1

INTRODUCTION

1-1 Development of Prestressed Concrete

The development of structural materials can be described along three different columns, as in Fig. 1-1. Column 1 shows materials resisting compression, starting with stones and bricks, then developing into concrete and more recently high-strength concrete. For materials resisting tension, people used bamboo, and ropes, then iron bars and steel, then high-strength steel. Column 3 indicates materials which resist both tension and compression, namely, bending. Timber was utilized, then structural steel, reinforced concrete and finally prestressed concrete was developed.

The main difference between reinforced and prestressed concrete is the fact that reinforced concrete combines concrete and steel bars by simply putting them together and letting them act together as they may wish. Prestressed concrete, on the other hand, combines high-strength concrete with high-strength steel in an "active" manner. This is achieved by tensioning the steel and holding it against the concrete, thus putting the concrete into compression. This active combination results in a much better behavior of the two materials. Steel is ductile and now is made to act in high tension by prestressing. Concrete is a brittle material with its tensile capacity now improved by being compressed, while its compressive capacity is not really harmed. Thus prestressed concrete is an ideal combination of two modern high strength materials.

The historical development of prestressed concrete actually started in a different manner when prestressing was only intended to create permanent compression in concrete to improve its tensile strength. Later it became clear that prestressing the steel was also essential to the efficient utilization of high-tensile steel. Prestressing means the intentional creation of permanent stresses in a structure or assembly, for the purpose of improving its behavior and strength under various service conditions.

Throughout this chapter, photographs of significant structures designed in prestressed concrete using this fundamental concept will be shown. Note that the basic idea and the high-strength materials have now become a vital part of modern structural engineering practice.

The basic principle of prestressing was applied to construction perhaps centuries ago, when ropes or metal bands were wound around wooden staves to form barrels (Fig. 1-2). When the bands were tightened, they were under tensile

The basic principle of prestressing is not limited to structures in concrete; it has been applied to steel construction as well. When two plates are joined together by hot-driven rivets or high-tensile bolts, the connectors are highly prestressed in tension and the plates in compression, thus enabling the plates to carry tensile loads between them. The Sciotoville bridge, of 720-ft (219.5 m) spans, had its members prestressed in bending during erection in order to neutralize the secondary stresses due to live and dead loads.[4] A continuous truss prestressed with high-tensile wires was built into the airplane hangars at Brussels, Belgium, and two similar ones were tested at the University of Ghent.[5]

Whether prestressing is applied to steel or concrete, its ultimate purpose is twofold: first, to induce desirable strains and stresses in the structure; second, to counterbalance undesirable strains and stresses. In prestressed concrete, the steel is preelongated so as to avoid excessive lengthening under service load, while the concrete is precompressed so as to prevent cracks under tensile stress. Thus an ideal combination of the two materials is achieved. The basic desirability of prestressed concrete is almost selfevident, but its widespread application will be advanced by engineers' acquaintance with its principles and practice and further development of its design and construction.

1-2 General Principles of Prestressed Concrete

One of the best definitions of prestressed concrete is given by the ACI Committee on Prestressed Concrete.

> Prestressed concrete: Concrete in which there have been introduced internal stresses of such magnitude and distribution that the stresses resulting from given external loadings are counteracted to a desired degree. In reinforced-concrete members the prestress is commonly introduced by tensioning the steel reinforcement.

It might be added that prestressed concrete, in the broader sense of the term, might also include cases where the stresses resulting from internal strains are counteracted to a certain degree, such as in arch compensation. This book, however, will deal essentially with prestressed-concrete structures as defined by the ACI Committee, and will limit itself to prestressing as introduced by the tensioning of steel reinforcement, known as tendons. The tendon, as defined in Appendix A, may consist of high-strength steel strands, wires, or bars as described in Chapter 2. This is presently by far the most common form of prestressed concrete and the greater part of this chapter as well as this book will discuss this type.

Three different concepts may be applied to explain and analyze the basic behavior of this form of prestressed concrete. It is important that a designer understands all three concepts so that he or she can proportion and design prestressed concrete structures with intelligence and efficiency. These will be explained as follows.

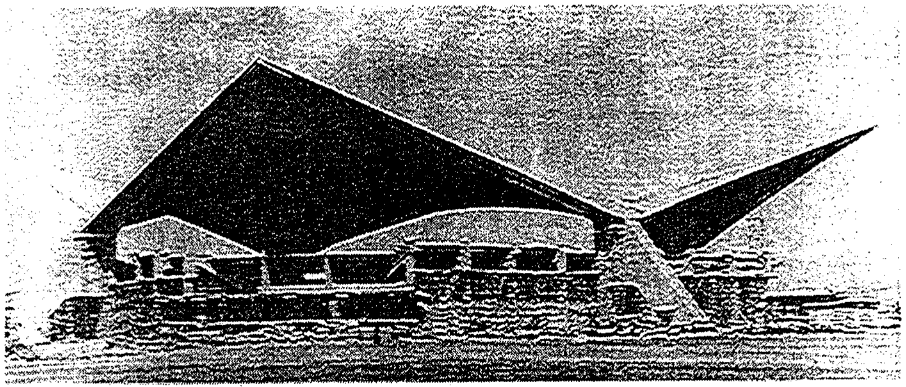


Fig. 1-11. Ponce Coliseum, Puerto Rico. Cantilevers 138 ft with 4 in. thin hyperbolic paraboloid shell and slender edge beams (T. Y. Lin International, Consulting Engineers). See also Fig. 15-12 for more details.

First Concept—Prestressing to Transform Concrete into an Elastic Material. This concept treats concrete as an elastic material and is probably still the most common viewpoint among engineers. It is credited to Eugene Freyssinet who visualized prestressed concrete as essentially *concrete* which is transformed from a brittle material into an elastic one by the precompression given to it. Concrete which is weak in tension and strong in compression is compressed (generally by steel under high tension) so that the brittle concrete would be able to withstand tensile stresses. From this concept the criterion of no tensile stresses was born. It is generally believed that if there are no tensile stresses in the concrete, there can be no cracks, and the concrete is no longer a brittle material but becomes an elastic material.

From this standpoint concrete is visualized as being subject to two systems of forces: internal prestress and external load, with the tensile stresses due to the external load counteracted by the compressive stresses due to the prestress. Similarly, the cracking of concrete due to load is prevented or delayed by the precompression produced by the tendons. So long as there are no cracks, the stresses, strains, and deflections of the concrete due to the two systems of forces can be considered separately and superimposed if necessary.

In its simplest form, let us consider a simple rectangular beam prestressed by a tendon through its centroidal axis (Fig. 1-13) and loaded by external loads. The tensile prestress force F in the tendon produces an equal compressive force F in the concrete, which also acts at the centroid of the tendon. In this case the force is at the centroid of the cross section. Due to the prestress F, a uniform compressive stress of

$$f=\frac{F}{A} \tag{1-1}$$

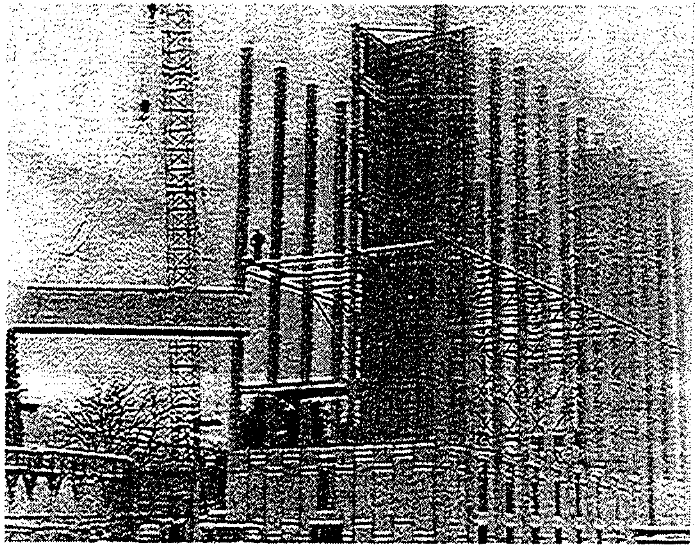


Fig. 1-12. An all-precast, nine-story office building under construction, University of California, Davis; 90-ft columns, floor panels, and exterior walls are all of precast, pretensioned concrete (Architect Gardner A. Dailey, T. Y. Lin International, Consulting Engineers). See also Fig. 14-7, photo of column being erected for this structure.

will be produced across the section that has an area A. If M is the external moment at a section due to the load on and the weight of the beam, then the stress at any point across that section due to M is

$$f=\frac{My}{I} \tag{1-2}$$

where y is the distance from the centroidal axis and I is the moment of inertia of the section. Thus the resulting stress distribution is given by

$$f=\frac{F}{A}\pm\frac{My}{I} \tag{1-3}$$

as shown in Fig. 1-13.

