11

Construction of
Prestressed Concrete

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In Memoriam

Professor Ben C. Gerwick, Jr., a world authority and pioneer in prestressed concrete, died December 25, 2006, a month after he so graciously expanded, upgraded, and completed the revision to this chapter which he originally wrote for the previous edition of the Handbook. He is fondly remembered as a prolific author of papers and books and as a foremost expert in the innovational designs of offshore-prestressed concrete structures.

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11.1 Introduction

The effective construction of prestressed concrete structures requires the practical application and implementation of sophisticated engineering technology in a safe and reliable manner under the constraints of time, budget, and the external environment. It incorporates the assembly of materials, equipment, and personnel and the execution of the work so as to attain the results envisioned in the design. The key elements in prestressed concrete construction are the following:

- The production of concrete that has stable, predictable properties, not only of strength but also of creep, shrinkage, elastic modulus, and durability (high strength is essential to attaining efficiency of structural performance)
- The forming (molding) of concrete into the design shape and within the specified tolerances
- The incorporation of mild steel reinforcement, accurately placed and held during concreting
- The placement of high-strength steel wires, strands, or bars to fit the design profile and the stressing and anchoring and corrosion protection of such elements
- Installation of the composite structural elements or assemblages described above, in their final positions, whether they are cast in place or prefabricated

During construction, prestressed concrete passes through a number of steps or stages, each of which must be considered. Then, after attaining the designed state, it undergoes a lifetime of relatively subtle but cumulatively important changes. Although conventional reinforced concrete passes through a similar life history, the changes and the importance of the stages are generally far less dramatic, and the consequences of oversights are not as severe; hence, in this chapter, the emphasis is on the practical attainment of safety and stability. We are working with an active, rather than a passive, structural system.

Environmental conditions are given considerable emphasis. Important prestressed concrete structures have been completed and now serve in Arctic, temperate, and tropical zones. They are successfully employed in the ocean, in the urban environments of large cities, and in remote deserts. Prestressed
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Concrete is used in buildings; bridges (Figure 11.1); offshore platforms (Figure 11.2); liquefied natural gas (LNG) import facility floating structures; towers; poles; tanks; wind, wave, and current energy structures; and railroad sleepers. Each of these uses has its own special criteria and practices. Each has its own constraints and limitations. The reliable performance of prestressed concrete (that is, its durability) throughout its design life requires careful consideration during design and construction. The requirements for such widespread use can be summed up in a few key words:

- Reliable, stable material properties
- Full consideration of the stages of construction of a prestressed concrete structure
- Durability with regard to long-term performance and serviceability

FIGURE 11.1 Prestressed concrete cantilever segmental bridge over the Columbia River Bridge on I-5.

FIGURE 11.2 Statfjord B offshore platform with prestressed concrete shafts. (From Gerwick, B.C., Jr., *Construction of Prestressed Concrete Structures*, John Wiley & Sons, New York, 1996. With permission.)
Various authorities have issued their precepts or commandments. These generally include the following:

- When prestress is applied, the concrete element must be allowed to shorten in the direction of the prestress. If the structure is restrained from shortening, it will not be prestressed.
- When the prestressing tendon is curved, it exerts a radial shear force.
- Prestressing applied to concrete too soon after casting, before it has gained strength and maturity, will lead to excessive creep. Prestress applied too late after concreting may result in extensive shrinkage cracks.
- Prestressing eccentric to the centroid of the concrete section produces bending. This bending (e.g., camber) tends to grow with age due to creep.
- The energy and hence force induced in a prestressing tendon by stressing are very large and result in a temporarily dangerous missile; safety precautions are essential.

## 11.2 Concrete and Its Components

The concrete material components must meet the general requirements for construction of reinforced concrete structures and, in addition, must usually conform to more stringent requirements to attain the design objectives.

### 11.2.1 Aggregates

Coarse aggregates are usually siliceous or limestone. Both gravels from riverine deposits and crushed rock are used. Desirable properties are hardness, soundness, nonreactivity, surface roughness, cubic as opposed to plate cleavage, low water absorption, and impermeability. Slightly reactive aggregates may often be utilized in specific applications if the proper chemistry of the cementitious materials is selected. Some limestones are not only porous but also permeable; their use in marine structures requires special actions to preserve durability. Lightweight (ceramic) aggregates are used extensively. Those of high strength, low creep, and low absorption are most appropriate to prestressed concrete application. Fine aggregates may be from natural deposits or they may be crushed from coarse aggregate. In any event, screening will be necessary to ensure a proper proportion of coarse sands and a suitable grading curve, preferably with a low percentage of the fine fractions, as a mix rich in cementitious material will fill the interstices while an excessive percentage of very fine particles will have a high water demand. The aggregates must be clean and free from salt and dirt. They should be properly stored above ground and protected from snow and ice and from excessive heat. Shielding from the sun may be provided by portable sheets of galvanized metal on temporary posts in the aggregate pile. To a large degree, cooling of aggregates may be accomplished by evaporation. A water soaker hose may be effective. Conversely, aggregates should be above freezing when batched. They may be heated by steam. Care must be taken to avoid accumulation of ice in the aggregate, whether by snow or the freezing of condensate, as ice particles may be unintentionally weighed and batched as coarse aggregate. Aggregates, both fine and coarse, should not contain or be encrusted with salts and silt. Washing is usually required, preferably with fresh water; but, if fresh water is not available, even brackish water can be used to remove the condensed salt crystals and silt.

### 11.2.2 Cementitious Materials

The practical construction of prestressed concrete is based on the use of Portland cement as the principal cementing agent. American Society for Testing and Materials (ASTM) cement Types I, II, and III are used. Type I can be used in geographical areas and applications where sulfate attack is not a problem. Type II, with closer control over the constituent compounds, especially tricalcium aluminate (C₃A), is widely employed where durability is a concern. Fly ash and metakaolin are pozzolanic materials that gain strength over a longer period of time than cement. They can be substituted for up to 20% or more of the cement. The silica of the fly ash binds up the soluble calcium hydroxide, substantially increasing impermeability. It also provides resistance to sulfate attack and alkali–aggregate reactivity while lowering
the heat of hydration and reducing thermal strains. Fly ash requires a separate silo and should be weight-batched separately from the cement. In some areas, fly ash is interground with the cement. For proper strength gain, continuous moisture is essential over an extended period of up to 30 days. This is usually best obtained by wet curing for 3 days followed by sealing with one or two coats of membrane-sealing compound. Finely ground blast-furnace slag (BFS) can be used with a limited portion of Portland cement to act as an efficient cementitious material with low heat of hydration and low permeability. Mix proportions of BFS to cement range from 50–50% to 70–30%.

11.2.3 Admixtures

Many revolutionary new admixtures are commercially available. The most important are water-reducing agents, especially high-range water reducers (superplasticizers), air-entraining agents, and microsilica, called silica fume. Corrosion-inhibiting admixtures, retarding admixtures, pumping aids, and viscosity admixtures are also available. Tests mixes are essential to ensure that the admixtures selected are compatible with the particular cement and other admixtures. The use of high-range water reducers (superplasticizers) is the best way to achieve the low water/cementitious material ratios essential for high-performance concrete. The usable life of high-range, water-reducing admixtures is typically 1-1/2 hours after mixing, so the concrete must be placed and consolidated within that period to prevent sudden premature stiffening. This life can be extended by adding retarders. Some high-range, water-reducing admixtures incorporate a retarder and hence have an extended slump life.

Air entrainment creates tiny air bubbles of proper distribution throughout the concrete, thus enabling the structure to resist a large number of freeze–thaw cycles. Its use is essential in cold regions. Its efficacy is dependent on in-place characteristics. Unfortunately, these can only be verified by microscopic examination of hardened concrete specimens, although other real-time tests give valuable indications as to the entrained air and can be used for control when they have been properly calibrated by a petrographic inspection. Day-to-day control can be exercised by use of a meter that measures the total air content (entrapped plus entrained air) in the fresh concrete mix. Microsilica or silica fume consists of very small particles of silica about 1/100 the size of cement grains which combine with gypsum to produce high early strength, very low permeability, improved bond, and enhanced fatigue endurance. Microsilica also increases electrical resistivity. It is used in percentages (by weight of cement) of 3 to 10%. More than 6% makes the concrete quite sticky and difficult to place and consolidate; however, this property of added cohesiveness can be beneficially used for concrete placed underwater. Microsilica can be introduced as a powder or in a slurry, or, in some cases, can be ground with the cement. If introduced as powder, it must be well mixed. Although most commercially available microsilica is a mineral byproduct of silicon production, rice-husk ash has recently been used as a source, with similar and possibly enhanced properties. Use of high-range, water-reducing admixtures is essential to the incorporation of microsilica in the mix.

Proprietary corrosion-preventing admixtures, based on calcium nitrite, are available. Similar admixtures that reduce the diffusion of chlorides in concrete are commercially available but are relatively expensive. Other thixotropic (viscosity-control) agents are available that promote the initial flow of concrete and self-leveling but gel when movement ceases, thus preventing bleed. They are often used for underwater concreting and for grouting post-tensioning ducts.

11.2.4 Water

Water for prestressed concrete is required to have no more than 650 ppm of chlorides and 1000 ppm of sulfate ion, although in many specifications, the latter is increased to 1300 ppm. Water furnishes the essential electrolyte that initiates the chemical reactions and promotes fluidity (workability) by coating the particles; however, excess water is inimical to strength and durability. For this reason, the water/cementitious materials ratio (w/cm) should be limited to a maximum of 0.42 and preferably 0.40. In practice, w/cm ratios of 0.32 for precast elements and 0.37 for cast-in-place concrete are attainable. In hot weather, ice may be added to the mix in place of water to lower the temperature of the fresh concrete. Alternatively, liquid nitrogen may be injected.
11.2.5 Batching of Concrete
Concrete is weigh-batched in the same manner as in conventional reinforced concrete practice except that in prestressed concrete construction, there are usually more dry components (e.g., cement, coarse aggregate, fine aggregate, fly ash, blast-furnace slag, microsilica) and more wet components in the form of admixtures, each of which must be accurately dosed. The moisture content of the aggregates must be ascertained from free-moisture meters in the bins and corrections made to the amount of water added.

11.2.6 Mixing of Concrete
It is obvious that mixing must be very thorough to blend the many components. For this reason, turbine mixers and shear mixers are favored. Even when the concrete is subsequently transported in ready-mix trucks, premixing at the plant is desirable. The order in which admixtures are added to the mix is important—particularly for air-entrainment agents and superplasticizers, as the latter may inhibit the proper development of entrained air. Adding half the dosage and then mixing for a brief period before adding the remainder can solve the problem in some cases.

11.2.7 Transporting and Placing
Transporting and placing follows conventional practice; ready-mix trucks, concrete pumps, buckets, and conveyors are used. For discharge of stiff mixes from the trucks, screw conveyors may be used. In some high-rise construction using slip forms, where the required rate of concreting at any one location is low, buckets have been used to raise the concrete to elevated hoppers, from which the concrete has been distributed by buggies running on runways. The loss of slump and of entrained air content when pumping concrete to high elevations must be considered.

11.2.8 Consolidation
Internal high-frequency vibration is the typical means of consolidation for cast-in-place concrete. It should also be used to supplement external vibration in all precast concrete elements except very thin (150-mm or 6-in. or less) members, as external vibratory energy is not effective at depth. Self-consolidating concrete (so-called flowing concrete) is now being used in thin and congested sections.

11.2.9 Curing
Membrane curing (curing compound) is generally considered to be the most reliable for vertical surfaces. For horizontal surfaces, wet curing is best, although sealing with polyethylene sheets is also widely practiced. Concrete containing fly ash, and especially that containing microsilica, requires special attention to curing to prevent surface crazing. For precast elements and occasionally for cast-in-place segments, steam curing is used to accelerate gain in strength. Steam curing at atmospheric pressure provides both moisture and heat and results in generally superior concrete; however, certain practical precautions are required with steam curing (see PCI, 1999):

- Concrete should have its initial set 3 to 4 hours before the temperature is elevated; otherwise, it may be damaged as it expands.
- The maximum curing temperature should be limited to 60°C (140°F) to prevent long-term development of delayed entringite.
- Steel forms expand before concrete; hence, changes in section must be detailed to accommodate length change so as not to crack the concrete. Soft rubber gaskets may be used between flanges of forms to absorb their early expansion.
- Concrete, once cured, should not be exposed to cold, drying winds until it has cooled to within about 10 to 15°C (20 to 30°F) above ambient. It is important not only to prevent sudden cooling of the outer surface while the inner core is still hot but also to prevent rapid evaporation of
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moisture. The latter may require supplemental water or membrane curing. Membrane-curing compounds evaporate with heat; hence, in hot weather a second coat may be required.

In cold weather, and especially with dry winds, the concrete must be protected by insulated forms or blankets (tarpaulins) until the surface temperature is no more than 15°C (30°F) above that of the core (Figure 11.3); otherwise, cracking will occur due to the early contraction of the outer layer.

11.2.10 Testing

Testing of high-strength and high-performance concrete is a demanding technology, requiring trained personnel and sophisticated equipment. Specimens must be taken and prepared carefully if the results are to be meaningful. Cylinders should be vibrated with a pencil vibrator in steel molds, because plastic and cardboard molds will give erroneously low results. The cylinders should be subjected to the same temperature regime as the structural element—for example, placed under the steam hood near each end and at the center of the bed. When removed, cylinders should be placed in a water bath containing lime and kept at 20°C (70°F) until one day before the test. They should then be removed to dry out before testing. Ends of the cylinders should be rubbed smooth to remove any surface irregularities. Numbers should never be etched in the top surface! Cylinders should be carefully capped with new capping compound or ground smooth to test without capping. Similarly, cubes, where used, should be ground and tested without capping. Be sure there is a strong screen around the testing machine, as high-strength concrete fails explosively. Testing of other properties is even more complex. Air-entrainment characteristics are determined by microscopic petrographic examination of thin slices cut from a core in the hardened concrete. Impermeability is very difficult to measure at the upper limits associated with high-performance concrete. The validity of the rapid chloride permeability tests of both ASTM and British Standards has recently been questioned. On many important projects involving prestressed concrete, various properties are specified. These include permeability and determination of the extent of microcracking. In practice, some of the values specified have proven to be extremely difficult to attain in the field. The contractor should therefore start the mix development and testing program at the earliest possible moment, working in cooperation with the engineer and technicians so as to avoid delays and rejections.
11.3 Reinforcement and Prestressing Systems

11.3.1 Reinforcing Steel

Because in prestressed concrete structures the role of primary reinforcement has largely been replaced by prestressing steel, an unfortunate tendency has been to denigrate the importance of supplementary conventional reinforcing. Conventional reinforcement fulfills the essential functions of distribution and resistance in the orthogonal directions to the prestressing, most typically in the transverse direction. It serves to augment prestressing steel in critical areas of concentrated stress. It serves as confinement, resisting the bursting and delamination stresses due to prestressing itself (Figure 11.4). It also resists punching shear under concentrated loads.

