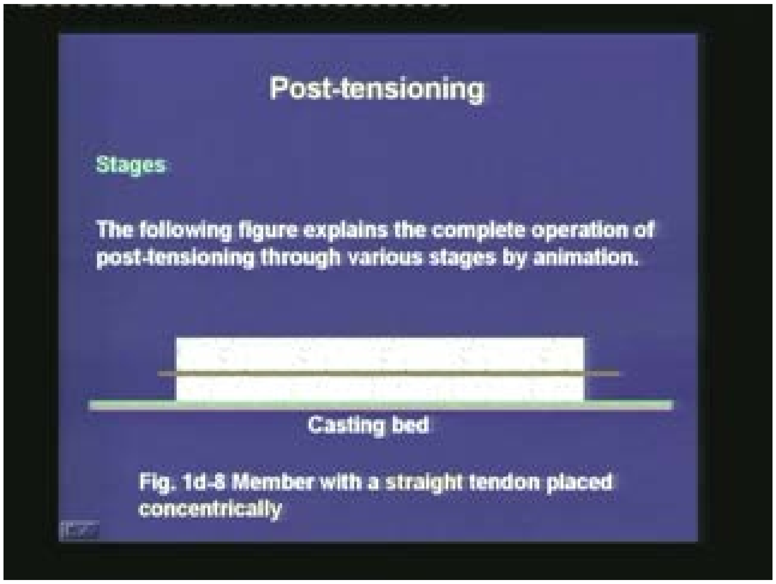

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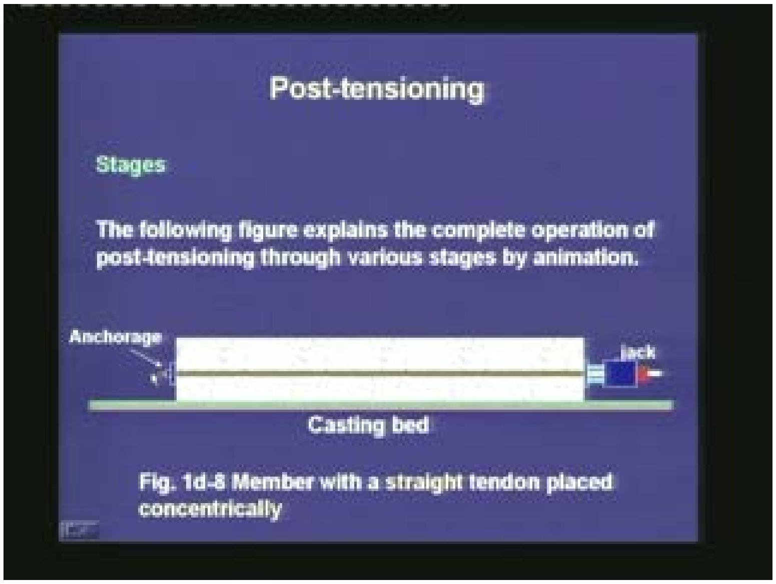

Then the end anchorage is placed at one end. On the other end, a jack is placed which gets reaction from the hardened concrete itself.

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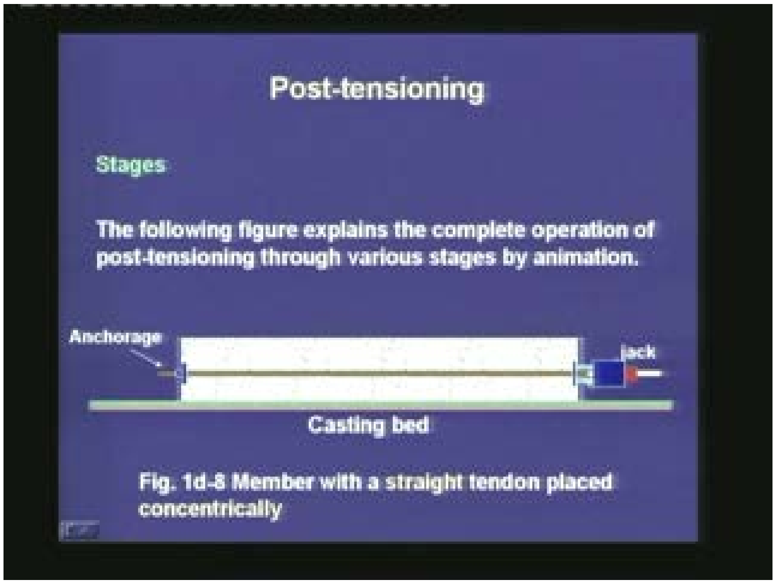

When the jack applies tension to the tendon, the concrete member undergoes elastic shortening. The tendon is subjected to the desired amount of tension, and then the jack can help the wedges to sit against the concrete member. Then the extra amount of the tendon is cut off from the two ends.

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Next, we shall see the same operation for a post-tensioned beam, with a curved tendon. The curvature of a tendon is designed based on the bending moment the member will be subjected to in its service period. The curved profile is fixed by placing the duct appropriately with hangers within the reinforcement cage of the prestressing member.

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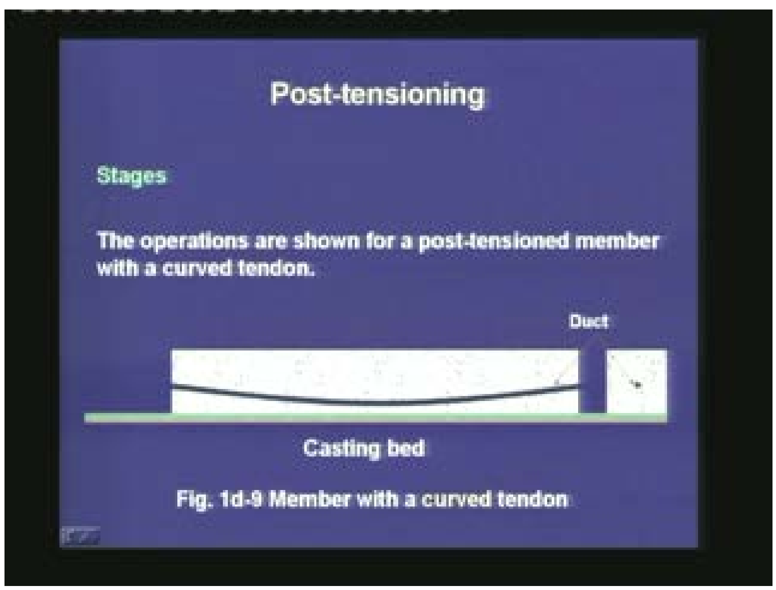

Now, in the casting bed after placing the mould, the concrete is cast with a curved duct inside it. Here, we can see that the profile of the duct is curved, which should be free of any obstacle.

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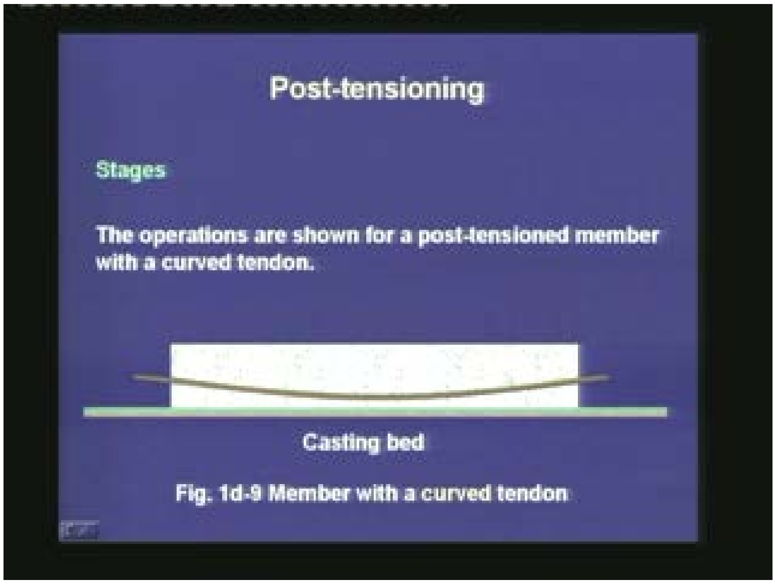

Once the concrete has cured and hardened, the tendon is passed through the duct, and the profile of the tendon becomes similar as the profile of the curved duct.