The solution is slightly more complicated when the tendon is placed eccentrically with respect to the centroid of the concrete section, Fig. 1-14. Here the resultant compressive force F in the concrete acts at the centroid of the tendon which is at a distance e from the c.g.c. as shown in Fig. 1-14. Due to an eccentric prestress, the concrete is subject to a moment as well as a direct load. The

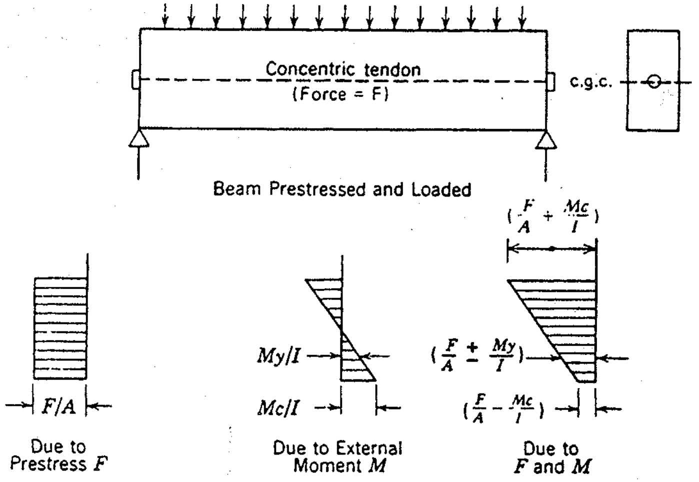


Fig. 1-13. Stress distribution across a concentrically prestressed-concrete section.

moment produced by the prestress is Fe, and the stresses due to this moment are

$$f=\frac{Fey}{I} \tag{1-4}$$

Thus, the resulting stress distribution is given by

$$f=\frac{F}{A}\pm\frac{Fey}{I}\pm\frac{My}{I} \tag{1-5}$$

as shown in the figure.

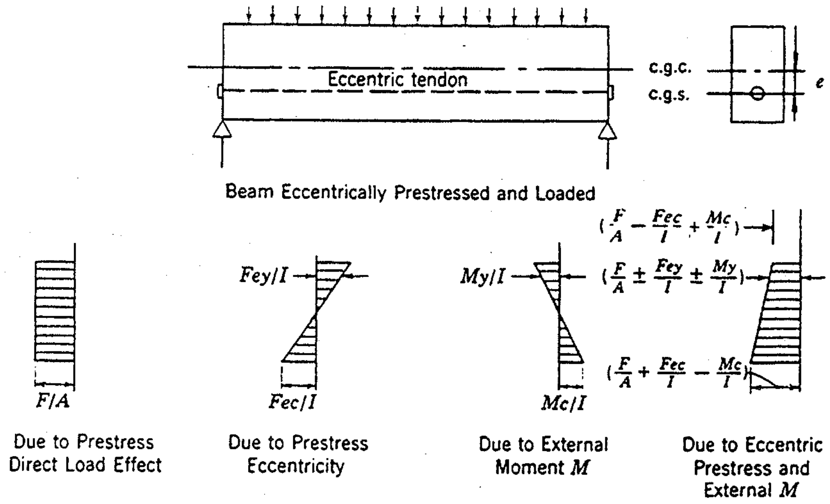


Fig. 1-14. Stress distribution across an eccentrically prestressed-concrete section.

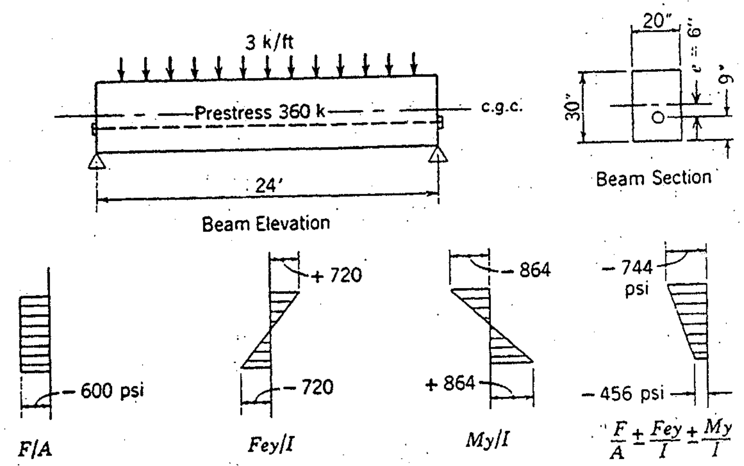


Fig. 1-15. Example 1-1.

EXAMPLE 1-1
A prestressed-concrete rectangular beam 20 in. by 30 in. has a simple span of 24 ft and is loaded by a uniform load of 3 k/ft including its own weight, Fig. 1-15. The prestressing tendon is located as shown and produces an effective prestress of 360 k. Compute fiber stresses in the concrete at the midspan section (span = 7.31 m, load = 43.8 kN/m and $F = 1601$ kN).

Solution Using formula 1-5, we have $F = 360$ k, $A = 20 \times 30 = 600$ in.^{2} (neglecting any hole due to the tendon), $e = 6$ in., $I = bd^3/12 = 20 \times 30^3/12 = 45{,}000$ in.^{4}; $y = 15$ in. for extreme fibers.

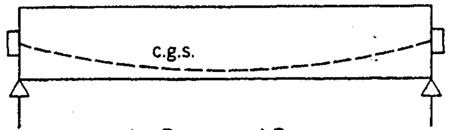
$$M = 3 \times 24^2/8 = 216 \text{ k-ft } (293 \text{ kN}-\text{m})$$

Therefore, assuming compressive stress negative, we have

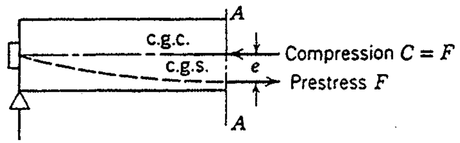
$$
\begin{aligned}
f &= \frac{F}{A} \pm \frac{Fey}{I} \pm \frac{My}{I} \\
&= \frac{-360{,}000}{600} \pm \frac{360{,}000 \times 6 \times 15}{45{,}000} \pm \frac{216 \times 12{,}000 \times 15}{45{,}000} \\
&= -600 \pm 720 \pm 864 \\
&= -600 + 720 - 864 = -744 \text{ psi } (-5.13 \text{ N/mm}^2) \text{ for top fiber} \\
&= -600 - 720 + 864 = -456 \text{ psi } (-3.14 \text{ N/mm}^2) \text{ for bottom fiber}
\end{aligned}
$$

The resulting stress distribution is shown in Fig. 1-15.

When the tendons are curved or bent, Fig. 1-16(*a*), it is often convenient to take either the left or the right portion of the member as a freebody in order to evaluate the effect of the prestressing force *F*. Note that the resultant compression on the concrete due to prestress alone is equal to the tendon force *F* acting at eccentricity *e*. Thus, in Fig. 1-16(*b*), equilibrium of horizontal forces indicates that the compression in the concrete equals the prestress in the steel *F*, and the stresses in the concrete due to eccentric force *F* is given by,



(*a*) Prestressed Beam

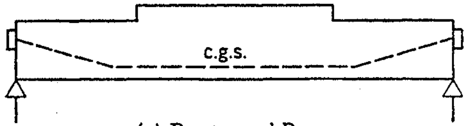


(*b*) Freebody

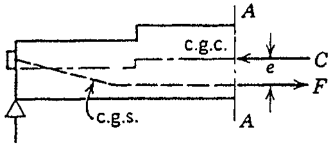
Fig. 1-16. Effect of prestress.

$$f = \frac{F}{A} \pm \frac{Fec}{I}$$

Thus, concrete stresses *f* at a section due to prestress are dependent only on the magnitude and location of *F* at that section, regardless of how the tendon profile may vary elsewhere along the beam. For example, if section *A*-*A* of the beam in Fig. 1-17 is identical with section *A*-*A* in Fig. 1-16, the concrete stresses due to prestress *F* with eccentricity *e* are identical for the two sections, regardless of variations in the shape of the beam or the cable profile away from the section. (This is true only for the statically determinate members wherein external reactions are not affected by the internal prestressing. See Chapters 10 and 11 for statically indeterminate systems.)