The role of reinforcing steel is secondary to the structural behavior and is concerned with stress distribution and crack prevention, so close spacing with small bars is preferable to large, widely spaced bars. Confining reinforcement usually consists of spirals, although hoops (welded rings) perform best under ultimate loads. Mechanically headed bars (Figure 11.5) have been used on a number of recent major structures. Subject to the design engineer’s approval, bundling of bars may be acceptable, especially in cast-in-drilled shafts and columns. This clustering of bars together often facilitates concrete placement. For splices, mechanical splices are best, although lap splices may be used.

Reinforcing bars typically develop anchorage by having an embedment length that extends beyond the location of high stress, preferably terminating in a confined zone or core. Bends, such as those of stirrups, are only about 70% effective in ultimate capacity, as the concrete under the bend crushes at high stress. Headed bars typically anchor the bar, develop its full strength, and permit the use of larger bars or those with higher yield strength. They are much easier to install than stirrups and reduce congestion of steel bars. It is a serious mistake by both designer and constructor to reduce anchorage lengths to the absolute minimum permitted by code or specifications, as practicable placement tolerances frequently result in inadequate length for anchorage. A typical concern arises with the provision of cover—that is, the thickness of concrete outside the reinforcing bars. Because cover is a major factor in durability, as well as in mechanical behavior, it is normally specified to a tolerance of –6 mm (–1/4 in.).

Main bars should be tied with wire at every intersection. Stirrups or hoops must be tied to the longitudinal bars at three intersections so as to prevent displacement along the bars during concreting (a typical problem in concreting that has serious consequences). Lap splices in reinforcement are another
source of difficulty. These can be more easily achieved if the bar is a little longer than the minimum required by code. The designer or the code should specify whether or not the overlapping bars must be tied together with soft iron wire. In general, this is good practice. Compression splices are rendered most efficient by being well tied together at both ends; otherwise, the concrete may locally crush under one or both bar ends. Lap splices, especially those in tension, must be confined on both orthogonal axes, transverse and through thickness.

Reinforcing bars require support. Both concrete dobie blocks and plastic chairs are used and are left in place in the completed concrete structure. Reinforcing bars are frequently epoxy coated to protect against corrosion. The electrostatic fusion process is most widely used. Problems sometimes occur with insufficient thickness of epoxy over the lugs of the deformations. Regardless of the method of manufacture or whether the bars are bent before coating or bent afterward, there will be some scratches and some "holidays" due to handling and placement. Fiber slings and pads must be used. Abraded areas must be touched up in the field after placing. Special care must be taken to ensure that the reinforcing steel is stored in a salt-free area before concreting—that is, where seawater chlorides cannot be carried by fog or spray to contaminate bars. In critical areas and special applications, corrosion-resistant or stainless-steel reinforcement is utilized, enabling a reduction in cover and providing long-term durability.

11.3.2 Prestressing Tendons and Assemblies

Prestressing tendons are made of cold-drawn wire, both parallel and stranded, or rods of high-yield strength steel. Bars and rods consist of heat-treated alloys, which have been prestretched beyond yield and tempered in the manufacturing process. They are rolled with spiral threads, either cut in upset ends or continuously rolled so the threads also act as deformations. Cold-drawn wire is typically low alloy that has been tempered. Wires are generally wound into seven-wire strands and prestretched. The seven-wire strand, with an outside strand diameter of 12 to 15 mm (0.5 to 0.6 in.) is most typical for both the pretensioning and post-tensioning systems discussed in Sections 11.5 and 11.6. For pretensioning, the strands are directly embedded in the concrete, gaining anchorage by bond on the twisted surface. For special applications, such as railroad ties (sleepers), a wire with a deformation is stranded into one outer layer of the strand to shorten the stress transfer length. For post-tensioning, anchorages are locked to a socket by serrated wedges, locking into a female sleeve. High-strength bars are used primarily for short
tendons. Wedges can be used to anchor bars although threaded connections are more often employed. These permit restressing to counter the set typical of wedge anchors.

Bars, wires, and strands are usually left black, or uncoated. They may be galvanized for corrosion protection; hot-dip process galvanizing appears to be most reliable. A chromate wash applied at the end of the galvanizing process will passivate the zinc and inhibit the liberation of individual hydrogen atoms that results from reaction with the alkali cement. Evidence indicates, however, that the protection resulting from galvanizing has a limited life of 10 to 15 years in seawater. Individual strands that are sheathed in plastic are now available. They are then bundled into tendons for post-tensioning application. Epoxy coating is occasionally applied to steel strands. Sand is dusted on while the epoxy is still wet to improve bond.

Prestressing steels, which are under high sustained stress, are subject to a long-term plastic rearrangement of molecules known as stress relaxation. This can produce long-term losses in prestress of the member up to 13%. By a special tempering process, the stress relaxation may be reduced significantly, to about 6%. Seven-wire strand has approximately 30% voids as compared to a solid bar of the same external diameter. Compact strand is available, in which the wires are shaped so they fit tightly together. This allows an approximately 15% increase in total force to be obtained within the same external dimensions and is a valuable technique for solving space problems in highly stressed members and in repairs. Prestressing wire and strand are shipped in coils that are wrapped with heavy, water-resistant paper (Figure 11.6). If the cover is torn, the entire coil may be corroded at regular intervals. Bars and rods are similarly shipped in bundles, wrapped for protection from moisture. For protection against corrosion, vapor-phase-inhibiting crystals may be inserted in the package. More frequently, however, the tendons are coated with water-soluble oil.

FIGURE 11.6 Seven-wire prestressing strand is shipped in coils to the precast concrete plant or jobsite. (Photograph courtesy of VSL Corporation, Campbell, CA.)
11.3.3 Anchorages and Splices

The anchorages and splice hardware for prestressing systems consist of cast alloy steels, machined to accurate dimensions with very close tolerances to provide a positive grip to the tendons under high forces (Figure 11.7). The anchorage includes, either separately or monolithically, a bearing plate that transfers force to the concrete. The concrete at the anchorage, being under a force that is typically several times its uniaxial compressive strength, must be confined, either by a ring integral with the anchorage or by hoops or spiral. The anchorage may also include the socket and wedges for gripping the tendon. Anchorages must be transported, stored, and handled with extreme care. Some European specifications require storage in a heated, dehumidified, warehouse. Anchorage assemblies must be clean and free from foreign material, except the grease specified by the system manufacturer. Damaged or visually defective anchorages should never be used. A failure may result in the other anchorage and the tendon being ejected at high velocity. Splices of prestressing tendons are similar to anchorages in that they anchor to both ends of the tendons. It is fundamental that the splice be free so as to allow the tendon to elongate upon stressing; thus, a recess or opening must be temporarily left in the concrete at the splice location. Post-tensioned anchorages are either encased or recessed for reasons of durability, fire protection, and appearance. A recessed pocket is formed in the end block with protruding steel ties that are temporarily bent aside. The surfaces of the pocket or recess are coated with bonding epoxy or latex, then a fine (small coarse aggregate) concrete is placed in a manner so as to eliminate a shrinkage and bleed pocket at the top. After the form is stripped, the joint may be sealed with a penetrant epoxy.

FIGURE 11.7 High-strength alloy steel bars are used to prestress this wall to enable it to resist the pressures of Arctic sea ice. (From Gerwick, B.C., Jr., Construction of Prestressed Concrete Structures, John Wiley & Sons, New York, 1996. With permission.)
11.3.4 Ducts

For post-tensioning, ducts are used to perform holes in the concrete structure during casting so that later, after the concrete has hardened, tendons may be inserted and stressed. Several types of ducts have been used, including steel pipe, semirigid steel ducting made of strips spirally wound to lock to each other, thin flexible metal tubular ducting, and plastic (Figure 11.8). Ducts are usually circular in cross-section, although flat ducts with a rectangular cross-section are used where the concrete cross-section and crossing bars or tendons constrict the available space.

Flexible metal ducts, made of thin corrugated steel and usually galvanized for temporary corrosion protection, are used for tendons of sharp or reversing curvature. These ducts are readily wound in coils and can be spliced by a short overlapping sleeve of similar material. These ducts are very flexible, so that they develop unwanted local curvature, called “wobble.” This can be prevented by insertion of a mandrel of smaller diameter, for example, electrical conduit. After the concrete has been placed, the mandrel is drawn forward and backward to prevent any bond with mortar that may have leaked into the duct, and then removed.

Semirigid metal ducts are bright steel strip, wound spirally with crimped overlaps (Figure 11.9). This ducting has less wobble but still requires use of a mandrel in those applications where even slight deviations have serious consequences. This material is normally furnished in straight lengths but can still be deviated over large-radius curves, depending on the sheet thickness used. Semirigid and flexible ducts are neither watertight nor mortar tight. If a mandrel is not used, a wire or single strand should be run back and forth to clean out any mortar leaking in from the concreting operation. For long, straight runs, especially long vertical runs, thin-walled pipe with screwed splice fittings is employed. Wall thicknesses of 1 to 2 mm are typically used. Splicing of metallic ducts is done by sleeving, with an adequate overlap of at least two diameters and tapping with waterproof tape; however, the latter has not proven to be fully reliable. Heat-shrink tape is now preferred.

Steel ducts may be epoxy coated externally where used in zones vulnerable to corrosion, such as transverse post-tensioning of bridge decks in geographical areas where salts are applied to prevent icing. Plastic ducts of polyethylene or polystyrene, with corrugations inside and out, are increasingly employed because they are watertight and grout tight, have controllable flexibility, and give long-term corrosion protection to the tendons. They can readily be fabricated to exact length and can be spliced, either by fusion or by use of sleeves and glue or heat-shrink tape. Plastic ducts should have a minimum thickness of 2 mm; plastic ducts are available both as circular tubes and as rectangular flat ducts.
When a plastic duct is installed on a profile or plan that is curved and wires or strands are later pushed in, the duct may be cut by abrasion, resulting in subsequent grout leakage. Ribbed ducts, in which the strand or wire will bear on enlarged ribs, have been used successfully to overcome this problem, as has lubrication with water-soluble oil. The ribs or corrugations enhance the bond between a plastic duct and the surrounding concrete. Use of 3- to 4-mm-thick plastic duct and pulling-in of the tendon as a bundle with a protective nose-piece ("Chinese finger") will also minimize the problem of abrasive cutting.

The integrity of ducts, after installation in the concrete, is critical to the successful completion of prestressing. The duct location and the tolerances determine the subsequent profile of the tendon. Any blockage, as by in-leakage of mortar during concreting or out-leakage and crossover of grout from one duct to an adjacent one, will prove very costly, time consuming, and, in some cases, impracticable to correct.

### 11.4 Special Provisions for Prestressed Concrete Construction

#### 11.4.1 Concreting in Congested Areas

It is typical of much prestressed concrete construction that certain zones, such as the ends of girders and locations of deviation of prestress, are heavily congested (Figure 11.10). Such areas may include, for example, zones in which post-tensioning anchorages, trumpets, spiral confinement, and transverse and vertical reinforcing steel bars compete for the limited space available. At the same time, such zones may make the highest demand on the concrete for compressive and tensile strength. Placing concrete of the required quality, without any voids, honeycomb, or segregation requires one or more of the following techniques:

- Bundling of reinforcing steel bars, especially stirrups, or substitution of headed reinforcement to give more clearance for the concrete
- Changing the concrete mix to reduce the maximum size of the coarse aggregate (e.g., to 10 mm), while increasing the cement content as necessary to obtain the required strength
- Use of flowing concrete
- Prior to concreting, marking the location of reinforcing steel on the forms to enable subsequent insertion of the vibrator
Prior to concreting, insertion of tremie tubes through the reinforcement, gradually withdrawing these as the concrete is placed

Prior to concreting, inserting the vibrator within a tube that penetrates through reinforcement (Figure 11.11), gradually withdrawing the tube as the concrete is placed, allowing the vibrator to consolidate concrete below the tube

In extreme cases, precasting of the end block in the horizontal position, then setting the end block in the forms and joining it to the cast-in-place concrete by protruding reinforcing dowels and the axial post-tensioning

11.4.2 Special Reinforcement at Location of Curvature of Prestressing Tendons

At locations where the centroid of prestressing deviates sharply in relation to the centroid of the concrete section, high radial stresses are introduced. These may cause cracking or, in extreme cases, actual pullout of the concrete in punching shear. It is important to tie this zone to the main concrete section. Typical zones where this phenomenon occurs and has led to damage in the past are at intermediate anchorages, especially where the anchorages are in bolsters or blisters protruding from the concrete section, and at deviation points for deflected-strand pretensioning. Similar conditions exist where external post-tensioning is constructed alongside an existing concrete section but is eccentric to it. In all of the above cases, U-stirrups or the equivalent are required. Their legs must be anchored deeply within the concrete core, preferably in a compressive zone.

11.4.3 Special Reinforcement to Distribute Anchorage Zone Strains

It has long been recognized that the concentrated forces at anchorages of post-tensioning tendons creates radial bursting forces that lead to cracking in the immediately surrounding concrete. All commercial producers of prestressing systems include appropriate confining reinforcement. Not so well recognized is that in the zone between two anchorages, or between the ends of two groups of pretensioned strands, splitting tension is developed. This requires distributed reinforcement to prevent detrimental cracking. When prestressing tendons are anchored at locations other than the ends of the member (e.g., the intermediate anchorages of continuity tendons or dead-end anchorages), the concrete behind the anchorage is subject to tension as the concrete in front of the anchorage tries to shorten. Either adjacent
prestressing tendons or conventional reinforcing bars are required to distribute these stresses back into
the body of the concrete behind.

In vertical walls and webs, looped U-tendons are often used to provide prestress against shear. These
situations occur in the vertical walls of silos, offshore platforms, and bridge piers and in the web of deep
girders. Adjacent U’s must overlap at the bottom; if the adjacent U’s are separated, then high-tensile
strains exist between them that can lead to cracking. Orthogonal reinforcing steel bars are needed.
Additional bars for the above cases should be well distributed over the zone where the potential crack
will initiate. The number and size of bars, while calculable by finite-element methods, are often deter-
mined on an empirical basis—for example, by provision of enough conventional reinforcement to transfer
50% of the prestress force to the zone behind. Failure to counter the tensile forces and strains can lead
not only to cracking but also to a serious reduction in shear capacity.

It can be argued that the above problems are the responsibility of the design engineer; however, the
counter-argument is that these local strains are associated with the anchorages of the prestressing system,
which are typically selected by the contractor or a subcontractor and, hence, to some degree, are their
responsibility. In any event, the occurrence of the cracking, etc. described above may initially be blamed
on the constructor and may have serious cost consequences. Conversely, the extra reinforcing required
is minimal compared with the overall project; therefore, it appears prudent for the constructor to ensure
that it is provided. The matter should be resolved before the concrete is cast.

11.4.4 Embedments
Steel embedment plates are frequently installed in the sides or surfaces of prestressed concrete members.
Frequently, these are square plates. As a result of at least three phenomena, cracks often originate at the
corners:

- *Steam curing*—The steel plate expands rapidly as the temperature rises, before the concrete expands
  and before it gains strength.
- *Concrete shrinkage*—The concrete surrounding the embedment is subject to both setting and
drying shrinkage.
- *Strains at sharp corners*—Such strains arise due to prestress.
Solutions that will prevent or minimize such cracks are as follows:

- Place soft wood or a neoprene strip around the embedment, which will later be removed and filled with epoxy, latex, cement mortar, or an equivalent material.
- Round the corners of embedment plates.
- Install short diagonal bars across corners.