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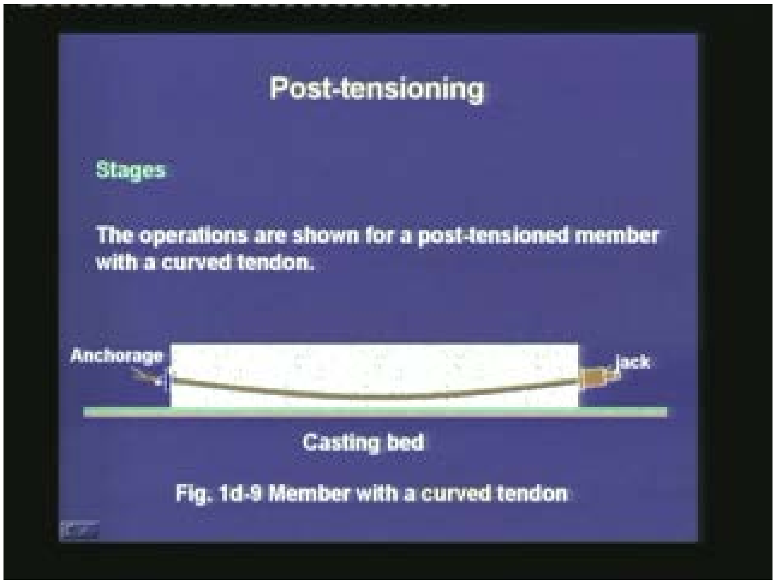

Next, we place the anchorages at one end and the jack in the other end.

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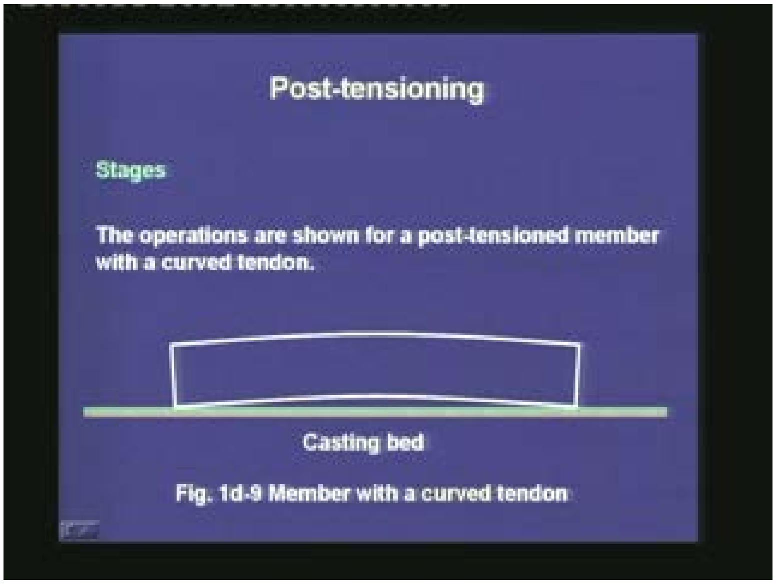

The jack gets the reaction from the hardened concrete. When it is applying the tension, since the tendon is curved, the member will have an upward displacement which is called cambering of a post-tensioned member. Due to the cambering, the member will hog up from the casting bed. Once the jacking operation is done, the extra amount of the tendons is cut off from the two ends.

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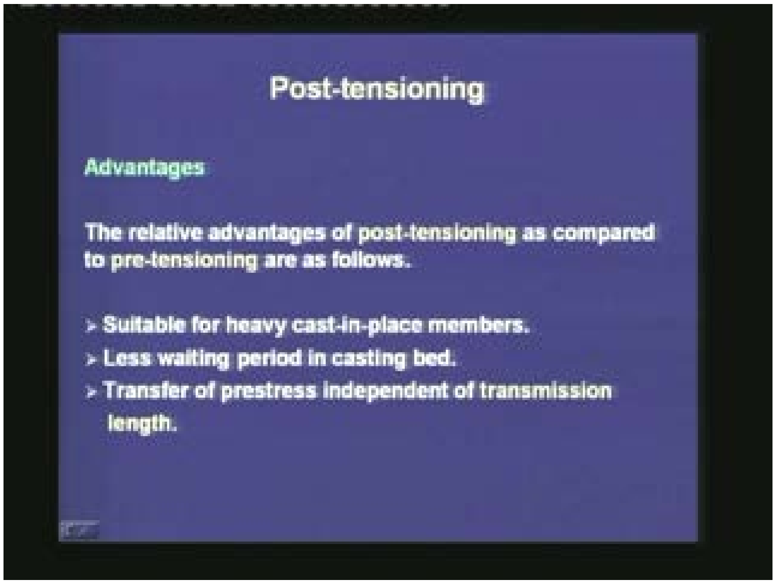

The post-tensioning operation has some advantages as compared to the pre-tensioning operation. First of all, the post-tensioning operation is suitable for heavy cast-in-place members. In my earlier lecture, I had mentioned that the pre-tensioning operation is suitable when the members are produced in bulk like electric poles, railway sleepers etc. These members are relatively lighter than the bridge decks, which are usually post-tensioned. If a bridge deck is heavy then it can be cast in place and the post-tensioning operation is done at the site, where the deck will be there; or else, if there are provisions for shifting the bridge deck from the casting yard to its final location, then the member can be precast in a yard. It can be post-tensioned after the member has hardened. Then it can be shifted from the precasting yard to its final location.

Compared to pre-tensioning, the post-tensioning has a less waiting period in the casting bed. I mentioned earlier that for pre-tensioning, the prestressing bed is occupied by the concrete member till it attains the required amount of strength before the transfer of prestress. This can be a hurdle when there is a high demand for the prestressed members. But in post-tensioned case, once the concrete is cast, the mould can be shifted or the casting bed may not be required for casting a subsequent member, and hence it does not create any hindrance in the production of the post-tensioned members. Usually, the rate of production of post-tensioned members is low as compared to that of the production of the pre-tensioned members.

Another important advantage of post-tensioning as compared to pre-tensioning is that the transfer of prestress is independent of the transmission length. Last time I mentioned that, in the pre-tensioned members, the transfer of prestress occurs along its length especially towards the end, which is called a transmission length or a transfer length. The bond between the steel and the concrete has to be good to transfer the prestress from the steel to the concrete in a pre-tensioned member; whereas in a post-tensioned member, the transfer of prestress is not dependent solely on the bond between the steel and the concrete. It is the anchorage blocks at the end which transfer most of the prestress from the steel to the concrete.

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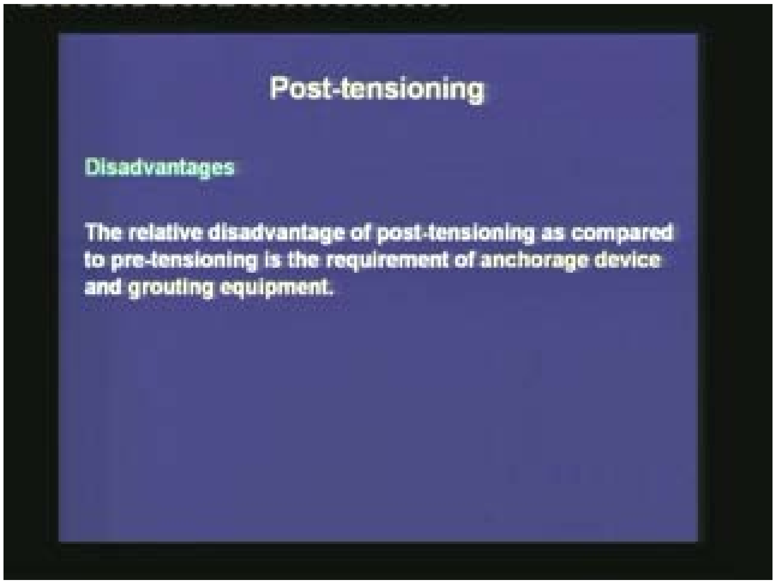

There are some disadvantages of post-tensioning as compared to pre-tensioning. The post-tensioning operation needs much more developed anchorage device as compared to pre-tensioning. In pre-tensioning, the anchorage devices are small. These are actually just some chuck assemblies for the individual strands; but in the post-tensioning operation, we shall see heavy-duty anchorage blocks for the transfer of prestress from the steel to the concrete.