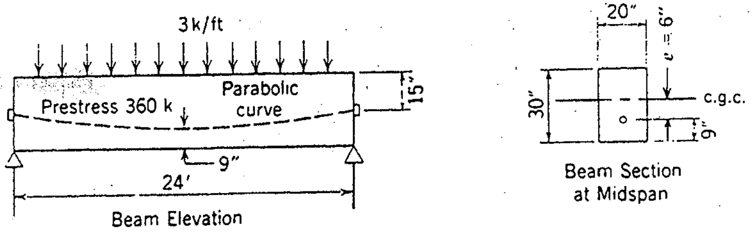


(*a*) Prestressed Beam



(*b*) Freebody

Fig. 1-17. Prestress effect is not related to variations away from section for a statically determinate member.



Beam Elevation

Beam Section at Midspan

Fig. 1-18. Example 1-2.

EXAMPLE 1-2
A concrete beam with the same span, loading, section, and prestress as in example 1-1 has a parabolically curved tendon as shown, Fig. 1-18. Compute the extreme fiber stresses at midspan.

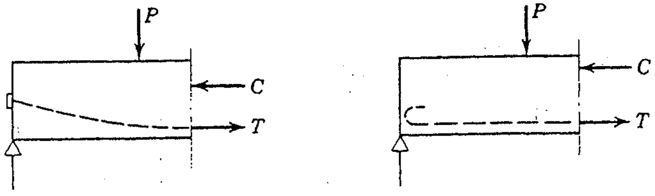
Solution The beam section at midspan is shown in the figure and is identical with the section in Fig. 1-15 for example 1-1. Hence exactly the same calculation for example 1-1 will apply, and the extreme fiber stresses are also the same at midspan,

Top fiber −744 psi ($-5.13\ \mathrm{N/mm^2}$) (compression)

Bottom fiber −456 psi ($-3.14\ \mathrm{N/mm^2}$) (compression)

Second Concept—Prestressing for Combination of High-Strength Steel with Concrete. This concept is to consider prestressed concrete as a combination of steel and concrete, similar to reinforced concrete, with steel taking tension and concrete taking compression so that the two materials form a resisting couple against the external moment, Fig. 1-19. This is often an easy concept for engineers familiar with reinforced concrete where the steel supplies a tensile force and the concrete supplies a compressive force, the two forces forming a couple with a lever arm between them. Few engineers realize, however, that similar behavior exists in prestressed concrete.

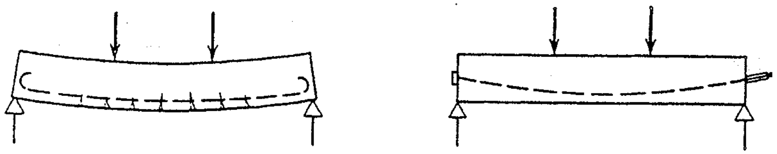
In prestressed concrete, high-tensile steel is used which will have to be elongated a great deal before its strength is fully utilized. If the high-tensile steel is simply buried in the concrete, as in ordinary concrete reinforcement, the surrounding concrete will have to crack very seriously before the full strength of the steel is developed, Fig. 1-20. Hence it is necessary to prestretch the steel with respect to the concrete. By prestretching and anchoring the steel against the concrete, we produce desirable stresses and strains in both materials: compressive stresses and strains in concrete, and tensile stresses and strains in steel. This combined action permits the safe and economical utilization of the two materials which cannot be achieved by simply burying steel in the concrete as is done for ordinary reinforced concrete. In isolated instances, medium-strength steel has been used as simple reinforcement without prestressing, and the steel was specially corrugated for bond, in order to distribute the cracks. This process avoids the expenses for prestretching and anchoring high-tensile steel but does not have the desirable effects of precompressing the concrete and of controlling the deflections.



Portion of Prestressed Beam

Portion of Reinforced Beam

Fig. 1-19. Internal resisting moment in prestressed- and reinforced-concrete beams.



Simply Reinforced—cracks and excessive deflections

Prestressed—no cracks and only small deflections

Fig. 1-20. Concrete beam using high-tensile steel.

From this point of view, prestressed concrete is no longer a strange type of design. It is rather an extension and modification of the applications of reinforced concrete to include steels of higher strength. From this point of view, prestressed concrete cannot perform miracles beyond the capacity of the strength of its materials. Although much ingenuity can be exercised in the proper and economic design of prestressed-concrete structures, there is absolutely no magic method to avoid the eventual necessity of carrying an external moment by an internal couple. And that internal resisting couple must be supplied by the steel in tension and the concrete in compression, whether it be prestressed or reinforced concrete. This concept has been well utilized to determine the ultimate strength of prestressed concrete beams and is also applicable to their elastic behavior.

Once the engineer sees this viewpoint, he or she understands the basic similarity between prestressed and reinforced concrete. Then much of the complexity of prestressing disappears, and the design of prestressed concrete can be intelligently accomplished and not performed by groping in the dark among a lot of complicated and confusing formulas.

The following example illustrates a simple application of the above principle in the analysis of prestressed-concrete beams; more extensive treatment will be presented in Chapter 6.

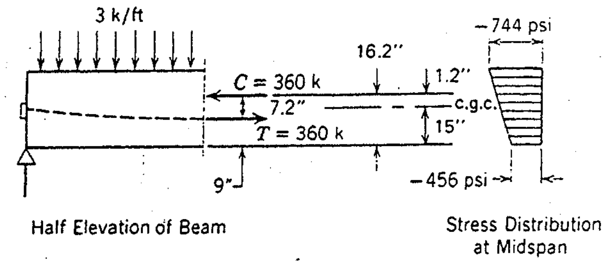


Fig. 1-21. Example 1-3.

EXAMPLE 1-3

Solve the problem stated in example 1-2 by applying the principle of the interal resisting couple.

Solution Take one half of the beam as a freebody, thus exposing the internal couple, Fig. 1-21. The external moment at the section is

$$M=\frac{wL^2}{8}$$

$$=\frac{3\times 24^2}{8}$$

$$=216\text{ k-ft }(293\text{ kN-m})$$

The internal couple is furnished by the forces $C=T=360$ k, which must act with a lever arm of

$$\frac{216}{360}\times 12=7.2\text{ in. }(183\text{ mm})$$

Since T acts at 9 in. from the bottom, C must be acting at 16.2 in. from it. Thus the center of the compressive force C is located.

So far we have been dealing only with statics, the validity of which is not subject to any question. Now, if desired, the stress distribution in the concrete can be obtained by the usual elastic theory, since the center of the compressive force is already known. For $C=360{,}000$ lb (1,601 kN) acting with an eccentricity of $16.2-15=1.2$ in. (30.48 mm),

$$f=\frac{F}{A}\pm\frac{Mc}{I}$$

$$=\frac{-360{,}000}{600}\pm\frac{360{,}000\times 1.2\times 15}{45{,}000}$$

$$=-600\mp 144$$

$$=-744\text{ psi }(-5.13\text{ N/mm}^2)\text{ for top fiber}$$

$$=-456\text{ psi }(-3.14\text{ N/mm}^2)\text{ for bottom fiber}$$

Third Concept—Prestressing to Achieve Load Balancing. This concept is to visualize prestressing primarily as an attempt to balance the loads on a member. This concept was essentially developed by the author, although undoubtedly also utilized by other engineers to a lesser degree.