### 11.4.5 High-Performance Concrete

The criteria for high-quality concrete has been presented in general terms in Section 11.2. High performance, above the range normally associated with high-quality reinforced concrete, is often required for prestressed concrete members (Figure 11.12). Typical high-performance requirements specify very high strength (above 60 MPa, or 8700 psi), enhanced impermeability (less than $10^{-10}$ m/sec), special requirements limiting microcracks, high abrasion resistance, and high tensile strength (above 4 MPa, or 600 psi). The attainment of these requires advanced concrete technology and strict control of field construction practices, including:

- Rescreening and rewashing of aggregates
- Selection of aggregates with surface roughness (e.g., crushed rock and crushed sand)
- Smaller coarse aggregate sizes
- Higher sand content
- Higher cement content
- Replacement or addition of fly ash
- Alternatively, use of blast-furnace-slag cement
- Addition of silica fume (microsilica)
- Use of a high-range, water-reducing agent or higher than normal doses of conventional water-reduction agents
- Special admixtures related to specific properties desired
- Precooling of concrete mix
- Curing practices

**FIGURE 11.12** Sylhan Viaduct in the French Alps combines high performance, high-strength concrete truss members with external tendons inside trussed extension. (Photograph courtesy of Bouygues, Paris, France.)
As stated in Section 11.2.3, development, testing, and approval of special mixture designs take time and therefore should be initiated as early as possible. Extensive treatment of this subject is given in Chapter 2.

### 11.4.6 Lightweight Concrete

Prestressed lightweight concrete has a substantial history of very satisfactory performance in highly demanding structures, including bridge girders (Figure 11.13) and offshore structures. In several important cases, beneficial properties other than light weight have been the rationale for selection. These properties include:

- Durability
- Insulation
- Fire resistance
- In conjunction with silica fume, enhanced fatigue resistance

Structural lightweight concrete has often been selected to reduce the inertial mass of structures in seismic regions and to reduce draft of floating structures. The performance of lightweight concrete is highly dependent on the specific aggregates selected, which in turn depends on the raw materials (clay or shale), the manufacturing process, and the temperature and duration at which they are fired in the kiln. Unfortunately, because of the previous widespread use of low-quality, lightweight aggregates for less-demanding applications, such as fireproofing, and because of the wide range of properties covering lightweight aggregates, most current codes require increased allowances for creep and shrinkage. It should be noted, however, that careful selection of the highest quality lightweight aggregates and the use of some natural sand can keep creep and shrinkage within the same ranges as with natural stone aggregates. Some properties of these high-quality lightweight concretes are inherently less than those of hard-rock (conventional) concrete of the same strength; these include modulus of elasticity, shear strength, and tensile strength. High-performance lightweight concrete has a unit weight of only 75 to 80% of conventional hard-rock concrete; however, compressive strengths of up to 62 MPa (9000 psi) can be obtained by the use of natural sand for the fine aggregate and the addition of microsilica. Microsilica is especially beneficial to lightweight concrete because it chemically bonds with aggregate particles which in turn gives better fatigue endurance under cyclic loads.
11.4.7 Modified-Density Concrete

By using natural sand to replace the lightweight fine aggregate in part or whole and using 50 to 60% of hard-rock coarse aggregate (by volume), a concrete having about 85 to 90% of the density of all-hard-rock concrete can be produced that has almost the same properties, including modulus, shear, and tensile strength as the comparable all-hard-rock concrete. This mixture has been used on a number of offshore structures where weight was critical for draft and stability.

11.4.8 Composite Construction

Composite steel–concrete construction is widely used for high-speed-railroad bridges in Germany, as well as for major bridges elsewhere. Composite construction has also been proposed for offshore structures where the membrane characteristic of the steel plate and its two-dimensional tensile reinforcement properties can be combined with the shell action of the concrete to resist concentrated forces. Connectors used to ensure shear transfer have included welded studs, shear rings, and special shear ribs. Prestressing has been suggested as a potentially synergistic way in which to utilize composite properties, as the steel is kept from local buckling if it is properly anchored to the concrete. The shear on the connectors that is created by the prestressing must be considered. The tendons must be located with consideration of the various moduli of elasticity. Composite construction using half-depth precast prestressed slabs and beams with structural concrete topping has been widely utilized for floor slabs of buildings and for decks of short-span bridges. Shear transfer may be accomplished by the roughened concrete surface alone in the case of light live loads or by means of reinforcing ties. Cleanliness of the surfaces and proper preparation (e.g., saturated or surface damp) are important to ensure bond. The constructor must ensure that the specified degree of roughness of the lower slab or beam is attained. Steel ties are very effective. Typically, the precast member is longitudinally pretensioned. Conventional reinforcing in the topping slab is used to distribute forces transversely and to provide live-load continuity, although in certain instances, especially bridge and wharf decks, the composite system has also been post-tensioned transversely. The designer of such a transversely post-tensioned structure must have adequately considered the effects of differences in moduli and the inherent eccentricity of two orthogonal layouts of tendons. In areas where significant eccentricity is unavoidable, use of steel ties will prevent delamination.

11.4.9 Architectural Prestressed Concrete

Many applications of prestressed concrete have a criterion for architectural and esthetic appearance. Prestressing can be used to help attain the criterion by preventing cracking. One- and two-way prestressing has been utilized for this purpose (Figure 11.14). Care must be taken that neither the ends of pretensioned strands nor the anchorages of post-tensioned tendons can rust and stain the surface. Pretensioned strands can be cut back by a small flame torch or by a welding rod and then plugged with latex cement mortar or a light colored epoxy mortar. Post-tensioned anchors should be recessed and later filled with concrete or mortar. In some cases, epoxy mortar is used. These plugs should be tied to the parent concrete by steel ties; otherwise, cracks may occur around the plugs and allow corrosion products to leach out. Alternatively, in some architectural applications, the architect has elected to emphasize the anchorage, in which case, heavy galvanizing or epoxy coating has been pre-applied.

Some architectural panels incorporate ceramic tiles as facing elements with a backing of concrete. Prestressing locks the ceramics in place and prevents cracking, which otherwise might reflect through the face. Great care must be taken in locating the tendons to offset the difference in modulus of the facing from that of the backing. Some architectural treatments of concrete involve processes that are corrosive to prestressing steel. Acid washing or etching is especially dangerous as residue may remain in ducts and recesses. Joints between segments require special attention if they are to be blended into the overall members. Any epoxy residue must be removed. Use of white cement as part of the mortar mix will help to prevent discoloration, as patches tend to be darker than the surrounding concrete. Steam curing may adversely affect colored concrete; condensation may drip onto colored concrete and leave unsightly marks.
Microsilica or antibleed admixtures can be used to prevent unsightly bleed holes. Fly ash or microsilica can be used to prevent efflorescence. These can also be used to reduce permeability and thus minimize the unsightly fungus growth that occurs in semitropical and humid environments.

### 11.5 Post-Tensioning Technology

#### 11.5.1 Principles

With post-tensioning, the concrete sections are cast first with all conventional passive reinforcement, then, after the concrete has gained sufficient strength, tendons are placed, usually through holes formed by ducts. These tendons are stressed so as to react against the concrete and precompress it. The concrete must be free to shorten under the precompression. The tendons are then anchored, and corrosion protection, such as grout or grease, is installed. There are many variations on the above procedures, of which the most common and important are described here.

#### 11.5.2 Storage of Tendons and Anchorages

Tendons and anchorages are high-strength steel, accurately made to very close tolerances. As such, they are subject to corrosion in storage or, even more insidious, to contamination that will lead to hidden long-term corrosion. Tendons and anchorages should be stored in a covered area, fully protected from the weather and raised off the ground. Some specifications require that the storage facility be dehumidified.

*FIGURE 11.14* Two-way pretensioned concrete wall units serve both structural and architectural purposes in the construction of new university building.
Usually, heat is applied to keep the relative humidity well below 50%. In some countries, including the United States and Canada, open storage is acceptable, provided the material is up off the ground and dry. Among the many cases of corrosion of tendons due to inadequate storage are the following:

- Tendons were stored in mud adjacent to a roadway on which salt was applied to prevent icing.
- Tendons were stored on a beach and subject to immersion at high tide.

11.5.3 Installation of Ducts and Anchorage Bearing Plates

Ducts, whether of steel strip or plastic, must be carefully placed to true profile and rigidly held so as not to be displaced during concreting. Their location and alignment determine the position of the tendons that are later installed. Ducts must be kept free from dents and flattening; otherwise, they will not permit the free installation of the tendons. Dents, bulges, and burred ends must not be allowed to occur during the subsequent placing of reinforcement, and care must be taken in the use of the vibrator when consolidating the concrete. Preferably, ducts should be supported on saddles of plastic or steel, rather than bearing directly on the reinforcing steel, which may dent the duct when the load of fresh concrete impinges on it. It is particularly difficult to align ducts accurately across splices. A temporary internal mandrel may be used to ensure proper alignment across splices. Sleeves, overlapping at least two diameters on each end, should be sealed with heat-shrink tape. Screw fittings can be used on ducts comprised of pipe. Although waterproof tape and epoxy have been used to seal overlapping sleeves, tests and experience have shown that these are not as reliable as the heat-shrink tape. The duct cross-section should be about twice the gross cross-section of the tendons and should allow 6-mm (1/4-in.) clearance all around to permit proper encasement in grout. The preferred anchorage for post-tensioning tendons is a recess pocket formed in the end of the concrete member. This is boxed out with forms attached to the end form.

When the duct is placed, the trumpet and bearing plate are attached by screws and sealed to prevent mortar inflow. This rigid attachment serves to ensure that the bearing plate is truly normal to the design tendon axis. Vent tubes and grout tubes must be properly affixed to the duct and taped securely to prevent rupture or leakage. Vents are installed at the high points of upward-curving tendons or at about 20-m intervals on near-horizontal ducts. A tube is also installed at each end just behind the bearing plate to act as an inlet when injecting grout and as a vent at the far end. Drains are used at low points in the tendon profile. They should be used at the bottom of U-ducts installed vertically, such as, for example, in the webs of girders (Figure 11.15 and Figure 11.16). The drain tube may also function as an intermediate grout tube. For the primary prestressing of major structures, such as bridge girders, provision of at least one extra longitudinal duct on each side will facilitate corrective action in case of excessive creep or blockage of a duct. Ducts should preferably be delivered to the job site with plastic covers already fitted. If not, covers should be fitted during installation to keep foreign material, including rain, from entering the duct.
11.5.4 Installing and Stressing Tendons

Groups of steel strands and bundles of steel wires can be preassembled with a nose-piece attached. A pull-wire is fed through the duct; one means to feed it through the duct is to blow it by compressed air acting on a rubber ball. A line is attached to the ball which can then be used to pull in the pull wire. The nose-piece is often a Chinese finger grip of spirally wound wire. The bundle is then pulled through the duct. It is usually more efficient, however, to push strands through one at a time, using a pushing feeder of mechanically driven rolls. The end of the strand is fused together by a torch so the individual wires do not separate. Water-soluble oil is brushed onto the strand as it enters the duct. When all of the strands have been pushed through the duct and through holes in the anchorages, they are pulled to a nominal tension by a single-strand jack and temporarily wedged. This ensures that all strands are of the same length. See Figure 11.17 for a graphic representation of the sequence. A multistrand jack is then fitted so as to extend the tendons to their designed stressing level, which is usually about 72% of the ultimate strength. The wedges are hydraulically pushed home (Figure 11.18). When there is considerable curvature in the tendon, the tendon is stressed from both ends. Cycling it by pulling from first one jack and then the other reduces frictional loss. Final stress in the tendon should match theoretical elongation, using calculations based on the modulus of elasticity as furnished by the manufacturer. The modulus varies with the lay of the strand. Allowable tolerance is usually set at 5%. Where this value is exceeded, the cause should be determined. It may be excessive friction, in which case adding water-soluble oil and cycling can help, or the cause may be in the assumed modulus. These data are recorded for each tendon. After the jack is removed, the ends should now be protected from rain and spray by a covering of polyethylene or similar material.

11.5.5 Scaffolding and Falsework for Post-Tensioned Cast-in-Place Construction

A great many building and bridge structures are constructed on scaffolding and falsework. After the cast-in-place concrete has gained strength, the structure is post-tensioned. This prestressing redistributes the dead loads, typically raising the span off of the central scaffolding and transferring it to the end supports.
FIGURE 11.17 Sequence for stressing post-tensioning tendon. (Photograph courtesy of VSL Corporation, Campbell, CA.)

FIGURE 11.18 The stressing operation. (Photograph courtesy of VSL Corporation, Campbell, CA.)
In the typical case, this redistribution and induced camber are beneficial to the construction process, making it easier to remove the scaffolding; however, the constructor must ensure that any temporary supports at the reaction points are capable of taking the increased dead load and lateral forces imposed on them. Prestressing also shortens the span. If one end is on neoprene bearing pads it will be free to move. The intermediate scaffolding will be distorted by the shortening but is usually able to accommodate this because of its height and flexibility; however, this should be verified in each case. If the ends are fixed, then the act of prestressing pulls the supports toward each other. The stiffer support will take most of the force and in turn will counter the prestressing, reducing its efficacy. Because of creep, the problem gets more severe as time goes on. This situation has unfortunately arisen on a substantial number of building projects where the effects were not adequately foreseen, resulting in spalling at the edges of bearing seats and, in at least one case, splitting of a stiff column. If a permanent connection must be made at both ends, and the supports do not have adequate flexibility to accommodate the shortening with only small opposing force, then it is best to temporarily place one end on a neoprene pad or sliding bearing, then fix it after the elastic shortening and early creep have taken place. Of course, long-term creep may still cause problems, but its magnitude will be less. Neoprene strips should be used at the edges of the bearing surface to allow minor rotation and to minimize the tendency to spall.

11.5.6 Corrosion Protection of Tendons

The standard method of providing corrosion protection of tendons is by injection of cement grout. If properly done, this encapsulates the strands and penetrates between the wires of the strands. In the case of ducts no larger than two times the gross area of the tendon, cement and water are the principal components of the grout. Sand or other fines are incorporated only in the rare cases of very large ducts. Water-reducing admixtures are necessary for corrosion protection. Fly ash may be used to replace up to 20% of the cement. Thixotropic admixtures are very valuable in reducing bleed, which leads to voids at high spots in the profile. Thixotropic grouts require a positive-displacement pump for injection. Special grouting admixtures have proven very successful for promoting full filling of ducts and preventing bleed pockets. Expansive admixtures, such as aluminum powder have been used but have sometimes created problems with excessive pressure and with the control of expansion. A thixotropic antibleed admixture is believed to be more effective.

The grout should be injected from one end. The first grout ejected from a vent is dark due to the water-soluble oil. Grout should be wasted until the ejected material has the same color and consistency as the grout to be injected. When the grout ejected from the first vent is deemed satisfactory, that vent is closed. When the end vent is discharging satisfactory grout, that vent is closed. This forces the grout through the tendon anchorages and seals the strands at these critical locations.

