12.1 Developments in Unbonded Post-Tensioning

12.1.1 Introduction

During the last three decades, unbonded post-tensioning has progressively become the predominant construction choice for commercial concrete buildings in the United States. The utilization of unbonded tendons is now standard practice for concrete structures. Because of their excellent performance record and their economical and versatile application, the total use of unbonded tendons increased from approximately 7500 tons in 1976 to over 180,000 tons of prestressing steel in 2005, adding up to over 1 billion square feet of slab constructed with unbonded post-tensioning. Early applications of unbonded tendons and their limitations in design and construction were soon succeeded by well-established analysis, design, detailing, and field procedures. Driven by durability considerations, post-tensioning
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manufacturers have implemented product improvements for corrosive environments. The most meaningful testimony for unbonded post-tensioned construction is the successful performance of over 1 billion square feet of concrete construction.

The four common types of tendon systems are monostrand tendons, single-bar tendons, multistrand tendons, and multiwire tendons. During the 1960s and early 1970s, several proprietary tendon systems were used for concrete building structures. Unbonded single-strand or monostrand (1/2-in.-diameter, seven-wire) tendons with various types of sheathing applications were used predominantly over construction using unbonded single-bar tendons in plastic (or metal) ducts and unbonded button-head wire tendon. The application of unbonded monostrand tendons offers an economical and versatile application for post-tensioning thin slabs and narrow beams. Together with the small tendon diameter, positioning monostrand tendons horizontally, side by side (maximum bundle of four), provides the maximum possible offset from the neutral axis (eccentricity) within a member cross-section. In addition, the monostrand post-tensioning system utilizes compact anchorage devices and anchor recess pocket formers, together with small, lightweight stressing jacks, thus permitting the stressing operation to be executed with hand-carried equipment. The relatively simple components of unbonded tendons, their proven performance, and the economical advantages they offer positioned unbonded post-tensioning to record an average annual growth of over 8.5% between 1986 and 2004, according to the Post-Tensioning Manual, 6th ed., hereafter referred to as the PTI Manual of the Tensioning Institute (PTI, 2006).

The use of 5/8-in.-diameter single-bar tendons (smooth rods) was discontinued due to the labor and material costs involved in splicing the standard bar length. In contrast, unbonded multiwire tendons (button-head wire tendons) were used until the mid-1970s for beams and transfer girders, which required large localized forces. The economical application of multistrand tendons has continued until today. Multistrand tendons originally intended as bonded tendons but kept ungrouted for surveillance (nuclear) are specifically excluded and not part of this review.

12.1.2 Unbonded Post-Tensioning System Technology

In the United States, the first unbonded monostrand tendons were used in the mid-1950s for building construction using greased and paper-wrapped seven-wire strand. The spirally applied continuous paper strip was intended to be a bond breaker between the strand and concrete, and the grease coating assumed the role of corrosion protection. Plastic sheathing introduced during the mid- to late 1960s assumed the roles of (1) bond breaker, (2) protection against damage by mechanical handling, and (3) providing a barrier against intrusion of moisture and chemicals. The strand coating, commonly referred to as grease, reduces the friction between the strand and the sheathing and provides protection against corrosion (Figure 12.1). Three principal polyethylene coating applications were used for several years—namely, a plastic tube into which the grease-coated strands were pushed (stuffed or push-through tendons); a continuous polyethylene strip positioned parallel with the strand, wrapped around the coated strand, and sealed with a seam along the longitudinal axis of the strand (heat sealed); and the extrusion of polyethylene over the coated strand. Primarily used in Canada until approximately 1990, the stuffed or push-through tendons were discontinued during the early 1970s in the United States. Heat-sealed
Unbonded Post-Tensioning System Technology in Building Construction

fabrication of monostrand sheathing was supplied until the early to mid-1990s. In corrosive environments, stuffed and heat-sealed tendons have the inherent shortcoming of either trapping or allowing access of corrosive substances in the oversized sheathing. Extruded polyethylene sheathing has demonstrated excellent performance since its first introduction in 1969. The extrusion process applies the sheathing, eliminating voids between the sheathing and the grease coating. The extrusion sheathing application, with encapsulation of anchor zones for corrosive environments, has been used almost exclusively in the United States since the latter part of the 1990s until today. Again, the sheathing progression for most parts of the United States was paper-wrapped, stuffed or push-through, heat-sealed, extruded, encapsulated, and, for special applications, electrically isolated sheathing (Figure 12.2). Electrically isolated monostrand tendons have had limited application (Schupack, 1980).