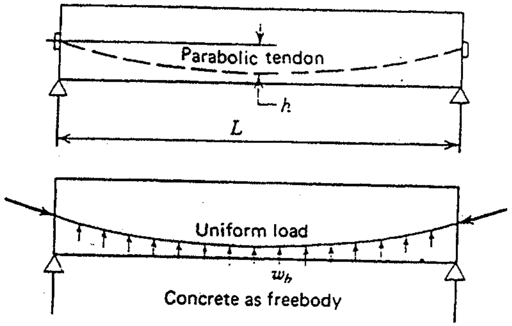


Fig. 1-22. Prestressed beam with parabolic tendon.

In the overall design of a prestressed concrete structure, the effect of prestressing is viewed as the balancing of gravity loads so that members under bending such as slabs, beams, and girders will not be subjected to flexural stresses under a given loading condition. This enables the transformation of a flexural member into a member under direct stress and thus greatly simplifies both the design and analysis of otherwise complicated structures.

The application of this concept requires taking the concrete as a freebody, and replacing the tendons with forces acting on the concrete along the span.

Take, for example, a simple beam prestressed with a parabolic tendon (Fig. 1-22) if

$F=$ prestressing force
$L=$ length of span
$h=$ sag of parabola

The upward uniform load is given by

$$w_b=\frac{8Fh}{L^2}$$

Thus, for a given downward uniform load w, the transverse load on the beam is balanced, and the beam is subjected only to the axial force F, which produces uniform stresses in concrete, $f=F/A$. The change in stresses from this balanced condition can easily be computed by the ordinary formulas in mechanics, $f=Mc/I$. The moment in this case is the unbalanced moment due to $(w-w_b)$, the unbalanced load. Figure 1-23 shows load balancing applied to the Arizona State Fair Colliseum roof structure.

For a beam with bent tendon, Fig. 1-24, the load from the tendon on the concrete can easily be determined by statics. This approach, while unnecessarily cumbersome for some simple cases, often becomes very effective for complicated structures, such as continuous beams, rigid frames, flat and waffle slabs, and some thin shells, which will be explained more fully in Chapter 11. When further extended, it can be used for the design and analysis of self-anchored,

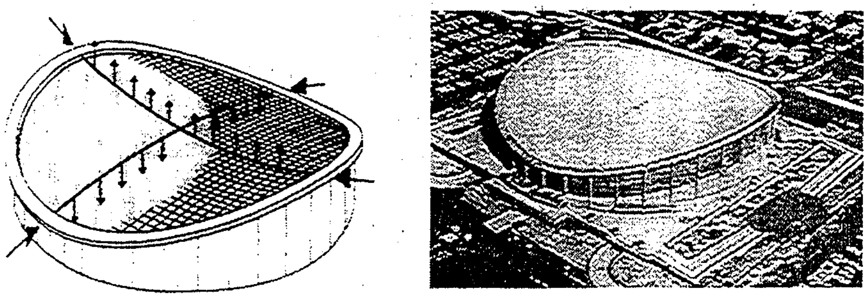


Fig. 1-23. Arizona State Fair Coliseum 380 ft diameter hyperbolic paraboloid shell of lightweight concrete waffles $2\frac{1}{2}$ in. thick (T. Y. Lin International, Consulting Engineers).

prestressed-concrete bridges, when the force from the steel cable on the concrete roadway and girders can be predetermined, and the stresses in the concrete analyzed without much difficulty.

EXAMPLE 1-4

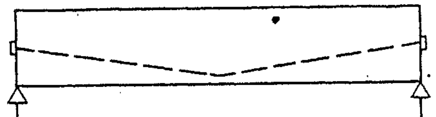
Solve the problem in example 1-2 by the method of load balancing taking the concrete as freebody, isolated from the tendon or steel, Fig. 1-25.

Solution The upward uniform force from the tendon on the concrete is

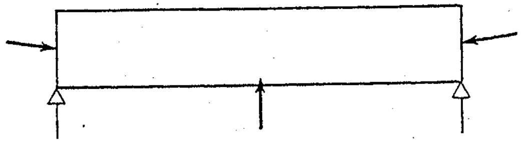
$$w_b=\frac{8Fh}{L^2}$$

$$=\frac{8\times360\times(6/12)}{24^2}$$

$$=2.5\text{ k/ft }(36.5\text{ kN/m})$$

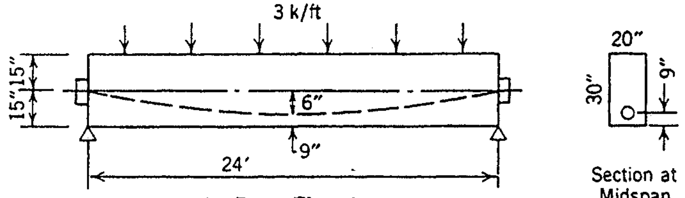


Beam with Bent Tendon

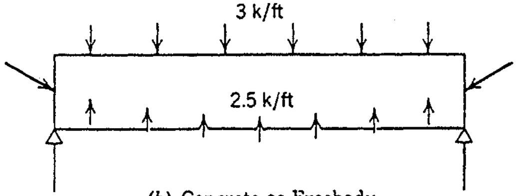


Freebody of Concrete, with
Tendon Replaced by Forces

Fig. 1-24. Prestressed beam with bent tendon.



(a) Beam Elevation



(b) Concrete as Freebody

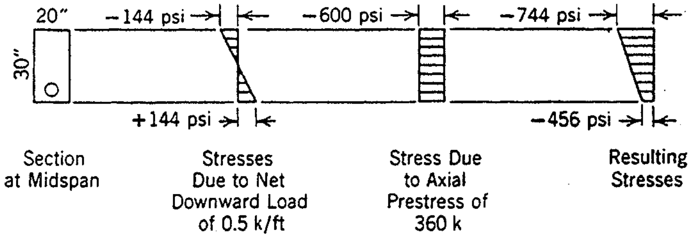


Fig. 1-25. Example 1-4.

Hence the net downward (unbalanced) load on the concrete beam is $(3-2.5)=0.5$ k/ft (7.3 kN/m), and the moment at midspan due to that load is

$$M=\frac{wL^2}{8}=\frac{0.5\times24^2}{8}$$

$$=36\text{ k-ft }(48.8\text{ kN}-\text{m})$$

The fiber stresses due to that moment are

$$f=\frac{Mc}{I}=\frac{6M}{bd^2}$$

$$=\frac{6\times36\times12{,}000}{20\times30^2}$$

$$=144\text{ psi }(0.993\text{ N/mm}^2)\text{ (compression top fiber; tension bottom fiber)}$$

The fiber stress due to the direct load effect of the prestress is very nearly

$$\frac{F}{A}=\frac{-360{,}000}{20\times 30}$$

$$=-600\text{ psi }(-4.14\text{ N/mm}^2)\text{ compression}$$

The resulting stresses are

$$-144-600=-744\ (-5.13\text{ N/mm}^2)\text{ top fiber comp.}$$

$$+144-600=-456\ (-3.14\text{ N/mm}^2)\text{ bottom fiber comp.}$$

the same as in examples 1-2 and 1-3.

1-3 Classification and Types

Prestressed-concrete structures can be classified in a number of ways, depending upon their features of design and construction. These will be discussed as follows.

Externally or Internally Prestressed. Although this book is devoted to the design of prestressed-concrete structures internally prestressed, presumably with high-tensile steel, it must be mentioned that it is sometimes possible to prestress a concrete structure by adjusting its external reactions. The method of arch compensation was mentioned previously, where a concrete arch was prestressed by jacking against its abutments. Theoretically, a simple concrete beam can also be externally prestressed by jacking at the proper places to produce compression in the bottom fibers and tension in the top fibers, Fig. 1-26, thus even dispensing with steel reinforcement in the beam. Such an ideal arrangement, however, cannot be easily accomplished in practice, because, even if abutments favorable for such a layout are obtainable, shrinkage and creep in concrete may completely offset the artificial strains unless they can be readjusted. Besides, such a site would probably be better suited for an arch bridge.

For a statically indeterminate structure, like a continuous beam, it is possible to adjust the level of the supports, by inserting jacks, for example, so as to produce the most desirable reactions, Fig. 1-27. This is sometimes practical, though it must be kept in mind that shrinkage and creep in concrete will modify the effects of such prestress so that they must be taken into account or else the prestress must be adjusted from time to time.