Vertical ducts present a special problem in that the strands act as wicks, promoting bleed. Use of a thixotropic admixture helps but is not always 100% effective. One solution is to have an extra hole in the top anchorage plate, through which a tube leads to a small tank above. This tank or receptacle is filled during grouting; the grout then can feed down to fill the duct as the column of grout subsides. Silica fume, as an admixture, also reduces bleed; however, the combination of silica fume and thixotropic or anti-washout admixture is frequently too viscous for effective injection. The anchorage pockets then must be completed. Preferably, small-sized bars have been placed that can be bent down into the pocket. The anchorage pockets should be filled with a fine concrete—that is, one made with small-size coarse aggregate, say 8 to 10 mm (pea gravel)—and a mix rich in cement. Silica fume may be added to minimize bleed. Frequently, the surface of the anchor and the pocket is coated with bonding epoxy. In other cases, latex-modified concrete is used to improve bond.

Shrinkage should be prevented by using the window-box technique, in which the concrete is filled to an elevation higher than the pocket, so if bleed occurs the grout will feed down into the space. Any excess concrete can be easily chipped off after a day or so. The joint around the pocket may be painted with an epoxy that has high capillarity and can be sucked into any shrinkage crack.
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In a number of cases, especially nuclear reactor containments, the tendons and the anchorages are encapsulated in grease instead of cement grout. The grease is injected in much the same manner as grout and periodically examined; also, where necessary, additional grease is injected. This technology is now giving way to an advanced system in which each strand of the tendon is sheathed in polyethylene and grease is injected so the strand is free to move within the sheath. This protection is very positive. A cluster of such sheathed strands is fed into a duct. They are then stressed and the duct is grouted or grease is injected, thus achieving a multiple protection system. The critical zone in such a system is at the anchorage, where the strands must be bared for the wedges to grip them. Caps with grease or grout fittings are provided that screw onto the anchorage so they too may be injected after stressing.

11.5.7 External Tendons

The term external tendons is used to describe post-tensioning tendons that are not directly incorporated into ducts in the concrete. Usually, these tendons are placed inside the box of a trapezoidal box girder, but they may also be outside. External tendons are unbonded. They are anchored at blisters or bolsters, usually near the ends of the member, and may be deviated at intermediate points along the profile. The tendons are typically encased in a heavy polyethylene sheath. At deviation points, a steel sleeve may be used to prevent the tendon from cutting into the polyethylene. The polyethylene sheath may be continued through the steel sleeve. The steel sleeve is preformed to the design radius. It should have belled ends to prevent stress concentrations (Figure 11.19). Large radial forces at the deviators must be resisted by proper reinforcing details. Deviators must be adequately anchored to the webs or flanges. One problem frequently encountered with external tendons is the failure to leave enough space at the anchorages in which to place a large multistrand jack on the prescribed angle. This must be considered in the working drawings.

11.6 Pretensioning Technology

11.6.1 General

Pretensioning denotes the process by which tensioned high-strength steel wires or strands are incorporated in a concrete segment. The process is relatively simple in concept, economical, and technically efficient; however, it requires a major plant facility that is able to temporarily restrain the forces in the tensioned
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11.6.2 Description of Process

In its simplest form, the pretensioning facility consists of a casting slab or bed on which the segments will be fabricated, reaction frames or stands at the end to temporarily resist the tendon forces, hydraulic jacks for tensioning, tarpaulins or hoods to cover the segments during curing, and lifting equipment to remove the completed segments for storage and shipment.

11.6.3 Tendon Installation and Stressing

The tendons most commonly employed are seven-wire strands with a nominal diameter of 15 mm (0.6 in.), an ultimate tensile strength of 1900 MPa (270,000 psi), and a 0.2% offset yield strength, which is 80% of ultimate. These strands are spaced apart to develop bond for stress transfer and are arranged in appropriate patterns to develop the design compressive stress in the concrete cross-section. Multi-wedge strand anchors are used to temporarily grip the ends of each strand so the jacks can impart the desired force and elongation. Both single-strand and multistrand jacks are used. After the strands are properly stretched, they are anchored to the stands at each end of the bed (Figure 11.20 and Figure 11.21). When
strands are stretched with a multiple jack, very large forces are stored. To prevent serious accidents, nuts should be progressively run up on the extension arms of the jack to limit travel in the event of a loss of hydraulic pressure. The achievement of the proper prestress can be determined both by gauge pressure readings of calibrated jacks and by the elongation. Most specifications require that these deviate not more than 5%. Variations are caused by difference in moduli of the strands or by frictional restraint at the ends and intermediate supports. It is important to keep foreign materials such as oil and grease off of the strands. Welding should never be permitted on or near the tendons as it will destroy the special properties that have been induced by cold drawing of the wires. Unstressed reinforcing steel can usually be most easily placed after the strands are tensioned. The entire reinforcing assembly can then be held in proper position by tying it to the strands or by using plastic chairs and dobie block or by hanging it from overhead spreader bars with plastic wires.

11.6.4 Forms

The forms for concrete segments are typically made of steel. Because the forms are standardized members, they minimize the effort and time required to set them in place and subsequently strip them. For some configurations, the forms may be fixed and tapered so the segment can be removed without moving the forms. For other shapes, mechanical means may be used to close and open the forms. The end gates of the forms are especially critical, as they must allow the strands, and perhaps some reinforcing bars, to pass through without leakage; hence, they may have to made up in small pieces. Rubber gaskets can be used to seal around the strands and at the sides. For some products, such as piles, it is important that the head be normal, or square, to the longitudinal axis. This can best be achieved by making the end gates up in pairs, spread apart and rigidly held in a frame.

11.6.5 Concreting

The concrete mix is designed to gain strength rapidly so the tendons may be released, transferring their force into the concrete; the segment is then removed to storage. The strength required for release is controlled by two factors: (1) adequate bond strength to limit the transfer length at the ends of the member, and (2) adequate strength to minimize the creep under sustained stress. Typical release strengths
range from 20 to 30 MPa (3000 to 4300 psi). Concreting follows normal practices of placement (Figure 11.22). External vibrators are often used; they may be moved progressively to brackets on the steel form or permanently mounted on them. They produce excellent consolidation and drive water and air bubbles from the outer exterior 100 to 150 mm (4 to 6 in.) of concrete thickness. For members thicker than about 200 mm (8 in.), internal vibration is also required, even with so-called flowing concrete; otherwise, in densely reinforced and congested zones, such as the end blocks of girders and the heads and tips of piles, honeycomb and rock pockets may occur.

### 11.6.6 Curing

To gain strength rapidly, accelerated curing is usually applied, which provides heat and moisture. Most commonly, such curing will consist of low-pressure steam. Ideally, adequate strength will be gained in 8 to 12 hours, enabling a daily cycle of production. Forms must be free when the tendons are released, as the concrete will shorten. If the forms are locked to the concrete (for example, by a change in the cross-section), then they also will be forced to shorten. A variety of means are used to prevent damage to the forms. Safe removal can be effected by lifting, sliding, or hinging. If tapered and smooth, of constant cross-section, and sufficiently rugged, then the concrete member may partially slide in the form. Multiple short forms may be designed to slide on the bed.

### 11.6.7 Release of Prestress

After curing is complete, the tendons are released from the stands, transferring force into the concrete. The concrete shortens under compressive stress. To ensure behavior as a prestressed concrete member, the shortening must not be restrained. In practice, when heavy segments are cast, the friction between the segment and the soffit of the forms may restrict the shortening. In many cases, this problem may be overcome by initially lifting one end of the segment before the other, thus allowing the member to shorten and become prestressed before the full load is realized. Any discontinuity in the cross-section, whether inherent in the design or accidental, such as a fin due to leakage from the forms, may prevent shortening. At this early stage the concrete segment is subject to drying shrinkage and thermal shrinkage, so cracks may occur. Also, steel forms expand under steam or heat curing more rapidly than concrete, forcing a crack. To prevent cracks at changes in cross-section, soft neoprene or rubber gaskets may be installed to
accommodate the dimensional changes. Covering and insulation of the surfaces after curing will postpone drying and thermal shrinkage strains until the concrete has more tensile strength.

Release of the pretensioning into the segments is preferably accomplished by use of a hydraulic jack. This requires reinstalling the jack, exerting a slight additional pull to loosen the wedges, then slowly backing down on the force, allowing the strands to slacken. Even then the friction of heavy concrete segments on the bed or in the forms may prevent their movement and prevent release of prestress into the individual segments. The release then is accomplished by burning the strands. This should be done in a balanced pattern, using low heat (yellow flame) and then cutting with the blue flame. The intention is to reduce the stress gradually. A sudden shock release increases the development length over which the prestress force is transferred to the concrete.

Over this transfer length, particularly near the ends of the segment, the prestress compression is not uniform over the concrete cross-section. Tension develops between strands and especially between groups of strands. Orthogonal reinforcement, in the form of short bars or mesh, is often needed at the ends to prevent splitting cracks. Although this supplemental reinforcement should be part of the design, in practice it is often left up to the fabricator and thus must be considered when preparing shop drawings for fabrication.

11.6.8 Cycle

The typical cycle in precast pretensioned fabrication is as follows:

- 4:00 a.m. Terminate steam-curing cycle.
- 5:00 a.m. Remove test cylinders from under the tarpaulins for testing; replace tarpaulins.
- 6:00 a.m. Test cylinders, and verify that the required release strength has been obtained.
- 6:30 a.m. Remove tarpaulins.
- 7:00 a.m. Detension tendons, and cut strands between segments.
- 8:00 a.m. Lift products out to storage, and store on timber sleepers at correct points to minimize deflection due to creep.
- 8:30 a.m. Clean forms.
- 9:00 a.m. Stretch new strand tendons the length of the bed.
- 10:00 a.m. Equalize lengths with single-strand jack.
- 10:30 a.m. Stress strands.
- 11:00 a.m. Place reinforcing steel, and place end stops or gates.
- 1:00 p.m. Place concrete, consolidate, and finish.
- 6:00 p.m. Turn on low-pressure steam, raising temperature 1°C every 2 minutes to 60°C (140°F). Hold temperature constant until 4 a.m.

Obviously, times and operations have to be adjusted to fit individual products and reinforcing steel patterns.

11.6.9 Tendon Profile

The efficient design of many segments, such as slabs, beams, and girders, requires that the profile of the tendons follow a path other than a straight line. This means that the strands must be deflected. Deflection has been accomplished in a number of ingenious ways. One such way is described in the following. Strands are initially stressed to a precalculated reduced stress. They are then pulled down or up at specific points, forcing the strands into a series of chords approximating the design path (Figure 11.23). This, of course, raises the stress in the strands to the desired value. The jack then brings the stress to the design level. By this method, frictional losses and variations of stresses between segments are minimized. Another method is to pull the tendons over a series of rollers, set at selected deviation points; unfortunately, the frictional losses with this method are cumulative and result in unequal tendon stresses in the several segments.
The hardware at the deviation points can be likened to the arrow in a stretched bow; thus, they are points of danger to personnel during placement of reinforcement and subsequent concreting until the concrete has at least reached final set. These points should be clearly marked with red paint on the tops of the forms, and all personnel must be kept clear. This is especially important for the vibrator operator.

The release of a member made with deflected strands requires special consideration. If the deflected strands are released first, the pull-down devices hold the segment tightly against the casting bed, preventing shortening and effective transfer of prestress. Conversely, if the deviation points are released first, the resulting upward force in an unstressed member could break it. For this reason, the first method is used—that is, first releasing the longitudinal strands and then releasing the pull-downs at the deviation points. In some advanced installations, provisions have been incorporated to allow limited longitudinal movement at the deviation points.

11.7 Prestressed Concrete Buildings

11.7.1 General

Buildings represent perhaps the largest overall use of prestressed concrete and certainly the most diversified use of precast pretensioned concrete segments. Standardized modular configurations have been extensively employed for roof slabs, floor panels, beams, and wall panels. Cast-in-place post-tensioned concrete has been widely used for floor slabs, especially of lift-slab construction and for heavy beams and girders. Post-tensioning permits the full integration of slabs, beams, and girders. Similar monolithic construction is attained with precast pretensioned construction by jointing and cast-in-place infill and topping. Because the construction process differs significantly between the two processes, they are treated separately in the following sections; however, the two systems may be combined in any particular building.

11.7.2 Precast Pretensioned Concrete

The most widely employed precast concrete segment is the double-tee (Figure 11.24). It is used for roof slabs and wall panels. In combination with cast-in-place topping, double-tees are used for floor slabs. Widths are modular; in the United States, this means either 4 or 8 ft (1.22 or 2.44 m).
11.7.2.1 Manufacture

The precast segments are cast in steel forms with tapered legs. The taper plus the slight flexibility of the steel forms permit the segments to be lifted out, or stripped, without adjustment to the forms. Inserts can be placed in the bottom of the legs to reduce their depth for shorter spans. Straight strands are employed for short spans, and deflected strands are employed for longer and more heavily loaded spans. Because the typical deflecting forces are low, much less than with bridge girders, the system of pushing up at the ends while holding down at the middle or third points is commonly employed. Shear reinforcement may be in the form of bent reinforcing bars or welded wire mesh. A few widely spaced strands may be run in the top slab to prevent shrinkage cracking. Transverse bars or diagonal bars will provide cross-slab reinforcement and can anchor embedments for connection between flanges of adjacent slabs. Where topping is to be placed for composite behavior, the top surface is roughened with a transverse broom finish. When double-tee segments are employed for walkways and small bridges, the legs are usually wider and deeper to accommodate the necessary strands and shear reinforcement. For longer spans, single tees with deeper and thicker stems are used (Figure 11.25). Another form of slab, the hollow-core slab (Figure 11.26), is made by several proprietary processes, resulting in a flat top and bottom with multiple longitudinal holes. Both lightweight and conventional concrete are used in manufacture. For lightweight concrete, the replacement of part or all of the fines with natural sand will reduce problems of creep and shrinkage.

11.7.2.2 Erection

Precast segments are typically transported by truck and erected by a large truck crane with extended outriggers. Proper procedures and safety practices must be followed to ensure safe and efficient operations. The Prestressed Concrete Institute has published a manual, *Erection Safety for Precast and Prestressed Concrete* (PCI, 1995), that includes sections on the following important aspects:

- Preplanning of the erection
- Site conditions
- Cranes
- Equipment
- Rigging

![Double-tee precast, pretensioned concrete slab.](https://example.com/image1124.png)
Preplanning of the erection is proving especially valuable to contractors, who use it to determine access for cranes and trucks, the swing of the crane and segment in three-dimensional space, and the sequence of erection and means for accurate positioning. Temporary bracing and staying may be required. Marking the exact seats of segments beforehand saves valuable time in the final positioning. Connecting or jointing details are quite critical. Tolerances must be considered, both relative to adjacent segments and cumulative. Details of embedment of strands or reinforcing or welding and bolting have proved to be very important, especially when the structures are subjected to dynamic loads such as earthquake, hurricane, and tornado.
Large truck cranes with outriggers are the most commonly used means of erection (Figure 11.27). It is essential that the outriggers be properly supported by timber mats or the equivalent to prevent settlement during the swing of the load. Care must be taken to ensure that neither the boom nor the rigging swing into already erected elements. Adequate room must be available for the counterweight during swing. Tower cranes are also employed; the weight of the units determines their capacity and reach.