**12.1.2.1 Material Specifications**

**12.1.2.1.1 Prestressing Steel**

Prestressing steel properties have essentially remained unchanged, conforming to ASTM A 416 Grade 250 or 270. The seven-wire low-relaxation strand, with a nominal diameter of 0.5 in. and a specified tensile strength of 270 ksi, is typically anchored near 70% of its ultimate strength. The material should be packaged at the source in a manner that prevents physical damage to the strand during transportation and protects the material from deleterious corrosion during transit and storage.

**12.1.2.1.2 Anchorages**

Tendon anchorages and couplings should be designed to develop the static and fatigue strength requirements of Section 2.2.1.1 and Section 2.2.1.2 of the Post-Tensioning Institute's Specification for Unbonded Single-Strand Tendons (PTI, 2000) and Section 4.1 of Acceptance Standards for Post-Tensioning Systems (PTI, 1998). Castings should be nonporous and free of sand, blow holes, voids, and other defects. The average compressive concrete bearing stress of anchorages should not exceed the limits set forth in Section 2.2.1.3 of the referenced specifications. For wedge-type anchorages, the wedge grippers should be designed to preclude premature failure of the prestressing steel due to notch or pinching effects under the static or dynamic test load conditions stipulated under Section 2.2.3 (PTI, 2000) and Section 4.1 (PTI, 1998), for both stress-relieved and low-relaxation prestressing steel materials. Anchors intended for use in corrosive environments should include design features permitting a watertight connection of the sheathing to the anchorage and a watertight closing of the wedge cavity for stressing and nonstressing (fixed) anchorages. Intermediate stressing anchorages should be designed to permit complete watertight encapsulation of the unbonded tendon.

**FIGURE 12.2** Unbonded tendon evolution: (a) paper-wrapped, (b) plastic sheath types, (c) encapsulated system, and (d) electrically isolated tendon.
12.1.2.1.3 Sheathing
Sheathing for unbonded single-strand tendons should be made of a material with the following properties:

- Sufficient strength to withstand unrepairable damage during fabrication, transport, installation, concrete placement, and tensioning
- Watertightness over the entire sheathing length
- Chemical stability, without embrittlement or softening over the anticipated exposure temperature range and the service life of the structure
- Nonreactivity with concrete, steel, and the tendon corrosion-preventive coating

Minimum thickness of the sheathing used in all environments and all applications other than ground-supported post-tensioned slabs for residential and light commercial construction should be 0.050 in. for polyethylene or polypropylene with a minimum density of 0.034 lb/in.³, or equivalent if other materials are used. Minimum thickness of sheathing used in ground-supported post-tensioned slabs for residential and light commercial construction should be 0.040 in. for polyethylene or polypropylene with a minimum density of 0.034 lb/in.³, or equivalent if other materials are used (Section 2.3.2.1 in PTI, 2000).

12.1.2.1.4 Corrosion-Preventive Coating
The corrosion-preventive coating material should have the following functions and properties:

- Provide corrosion protection to the prestressing steel.
- Provide lubrication between the strand and the sheathing.
- Resist flow within the anticipated temperature range of exposure.
- Provide continuous nonbrittle coating at lowest anticipated temperature of exposure.
- Be chemically stable and nonreactive with prestressing steel, sheathing material, and concrete.

The film should be an organic coating with appropriate polar, moisture-displacing, and corrosion-preventive additives. According to Section 2.4.3 of Specification for Unbonded Single-Strand Tendons (PTI, 2000), the minimum weight of post-tensioned coating material on the prestressing strand should be not less than 2.5 lb per 100 ft for 0.5-in.-diameter strand and 3.0 lb per 100 ft for 0.6-in.-diameter strand. The amount of coating material used should be sufficient to ensure essentially complete filling of the annular space between the strand and the sheathing. The coating should extend over the entire tendon length.