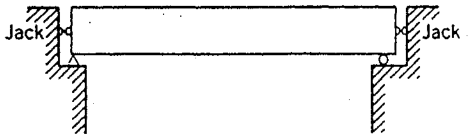


Fig. 1-26. Prestressing a simple concrete beam by jacking against abutments.

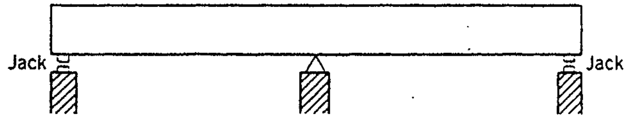


Fig. 1-27. Prestressing a continuous beam by jacking its reactions.

Linear or Circular Prestressing. Circular prestressing is a term applied to prestressed circular structures, such as round tanks, silos, and pipes, where the prestressing tendons are wound around in circles. This topic is discussed in Chapter 13. As distinguished from circular prestressing, the term linear prestressing is often employed to include all other structures such as beams and slabs. The prestressing tendons in linearly prestressed structures are not necessarily straight; they can be either bent or curved, but they do not go round and round in circles as in circular prestressing.

Pretensioning and Posttensioning. The term pretensioning is used to describe any method of prestressing in which the tendons are tensioned before the concrete is placed. It is evident that the tendons must be temporarily anchored against some abutments or stressing beds when tensioned and the prestress transferred to the concrete after it has set. This procedure is employed in precasting plants or laboratories where permanent beds are provided for such tensioning; it is also applied in the field where abutments can be economically constructed. In contrast to pretensioning, posttensioning is a method of prestressing in which the tendon is tensioned after the concrete has hardened. Thus the prestressing is almost always performed against the hardened concrete, and the tendons are anchored against it immediately after prestressing. This method can be applied to members either precast or cast in place.

End-Anchored or Non-End-Anchored Tendons. When posttensioned, the tendons are anchored at their ends by means of mechanical devices to transmit the prestress to the concrete. Such a member is termed end anchored. A posttensioned member may have its tendons held by grout after mechanical end anchorage has allowed the stressing to be accomplished, but the end anchorage hardware is still required during construction. Grouting is described below in connection with bonded or unbonded classification of posttensioned members. In pretensioning, the tendons generally have their prestress transmitted to the concrete by their bond action near the ends. The effectiveness of such stress transmission is limited to wires of small size, and to larger diameter strands which possess better bond properties than smooth wires. The most common type material for pretensioning is seven-wire strand, which is also used in many posttensioning systems. Different types of end anchorages will be discussed in Chapter 3.

Bonded or Unboned Tendons. Bonded tendons denote those bonded throughout their length to the surrounding concrete. Non-end-anchored tendons are necessarily bonded ones; end-anchored tendons may be either bonded or unbonded to the concrete. In general, the bonding of posttensioned tendons is accomplished by subsequent grouting; if unbonded, protection of the tendons from corrosion must be provided by galvanizing, greasing, or some other means. Typically, the unbonded tendon is greased and wrapped with paper or plastic material to prevent bonding to the surrounding concrete. Sometimes, bonded tendons may be purposely unbonded along certain portions of their length.

Precast, Cast-in-Place, Composite Construction. Precasting involves the placing of concrete away from its final position, the members being cast either in a permanent plant or somewhere near the site of the structure, and eventually erected at the final location. Precasting permits better control in mass production and is often economical. Cast-in-place concrete requires more form and falsework per unit of product but saves the cost of transportation and erection, and it is a necessity for large and heavy members. In between these two methods of construction, there are tilt-up wall panels and lift slabs which are constructed at places near or within the structure and then erected to their final position; no transportation is involved for these. Oftentimes, it is economical to precast part of a member, erect it, and then cast the remaining portion in place. This procedure is called composite construction. The precast elements in a structure of composite construction can be more easily joined together than those in a totally precast structure. By composite construction, it is possible to save much of the form and falsework required for total cast-in-place construction. However, the suitability of each type must be studied with respect to the particular conditions of a given structure.

Partial or Full Prestressing. A further distinction between the types of prestressing is sometimes made depending on the degree of prestressing to which a concrete member is subject. When a member is designed so that under the working load there are no tensile stresses in it, then the concrete is said to be fully prestressed. If some tensile stresses will be produced in the member under working load, then it is termed partially prestressed. For partial prestressing, additional mild-steel bars are frequently provided to reinforce the portion under tension. In practice, it is often difficult to classify a structure as being partially or fully prestressed since much will depend on the magnitude of the working load used in design. For example, highway bridges in this country may be designed for full prestressing, though actually they are subject to tensile stresses during the passage of exceptionally heavy vehicles. On the other hand, roof beams designed for partial prestressing may never be subject to tensile stresses since the assumed live loads may never act on them. Partial prestressing is further discussed in section 1-6 and in Chapter 9.

1-4 Stages of Loading

One of the considerations peculiar to prestressed concrete is the plurality of stages of loading to which a member or structure is often subjected. Some of these stages of loading occur also in nonprestressed structures, but others exist only because of prestressing. For a cast-in-place structure, prestressed concrete has to be designed for at least two stages; the initial stage during prestressing and the final stage under external loadings. For precast members, a third stage, that of handling and transportation, has to be investigated. During each of these three stages, there are again different periods when the member or structure may be under different loading conditions. These will now be analyzed. Table 1-2 summarizes the permissible stresses.

Initial Stage. The member or structure is under prestress but is not subjected to any superimposed external loads. This stage can be further subdivided into the following periods, some of which may not be important and therefore may be neglected in certain designs.

TABLE 1-2 Permissible Stresses for Flexural Members (ACI Code)

Steel Stresses—not more than the following values:

1. Due to tendon jacking force,

$$0.80f_{pu} \quad \text{or} \quad 0.94f_{py}$$

whichever is smaller, but not greater than maximum value recommended by manufacturer of prestressing tendons or anchorages.

2. Pretensioned tendons immediately after transfer of prestress or posttensioned tendons after anchorage,

$$0.70f_{pu}$$

Concrete Stresses—not more than the following values:

1. Immediately after transfer of prestress (before losses), extreme fiber stress

Compression–$0.60f'_{ci}$

Tension–$3\sqrt{f'_{ci}}$ (except at ends of simply supported members where $6\sqrt{f'_{ci}}$ is permitted)

2. At service load after allowance for all prestress losses,

Compression–$0.45f'_c$

Tension[a]–$6\sqrt{f'_c}$

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[a] When analysis based on cracked sections and bilinear moment-deflection relationships show that immediate and long-time deflections satisfy Code limits, maximum tension is $12\sqrt{f'_c}$.

Before Prestressing. Before the concrete is prestressed, it is quite weak in carrying load; hence the yielding of its supports must be prevented. Provision must be made for the shrinkage of concrete if it might occur. When it is desirable to minimize or eliminate cracks in prestressed concrete, careful curing before the transfer of prestress is very important. Drying or sudden change in temperature must be avoided. Cracks may or may not be closed by the application of prestress, depending on many factors. Shrinkage cracks will destroy the capacity of the concrete to carry tensile stresses and may be objectionable.

During Prestressing. This is a critical test for the strength of the tendons. Often, the maximum stress to which the tendons will be subject throughout their life occurs at that period ($0.80f_{pu}$ or $0.94f_{py}$, Table 1-2). It occasionally happens that an individual wire may be broken during prestressing, owing to defects in its manufacture. But this break is seldom significant, since there are often many wires in a member. If a bar is broken in a member with only a few bars, it should be properly replaced. For concrete, the prestressing operations impose a severe test on the bearing strength at the anchorages. Since the concrete is not aged at this period while the prestress is at its maximum, crushing of the concrete at the anchorages is possible if its quality is inferior or if the concrete is honeycombed. Again, unsymmetrical and concentrated prestress from the tendons may produce overstresses in the concrete. Therefore the order of prestressing the various tendons must often be studied beforehand.