Because of the large number of relatively light segments that are typically erected in a building, attention must be given to the detailing and construction of the lifting inserts. These must be compatible with the hooks and slings employed by the rigger, and they must be properly anchored into the member to resist inclined as well as vertical forces. Local pullout can cause a serious accident. Adequate factors of safety must be provided to take care of the dynamic amplification of lifting and minor accidental lateral impact.

When a cast-in-place concrete topping slab is placed on top of precast pretensioned slabs, the latter often require temporary shoring to sustain the dead load of the fresh concrete without excessive deflection (Figure 11.28). This shoring is typically made tight and the grade adjusted by the use of either wedges or screw jacks. These must be set in such a manner that they do not become loose or tip while the top concrete is being placed. The shores react against a lower slab, which may have been placed only a week before, in which case the topping may not have adequate strength. Serious progressive collapses have occurred when the shoring has not been carried far enough or was not strong enough to carry the accumulated loads. Other serious collapses have occurred when the shoring was removed too early. The in-place strength of concrete should be ascertained by companion cylinders stored alongside or through nondestructive testing (e.g., Schmidt hammer). Particular care must be taken during winter when low temperatures delay the strength gain.

Creep must be considered by both the designer and erector, as lengths and camber will change with time. For that reason, it is desirable to let the precast segments mature a reasonable length of time before erection (e.g., 1 to 3 months). Rigid welded connections at both ends are to be avoided. Bearing slabs must be of adequate length and adequately reinforced. Neoprene bearing pads will allow minor rotation and shortening. Shear at the ends of slabs becomes increasingly critical with time due to the tensile stresses induced by creep and the increase in the transfer length of pretensioned strands with time. The erector needs to consider this when preparing the shop drawings.

Camber is affected by a number of factors, including eccentricities of prestressing, the modulus of elasticity of the concrete, creep, differential temperature from top side to bottom, and differential moisture. The cumulative effect of these factors and of various tolerances may create difficulties, especially in
thin, highly stressed slabs such as those most often employed in roofs. These difficulties may in turn cause problems in waterproofing. In extreme cases, loss of camber may lead to ponding of rainwater, which in turn increases downward deflection and ponding of more water, leading to progressive collapse. The camber of adjacent segments may not fully match. Adjacent sections usually can be pulled to match with minimal force, provided the differences in camber and the stiffness of the members are not too great. Where excessive force is required, typically more than 100 kg (220 lb), the design engineer should be consulted. Excessive camber may be reduced by tensioning of embedded polyethylene-sheathed and greased strands installed for this contingency.

11.7.3 Cast-in-Place Post-Tensioned Buildings

Both bonded and unbonded tendons are employed for cast-in-place post-tensioned buildings. Unbonded tendons are extensively used in flat slabs, both lift slabs and cast-in-place slabs. The advent of polyethylene-sheathed and greased strands has made this process reliable and durable. The details of this type of construction are presented in Chapter 10 and Chapter 12. Conventional post-tensioning in ducts, with subsequent encasement of the strands in grout, is typically employed for deep beams and girders. In parking garages, this method is often employed for the ramp (Figure 11.29). For lift-slab construction and wherever precast columns are used, post-tensioning through the columns is desirable to ensure shear friction transfer from the slab, so as to offset subsequent shrinkage. A key detail in post-tensioned building construction is the protection of anchorages to prevent moisture in leakage and to safeguard against fire. Both conventional and polyethylene-sheathed tendons have bare strands through anchorage zones; thus, this is the most vulnerable area for potential corrosion. Recessed anchorages, filled with concrete and tied to the structural slab, are the most reliable.

11.8 Prestressed Concrete Bridges

11.8.1 General

Prestressed concrete has been quite successfully used in the field of bridges, ranging from low- to medium-span precast pretensioned bridges to post-tensioned girder spans 250 m (820 ft) in length and, beyond that, to cable-stayed concrete bridges 600 m (2000 ft) long (which are a derivative form of post-tensioning).
Prestressed concrete bridges are now used worldwide in remote developing countries as well as in the urban centers of highly developed countries. Prestressing has proven very versatile in its application and can be used to solve many complex problems of curvature and skewness. It has become the standard by which alternative materials and systems are measured. This success, however, has not come without some problems. Some of these are common to all reinforced concrete—for example, the corrosion of steel in bridge decks on which salts are applied to prevent icing. Many of the problems peculiar to prestressing are due to the widespread adoption of this new technology, sometimes without proper attention to details of design and workmanship. Although in most cases these problems were resolved on the site, they have proven costly and cause delays to the constructor. Fortunately, most problems are now in the past, in that we understand their causes and have adequate solutions available.

11.8.2 Precast Pretensioned Bridge Girders

The precast, pretensioned I-beam girder is widely used for trestle-type bridges, viaducts, and overcrossings (Figure 11.30). This element has proven to be adaptable to mass production, with resultant economies and reductions in cost. The girders are manufactured on long-line pretensioning beds, with deflected strands as described in Section 11.6. They are then transported, principally by truck and dolly, so the support is within 1 m (3 ft) of each end. Long and deep-webbed girders are hog-rodded to prevent buckling during transport.

Girders must be positively restrained against tipping. At this stage, there is no additional dead load from the slab acting; hence, the girder stresses are usually within safe limits only when they are near vertical. If tipped too far, they may fail explosively due to overcompression in the top flange. Blocking and chaining are used to prevent tipping. (Note that wire rope stretches under sustained and repeated loads, so chains or structural members are the only safe means for providing restraint.)

The girders are usually erected by crane. When one crane is used, slings leading at 45° to the horizontal or more (60° is preferable) are employed. This limits the height to which the girders can be lifted. These slings develop a horizontal thrust due to their angle, which may overload the compression flange of the girder, especially because of the low buckling resistance of the girder in the y–y (transverse) direction. To overcome this problem, a spreader beam with vertical slings from the girder to the beam is often used (Figure 11.31). The axial compression of the spreader is then utilized to resist that imposed by the inclined slings. A pipe strut is usually used for the spreader beam, but trusses are employed for very long girders.

FIGURE 11.29 Cast-in-place concrete floor slab will be post-tensioned in both directions. (Photograph courtesy of VSL Corporation, Campbell, CA.)

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The process of lifting and setting precast girders is a demanding one due to the dynamic forces caused by inertia and swinging, as well as to long and high lifts. Most erection is carried out by crawler and truck cranes; the latter use their outriggers for stability.

The picking inserts in the girders must be properly anchored deep into a compressive zone and must be capable of taking the force at an angle. Slings must be properly designed to meet the amplified load due to angle. Both must be adequate for the dynamics of inertia force and acceleration. The latter is especially critical when floating equipment is used for lifting due to the potential dynamic motion of the barge hull. The rules of crane and rigging safety must be carefully followed.
When bridge girders are erected, they are initially vulnerable to tipping. Tipping may be caused by girders being set on a superelevation, by wind, or by contact with a line from a second girder while it is being lifted. For this reason, long and deep I-beam girders should be braced as soon as they are set. Cast-in-place decks are designed to act compositely with the precast girders. To ensure full transfer of horizontal and vertical shear across the joint, the top flange of the precast girder is roughened and multiple stirrups are employed to tie the girder and deck together. Transverse diaphragms are cast between the end blocks of the girders and sometimes at intermediate locations, although the latter have proven to be less prevalent than was necessary in the early years of this new technology. Experience and tests have shown that the deck slab provides adequate transfer in most cases.

Girders are usually set on neoprene bearing pads. To facilitate accurate and rapid setting, it is helpful to mark a line on the pad for the planned ends of the girder, so no further measurements in either direction need to be made. The cantilever suspended span concept has been used to extend the span of precast prestressed girders. The two side spans are continued over the main piers and are haunched and prestressed for negative moment. Either pretensioning or post-tensioning may be used to provide the required moment capacity. The suspended span, designed for simple span behavior, is then installed. At the interim stage, when the side spans are set but do not have the relieving load of the suspended span, they may be overstressed by the prestressing. This can be countered by the addition of mild steel reinforcement at the bottom of the haunch or by the use of temporary counter prestress.

In the typical bridge, the deck acts as the compressive flange, while the web transmits the shear to the bottom flange. The bottom flange has to have enough prestress to resist both superimposed dead load and design live loads. The top flange has to be large enough to accommodate the tendons necessary to sustain the dead-load compression. In longer girders, this frequently results in temporary excessive precompression in the bottom flange. Enlarging the bottom flange results in a bulb tee, which has the desired stress characteristics at all stages and provides the necessary room for the prestressing tendons. Other cross-sectional shapes have been employed for shorter span bridges. These include the double-tee and the triple-tee, or M shape. The typical double-tee used in buildings has a rather narrow web, which may not provide adequate cover for durability or adequate strength for shear. Special forms with a wider web may be used.

Precast prestressed slabs are also employed for short spans and have the advantage of minimum depth and a flat underside. For slightly longer spans, hollow cores may be formed to reduce weight. These slabs may also have a cast-in-place composite topping. To temporarily support the load of fresh concrete, the precast member may require shoring at its midspan or third points.

### 11.8.3 Post-Tensioned Girders, Cast-in-Place on Falsework

This is a widespread application of prestressed concrete. Falsework shoring is set up, is adequately supported on the ground (or on the new foundations or on piling), and is capable of resisting the dead load of the concrete with minimal deflection. Provision should be made to offset the calculated deflection, whether it be elastic bending of falsework beams or elastoplastic deformations of the ground support. It is important that the shores be adequately braced for both transverse and longitudinal movement during casting of the concrete (Figure 11.32) and subsequent stressing.

For continuous structures, the concrete is usually cast in progression from the center of the span to each end, so as to reach its deflected profile prior to casting the concrete over the piers, thus preventing cracking in the negative moment zone. As the cast-in-place sections are prepared, the ducts are placed to the required profile and alignment. At vertical construction joints, the sections are spliced. Because splices and construction joints are a principal source of problems that occurred in the early years of this technology, attention must be paid to the details, as described in Section 11.3.4. This includes accurate prolongation of the profile across the joint (e.g., by the use of mandrels), the application of heat-shrink tape to the ends of splice sleeves, and proper preparation of the construction joint surfaces (Figure 11.33).

In the negative moment zone, over the piers, the design often calls for several ducts with their tendons lined up one above the other in groups of two, three, or more. Space between these ducts may be very
limited, so the potential exists for an upper duct to pull through into the one below. To prevent this, small reinforcing bar hairpins may be placed transversely, between each pair of ducts. In extreme cases, the lower tendon must be stressed first and grouted, then the second tendon is stressed and grouted, and so on. It generally proves economical and practicable to space the tendons so the shear strength (in double shear) of the concrete and the dowel effect of the transverse bar are adequate to resist the radial component of the tendon force.

**FIGURE 11.32** Structural steel falsework supports high-level cast-in-place post-tensioned bridge (Ma Wan Viaduct, Hong Kong).

As cautioned in Section 11.4.9, the design of supporting falsework must consider not only the stage when the concrete is cast, and hence imposes its dead load on the supports, but also the stage when the prestressing force has transferred the dead load, distributing it with concentrated forces under the zones of concave curvature downward while relieving the load on the zones of convex curvature.

The cumulative effect of shortening between joints of multispan continuous girders must be considered. Intermediate supports must be able to accept the curvature imposed by this shortening or, better, be temporarily freed from it by temporary devices that allow the girders to move the short increment of prestress deformation. Stressing from each end will minimize the actual movements over the intermediate piers. Some very important bridges of moderate span have been cast-in-place and post-tensioned with temporary support on a steel deck truss. When the span is post-tensioned, it rises up off the truss so it is independently supported directly on the piers. The truss can now be slid forward past the pier to the adjacent pier and the process repeated for the adjacent span. This results in a series of simple spans that can subsequently be made continuous for live load by post-tensioning for negative moment over the supports. To facilitate the sliding of the truss from one span to the next, the pier must have an appropriate configuration, such as a division into two shafts between which the truss slides or the provision of steps on the outside of the piers on which individual trusses may be slid forward.

Transverse post-tensioning of the deck is increasingly employed, especially for box girders with cantilevered deck flanges. Because space is limited, ducts must be kept small. Rectangular ducts encasing four side-by-side strands are frequently employed. Tendons may have a dead-end anchorage in the concrete at one end and a stressing anchorage in a pocket at the other end. To provide additional corrosion protection, plastic ducts may be used. In other cases, plastic-sheathed and greased strands are employed with special care being taken to protect the anchorages.

The primary longitudinal post-tensioning tendons are located in the upper flange in the negative moment region near the piers. This means that the transverse tendons should go over them above the webs and under them near the transverse centerline. This is a three-dimensional problem of location, and some eccentricity is unavoidable. To prevent delamination, hairpin dowels at 600-mm (24-in.) spacing may suffice.

11.8.4 Post-Tensioned Precast Segmental Bridges

The concept here is that short segments of the full cross-section of the bridge are cast in a prefabrication site or casting yard. These segments are then transported to the site and erected on falsework or on a truss, as described in the previous section. The segments are then jointed and post-tensioned. Because the segments are cast as relatively small, discrete units, it is possible to obtain close tolerances for reinforcing and duct placement, as well as for finished concrete dimensions. The ability to obtain high-strength and high-performance concrete is enhanced. At the same time, segments are kept to a reasonable size for transport and erection. After erection, segments are carefully aligned to the correct profile; thus, dead-load deflection is taken care of prior to stressing.

Joints may be constructed by a variety of means. Cast-in-place joints, typically 500 to 1500 mm (1.6 to 5 ft) in width, can be constructed in which the reinforcing steel is made continuous by lap splices, welded splices, or couplers. Ducts can be readily spliced by sleeves and sealed by heat-shrink tape. Thin grouted joints, typically 75 mm (3 in.) in thickness, were used in the past but have not proven to be successful because of difficulty with duct continuity.

Vertical joints usually require shear keys. In the past, trapezoidal keys were widely used, but experience has shown them to be subject to diagonal cracking at the corners. Installing a short diagonal bar across the potential crack is one solution. More recently, curved shear keys, corrugated on a large pitch, have been used for both cast-in-place and precast concrete segments.

Dry joints have been used for many bridges in which the precast concrete deck girder segments have been match cast. Match casting consists of constructing each successive segment with its trailing edge cast against the leading edge of the preceding segment (Figure 11.34 and Figure 11.35); thus, a perfect fit is ensured. Ducts are extended from the first segment to the second by use of a mandrel.
Some problems with fit have occurred with match casting when steam curing has been employed. The segments tend to warp in unequal fashion with the heat. To prevent this, it is best to steam cure the first and second segments together, prior to separation. A bond breaker must be used on the common joint surface. After separation, a light sand blasting, wire brushing, or water-jet blasting can be employed to clean the mating surface.