Transporting this anchorage device and the supply may be a hindrance for a project which is in a remote area. The second disadvantage is that, for a grouted post-tensioned beam, the grouting equipment itself has to be transferred to the location where the tensioning operation is done. If the post-tensioning is done at site and if the site is remote, then transporting the grouting equipment is another necessary task for the post-tensioning operation.

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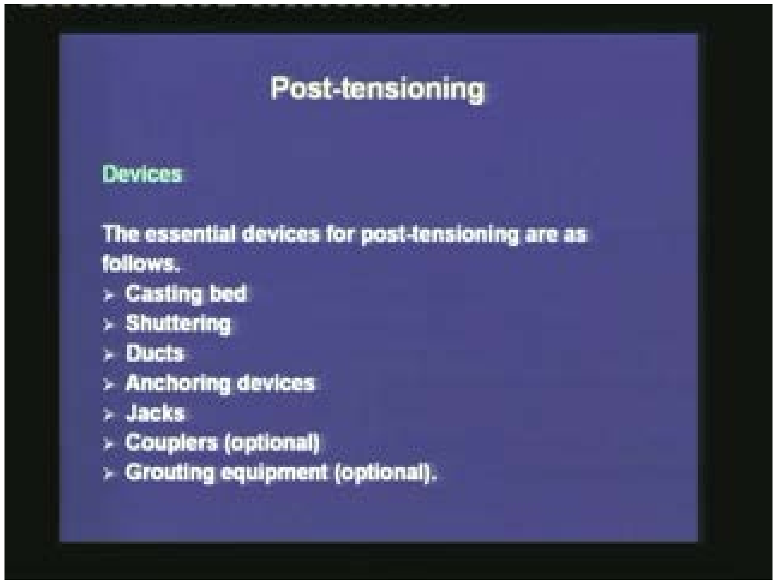

We shall move on to the devices that are used for post-tensioning. Just to recollect, in pre-tensioning, we had seen that the main devices were a prestressing bed, the end abutments with appropriate foundations, some jacks; then we need some cutters for the tendons and if we avoid a prestressing bed with end abutments, then we need some sort of stress bench which is a self-equilibrating system. In post-tensioning, we do not need a sophisticated stress bench or a prestressing bed. We just need a simple casting bed and the shuttering can be placed on the casting bed itself; but we need additional ducts because, we have to place the tendon after the hardening of the concrete. We also need anchorage device which is more complicated than what we have seen for the pre-tensioned case. We need jacks just like as we used in pre-tensioning operation. Usually, the jacks used for post-tensioning operations are even larger, because post-tensioning operation is done for larger members. We may also need couplers. The couplers are devices which join two prestressing strands end-to-end; and we may also need the grouting equipment, if we want to have grouted post-tensioned members.

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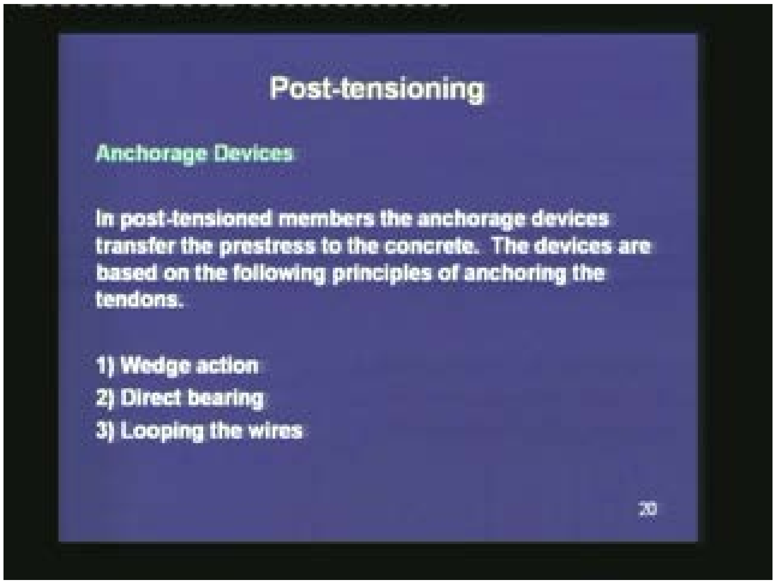

We shall move on to the anchorage devices for the post-tensioned beams. This is a very important device for the post-tensioning system because unless it is properly designed, it will not be able to transfer the prestress to the concrete. The anchorage devices are designed based on the following principles: the first is the wedge action, the second is the direct bearing against the concrete and the third is the looping of the wires.

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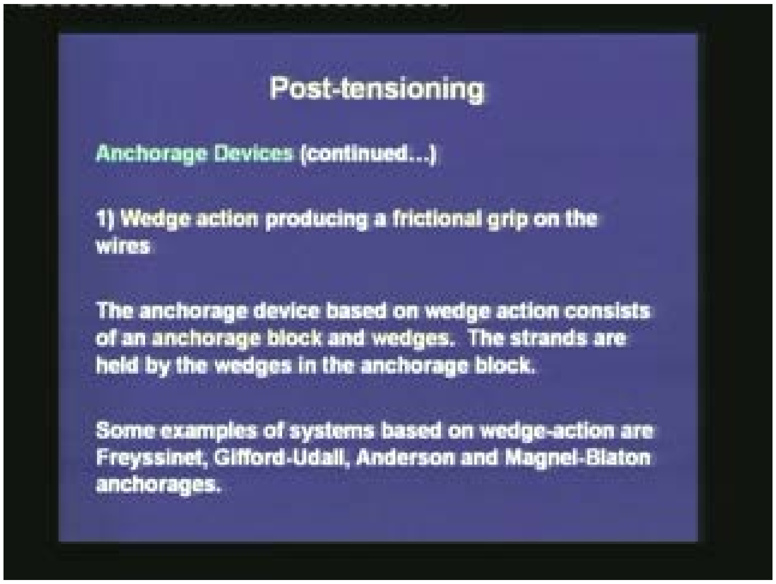

Let me explain the wedge action first by a sketch.

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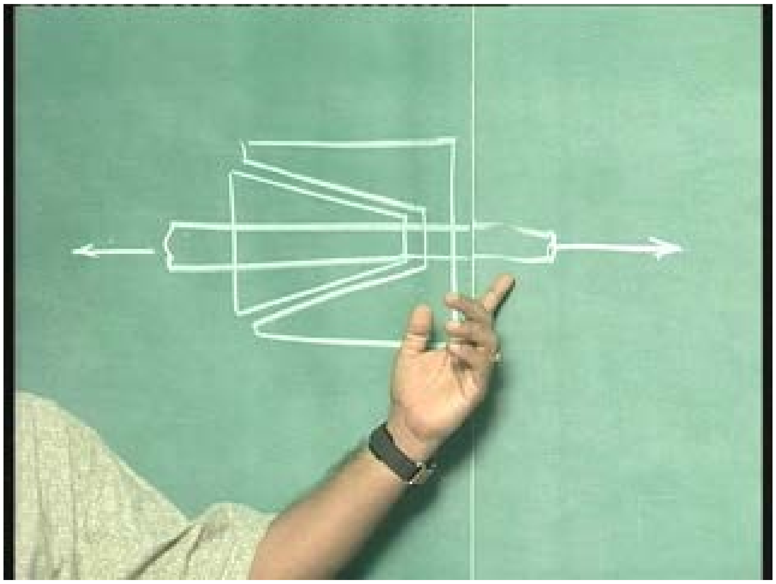

When the wedge is being pulled by the tendon, it gradually sits in this block and due to the friction action, the wedge is not able to move any further. Hence, the tension in the strands can be maintained by this wedge action, which acts on the principle of friction between these two blocks. Thus, the wedge action produces a frictional grip on the wires.