At Transfer of Prestress. For pretensioned members, the transfer of prestress is accomplished in one operation and within a short period. For posttensioned members, the transfer is often gradual, the prestress in the tendons being transferred to the concrete one by one. In both cases there is no external load on the member except its own weight. Thus the initial prestress, with little loss as yet taking place, imposes a serious condition on the concrete and often controls the design of the member. (Table 1-2 shows permissible steel and concrete stresses.) For economic reasons the design of a prestressed member often takes into account the weight of the member itself in holding down the cambering effect of prestressing. This is done on the assumption of a given condition of support for the member. If that condition is not realized in practice, failure of the member might result. For example, the weight of a simply supported prestressed girder is expected to exert a maximum positive moment at midspan which counteracts the negative moment due to prestressing. If the girder is cast and prestressed on soft ground without suitable pedestals at the ends, the expected positive moment may be absent and the prestressing may produce excessive tensile stresses on top fibers of the girder, resulting in its failure.

Decentering and Retensioning. If a member is cast and prestressed in place, it generally becomes self-supporting during or after prestressing. Thus the falsework can be removed after prestressing, and no new condition of loading is

imposed on the structure. Some concrete structures are retensioned, that is, prestressed in two or more stages. Then the stresses at various stages of tensioning must be studied.

Intermediate Stage. This is the stage during transportation and erection. It occurs only for precast members when they are transported to the site and erected in position. It is highly important to ensure that the members are properly supported and handled at all times. For example, a simple beam designed to be supported at the ends will easily break if lifted at midspan, Fig. 1-28. Figure 1-6 shows a correct way to lift a prestressed simple beam.

Not only during the erection of the member itself, but also when adding the superimposed dead loads, such as roofing or flooring, attention must be paid to the conditions of support and loading. This is especially true for a cantilever layout, when partial loading may result in more serious bending than a full loading, Fig. 1-30.

Final Stage. This is the stage when the actual working loads come on the structure. (Table 1-2 shows permissible stresses.) As for other types of construction, the designer must consider various combinations of live loads on different portions of th structure with lateral loads such as wind and earthquake forces, and with strain loads such as those produced by settlement of supports and temperature effects. For prestressed-concrete sturctures, especially those of unconventional types, it is often necessary to investigate their cracking and ultimate loads, their behavior under the actual sustained load in addition to the working load. These will be discussed as follows.

Sustained Load. The camber or deflection of a prestressed member under its actual sustained load (which often consists only of the dead load) is often the controlling factor in design, since the effect of flexural creep will eventually magnify its value. Hence it is often desirable to limit the camber or deflection under sustained load.

Working Load. To design for the working load is a check on excessive stresses and strains. It is not necessarily a guarantee of sufficient strength to

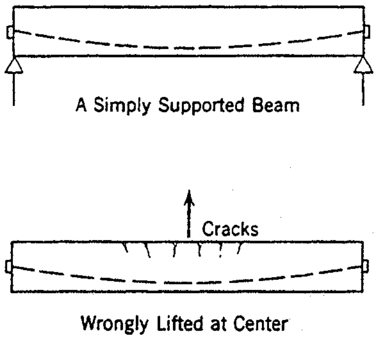

Fig. 1-28. Failure of beam due to careless handling.

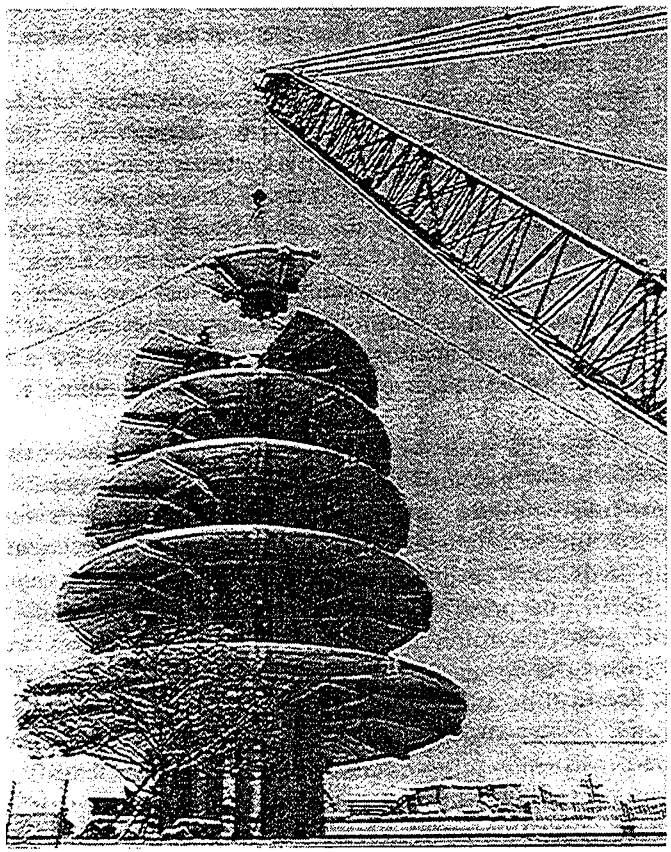

Fig. 1-29. Precast Pagoda Japanese Center, San Francisco, California, wound with circular posttensioning (T. Y. Lin International, Consulting Engineers).

carry overloads. However, an engineer familiar with the strength of prestressed-concrete structures may often design conventional types and proportions on the basis of working-load computations, then check strength.

Cracking Load. Cracking in a prestressed-concrete member signifies a sudden change in the bond and shearing stresses. It is sometimes a measure of the fatigue strength. For certain structures, such as tanks and pipes, the commencement of cracks presents a critical situation. For structures subject to corrosive influences, for unbonded tendons where cracks are more objectionable, or for structures where cracking may result in excessive deflections, an investigation of the cracking load seems important.

Ultimate Load. Structures designed on the basis of working stresses may not always possess a sufficient margin for overloads. Since it is required that a structure possess a certain minimum factored load capacity, it is necessary to determine its ultimate strength. In general, the ultimate strength of a structure is defined by the maximum load it can carry before collapsing. However, before this load is reached, permanent yielding of some parts of the structure may already have developed. Although any strength beyond the point of permanent yielding may serve as additional guarantee against total collapse, some engineers consider such strength as not usable and prefer to design on the basis of usable strength rather than the ultimate strength. However, ultimate strength is more easily computed and is commonly accepted as a criterion for design in prestressed concrete as with other structural systems. Table 1-3 summarizes the basic ACI Code strength requirements.

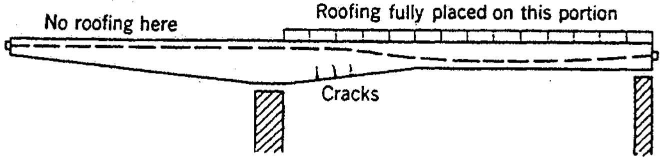

Fig. 1-30. Cracking of beam due to wrong sequence in adding superimposed load.

Table 1-3 Load Factors and Required Strength Under ACI Code

ACI Code Load Factors

$U = 1.4D + 1.7L$ (ACI 9-1)

where wind is included, see if one of the following is greater:

$U = 0.75(1.4D + 1.7L + 1.7W)$ (ACI 9.2)

or

$U = 0.9D + 1.3W$ (ACI 9-3)

where U = required strength

D = dead load

L = live load

W = wind load

Basic Required Strength[a]

Required Strength	$\leqslant$	Design Strength of Member
Req'd strength from factored loads	$\left\{\begin{matrix} M_u \leqslant \phi M_n \\ P_u \leqslant \phi P_n \\ V_u \leqslant \phi V_n \end{matrix}\right\}$	Member design strength is the strength reduction factor[b], ϕ, times the best estimate of member strength (nominal strength) $\phi = 0.90$ – flexure, M $\phi = 0.85$ – shear, V $\phi = 0.75$ – spiral column, P

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[a] Other equations in ACI 318-77 include load factors for earthquake, lateral earth pressure, lateral liquid pressure, and temperature effects in checking strength.

[b] See ACI Code for other ϕ values where the kind of stress is different from these; such as bearing pressure, axial tension, or flexure of plain concrete.