With dry joints, a thin O-ring seal can be placed in a recess around each duct to seal against grout leakage and cross-over of grout between ducts. Alternatively, thorough swabbing of the duct may suffice but the results need to be verified. Dry or match-cast joints have been greatly improved by the use of epoxy glue on the mating surfaces. Typically, during erection, the second segment of the joint is raised. It is positioned by the use of two mating dowels, either cast in the segment or temporarily affixed to the top. After verifying proper fit, the segments are moved apart and epoxy glue is applied with a gloved
hand. Because epoxy is incompatible with free moisture, the surface must be protected from rain, etc.
during this process. The second segment is again pulled into contact with the first and a temporary
precompression is applied by stressing bars at the top, bottom, and both sides. The precompression on
the concrete surface of the joint should be 0.3 MPa (44 psi). The epoxy sets under the applied pressure.
Many such matings have been successfully made using only epoxy glue to seal the ducts at the joint;
however, use of a thin O-ring gasket is believed to be a conservative and justified step to prevent
inadvertent blockages in later grouting.

Assembly of complete and multiple spans has been successfully carried out both by erection on
falsework and by lifting up a completed span with one or two crane barges. In some instances, the full
span, less the two pier-head segments, has been assembled, jointed, and prestressed on a barge, then
lifted up from the preset pier heads. Prestressing such an assembly on a barge requires the consideration
of the extreme loads imposed on the barge deck at the girder ends due to the post-tensioning. Additional
posting or support of the deck may be required.

11.8.5 Cast-in-Place Cantilever Segmental Bridge Construction

This process has been successfully employed on spans up to 200 m (660 ft) and more (Figure 11.36).
With cable-stayed concrete segmental bridges that employ the external tendon principle, much longer
spans—500 m (1600 ft) and longer—have been attained. The concept is to cast two segments, one on
each side of a pier. The casting is followed by prestressing the segments over the pier to resist the negative
moment in cantilever. Two more segments can then be cast and post-tensioned, and so on. Each stage
must be carefully analyzed to ensure adequate prestressing for the dead load of that segment plus the
forms and the weight of the next segment during its casting. Because it is generally not feasible to cast
two segments simultaneously, one on each side of the pier, the pier shaft must be adequately reinforced
to withstand, out of balance, the temporary bending that is induced. These cantilevered decks are typically
extended to near midspan. After a waiting period, to allow as much of the creep as practical to take place,
the two extended arms are locked together and a closure pour is made.

At the initial stage of this process, a pier-cap segment is first constructed which is temporarily locked
by vertical post-tensioned bars to the pier shaft. A small skid derrick is then erected on the pier-cap
segment. The derrick lifts up a prefabricated form for the first cantilevered segment. Reinforcing steel
and ducts are placed and the segment concreted. The concrete mix is designed to attain adequate strength
for prestressing within 1 to 3 days. This segment is then post-tensioned to the pier cap segment, and the
skid derrick is moved out onto it and temporarily bolted to the deck. This leaves room on the pier cap
to install a second small skid derrick headed in the other direction. It now raises the forms and constructs
and stresses its cantilevered segment. Now the process can proceed in parallel on each arm of the deck.
A typical cycle requires 4 to 7 days for each pair of segments. In many designs for continuous bridges,
a hinge is required near the quarter point. To permit the cantilever segmental process to continue past
the hinge, it is temporarily locked with removable post-tensioning bars. In other designs, a hinge is placed
at midspan. To prevent undesirable movements as heavy live loads cross the hinge, complex devices that
transfer shear but no moment are installed.

The cantilever segmental process is very demanding for the contractor; accurate and thorough quality
control are essential. Prestressing ducts must be accurately placed to close tolerances and rigidly held in
position so as not to be displaced during subsequent concreting and vibrating. At the ends of each
segment, the ducts are held in exact location by the end bulkhead of the form. To ensure that the profile
of a duct is continuous across the joint, without a small, sharp bend, a pipe mandrel should be inserted
which can be extended into the duct in the next segment when it is formed. Pipe mandrels also serve
the secondary purpose of ensuring that the duct remains clear and open when adjacent tendons are
grounded. Each time a form is extended from the preceding segment, it is purposely set sufficiently high
at its leading end to counter the deflection under the weight of the fresh concrete. Concrete placement
should proceed from the outer end back toward the previously completed segment.

Segments are typically very congested by conventional reinforcement in three directions and longitudi-
dinal and transverse post-tensioning tendons. Near the piers, vertical post-tensioning tendons are often
installed as well. This congestion makes concreting difficult. Fortunately, the use of high-range, water-
reducing admixtures (superplasticizers) makes obtaining a very workable mix feasible while still achieving
high early strength and high long-term strength.

Because of the congestion in the deck near the pier, the horizontal section through the middle of the
top deck may have a greatly diminished concrete section; the area is largely occupied by closely spaced
longitudinal and transverse ducts. Thus, horizontal shear transfer across this section is diminished and
may result in laminar cracking due to the unavoidable eccentricities in the prestressing centroid in the
two directions. This problem has been successfully prevented in a number of cases by provision of small-
diameter hairpin stirrups in the deck at a nominal spacing of about 0.6 m (24 in.) in each direction.
Whereas laminar cracking should be considered for design, it should also be considered by the contractor
because laminar cracking is not readily apparent at early ages and repairs are very difficult, usually
requiring stitch bolting. Creep and shrinkage, as well as elastic deformations, affect the profile of the
completed bridge; thus, it is necessary to take accurate readings at the same time each day, preferably
early in the morning before the heat of the sun distorts the structure. This allows corrections to be
calculated by the engineer and implemented on the next segment.

In lieu of the temporary support of forms by a small skid derrick or overhead frame, a gantry may be
used, extending over at least 1-1/2 spans. This gantry is moved forward after the two cantilever arms are
completed on one pier. When its leading edge reaches the next pier, temporary supports are placed,
allowing the gantry to move forward one half span farther. The rear end of the gantry, now over the first
pier, is locked to it by post-tensioning bars. The gantry can now support the forms and the fresh concrete
of the cantilever segments as they are constructed.

Earlier, the installation of near-vertical tendons in the webs was mentioned. These tendons resist the
high shear forces near the piers. Frequently, these are installed in U-shaped ducts, with the two anchors
in the deck slab. During construction, these ducts must be covered to prevent rain and curing water from
entering as well as to protect them from being clogged by debris. Even soda bottles have been found
wedged in the U at duct bottoms! Grouting of these vertical ducts must employ the special procedures
discussed in Section 11.5 to ensure complete filling of the duct.

Continuity tendons are installed after the closure has been completed. They are designed to provide
positive moment capacity over the mid-portion of the span. Typically, their anchorages are in bolsters
(blisters) on the webs or bottom flange and the tendons are installed in the bottom flange. Anchorage
bolsters should be staggered in balanced pairs, with adequate longitudinal spacing and reinforcing to distribute the tensile strains behind them. Proper reinforcing details are also required to resist the pullout forces of the sharp curvature at these anchorages.

### 11.8.6 Precast Cantilevered Segmental Construction

In this type of construction, the segments are prefabricated in a casting yard, using the match-cast process. They may be cast as individual segments (short-line-process) that are subsequently placed against their partner for concreting or by the long-line method, where the entire girder is cast with segments separated by a bond breaker. Care is taken to ensure the correct positioning of the longitudinal ducts and their extension into the next segment through the use of pipe mandrels (Figure 11.37). The erection process in the field may proceed in a manner similar to that described for cast-in-place segments. In this case, the skid derricks or frames must lift a segment that is positioned directly underneath and raise it into position. Epoxy glue is then applied to the faces of the segments. The tendons are then installed and stressed. The process is inherently very rapid, in that a pair of segments can be completed each day. In some cases, using multiple shifts, two pairs of segments have been completed per day.

The gantry scheme of erection is especially well adapted for this concept. The precast segments can be transported along the completed deck, oriented at right angles to their final position. They can be lifted by the rear end of the gantry and run forward to their final location, where they are turned 90° for erection. Usually, a longer gantry is used, extending over 2-1/2 or even 3 spans. This enables the work to proceed further ahead while previous spans are being post-tensioned and grouted and closures are being effected. If the gantry has adequate capacity, several segments may be suspended from it, thus minimizing the amount of post-tensioning required. If the gantry is of adequate length and strength so it can support the entire double cantilever midspan to midspan, then the required post-tensioning will be reduced to that required for the permanent structure. Because the segments are precast and the concrete has attained greater maturity, the creep and shrinkage are reduced. Nevertheless, the profile and alignment have to be checked daily. Minor corrections can be made as needed by the insertion of wire mesh shims. Alternatively, corrections may be accomplished by additional post-tensioning. A few more strands may be inserted in an existing duct, compact strands may be used, or an additional tendon may be placed in a spare duct.

One significant disadvantage of precast segmental construction is the lack of mild steel reinforcement across the joints, which would minimize crack width under ultimate load conditions as well as improve

![FIGURE 11.37 Erecting precast match-cast segment in cantilever construction.](image-url)
stress distribution. This is especially needed at the ends of transversely cantilevered deck flanges, where shear lag may reduce the effective prestress. The latter problem can be resolved by including a high-strength bar in the end of each flange that is stressed at each segment. Couplers can be used to extend the bar from one segment to the next.

Perhaps the best means of providing the desired monolithic behavior and ductility is to include additional ducts, spaced out over the contact surfaces where no primary tendons cross, and to install unstressed strands and grout them so as to provide a nominal steel area across the joint, which is adequate to ensure that if the joint does open the steel, both stressed and passive, is not elongated beyond yield strain. Another method is to provide mild steel dowels in slots or holes across each joint that are subsequently grouted.

### 11.8.7 Incremental Launching

The incremental launching method is suitable for straight bridges (on a tangent) and for bridges of a constant circular alignment and superelevation; unfortunately, it is unsuitable in its current state of development for constructing spirals. The bridge may be on a straight-line profile or a constant vertical curve. With this process, all work is carried out from one end, in a job-site facility. A segment, typically 6 m (20 ft) long, is cast to its full cross-section. A second segment is then cast immediately behind and post-tensioned to the first. Both segments are seated on bearing plates of stainless steel that slide on Teflon® with a friction coefficient of 0.03 to 0.05. Large hydraulic jacks are installed below the first segments and arranged so they can pull the two segments forward.

As each succeeding segment is cast, it is post-tensioned to the preceding assemblage, and they are pulled forward as a group. Obviously, because the leading segments overhang the abutment, they must be counterbalanced by the segments still at the casting site. A trussed steel nose extension is attached to the leading segment. When the nose reaches the next pier, it is guided onto Teflon® and stainless-steel bearings. The nose is slightly tapered so it can engage the sliding bearings. Despite the elastic downward deflection, the nose raises the bridge to grade as it progressively slides past the second pier. Side guides should be provided at each pier bearing to prevent the bridge from creeping laterally. This is especially important when the bridge is superelevated or on a curved alignment. Because all work is carried out at one location, it is feasible to provide an enclosure so work can be carried out regardless of weather conditions.

Stage post-tensioning is critical to this method. During launching, because the girders are alternating between positive and negative moment, the post-tensioning must be more or less concentric. For the final service condition, after the bridge is in final position, the centroid of prestress must be raised over the piers and deflected downward over the central portion. To physically accomplish this, several methods have been employed. Through the use of external tendons located inside the box of a box girder, the tendons are jacked to their required profile, then secured to the webs with stirrups and concreted in place. This requires an accurate computation of the increase in the stress due to deflection. The process is conceptually similar to the deflection of pretensioned strands. Additional prestressing tendons with exaggerated profile are added to move the centroid of the total prestress to the desired location. These additional tendons can be internal tendons (i.e., in preplaced ducts) or external tendons inside the central opening of the box girder.

### 11.8.8 Lift-In and Float-In Erection

Lift-in and float-in erection are processes in which the span is preassembled and post-tensioned, either on a barge or on shore, then transported to the specific site and positioned beneath the piers. For the lift-in process, heavy lift jacks can be placed on the pier caps so as to raise the complete span. When the span is to be erected one girder at a time, the lifts may be made by skid derricks on top or by floating cranes below. On overland projects, the bridge span may be constructed at ground level and then raised by lift jacks to the pier tops, then a cast-in-place closure is constructed. This closure should incorporate
a shear key or keys. The lifted-in span is connected to the pier caps by post-tensioning through the pier cap. Float-in spans are similar, except that in this case, the tide plus ballasting or deballasting may be used to place the span onto the pier caps. This concept is most suitable for low-level bridges and trestles. Float-in may also be used with a large crane on a catamaran-type barge (see Figure 11.39). The crane picks the girder, and the barge then moves to straddle the pier. The crane then lowers the girder onto its bearing. This process has been used for very large spans over 100 m in length and up to 8000 t in weight (Figure 11.38 through Figure 11.41).
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**FIGURE 11.40** Construction of one of the five bridges of the King Fahd Causeway connecting Bahrain to Saudi Arabia.

**FIGURE 11.41** Prestressed concrete girders being erected at Prince Edward Island Bridge in eastern Canada.
11.8.9 External Tendons for Bridges

This relatively new technology was introduced in Section 11.5.7. External tendons are located outside the concrete cross-section of the bridge girder, although they may be inside the box of a box girder. External tendons may constitute the entire primary post-tensioning or a portion of the total, the remainder being internal, grouted tendons. The external tendons are anchored at or near the ends in typical recessed pockets. The tendons themselves are multistrand cables encased in a polyethylene sheath. At several locations along the span, either at third or quarter points, the tendons are deviated to the correct profile by structural concrete deviators—that is, partial diaphragms anchored to the webs. Because the forces on these deviators are concentrated, the deviators must be heavily reinforced themselves as must their ties to the concrete webs.

The bending at the deviator must be over a curve of substantial radius to minimize the normal bearing stress on the strands that acts concurrently with the axial elongation changes under varying live load. A steel sleeve with belled ends is used, which is pre-bent to the required radius. The polyethylene duct may be spliced to the steel section or run through this sleeve. Steps to minimize cutting of the plastic when pulling in the strands must be taken. These include pulling as a bundle with protective nose piece, pulling slowly, and use of a thicker plastic duct. The strands are grouted in the duct. The duct is usually left free in the steel sleeve.

One of the advantages of using external tendons in bridges is the ability to remove and replace one or two tendons at a time. This is feasible only if the anchorages are accessible for removal and subsequent replacement and restressing. Anchorages may have screwed-on, grease-filled caps. Although such replacement is frequently a design criterion for bridges that will be treated with salts in the winter to prevent icing, and therefore exposed to a very corrosive environment, the protection afforded by polyethylene sleeves and caps plus grout is believed to be essentially permanent. The use of external tendons has also been applied to concrete truss spans, in which the truss members can be used as the deviators. In this case, because the tendons are exposed to daylight, the polyethylene should be pigmented to minimize ultraviolet degradation of the polyethylene.

11.9 Prestressed Concrete Piling

11.9.1 General

Prestressed concrete piling are used on a very large scale as bearing piles for building foundations, as bridge superstructures, and as support for wharves and quays and tanks and towers. They have been used for offshore terminals and for fender piles and sheet piles for quays and bridge piers (Figure 11.42, Figure 11.43, and Figure 11.44). Piles up to 600 mm (24 in.) in cross-section and, occasionally, to 800 mm (36 in.) are typically pretensioned, using standard pretensioning practices as described in Section 11.6. Further specifics for manufacture of piles will be given later in this section. Cylinder piles, 800 to 1650 mm (36 to 66 in.) in diameter have been produced both by pretensioning and by post-tensioning, the latter again using standard post-tensioning processes. Fender piles and sheet piles are usually pretensioned. Sheet piles may incorporate sheathed and greased tendons arranged in a vertical profile to suit the final service conditions. They are stressed from the top only after the sheet pile is at final grade.