12.1.3 Durability of Unbonded Tendons
Post-tensioned concrete members inherently provide enhanced durability due to the limitation of cracks that provide access to reinforcement for corrosive agents. The use of post-tensioning typically eliminates most slab joints, which, if not eliminated, may give corrosive agents access to beams and columns. The excellent durability performance of existing concrete structures in corrosive environments reflects the potential of unbonded monostrand tendons. Most of these structures were built without specific durability design and construction considerations. The visual inspection of a 15-year-old parking structure in Baltimore, Maryland, following demolition confirmed that no significant corrosion had occurred on the unbonded tendons over the 15-year service life (Suarez and Posten, 1990).

The distinguishing characteristic of an unbonded tendon is that, by design, it does not form a bond along its length with the surrounding concrete. The axial force in the stressed tendon is transferred to the concrete primarily by the anchors provided at each end. Because the force of an unbonded tendon is primarily resisted by the anchors at each end, the long-term integrity of tendons and anchors throughout the service life of an unbonded tendon are of concern.

The Post-Tensioning Institute originally published Specification for Unbonded Single-Strand Tendons in 1993; the second edition, published in 2000, includes special durability requirements for tendons used in structures exposed to aggressive environments. These specifications provide for watertight encapsulation of the strand within the tendon sheathing over its entire length, including watertight
Unbonded Post-Tensioning System Technology in Building Construction

The specifications further require the use of a specially formulated corrosion-inhibiting grease and include many other secondary provisions to ensure enhanced durability.

Nevertheless, some buildings constructed with unbonded tendons have suffered durability shortcomings. A survey of 215 concrete structures in Toronto, Ottawa, and Montreal concluded the following: “The evidence indicates that durable structures can be built, and that poor performance must be attributed to design and construction practices whose effectiveness falls short of that required by the environment” (Litvan and Bickley, 1987). A map that divides the United States into five principal environmental zones is available to help with understanding and evaluating environmental considerations when selecting appropriate unbonded tendon systems. The selection of zones was in part based on the geographical use of deicing salts and presence of airborne salts from oceans. Detailed information on the zoning requirements and related system recommendations can be found in Walker (1990).

To improve the quality and consistency of unbonded post-tensioned tendons, the Post-Tensioning Institute developed plant certification requirements and issued in 1998 Acceptance Standards for Post-Tensioning Systems. To further a better understanding of the durability aspect, the Post-Tensioning Institute issued the second edition of Specification for Unbonded Single-Strand Tendons in 2000. The specifications provide for tendons in both normal and aggressive environments.

FIGURE 12.3 Encapsulated system for tendons in corrosive environments (stressing end).

Notes:
1. Locate anchor at bulkhead per project plans.
2. Install grommet flush between bulkhead and anchor for tight seal.
3. Slide sleeve tight against anchor. Be sure no bare strand is exposed. Tape if necessary.
4. After stressing, cut strand to within 1/8” of end of end cap and grease end cap prior to inserting it tight against anchor.
5. Patch stressing pocket per project plans.

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Anchorage</td>
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<tr>
<td>2</td>
<td>Protection sleeve</td>
</tr>
<tr>
<td>3</td>
<td>Grommet</td>
</tr>
<tr>
<td>4</td>
<td>Monowedges type 1.5</td>
</tr>
<tr>
<td>5</td>
<td>Strand (greased and coated)</td>
</tr>
<tr>
<td>6</td>
<td>End cap</td>
</tr>
</tbody>
</table>

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12.2 General Notes and Standard Details

12.2.1 General Notes

This section is intended to offer a sample layout of general notes for the construction of an unbonded post-tensioned concrete structure, typically outlined on structural drawings. The sample notes are limited to the post-tensioning activity of the concrete frame or member only. The notes are neither considered complete nor applicable for every project that includes the construction of unbonded post-tensioned members; however, with minor revisions and additions and deletions, the notes have been used by the author on over 500 concrete structures. The design engineer should be aware that the concrete frame may develop cracking as a result of concrete creep, shrinkage, temperature deformation, and elastic shortening on members that are partially or fully restrained from movement. For this reason, notes should be added on the drawings that disclose the likelihood of potential concrete cracking and allow for a funding mechanism for crack repair in the form of a postconstruction material maintenance allowance.