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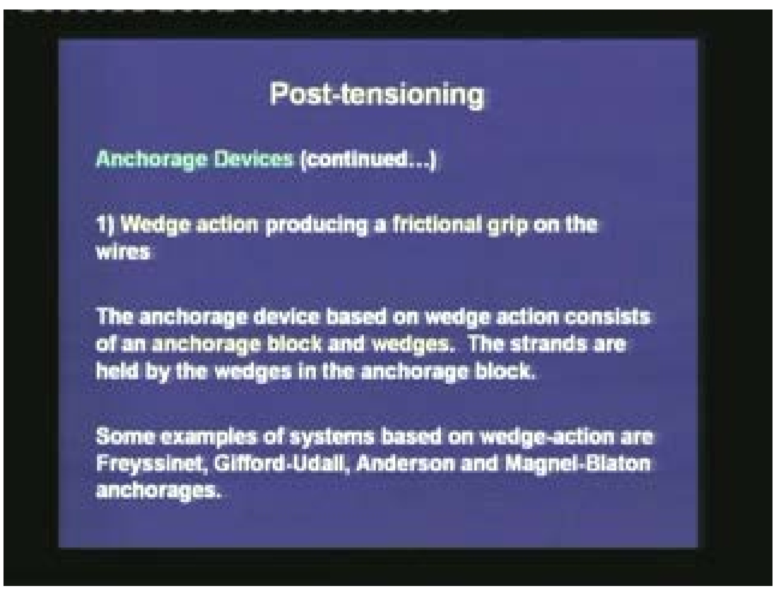

The anchorage device based on wedge action consists of an anchorage block, which is a substantially large block that can hold several wedges at a time. There are several individual wedges within the anchorage block. The strands are held by the wedges in the anchorage block. There are several patented systems of this wedge-based anchorage blocks. Some of these systems are the Freyssinet, Gifford-Udall, Anderson and Magnel-Blaton anchorages. The detail specifications of this anchorage blocks are available in the catalogues, which provide all the geometric specifications, the load carrying capacities and the materials used for the anchorage blocks.

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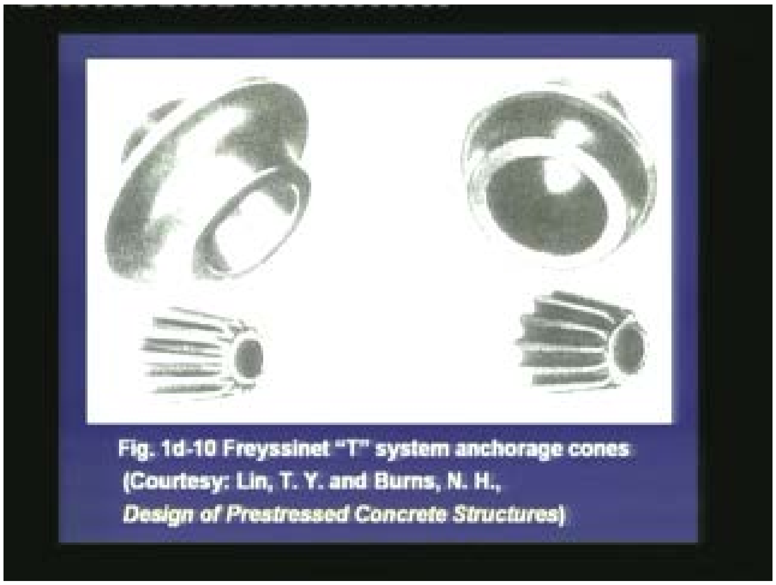

This is a simple Freyssinet T system anchorage cone. Here, we can see that these wedges will sit inside these blocks during the tensioning operations of the strands. This wedge is for an individual strand of the prestressing tendon.

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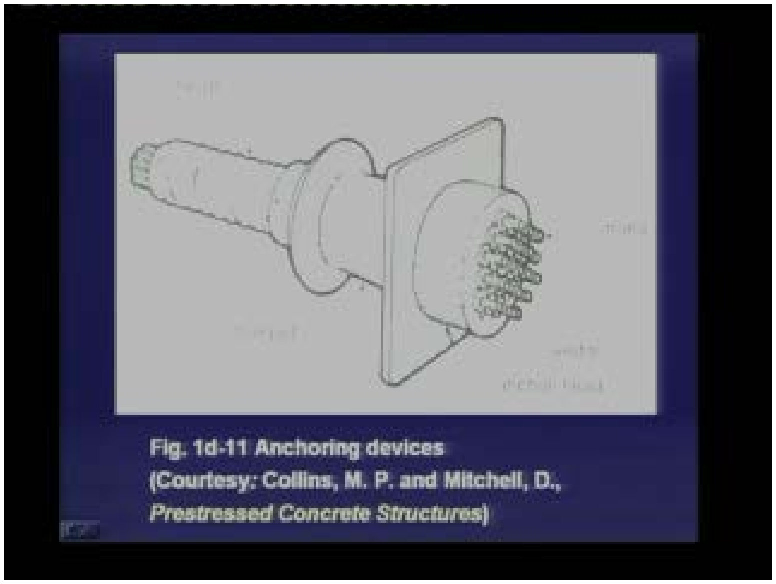

Fig. 1d-11 Anchoring devices
(Courtesy: Collins, M. P. and Mitchell, D., *Prestressed Concrete Structures*)

In an anchorage block, there are several strands which can be held in place by the wedges. The anchorage block consists of an anchor head, which rests on a bearing plate. The bearing plate will get the reaction against the concrete. There is a conduit in the shape of a trumpet, which gets attached to the sheath of the duct. The strands are passed through this sheath and the anchorage block. Then they are fixed to this anchor head by the individual wedges for the strands.

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Fig. 1d-12 Anchoring devices
(Courtesy: VSL International Ltd)

In this photograph, we can see the assembled unit of the anchorage block. At the end, we can see the anchor head which can accommodate several wedges for the strands. There can be a hole in the bearing plate through which the grout can be passed, and then we have the trumpet shaped conduit which is attached to the duct placed inside the concrete.

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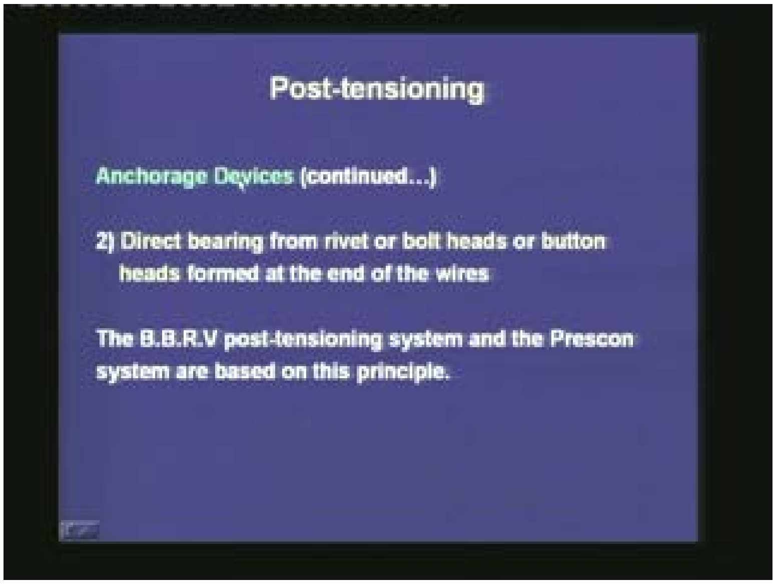

The second type of anchorage device is based on direct bearing from rivet or bolt holes or button heads formed at the end of the wires. Again, there are different types of patented system. The B.B.R.V post-tensioning system and the Prescon system are based on this principle of direct bearing of the button heads or the rivets against the concrete.