11.9.2 Durability of Piles

Piling for most land foundations, such as for the support buildings, are generally fully embedded in a benign environment of soil below the water table with little oxygen; hence, corrosion of steel has not been a problem. Exceptions may arise when piles are driven through garbage dumps or highly corrosive soils. For piling that extends above the permanent water table, durability must be considered. At sites up to 70 km (42 miles) from the sea and especially in arid zones, chlorides pose a threat to the steel. Corrosion has occurred in serious amounts in the Middle East for piles in both water and land foundations. Preventing corrosion of prestressing steels and conventional reinforcing in marine environments requires
a dense, highly impermeable mix of at least 350 kg/m$^3$ (600 lbs/yd$^3$) of cement containing at least 5 to 10% C3A, with a low water/cementitious materials ratio, preferably less than 0.43. Fly ash may be used to replace 15 to 20% of the cement. In marine installations subject to freezing, the problems of freeze–thaw

FIGURE 11.42  Prestressed concrete cylinder pile for pier of Napa River Bridge in California. (From Gerwick, B.C., Jr., Construction of Prestressed Concrete Structures, John Wiley & Sons, New York, 1996. With permission.)

FIGURE 11.43  Spreading spirals along tensioned strands of prestressed concrete piling.
attack may be especially severe. High tide and waves saturate the concrete, while low air temperatures cause the concrete to freeze during low tide. Some sections of the pile may see two cycles of freeze–thaw a day throughout the depth of winter. Substantial air entrainment is required, with the proper spacing factor and specific surface, as shown by petrographic analysis of hardened specimens or cores. Coatings other than those that breathe water vapor can be counterproductive, as the moisture migrates to the cold face and is trapped behind the impermeable coating, where it then freezes, popping the cover off. Thus, high strength, high impermeability, minimum water absorption by aggregates, low water/cementitious materials ratios, and adequate air entrainment are all required for this environment.

11.9.3 Manufacture

The manufacture of pretensioned piling is a mass-production process, typically involving a small number of standardized cross-sections; hence, economy of production is of great importance. Forms may be double or quadruple so that two to four lines can be manufactured simultaneously. Preferably, the forms are designed so as to require minimal effort for setting and release. Flexible steel side panels may be held in position during concreting by intermittent straps across the top which are easily removed to lift out the hardened pile. Or, the side forms may be stiff enough to hold the fresh concrete without significant deflection yet be tapered so the member may be lifted out directly. A draft of 1 on 50 is usually adequate for steel forms of moderate stiffness. For hollow-core and cylinder piles, the two upper sloping surfaces may be formed by portable panels that clamp to the fixed form and use a neoprene gasket between (Figure 11.45). Alternatively, the upper sloping forms may be hinged.

The internal voids of hollow-core and cylinder piles have been formed in many ways. All of the methods used face the problem of keeping the void form accurately centered so it will not float up when the concrete is vibrated. One method that has proven capable of consistently producing high-quality cylinder piles is to use an internal steel form that is collapsible. A form segment is typically half the length of a pile, so after lift-out of the completed pile each half-length segment may be retracted.

In a typical manufacturing sequence, the internal void forms are set up in the lower half of the fixed outer form and are then blocked up. Coiled spreading spirals of an appropriate amount are then set at the ends of the piles (Figure 11.43). The strands are pulled down the bed, through the coiled spiral but outside the inner void form. The strands are now properly spaced around the circle and tensioned with a single-strand jack. They may be fully tensioned to the desired value (70 to 75% of ultimate) or only...
partially tensioned, with the remaining tension applied by a large jack. The spirals are then distributed to their correct spacing and tied to the strand as needed.

At appropriate stages, end forms (end gates) are set in place; these are usually fabricated in several segments. Rubber or plastic stops are used to seal against mortar leakage where the strands penetrate the end gates (Figure 11.46). The upper side forms are set in place and the pile is ready for concrete. In a properly designed pile, the spirals or hoops will be very closely spaced at the head and tip. Additional longitudinal bars or tubes may also be inserted at the pile head. The head and tip are zones where the highest concrete quality is essential, so vibration must be thorough. To permit this, the spirals may be bundled and a pencil vibrator used to penetrate between them.

After the piles in a line have been cast and cured, the upper forms are laid back, the strand tension is released, and the strands are cut between piles. This is an especially critical time for cylinder piles, as well as for all large piles, in that the upper surface of the pile is now exposed to both rapid drying
shrinkage and thermal shrinkage as the top cools off while the warm bottom half and inside is still protected by the forms. Application of membrane-curing compounds and blanketing the pile will prevent the longitudinal cracks that often occur, especially in winter and on windy days.

Cylinder piles are also manufactured by sliding a long internal mandrel along the bed to form the void. The mandrel may be coated so it slides with minimal friction. The rate of progress is matched by the stiffening of the concrete to prevent slumping of the top as the tail end of the mandrel passes. Internal heat has been used to accelerate the rate of stiffening. During the main part of the mandrel slide or slip, the cement paste from the concrete will lubricate the mandrel, but at the beginning it is necessary to coat the mandrel with fluid paste or at least to wet it. Particular attention has to be given to the ends of the piles to prevent the drag of the mandrel from causing cracks or spalls. Slumping of the top and displacement of the strands will cause eccentricity in the cross-section and even delamination, which may then lead to breakage or spalling during driving, as well as reduce the performance of the piles under lateral loads. The bottom strands must be supported in such a way as to maintain their cover. Also, cylinder piles are manufactured by the assembly of short concrete pipe segments. Jointing can be by epoxy or by a 200-mm-wide cast-in-place joint. The pile is then tensioned by running strands through preformed holes, and the tendons are grouted. This process has been used for cylinder piles from 1 m to 3.5 m in diameter.

Piles are lifted from the forms by one of several means. Except in the splash and tidal zone of marine piles (and to a lesser extent the submerged zone), lifting inserts or bundled loops of strand may be used (Figure 11.44). Lifting inserts must be adequately embedded in the pile. Spacing of these inserts may be designed to minimize negative bending moments. Because these negative moments peak at the lifting points and the load is augmented by friction in the forms for large and heavy piles, short lengths of mild-steel bars may be incorporated in the top of the pile.

Where inserts are not permitted, a thin band may be preplaced in the forms, enabling the pile to be raised a short distance by a jacking frame so it can be progressively blocked about 50 mm (2 in.) above the soffit. A lifting wire rope choker can then be inserted so slings from an overhead gantry or crane can lift the pile clear. Piles should be blocked at the same picking points while they are in storage to prevent development of a sweep due to creep. While in storage, the projecting ends of the strands, especially those at the pile head, should be burnt back into the concrete (Figure 11.47). A daub of epoxy mortar may be applied if desired. During load-out and transport, piles should be supported so they do not develop a net tension in the concrete (Figure 11.48). For truck transport, the dynamic amplification must be considered, especially for the overhanging ends.
11.9.4 Pile Installation

Although one of the primary benefits of prestressing for piles is that they can be driven in a wide range of soil conditions and achieve the required penetrations, even though this requires prolonged hard driving, a number of very specific steps can be taken to prevent pile damage or breakage. Lofting the pile (that is, lifting it from the horizontal to the vertical) typically requires two or more lifting points (Figure 11.49). The slings or lines to these points will typically be at an angle, and this angle will vary during the lift. This means that the vertical components of the force in the lines will be different; thus, the situation differs from that in the manufacturing yard where all lifting forces are normal to the pile. Fortunately, it turns out that in most cases the maximum moments in the pile occur during initial lofting, so the calculation of angles and resultant moments and stresses is relatively
A dynamic amplification factor should be applied to the dead load of the pile. For very long piles, the moments and stresses should be checked through the several stages of lofting from horizontal to vertical.

Most cases of damage to prestressed concrete piles occur during the initial and early phases of driving. This is a consequence of the fact that the tension capacity of the pile is limited to the sum of the precompression due to prestress and the tensile strength of the concrete; the latter is less than 10% of the compressive strength. High tensile stresses during driving are due to a rebound wave of the pile hammer blow from the pile tip in soft driving, when the tip has little or no resistance. Consider the following three typical cases. First consider a pile driven by a diesel hammer (Figure 11.50). Initially, the pile tip is in soft clay or mud. To start the diesel hammer, it has to be raised to almost full stroke, typically about 2-1/2 m (8 ft). Thereafter, in soft driving, the diesel hammer automatically delivers soft blows, but that first blow at full stroke is the one that cracks the pile. The tensile rebound wave is greater than the tension capacity of the pile. This cracking may or may not be noticed, so driving continues. Eventually, the pile encounters hard driving, and the hammer delivers maximum compressive stresses across the cracks. This leads to local crushing at the crack and eventually to fatigue of the strands. Finally, the pile plunges, obviously broken somewhere below ground. Typically, the hard driving is blamed, but the initial damage was done on the first blow (Figure 11.51).

A second case arises when the pile is driven through compacted soil that overlies softer materials such as mud. The pile is subjected to hard driving when in the compacted soils. Then it suddenly breaks through and plunges 3 m (10 ft) or more. The single hammer blow, with little tip resistance, is what has caused the cracking. A somewhat similar situation arises when the pile is required to penetrate a
hard stratum. The contractor employs jetting to reduce the end bearing. Prolonged jetting erodes a hole. The pile drives through with relative ease due to the low tip resistance. In this case, the tension is exacerbated by the fact that the pile is gripped by skin friction along its sides while there is essentially no resistance at the tip, so the compressive wave from the hammer blow is literally driving the end off. In all of these cases, the actual breakage may not occur until there is subsequent sustained hard driving. Prevention of damage due to tensile rebound stresses begins with placing a cushion block on top of the concrete pile. This block is contained within the driving head or helmet on which the pile hammer ram delivers its blow. The material and thickness of this pile cushion block is selected so as to attenuate the peak compressive force, which lasts only a few milliseconds during each blow. When properly selected, this cushion block can actually aid penetration by lengthening the period of application of compressive force while reducing its peak. The best material, after thousands of trials, has proven to be softwood, such as pine or spruce, laminated in multiple layers. To hold this softwood block together, plywood sheets may be nailed top and bottom and inserted in between every third or fourth lamination. The required thickness varies with the pile, the soil, and the hammer. Thicknesses of 150 to 350 mm (6 to 14 in.) are typical. The cushion block compresses during driving. Except when it breaks into pieces and falls out or catches fire and burns up, it is not necessary to replace the block during the driving of any one pile. Exceptions occur for piles in highly stratified ground, where soft soils lie below hard soils. A new cushion block should be used for each pile. Even if the cushion block appears undamaged, its attenuating compressibility has been greatly reduced. For the typical case of a diesel hammer driving a pile whose tip is in soft mud, the pile may be driven down to moderate tip resistance by using the diesel hammer as a drop hammer—that is, raising the ram half distance and dropping it to prevent the damage resulting from a high starting blow. For the second case, predrilling through the fill is indicated. In both cases, the pile may be pulled down through the soft soil by a line rigged to the hoist engine.
The third case is more complex, especially where penetration of the intermediate hard stratum proves difficult and requires extensive jetting. Steps that may be used are as follows:

- Increase prestress; however, this is costly and piles may have already been cast.
- Limit the jetting at the tip but increase the jetting higher up along the sides to reduce skin friction.
- Install a new, thick cushion block when driving through the hard stratum and before redriving the pile.
- Prebore by jet or augur to break up the hard stratum.

Hundreds of thousands of prestressed concrete piles have been driven successfully without breakage, provided they had the required design and a suitable cushion block was used.

The design prestress should ensure that, if a crack does occur for any reason, the steel strand will not be stressed beyond yield. Cracking will occur when the residual prestress in the concrete (after losses that have occurred to that date) plus the effective tensile strength of the concrete exceed the yield strength of the strand. To prevent this requires an adequate area of steel strand plus any supplemental reinforcement.

Values of 5 MPa (725 psi) have been successfully used for hundreds of thousands of prestressed concrete piles driven in normal soils, where moderate to hard resistances were encountered throughout the driving cycle. Values of 7 to 8 MPa (1000 to 1160 psi) have been used for piles subject to potentially severe tensile rebound stresses; however, the calculated value is extremely sensitive to the assumed tensile strength of the concrete, which is progressively degraded by repeated hammer blows in soft soil. Prestress as high as 10 MPa (1450 psi) may be employed for sensitive conditions and piles with high importance, for instance, large-diameter cylinder piles.

Driving of a concrete pile produces high axial compression, which is additive to the prestress. The Poisson effect develops high transverse (circumferential) strain, typically about 0.22 that of the axial compression. Because this often exceeds the tensile strain capacity of the concrete, longitudinal cracks develop. These can be resisted by spirals or hoops. The matter is complicated by the cover, so the confining reinforcement has to bond to the concrete cover (e.g., through adhesion); thus, epoxy-coated spirals, if used, must have sand embedded in the epoxy.

To prevent the pile head from spalling, additional spiral confinement should be placed close to the head. This can be a circular hoop placed just beneath the chamfer at the corners of the head, perhaps 50 mm from the head, and of adequate diameter to extend to the sides, as cover is not normally a requirement at this location. The tip of the pile should be square, not pointed or wedge shaped, because these shapes tend to wedge the pile out of vertical and, in the case of batter piles, out of proper inclination. Extra spiral, similar to that for the pile head, will prevent local spalling when rip-rap or boulders may be encountered.

### 11.10 Tanks and Other Circular Structures

The first application of prestressing technology was circular tanks, for which circumferential wrapping with high-strength wire under tension was used to create precompression in the walls of the tank. Walls were cast in place using jump forms or slip forms. When cast-in-place walls are employed, concrete construction may be by slip forms. Flowing, self-consolidating concrete may be more readily placed, especially in thin, heavily-congested walls. Today, such walls are often made of precast concrete staves, set vertically and joined by grout infill or, with wider openings, concrete infill. The wires or strands are then wound under tension. These are then encased by mortar, usually applied pneumatically by a wet shotcrete process. Placing and tensioning of the wires are almost always performed by a specialist contractor using a proprietary process. Both black and galvanized wires are used. In this section, only those elements of work performed by the general contractor are discussed.

The circular wall is usually set on neoprene pads to permit inward deformation under prestressing and hence the development of a state of prestress in the concrete at the base. In seismic regions, special shear keys or restrainer strands connect the base slab and the walls. The details must be executed with great care, not only to ensure safety during earthquakes but also to ensure proper performance and leak
tightness under normal service conditions. When precast staves are used, they are erected to true position and verticality and temporarily supported by tilt-up braces. By marking the location of each stave or panel beforehand, minor errors in position will be minimized and prevented from accumulating.

Tanks may also be prestressed by internal post-tensioning. If the joints between panels are relatively wide, 200 mm or more, they may be treated like similar joints between bridge segments, with overlapping reinforcing and sleeving of ducts so that they may be internally post-tensioned. Anchorages are in blisters spaced at 120°, so each tendon covers 240° and alternate tendons overlap. Blisters must be adequately tied to the wall by stirrups to resist the radial stresses. Tendons are usually stressed from both ends to offset the friction due to curvature.