12.2.1.1 General


Marking of tendon location. If desired by the owner, the tendons may be marked using the dye-transfer method or by paint marking the formwork along the tendon lines just prior to placement of concrete. The paint transfers to the concrete soffit to permanently locate tendons (Section 6.4, PTI, 2006).

Power-driven fasteners. No power-driven fasteners or inserts shall be shot or drilled into the post-tensioned slab after concrete is placed without the written authorization of the engineer.

Openings. All openings, penetrations, and inserts shall be preplanned to the fullest extent possible. No changes shall be made in the field without prior approval of the engineer.

Formwork. For multilevel structures, the formwork shall extend beyond the slab edge, or scaffolding shall be provided to allow adequate room for the stressing operation.

Shop drawings. The contractor shall submit shop drawings showing tendon layout, dead-end and stressing-end locations, and tendon support layouts with details necessary for installation to the engineer for approval. The contractor shall supply the engineer with two sets of shop drawings a minimum of three weeks prior to fabrication. The review of shop drawings by the engineer is only for general compliance with the structural drawings and specifications. A set of approved shop drawings must be filed with the city engineer by the contractor.

Post-tensioned slab review. The tendon and mild reinforcement layout of a post-tensioned slab shall be reviewed by the engineer or the engineer’s designated representative prior to concrete pour. The engineer shall be notified at least 48 hours in advance.

Field foreman. The field foreman responsible for the placement, stressing, and finishing of all break post-tensioning material shall have a minimum of five (5) years of specialized experience in this capacity for this type of construction.

12.2.1.2 Materials

Strand quality. One sample of each reel or heat shall be tested by an approved laboratory. Test results or mill certificates shall be submitted to the engineer before stressing of tendons. Post-tensioning tendons shall be stress relieved or be of low-relaxation quality and shall conform to the following:

PT hardware quality. All anchorages, couplers, and miscellaneous hardware shall be standard products and approved by governing agencies and the engineer.

Tendons. Unbonded strands shall be encased in slippage sheathing that shall consist of a sealed durable waterproof plastic tubing (minimum thickness as specified by PTI) capable of preventing the penetration of moisture and cement paste and that will contain a rust-inhibiting grease coating.
Tears in the sheathing shall be repaired to restore the watertightness of the sheathing. The sheathing application shall be limited to the extrusion process. Tendons shall be secured during shipping and supported during handling to avoid damage to the tendon sheathing. During shipping and storage, the tendons shall be covered or protected to avoid moisture access to post-tensioning material.

12.2.1.3 Installation

Installation of unbonded tendons. If the post-tensioning supplier does not install the material supplied, detailed instructions for the installation and stressing of tendons shall be furnished. The contractor responsible for hiring the independent post-tensioning placer shall ensure that the installation crew meets the standards set forth above. The supplier shall provide technical assistance necessary to properly install, stress, and finish all post-tensioning material.

Tendons. Tendons shall be shop fabricated with preassembled fixed-end anchorages. Anchor casting with plastic pocket formers shall be used at all stressing ends to recess the anchor in enough concrete to achieve required cover.

Banded layout. The banded tendon placement layout shall be used for two-way post-tensioned slabs.

Tendon placement. Care shall be taken that tendons are located and held in their designated positions. Tolerances for the location of the prestressing steel shall not be more than ±1/8 in. vertically, except as noted or approved by the engineer. Access to stressing ends shall be maintained where shown.

Strand bundles. The maximum allowable number of strands per bundle is four (4) for slabs and six (6) for beams.

Tendons over columns. For two-way slab construction, a minimum of two (2) tendons in each orthogonal direction shall be placed directly over the supporting column.

Tendon adjustments. Small deviations in the horizontal spacing of the slab tendons will be permitted when required to avoid openings, inserts, and dowels with specific locations. Where locations of tendons seem to interfere with each other, one tendon may be moved horizontally to avoid the interference.

Twisting. Twisting or entwining of individual wires or strands within a bundle or a beam shall not be permitted.

Vertical profiles. Profiles shall conform to controlling points shown on the drawings and should be in approximate parabolic drape between supports, unless noted otherwise. Low points are at midspan unless noted otherwise. Harped tendons shall be straight between high and low point controls.