In addition to the above normal loading conditions, some structures may be subject to repeated loads of appreciable magnitude which might result in fatigue failures. Some structures may be under heavy loads of long duration, resulting in excessive deformations due to creep, while others may be under such light external loads that the camber produced by prestressing may become too pronounced as time goes on. Still others may be subject to undesirable vibrations under dynamic loads. Under a sudden impact load or under the action of earthquakes, the energy absorption capacity of the member as indicated by its ductility may be of prime importance. These are special conditions which the engineer must consider for his individual case.

The above discussion outlines the relatively new and complex problems encountered in the design of prestressed-concrete as compared with reinforced-concrete structures. It is unfortunate that the design of prestressed concrete is more complicated, but the difficulty is by no means excessive. The new problems must be understood and solved. Ignorance of the situation might result in tragic failures such as are experienced by careless practitioners in almost any new field of endeavor.

With some experience in design, many of the loading stages mentioned above are automatically eliminated from consideration by inspection. Calculations will actually have to be made for only one or two controlling conditions. Besides, as will be shown in later chapters, calculations can be greatly simplified if the correct methods of approach and analysis are chosen. It is the observation of the authors that an engineer who belittles the complications of prestressed-concrete design will encounter problems beyond his expectations, while the majority of engineers will find it not as difficult as they may imagine.

1-5 Prestressed vs. Reinforced Concrete

As it is assumed that readers are already acquainted with reinforced concrete, it will be interesting to compare prestressed concrete with it. The most outstanding difference between the two is the employment of materials of higher strength for prestressed concrete. In order to utilize the full strength of the high-tensile steel, it is necessary to resort to prestressing to prestretch it. Prestressing the steel and anchoring it against the concrete produces desirable strains and stresses which serve to reduce or eliminate cracks in concrete. Thus the entire section of the concrete becomes effective in prestressed concrete, whereas only the portion of section above the neutral axis is supposed to act in the case of reinforced concrete.

The use of curved tendons will help to carry some of the shear in a member. In addition, precompression in the concrete tends to reduce the principal tension, increasing shear strength. Thus it is possible to use a smaller section in prestressed concrete to carry the same amount of external shear in a beam. Hence more efficient I-shaped sections with thin webs become desirable with prestressed concrete.

High-strength concrete, which cannot be economically utilized in reinforced-concrete construction, is found to be desirable and even necessary with prestressed concrete. In reinforced concrete, using concrete of high strength will result in a smaller section calling for more reinforcement and will end with a more costly design. In prestressed concrete, high-strength concrete is required to match with high-strength steel in order to yield economical proportions. Stronger concrete is also necessary to resist high stresses at the anchorages and to give strength to the thinner sections so frequently employed for prestressed concrete.

Each material or method of construction has its own field of application. When welding was first developed in the 1930's, some engineers were overenthusiastic and believed that it would replace riveting altogether, which it has not done even yet. Prestressed concrete is likely to have a similar course of development. Not for a long time will it be used in as great quantity as reinforced concrete.

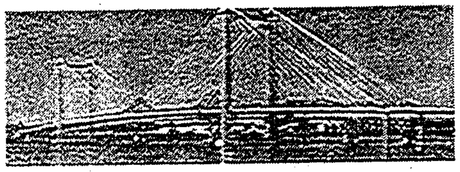
But this relatively new type of construction, basically sound in its strength and economy, has had a rapid rate of growth (Fig. 1-9) and is adaptable to new and unprecedented situations and requirements. The advantages and disadvantages of prestressed concrete as compared with reinforced concrete will now be discussed with respect to their serviceability, safety, and economy.

Serviceability. Prestressed-concrete design is more suitable for structures of long spans and those carrying heavy loads, principally because of the higher strengths of materials employed. Prestressed structures are more slender and hence more adaptable to artistic treatment. They yield more clearance where it is needed. They do not crack under working loads, and whatever cracks may be developed under overloads will be closed up as soon as the load is removed, unless the load is excessive. Under dead load, the deflection is reduced, owing to the cambering effect of prestress. This becomes an important consideration for such structures as long cantilevers. Under live load, the deflection is also smaller because of the effectiveness of the entire uncracked concrete section, which has a moment of inertia two to three times that of the cracked section. Prestressed elements are more adaptable to precasting because of the lighter weight.

So far as serviceability is concerned, the only shortcoming of prestressed concrete is its lack of weight. Although seldom encountered in practice, there are situations where weight and mass are desired instead of strength. For these situations, plain or reinforced concrete could often serve just as well and at lower cost.

Safety. It is difficult to say that one type of structure is safer than another. The safety of a structure depends more on its design and construction than on its type. However, certain inherent safety features in prestressed concrete may be mentioned. There is partial testing of both the steel and the concrete during prestressing operations. For many structures, during prestressing, both the steel and the concrete are subjected to the highest stresses that will exist in them during their life of service. Hence, if the materials can stand prestressing, they are likely to possess sufficient strength for the service loads.

When properly designed by the present conventional methods, prestressed-concrete structures have overload capacities similar to and perhaps slightly higher than those of reinforced concrete. For the usual designs, they deflect appreciably before ultimate failure, thus giving ample warning before impending collapse. The ability to resist shock and impact loads and repeated working loads has been shown to be as good in prestressed as in reinforced concrete. The resistance to corrosion is better than that of reinforced concrete for the same amount of cover, owing to the nonexistence of cracks and high quality of concrete used for prestressed members. If cracks should occur, corrosion can be more serious in prestressed concrete. Regarding fire resistance, high-tensile steel is more sensitive to high temperatures, but, for the same amount of minimum cover, prestressed tendons can have a greater average cover because of the



(a.) Completed Bridge–(with all 62 precast prestressed segments and cable stays in place).

(b.) During Construction–(lifting of precast prestressed segment in progress).

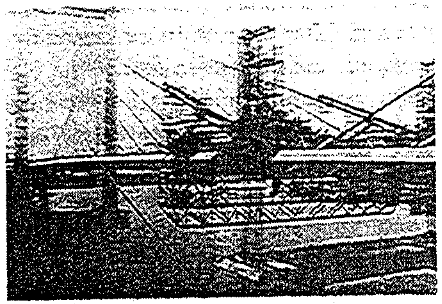


Fig. 1-31. Pasco-Kennewick Cable Stayed Bridge. The main center span is 981 ft (299 m) and the two adjacent spans are 406.5 ft (124 m). Of its total length of 2503 ft (760 m), over 1800 ft (550 m) are supported by steel stay-cables. This portion of the bridge is composed of 62 precast prestressed concrete segments 80 ft (24 m) wide and 27 ft (8.2 m) long. A uniform depth of 7 ft (2.1 m) was maintained for the continuous posttensioned girders (*Owners:* Cities of Pasco and Kennewick, Washington; *Engineer:* Arvid Grant & Associates, Inc.; *General Contractor:* Peter Kiewit Sons' Co.). (Prestressed Concrete Institute)

spread and curvature of the individual tendons. These problems are discussed in Chapter 16.

Prestressed-concrete members do require more care in design, construction, and erection than those of ordinary concrete, because of the higher strength, smaller section, and sometimes delicate design features involved. Although prestressed-concrete construction has been practiced only since the late 1940's, it is possible to conclude from experience that the life of such structures can be as long as if not longer than that of reinforced concrete.