The joints between panels are filled with high-strength grout or concrete. This grouting is very critical as it must fill the complete joint with a high-strength material that will be able to withstand 70% or so of the ultimate strength of the wall panels, applied within a short period after grouting. The encasement with wet shotcrete is then applied, first by washing the wall with fresh water to remove any contaminants, such as wire-drawing lubricant or water-soluble oil, then by applying a flash coat of neat cement grout, and finally by placing several coats of shotcrete. Where the tanks are to be backfilled (i.e., buried tanks), a coating of epoxy asphalt is also applied. The long-term performance of shotcrete is determined by its impermeability and is dependent to a large degree on the expertise of the nozzle man, who must direct his spray at a slight angle so rebound is not entrapped.

A critical location in tank construction lies at the top of the wall, where any small crack, even a microcrack, between wall concrete and shotcrete can result in progressive corrosion due to moisture infiltration and freeze–thaw attack. This location should be covered by monolithic concrete or epoxy asphalt, as specified or approved by the design engineer. The walls of tanks that will contain sewage or organic materials, hot chemicals, etc. must be free from cracks such as those due to drying shrinkage or thermal strains. Coating the interior surface with a suitable polyurethane material, durable to the contained fluids and able to span minor cracks, should be considered. Where a circular structure such as a penstock is in contact with the soil, or backfilled, epoxy asphalt coatings may provide protection against contamination and penetration of salts from the soil. In freeze–thaw or deep-freeze environments, a special problem arises from the fact that the concrete is saturated and the freeze front will form in the middle of the wall. This can lead to delamination and the spalling of the exterior concrete. An internal coating or membrane appears to be essential.

Containments for nuclear power reactors and for high-temperature gas reactors are usually thick-walled structures with either internal post-tensioning or exterior wrapping. The construction of these structures is similar to that of tanks, but the walls are much thicker and of higher strength concrete, the reinforcing is much denser and more complex, and the post-tensioning ducts and anchorages are very thickly congested. A thin ductile steel liner or membrane must be attached. Because thermal strains in the thick concrete wall have to be minimized, the fresh concrete mix should be precooled using ice or liquid nitrogen, and walls should be protected or insulated after the forms are stripped.

Prestressed concrete tanks may be used as primary or secondary barriers for containment of cryogenic liquids such as liquefied petroleum gas and liquefied natural gas. These applications are highly specialized, especially in providing critical design details for base and roof connections adequate to accommodate the thermal shortening; hence, they require specialty contractors.

### 11.11 Prestressed Concrete Sleepers (Ties)

Sleepers are a mass-produced element made complex by the need to anchor prestress in a short length, to vary the prestress profile to match the moments, to affix the rail, and to develop adequate electrical resistivity (Figure 11.52). Pretensioned concrete sleepers have been used for the Amtrak from Boston to Richmond as well as on heavy-rail coal railroads in the Southwest and Metro systems nationwide. Their heavy weight is of benefit to anchor welded rail. They must be durable under conditions of freeze–thaw and saltwater dripping from refrigerated cars. Chemistry of the cement and concrete requires careful control because some problems have occurred when durability was not adequately considered. Microsilica
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Concrete has been used to provide the necessary high strength, bond strength, and impermeability as well as electrical resistivity. To provide adequate bond, the lay of the strand may be shortened or deformations provided in the strand during manufacture. Any corrosion-protection oil must be soluble. Sleepers can also be manufactured by post-tensioning.

### 11.12 Prestressed Concrete Floating Structures

Concrete has been utilized for floating structures ever since World War I, initially prompted by war-time shortages of steel but subsequently used for reasons of economy and performance, the latter being primarily structures that do not require mobility. It especially lends itself to offsite prefabrication of bridge piers, offshore platforms, floating bridges, and, most recently, river navigation structures (Figure 11.53, Figure 11.54, Figure 11.55). Permanently floating concrete structures include barges for support of construction operations, floating breakwaters, floating oil storage, and floating marine terminals. The U.S. Navy is currently testing a half-scale floating pier module in San Diego Bay. The benefits of prestressing have been
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The ability to resist the cyclic bending, shear, and torsional stresses in the hull due to the waves. Other benefits are the minimization of cracking, the resistance to fatigue, and the resistance to thermal strains. Prestressing is used to connect prefabricated elements and subassemblies. In recent years, renewed interest is being exhibited in mobile vessels, either towed or self-propelled. The main deterrent to such use has been the much greater weight compared to steel vessels. With the advent of high- and ultra-high-performance concretes and corrosion-resistant tendons and reinforced concrete, vessels can be constructed with thinner sections, hence less weight and smaller draft.
11.13 Prestressed Concrete Pavements

Prestressed concrete pavements have been used for major airport runways, taxiways, heavy industrial floors, container terminal yards, etc., especially where it is desirable to minimize irregularities and provide a truly level surface during service. Post-tensioning is usually employed and is centered in the concrete cross-section. Because the pavement is subject to water collection, major changes in temperature, etc., providing a crack-free structure is important. Cracks prior to stressing must be avoided by such means as precooling the mix, placing concrete at night, and covering the concrete for several days with ponding, wet burlap, or polyethylene. To permit shortening under prestress, the slab is usually placed on a bed of sand 50 mm (2 in.) thick that is covered by a polyethylene sheet. Splices in post-tensioning ducts and couplers in bar tendons are made at the longitudinal joints. These construction joints are an obvious location of leakage and subsequent corrosion and so must be made with great care. The edges of slabs tend to warp upward due to thermal strains. Many designs incorporate an edge beam so the weight of the concrete offsets the thermal strains and any design eccentricities in the centroid of prestressing.

11.14 Maintenance, Repair, and Strengthening of Existing Prestressed Concrete Structures

11.14.1 Maintenance

Although prestressed concrete structures, properly designed and constructed, have proven highly durable in a wide range of environments, in numerous cases corrosion has seriously damaged both the conventional reinforcing steel and the prestressing tendons. The most prevalent cases are the following:

- Decks of prestressed concrete bridges to which deicing salts have been applied during winter
- Decks of parking structures where tires have carried salts from the adjoining streets
- Piling and the underside of wharf decks of coastal marine structures in tidal and splash zones
- Unbonded tendons, wrapped in paper and bitumastic, in an area near the seacoast where chlorides are present in the fog
- Walls of graving docks that are intermittently flooded by seawater and then dewatered for extended periods of time

In the above microenvironments, chloride contamination is the principal cause of corrosion. Chloride ions penetrate the concrete to the reinforcing and prestressing steel and depassivate it. With the presence of water and the permeation of oxygen, electrochemical corrosion proceeds. Carbonation from CO₂ in the atmosphere can cause similar corrosion attacks but the penetration is slower and more easily prevented. Prevention of these attacks must be primarily focused on initial design and construction, where steps can be implemented to make the concrete more impermeable, to give adequate cover over the steel, and to limit cracking.

The lives of existing prestressed concrete structures that have not been significantly damaged may be prolonged by a rigorous maintenance program. The following program may serve as a checklist:

- Wash down concrete surfaces on which salt has been deposited by spray, accident, or intention.
- Periodically treat the surfaces with silane to render them relatively impermeable to water that contains chlorides.
- Seal static cracks with epoxy injection or coatings.
- Seal active cracks with flexible membranes, such as polyurethane, which have crack-spanning ability.
- Where feasible, reduce the relative humidity in enclosures to below 50%; this is applicable to such structures as seawater pump rooms.
- Apply penetrating corrosion inhibitors; these are a relatively new development that may work in special cases, particularly where the concrete can be dried so water in the pores does not impede penetration of the corrosion inhibitor.
Where applicable, keep the structure flooded with water, even seawater, to maintain the concrete fully saturated. The oxygen content of seawater is only a few percent of the oxygen content in the atmosphere, and oxygen does not penetrate saturated concrete very rapidly. This applies to prestressed concrete penstocks, conduits, sewers, and piping, especially during the period between completion of construction and initiation of service.

Repair and seal laminar cracks by stitch bolting and epoxy injection.

Where freeze–thaw attack is eroding the cover of concrete over the reinforcement, provide insulation and coating or covering.

Install a cathodic protection system, connected to both the reinforcing steel and the prestressing steel. This step is normally instituted after serious corrosion of the reinforcement or prestressing has developed but can be provided for by bonding of the steel and by installing studs for future electrical connection if needed.

11.14.2 Repairs

In many cases, serious damage to a prestressed concrete structure will have only penetrated to the conventional mild steel, causing delamination, spalling, and cracking; thus, conventional repairs can be instituted. These include removal of the damaged concrete, cleaning of existing rebar, replacement of badly corroded rebar, and patching with new concrete or mortar. The problem that often arises is that the new salt-free concrete becomes cathodic to the adjoining chloride-contaminated concrete, leading to accelerated corrosion at the periphery of the patch. Various techniques have been developed to prevent or minimize this process, such as fastening zinc bracelets of the ends of the rebar or coating of the bars by zinc silicate. For concrete piles that are suffering visible deterioration to the concrete cover in the tidal and splash zones, it is necessary to shut off further ingress of seawater with its dissolved ions of sulfate and chloride. Although coatings and jackets have been used in the past with marginal results, the current state of the art is encasement in a sleeve of high-density polyethylene (HDPE) with an inner wrap of felt impregnated with a petrolatum jelly that blocks all further inflow of seawater and air (see Figure 11.56). The following section primarily addresses the repair of those structures in which the prestressing tendons have become corroded.

Prior to undertaking repairs, the existing structure should be adequately shored. The shores must extend down to firm and adequate support. In cases where the damage is due to corrosion, after the structural situation is rectified cathodic protection may be applied to prevent further corrosion. In the case of exposed beams, new external tendons can be installed on each side. They are tied to the existing beam by drilled and grouted dowels and then encased in new concrete.
Bolting steel plates on the bottom and sides of existing beams or gluing on carbon-fiber sheets provides external strengthening sufficient to offset the loss of prestress. The structure then becomes essentially a reinforced concrete structure instead of a prestressed concrete structure. The current state of the art is to affix carbon-fiber strips by epoxy glue.

For temporary repairs to badly corroded structures, structural steel beams may be placed to provide additional support in critical areas. Wedging or shimming may be used to ensure contact and predeflect the steel. Cathodic protection or coatings may be applied for corrosion protection of the steel. Overlays of concrete with new tendons, such as polyethylene-encased and greased strands, may be used in certain cases. In cases where the damage to the tendons is localized, new short tendons, such as bars, may be placed in adjacent slots cut in the concrete, anchored at the ends, and stressed at the center by special center-pull jacks. Where tendons in a deck are corroded but the concrete is still sound, slots may be cut and new tendons installed, stressed, and encased in concrete one at a time. Existing tanks may be repaired by additional circumferential prestressing, followed by shotcrete to give corrosion protection to the new tendons. Righthand–lefthand threaded coupler sleeves may be used to splice the bars.

11.14.3 Strengthening Existing Structures

This is the arena where prestressing has a major role to play, as it is ideally adapted to providing greater strength and correcting unacceptable deflections. Post-tensioning by means of external tendons has been used to correct excessive sag in long-span bridges and to provide additional load capacity. It has been used to transversely tie cantilevered additions to existing bridges to widen them. When new structural elements are added adjacent to existing structures, post-tensioning can tie them so both new and old deform together, sharing the load. In these cases, post-tensioning has been applied either by drilling holes through the existing structure or by placing external tendons. The external tendons must be adequately tied to the existing concrete by dowels. Post-tensioning is extensively employed to strengthen existing buildings and bridges for earthquake resistance. It has been used effectively to transfer the loads from existing columns to new underpinning. Construction follows the general guidelines for post-tensioning with the following special provisions:

- Seats for anchorages must be carefully prepared by mortar or grout to ensure that the anchor plates can be fully seated on a plane normal to the trajectory of the tendon. The concrete beneath must have the ability to accept high compressive stress without bursting or cracking due to the concentrated load; thus, it may be necessary to remove and replace defective concrete. Adequate confining reinforcement is essential.
- Where external tendons are placed and are to be bonded to the existing concrete, the surface should be roughened and cleaned and a bonding epoxy applied.
- Adequate corrosion protection and, where applicable, fireproofing must be provided for the anchorages.
- In planning for strengthening, consideration must be given to access for the jacks and bearings for them to react against.
- The retrofitted structure must be able to accommodate the elastic and plastic shortening due to prestress.

11.15 Demolition of Prestressed Concrete Structures

Buildings and bridges must eventually be demolished and removed to make room for larger structures or other uses. Such demolition can be piecemeal, using the time-honored methods of headache ball, concrete saw, drill, and burning torch, or by more modern approaches that use diamond saws, hydraulic jacks (feathers) or controlled explosives that can topple the entire structure within a matter of seconds, turning it into rubble. Prestressed concrete structures require special considerations, due to the fact that tremendous amounts of energy are stored in the stressed tendons. Sudden release can produce a missile
that can fly 100 m or more with a velocity sufficient to penetrate a board fence. More serious is the potential for injury to workmen or the public.

When removing a structure in stages, it is usually necessary to shore under the span being demolished to prevent its collapse. The shores should be wedged up to fit tightly against the member to prevent erratic loading as the tension is released. Heavy timbers or blasting mats should be placed behind the end anchorages to absorb impact energy. Post-tensioned tendons and especially unbonded tendons must be destressed gradually. One method is to heat the tendon with the yellow flame of a burning torch, allowing it to slowly elongate. The other, applicable to large post-tensioning tendons, is to cut one wire at a time. Controlled heating is the most reliable method.

When the precompression in the structural element is fully released, the element will transfer its load onto the shores, so they must be designed to take the resultant loads. Bonded, post-tensioning, multi-strand tendons are more difficult to release. Because their transfer length is typically short, they have to be cut at frequent intervals, but the projectile phenomenon is not as great a factor. When demolishing by explosives, millisecond delays should be used to ensure that unbonded tendons are cut close behind the anchorages prior to the release of the main spans. Demolition of a small area to repair a damaged zone should follow isolation of the concrete by a saw cut, so spalling, etc. will not extend farther than intended. Stitch bolts through the thickness may be installed around the periphery. The concrete can then be removed by a small chipping gun or jet blast of water, taking care not to seriously damage the tendons. The tendons may be clamped at their ends or bonded by epoxy injection if they have not already been bonded by grout. They are then heated to relieve tension and cut for splicing or other remedial repair.

11.16 The Future of Prestressed Concrete Construction

Prestressed concrete is now accepted for a wide range of applications such as those described in the preceding chapters. It not only enhances the tensile capacity of the structural elements but also enables the control of deformations and service performance. It prevents cracking, thus enhancing durability (Figure 11.57 and Figure 11.58). In the future, it will give an expanding capability to the architect and his structural engineer. Magnificent buildings and bridges will be translated from creative ideas into
realities. Mass production of prefabricated elements, both prestressed by themselves and prestressed to create a monolithic whole, will be even more widely employed. The continued creative imagination and innovation of designers, and constructors will allow the horizon to expand exponentially.

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References

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(a) Unbonded post-tensioning reinforcement. (Photograph courtesy of FBA, Inc., Belmont, California.) (b) High-rise building with prestressed post-tensioned floors. (Photograph courtesy of Portland Cement Association, Skokie, IL.)