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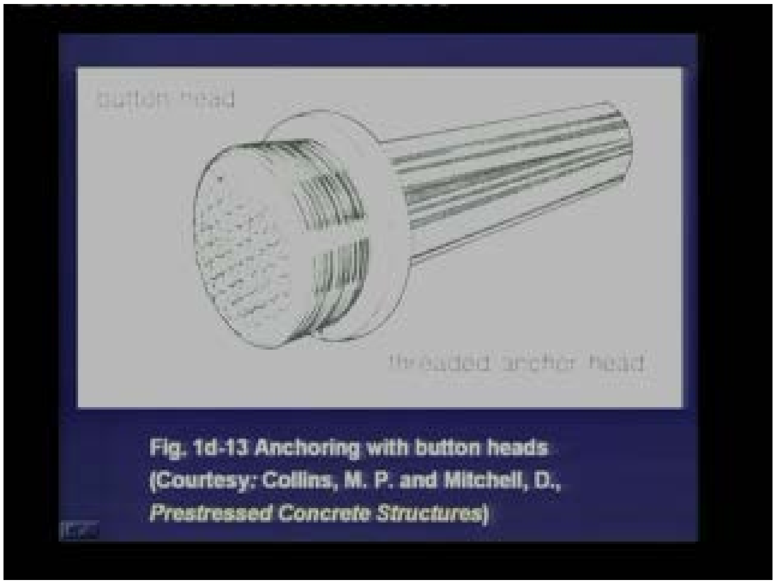

In this case, we can see that the individual wires have a button head, which is resting in the anchor head block. The anchor head is resting on the bearing plate, which rests against the concrete. This does not use the wedge action as shown before. Here, the button heads are just bearing against the anchor head, which is bearing against the plate, and which is further bearing against the concrete.

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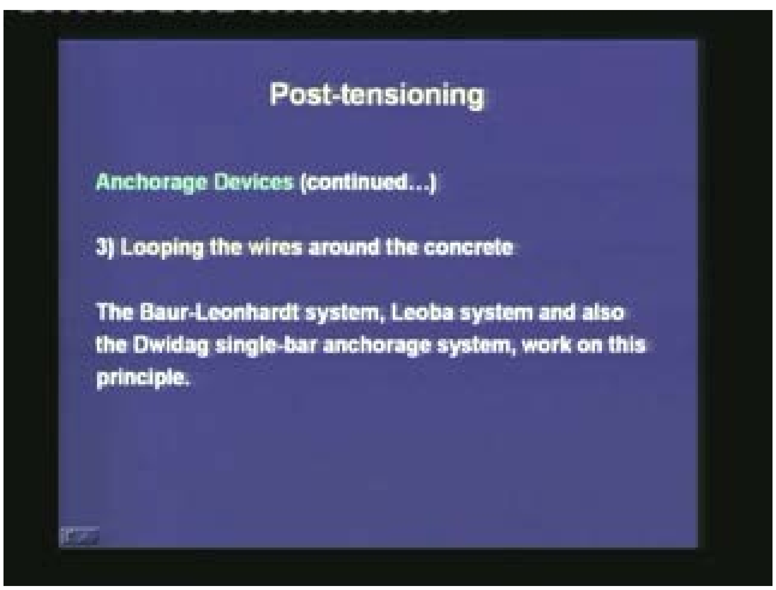

In the third system which can be done for strands with small wires, the principle is based on looping the wires around the concrete. Once the wires have been looped and the concrete has hardened, the strand can be tensioned. The loop does not allow movement against the concrete. The Baur-Leonhardt system, the Leoba system and the Dwidag single-bar anchorage system work on this principle. As I said, this principle can be used only for a single wire or a single strand at a time.

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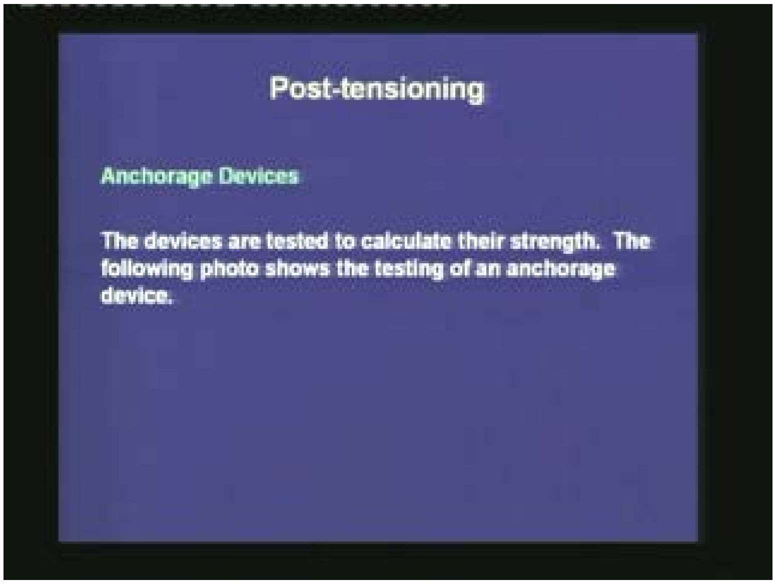

The anchorage devices, before they are patented or if they are used for some special purpose, are tested for their strength. The following photo shows the testing of an anchorage device.

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In this test set up, we can see that there is a reaction frame against which there are some jacks. The jacks are holding another horizontal beam, which is holding the strands at one end. The anchorage device has been placed at the top and as the jack is applying the load, the lower beam is moving downwards. Hence it is applying tension in the tendons, which is transferring the tension to this anchorage block. The anchorage block can be tested for its strength like this.

This type of test can be done not only for the strength but also for the fatigue characteristics. In bridge decks, the loads are usually dynamic in nature, and it can fluctuate over many cycles. In order to see the performance of the anchorage device for varying loads these blocks can be subjected to fatigue testing.

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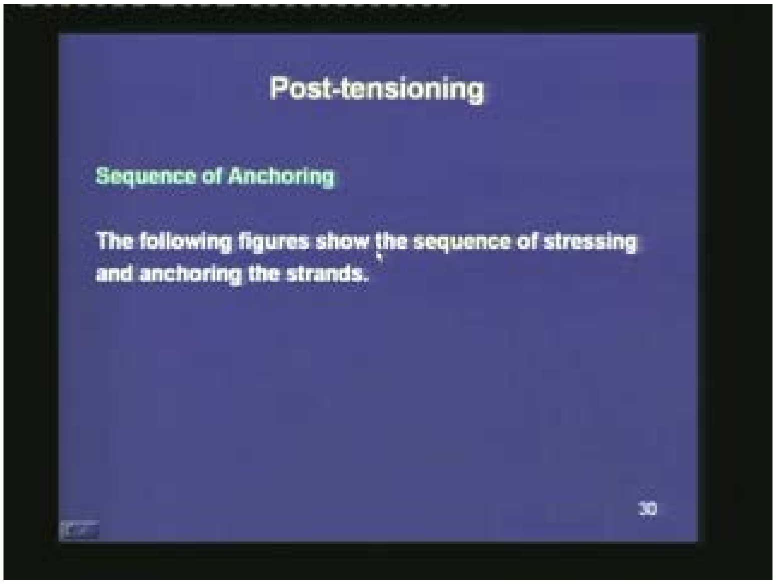

The sequence of anchoring is important to have proper anchorage of the strands against the concrete. The following figure will show the sequence of stressing and anchoring the strands.

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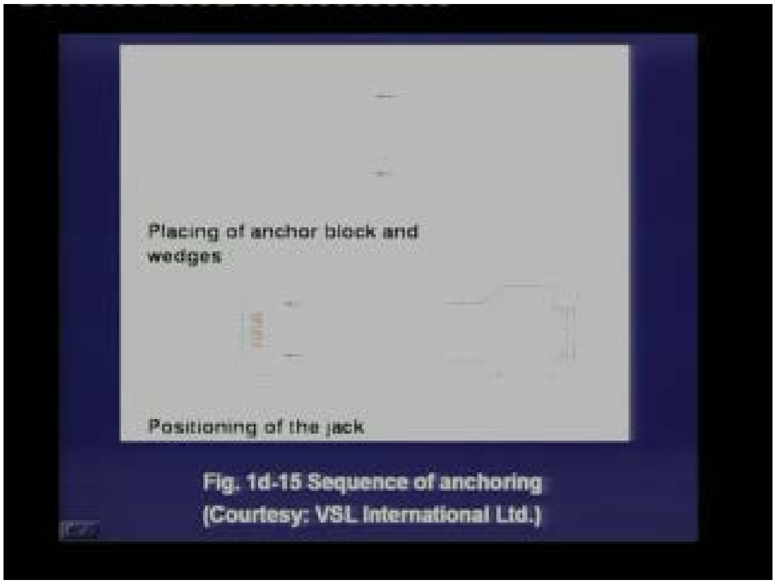

First, when the strands or tendons are passed through the ducts, the wedges are placed in the anchor block. Then a double acting jack is placed against these wedges.