Economics. From an economic point of view, it is at once evident that smaller quantities of materials, both steel and concrete, are required to carry the

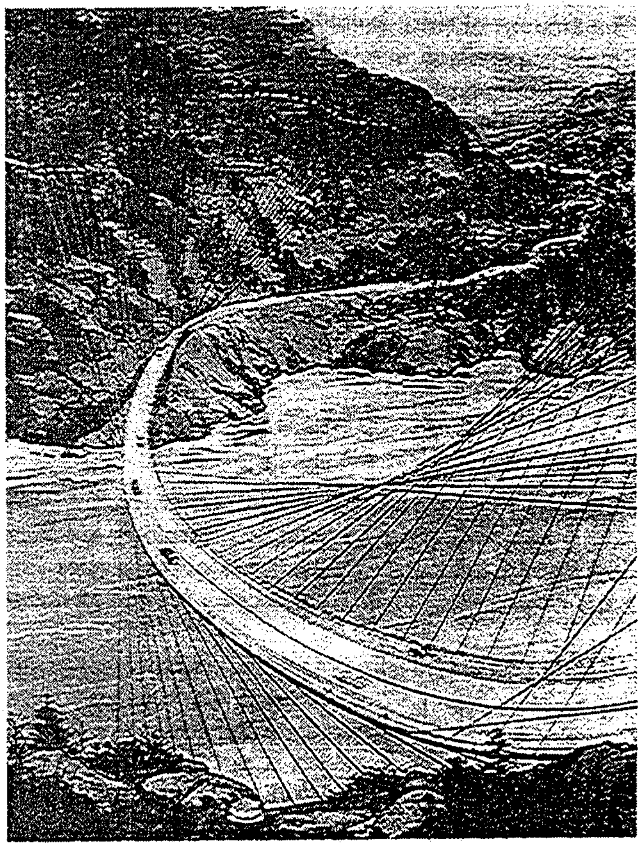


Fig. 1-32. Ruck-a-Chucky Bridge with 1300 ft curved span to be posttensioned with cable stays from rock walls of canyon. (T. Y. Lin International, Consulting Engineers). Photo courtesy Popular Science Magazine.

same loads, since the materials are of higher strength. There is also a definite saving in stirrups, since shear in prestressed concrete is reduced by the inclination of the tendons, and the diagonal tension is further minimized by the presence of prestress. The reduced weight of the member will help in economizing the sections; the smaller dead load and depth of members will result in saving materials from other portions of the structure. In precast members, a reduction of weight saves handling and transportation costs.

In spite of the above economies possible with prestressed concrete, its use cannot be advocated for all conditions. First of all, the stronger materials will have a higher unit cost. More auxiliary materials are required for prestressing, such as end anchorages, conduits, and grouts. More complicated formwork is also needed, since nonrectangular shapes are often necessary for prestressed concrete. More labor is required to place 1 lb of steel in prestressed concrete, especially when the amount of work involved is small. More attention to design is involved, and more supervision is necessary; the amount of additional work will depend on the experience of the engineer and the construction crew, but it will not be serious if the same typical design is repeated many times.

From the above discussion, it can be concluded that prestressed-concrete design is more likely to be economical when the same unit is repeated many times or when heavy dead loads on long spans are encountered. It should also find suitable application when combined with precasting or semiprecasting such as composite or lift-slab construction. Each structure must be considered individually. The availability of good designers, of experienced crews, of pretensioning factories, and of competitive bidding often helps to tip the balance in favor of prestressed concrete.

1-6 Partial Prestressing

As previously mentioned in section 1-3, the use of partial prestressing has become common practice. Partially prestressed members are those which are designed to allow significant tensile stresses to occur at service loads, and such tensile regions are usually additionally reinforced with nonprestressed reinforcement.

Most design codes for both buildings and bridges now allow significant tensile stresses at service load (Table 1-2 shows ACI Code values), thus partial prestressing is very common. Some fully prestressed structures have developed too much upward deflection (camber), which is not desirable. Partial prestressing has accomplished the purpose of eliminating or controlling crack width at service loads by setting allowable tensile stresses which are slightly less than cracking stress for the concrete.

It is clear that most prestressed concrete design now technically falls under this classificiation rather than fully prestressing to eliminate tensile stresses as practiced earlier. But caution is still required for partial prestressing when cracking is possible at service loads, because we may get excessive live load deflection of the cracked section. Because our state of the art is such that we do have both research and actual design experience to support the widespread use of partial prestressing we can design to control stresses, and to insure deflection as well as crack control. At the same time, strength can be enhanced by the addition of supplemental flexural reinforcement. Table 1-3 gives required load factors from the ACI Code.

The special considerations described above (section 1-5) should help the reader to visualize the general comparison of reinforced concrete and prestressed concrete in various ways as we find it in practice. The designer finds the degree of prestressing which gives the desired control of stress at each of the loading stages described in section 1-4 to assure satisfactory performance for a given situation. The main concern is to produce a satisfactory structure whether the final design is "partially prestressed" or "fully prestressed" concrete. More complete discussion of partial prestressing and nonprestressed reinforcements is given in Chapter 9.

1-7 Design Codes for Prestressed Concrete

The first design guides for prestressed concrete were in the form of recommended practice, rather than building codes. In the United States, the "ACI-ASCE Joint Committee Recommendations for the Design of Prestressed Members" published in 1958, included the state-of-the-art knowledge which had developed with the limited use of prestressed concrete by the mid-1950's.

The Prestressed Concrete Institute published the first U.S. Building Code for prestressed concrete in 1961. At that time, the American Concrete Institute Building Code (318-56) contained no reference to prestressed concrete, but the inclusion of new material on this subject was being considered for the next revision.

In 1963, the ACI Code (318-63) included a chapter covering prestressed concrete, much of which was carried forward into the 1971 revision of the ACI Code (318-71). Since 1971, annual revisions have been made, and the ACI Code[6] with current revisions is the design code used throughout this book. A similar evolution occurred with the AASHTO "Standard Specification for Highway Bridges." The major provisions for prestress concrete in the current Standard Specification for Highway Bridges (AASHTO)[7] with latest revisions are very similar to those of the ACI Code. The only major differences are the allowable stress values and load factors which have been traditionally more conservative for bridges than buildings.

Both the ACI Code[6] for buildings and the AASHTO Specification[7] for bridges in the United States have evolved with information from around the world. It is

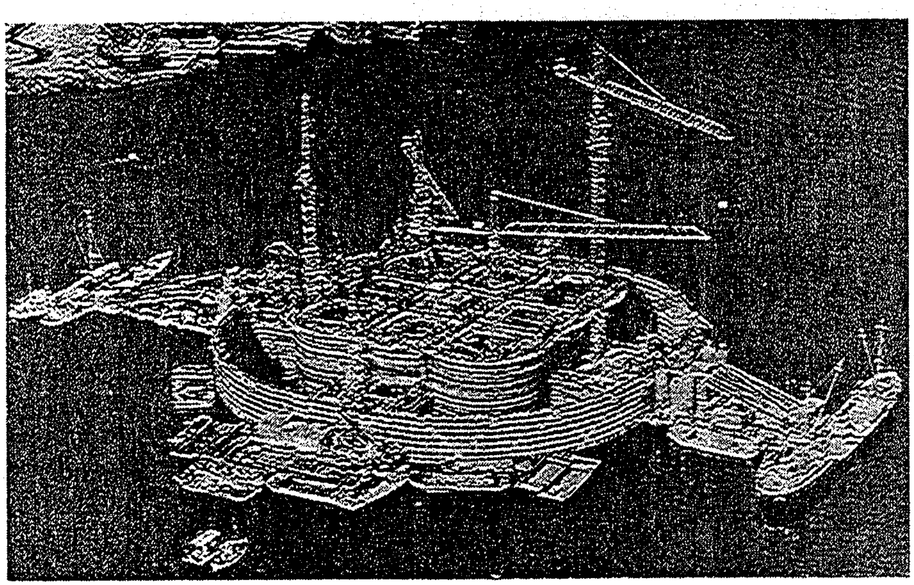


Fig. 1-33. Ekofisk Offshore Reservoir in the North Sea with combined precast and cast-in-place concrete posttensioned to form completed structure.

the feeling of the authors that design following the ACI Code (or similar provisions in AASHTO) will produce very satisfactory prestressed concrete structures, although this document may not be legally binding in some other countries. In examples throughout this book, many design provisions of the ACI Code are followed. It is noted that similar provisions are embodied in most codes throughout the world.

Since the early attempts at prestressing, outlined at the beginning of this chapter, a major industry has developed as is obvious from the photos of major structures using prestressed concrete throughout the world. We clearly have the materials and technology to be confident that out structures using this material will be safe and serviceable. We can rationally design for fire resistance and corrosion resistance following guidelines of our present codes and specifications.

Many special applications have been developed for prestress concrete in addition to buildings, bridges, and containment structures. Special products previously made with other materials have emerged; for example, railroad ties[12,13] and power line poles. Some of these situations will not necessarily fall under the Code provisions developed for buildings and bridges, but they will be helpful for guidance. There is some question whether fatigue is potentially a problem for some of these special situations. Continued research and development will solve any problems associated with fatigue and, in turn, our codes will be still further improved.

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