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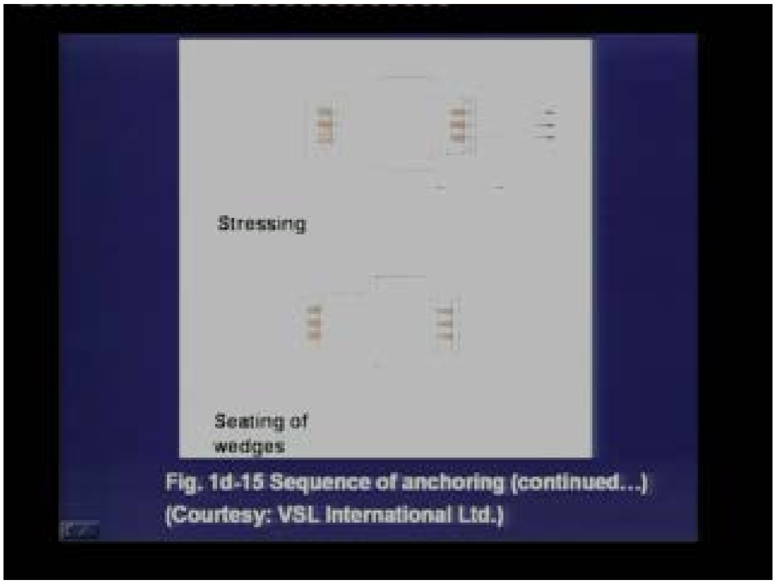

Next, another set of anchor blocks and wedges are placed on the other side of the jack. The jack applies the load when the piston moves out this anchorage block outside. Once the required amount of tension is applied, then the double acting jack applies a push to the anchor block on the left, which helps to seat the wedges inside the sockets. Finally, after this operation is done, the extra amount of the tendons is cut and the jack is taken out.

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Fig. 1d-16 Final form of anchorage device
(Courtesy: VSL International Ltd)

This photograph shows an assembled unit of the post-tensioned anchoring system. Here we can see the duct through which the tendon passes. There is the trumpet shaped conduit, which is attached to the bearing plate. The anchor head rests against the bearing plate. There are several wedges. Each wedge is holding a strand. Once the tensioning operation is done, and the wedges are sitting properly in the anchorage block, there can be a capping of the anchorage block which can be done by a cement mortar grout. This capping is helpful to resist any corrosion in the anchorage block. The proper functioning of prestressing is very much dependent on checking the corrosion of the prestressing tendons over time.

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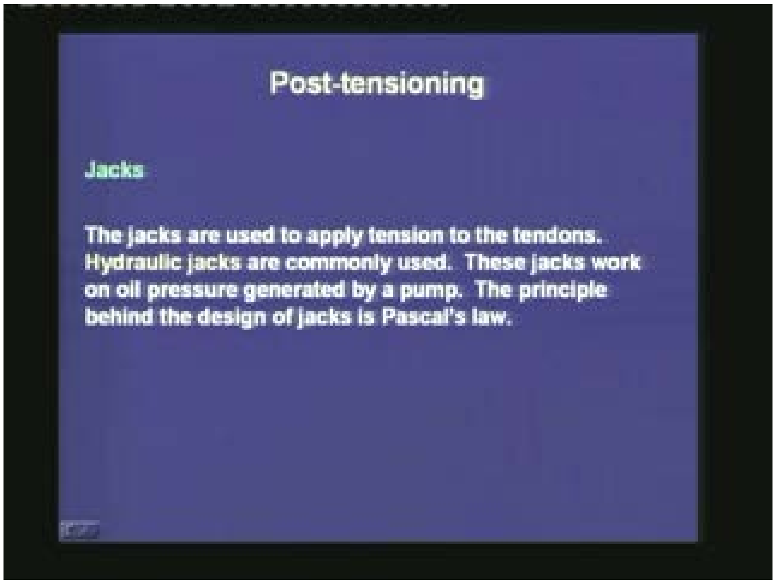

During the tensioning operation, the jacks are the most important equipment that we need. As I said, there can be several types of devices to apply the prestressing force. The most common is the hydraulic jacks which work on the principle of oil pressure. The design of these hydraulic jacks is based on Pascal's law.

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This photograph shows some double acting jacks. A double acting jack means that the piston can move in both the directions. There are two ports, an inlet and an outlet, for the oil. When oil enters through one port, the piston moves in one direction, and when the oil enters through the other port, the piston moves in the other direction. This type of double acting jacks are necessary because in one side, we need to push the anchorage blocks to apply tension whereas, on the other side we need to push back the anchorage block and the wedges before we can cut-off the prestressing tendons. The double acting jacks are almost essential for this type of post-tensioning operation. The other types of prestressing force devices are mechanical systems or electro-chemical systems, which are not suitable for post-tensioning operation.

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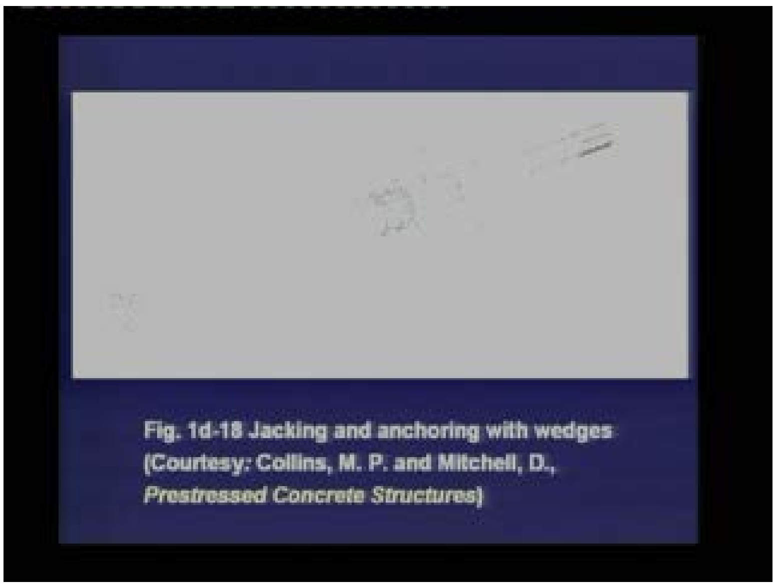

In this figure, we can see the assembly of the jack, the anchorage blocks and the other devices for the anchoring of the tendons. The strands pass through the duct. It goes through the trumpet shaped guide, and then it passes through the bearing plate. It passes through one anchorage block with a set of wedges. Then it passes through the double acting jack and on the other side of the double acting jack, there is another set of anchorage block and wedges.

Here we can see that once the piston moves in one direction, the tension is applied. Once the tension is applied, then the piston on the other side moves back to the other anchorage block and places it against the bearing plate; the wedges are appropriately seated in the anchorage block and then the extra amounts of the strands are cut.

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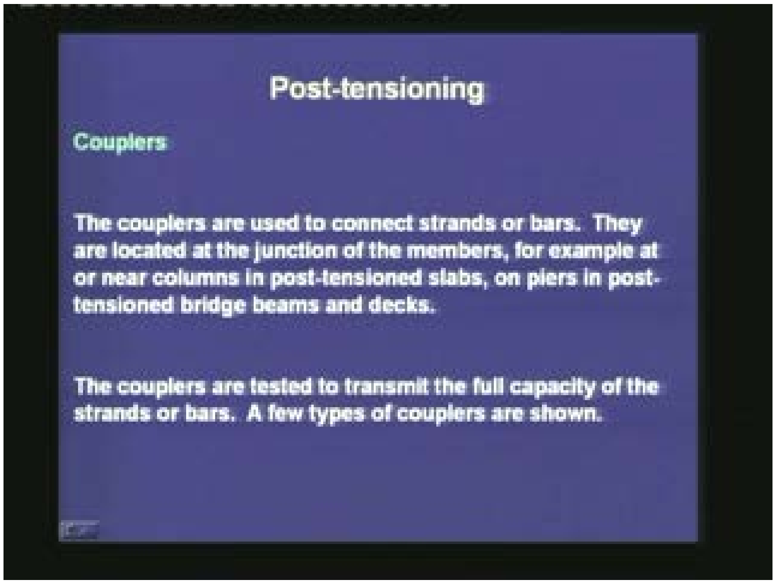

Another device that we may need in the post-tensioning operation is the couplers. The couplers are used to connect strands or bars. They are located at the junction of the members. Usually, we avoid couplers within the member itself, but when the post-tensioning operation is done for a continuous system, like a continuous beam or a slab, at the time, the couplers are located at the junction of the members. Usually, for slabs, they are located near the columns or they are located in the piers for the post-tensioned bridge girders. The couplers are also manufactured products. They are tested to transmit the full capacity of the strands or the bars. A few patented examples of the couplers will now be shown.

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Fig. 1d-19 Coupler for strands
(Courtesy: VSL International Ltd)

The couplers also act on the principle of wedge action. There will be ducts on both the sides, through which the strands are passed. In one end, there is a wedge system. On the other end also, there is a wedge system. The strands from both the ends are held in place by wedge action inside the coupler. All these devices are inside a sleeve which can be filled up with grout, once the tendons are coupled together. Each type of coupler is tested so that the strands attain their strength before the coupler fails.

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Fig. 1d-20 Couplers for strands
(Courtesy: Dywidag – Systems International)

This is another photograph where we can clearly see that the strands from the two sides are coupled together at this junction. All the strands from the two sides are subjected to wedge action. Each individual strand is sitting in a wedge unit and like that, it is held in position, by the coupler. There is a tube for grouting. Once the coupling is done, then grout is passed through it to fill up the annular space in the coupler, so that there will not be corrosion of the tendons.

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This is another angle of the unit and here also, we can clearly see that there are two sets of wedges which hold the tendons from two sides in place within the coupler. In one side, the outer sheath has been removed to show the anchoring of the strands. On the other side, we can see how the strands are being held in place by the principle of wedge action.

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As I mentioned before, there are several patented types of couplers. Here, this is another type of coupler where the individual strands are coupled together. Instead of the whole group being coupled at one location, the individual strands are coupled at different locations. Here, the couplings of the individual strands are staggered. One-third of the strands are coupled at one location. Next, at an offset another one-third is being coupled, and again there is an offset of the coupling of the remaining one-third of the strands. In this whole unit, the coupling of the individual strands has been staggered. It makes sure that there is no weak point at the location of the coupling of the strands. Once the coupling is done, then grout is pumped through one side which fills up the annular space, and the excess amount of grout gets pumped out from the other side.

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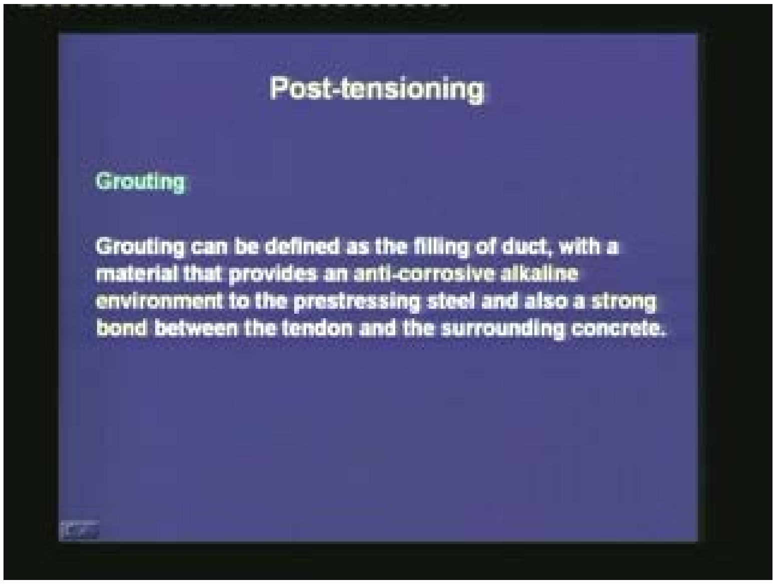

Another important device which we need for a post-tensioning operation is the grouting equipment. The grouting can be defined as filling a duct, with a material that provides anti-corrosive alkaline environment to the prestressing steel, and also a strong bond between the tendon and the surrounding concrete. If we design a beam as a grouted post-tensioned beam then we assume strain compatibility between the prestressing tendons and the concrete. In order to ensure this throughout the service life of the prestressed member, the quality of the grout and the quality of the grouting operation both have to be good, for proper bond between the steel and the concrete throughout the length of the prestressed member.

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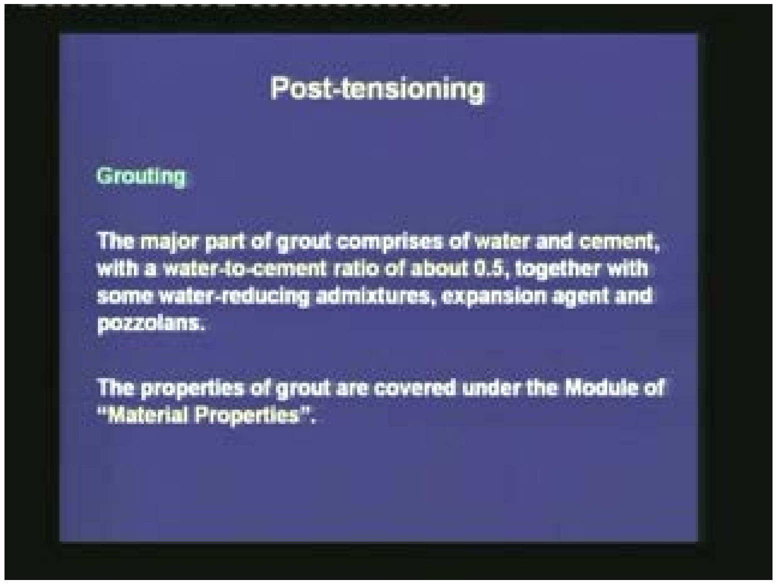

The major part of the grout comprises of water and cement, with a water-to-cement ratio of about 0.5 and in addition to that, there can be some water reducing admixtures. There can be some expansive agents or pozzolans. The properties of grout will be covered in the module of material properties. There we shall see that the code IS: 1343 provides some specifications for the grout, so that, the grout provides an anti-corrosive environment for the tendons. It also should not shrink too much, because if it shrinks then again the bond between the concrete and the steel will be disrupted. Thus, it should not shrink and it should provide a proper anti-corrosive environment. The grout itself should be strong enough, and have a minimum strength to sustain the transfer of the prestress.

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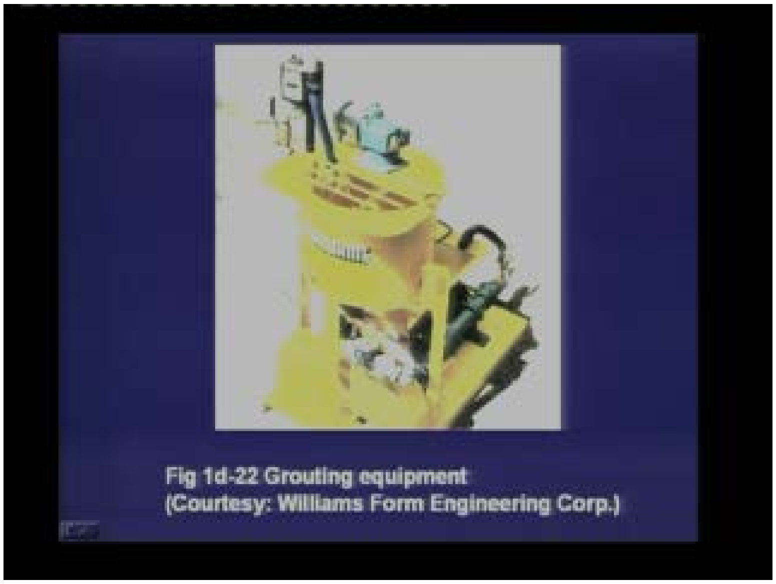

This photo shows a grouting equipment. The drum is similar to a concrete mixture that we see in most of the construction sites. In this mixing unit, water and cement, and any other admixture like water reducing admixture, or expansive agents, or the pozzolans can be mixed. After a proper mixing, the pump will push the grout material through the tube and this tube is attached to the grout hole in the bearing plate of the anchorage block. Through that, the grout is pushed till it fills the complete annular space between the strands and the duct. Filling of the full space is ensured by the movement of the excess amount of grout through the other end. As we have seen earlier, there are vent tubes for the escape of air, and there can be drain pipes for the escape of excess amount of water. Again, as I said that the grouting operation is very important to ensure that there is a proper bond between the prestressing steel and the grout and the concrete, so that there will be a stress transfer from the prestressing steel to the concrete.

Another important feature of the post-tensioning operation is that during the post-tensioning operation itself, the tendons are subjected to the highest amount of stress. The quality of the concrete near the anchorage block has to be extremely good because the end blocks are subjected to high stresses. That is why, unless the concrete is able to sustain the high stresses during the post-tensioning operation, the post-tensioning will not be successful. In a way, the post-tensioning operation itself is the testing time for the anchorage block and for the concrete behind the anchorage block. For designing the end block for post-tensioning operation, we shall again come back to it when we look into the design of special reinforcement that is provided in the end block of the concrete, to resist the effect of the concentrated stresses.

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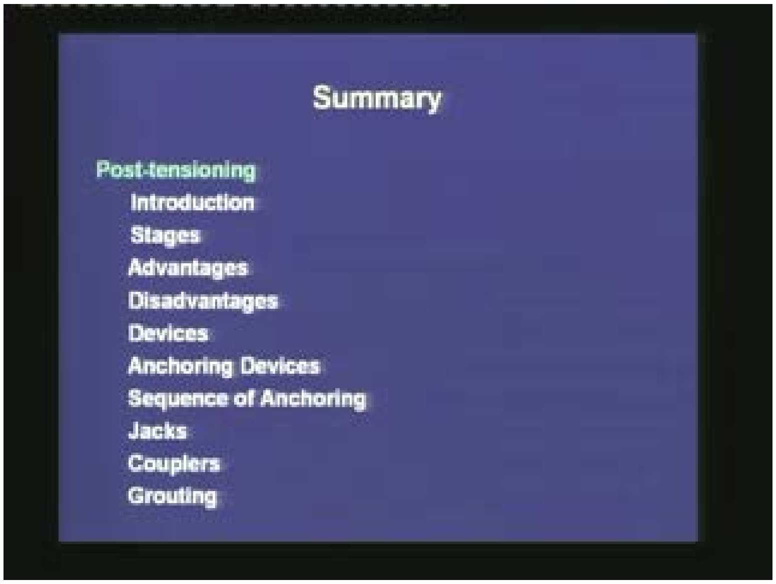

Thus in this lecture, we covered the systems and devices for the post-tensioning operation. Post-tensioning is the type of prestressing where the tendon is tensioned after the hardening of the concrete. The important stages of post-tensioning are, at the first, the concrete is cast with a duct inside it. The duct can have a curved profile depending on the moment the member will be subjected to during its service life. The duct should be free of any debris and also, it should not get bent too much so that there will be difficulty in passing the tendon later on.

Once the concrete is cast, cured and hardened to the desired strength, the tendon is passed through the duct. It is anchored at one end, the jack is placed on the other end and the tension is applied. Once the tension is applied, the double acting jack helps to place the anchorage blocks and the wedges on the concrete. The excess amount of the tendon is cut off and the jacks are removed. For grouted post-tensioned beams, grout is pumped through one end of the beam till the grout fills up the full annular space between the prestressed tendon and the duct. It is ensured by having excess amount of grout escaping through the other end.

The advantages of post-tensioning as compared to pre-tensioning are: the post-tensioning is suitable for heavy, bulky sections. Especially, if we do not have equipments to transport the heavy members, and if we have to cast the members at site, then post-tensioning can be adopted to prestress the member. Post-tensioning can also be used for precast members, where the members are made in a controlled environment and then we need some transportation device to transport the member from the precasting yard to the site.

Another advantage of post-tensioning is that it does not depend on the transmission length for the transfer of prestress. The transfer of prestress in a post-tensioned member mostly occurs by the anchorage blocks. Hence, the design of the anchorage blocks and the design of the end block in the concrete adjacent to the anchorage block are important. We do not solely rely on the bond between the prestressed tendon and the concrete, as we do for the pre-tensioned members.

The disadvantages of post-tensioning system as compared to pre-tensioning is that for post-tensioning, we need additional anchorage devices which are much more involved than pre-tensioned members, and also we need some grouting equipment for the bonded pre-tensioning system. Transporting these equipments, transporting the jacks can be difficult, if the post-tensioning operation is done in a remote site.

The devices that we need for a post-tensioning operation is an ordinary casting bed, the shuttering, ducts, the anchorage device, and the jacks. We may also need couplers, if we have post-tensioning for continuous systems; and we may also need the grouting equipment, if we prefer a grouted post-tensioned system. The sequence of anchoring is extremely important: first, the tendons are passed through the duct; then at one side the anchorage block is placed; on the other side, a set of anchorage blocks and the jacks are placed. The jacks are usually double acting jacks, which mean that the pistons can move in either direction.

Once we pass the tendons through the jack, another anchorage block is placed at the end of the jack. First, the piston moves away from the member which helps to apply tension in the tendons. Next, the other piston moves inwards, which ensures the sitting of the wedges and the anchorage blocks in the concrete; then the extra amount of tendons is cut and the jacks are removed. The jacking operation itself is a difficult operation. It is the testing time for the quality of the concrete and the anchorage block. Extreme care has to be taken when high prestressing force is applied to heavy members because, unless the concrete is of good quality, if there are any honeycombs in the concrete then the end block will not be adequate and the anchorage will not be satisfactory. Hence, extreme care is required during the post-tensioning operation.

The jacks have to be of high capacity, because most of the post-tensioning operation involves high prestressing force. Double acting jacks are preferred, because then it is convenient to set the anchorage block on the prestressed member. If we are prestressing continuous systems, like say flat slabs in buildings or continuous bridge decks, then we need couplers to join the strands. We had seen different types of patented couplers. In one type, we have seen all the strands from the two sides being anchored at one location. The couplers use the principle of wedge action. The whole unit is placed within a casing. Once the coupling is done, then it is filled up with grout to check any corrosion. There can be other types of couplers where all the strands are not coupled at one location. The coupling of the individual strands is staggered to avoid any weak location. The couplers have to be tested before they are used for a specific purpose. Even the anchorage devices are also tested to check their strength, and to check their performance under time varying load. To check their fatigue characteristics is also important when the anchorage devices are used for bridge decks.

Another equipment we have learnt about is the grouting equipment. Grouting is an important stage of post-tensioning where we ensure that the grout is of good quality. It will provide an anti-corrosive environment so that it will check any sort of corrosion of the prestressing tendons. Also, the grout should be strong enough to transfer the bond between the tendon and the concrete. The grout should be strong throughout the service life of the prestressed member.

To summarize, today we covered post-tensioning. We saw the stages, the advantages and disadvantages of post-tensioning. We covered the devices for post-tensioning: we learnt about the anchorage devices, the sequence of anchoring, the jacks, the couplers and the grouting equipment.

Thank you.