Horizontal profiles. Should the tendons be horizontally curved to miss an opening or other obstructions, tendon bundles shall be flared with a minimum distance of 2 in. between each individual tendon while horizontally curved. In addition, #3 hairpins at 12 in. on-center for each tendon shall be installed, transferring the horizontal radial force via the hairpin mild reinforcing to the concrete.

Prestress cover. All dimensions showing the location of prestressing tendons are to the center of gravity (CGS) of the tendon unless noted otherwise.

Minimum chairing. Tendons shall be secured to a sufficient number of positioning devices to ensure correct location during and after the placing of concrete and shall be supported at a maximum of 3 ft, 6 in. on-center. Chairs greater than 2.5 in. shall be stapled to the formwork.

Support bars. Support bars located at the face of drop panels shall be #6 or greater. Drop panels greater than 4 ft in width shall have additional #6 or greater support bars at the center, with a maximum support bar spacing of 4 ft for larger panels. All other support bars shall be minimum #4 bars. Continuous support bar lap splices shall be 24 in. minimum.

Anchors. Anchorages shall be recessed a minimum of two (2) in. Place two (2) #4 bars continuous behind all anchorages unless otherwise noted. Splices shall be 24 in. minimum and staggered. Special anchorage zone reinforcement shall be provided for groups of six or more anchors for 1/2-diameter strand tendons spaced at 12 in. or less on center.
Blockouts. All pockets or blockouts required for anchorage shall be adequately reinforced so as not to decrease the strength of the structure. All pockets should be waterproofed to eliminate water leakage through or into the pocket.

Pipes and conduits. Plastic or metal conduits may be embedded in the slab providing that the following criteria are met:

A. Plumbing pipe and electrical conduit layout proposed to be within the slab cross-section must be specifically approved by the engineer of record.
B. Maximum pipe or conduit size shall be 1.5-in. diameter (O.D.), located within the middle third of the slab cross-section, and supported independently from all reinforcement.
C. Center-to-center spacing of conduits shall not be less than three (3) times the diameter of the largest conduit.
D. No aluminum pipes, conduit, or embedment shall be permitted in post-tensioned concrete slabs.
E. Conduits must not interrupt the post-tensioned tendon layout or profile.
F. No pipe or conduit may be placed within the column shear cone.
G. It is undesirable to have excess amounts of conduit entering the slab from one location. If this condition exists, the conduits must be fanned out immediately.

Penetrations. Penetrations shall not be permitted in beams or drop caps unless permitted on post-tensioning drawings or typical details.

12.2.1.4 Concrete Placement

Concrete consolidation. The contractor shall take precautions to ensure complete consolidation and densification of concrete behind all post-tensioning anchorages.

Concrete placement. When concrete is placed in post-tensioned slabs, special care shall be taken at all column drop caps (panels). Insert the pump hose into the column drop panel below reinforcement and fill until concrete reaches the top reinforcing layer. Monitor concrete elevation to avoid flotation of top reinforcing. After the drop panel is full of concrete, place concrete over the top reinforcing layer to specified slab thickness. Vibrate adequately in and around column drop panels.

Pumped concrete. If concrete is placed by the pump method, horses shall be provided to support the hose. The hose shall not be allowed to ride on the tendons.

Chlorides. Grout or concrete containing chlorides shall not be permitted.

12.2.1.5 Stressing of Tendons

Tendon stresses. Such stresses shall conform to the following:

- Maximum tendon jacking stress, 216 ksi
- Maximum tendon stress at anchorage immediately after prestress transfer, 189 ksi

Effective force. Forces shown on structural drawings are effective forces after all losses. All losses (short- and long-term losses) due to creep, shrinkage, tendon relaxation, and elastic shortening, including friction losses and losses due to wedge seating, may be assumed as 14 ksi. Thus, the effective force per tendon may be assumed to be 24.8 kips for stress-relieved tendons and 26.8 kips for low-relaxation tendons, when tendon length is less than 100 feet. For variance from this value or for tendons over 100 feet, the post-tensioning supplier shall provide friction and long-term loss calculations for the engineer’s approval. Friction losses may not be averaged or assumed to redistribute along the tendon length. The available effective force shall be established at a location along the tendon length where the force demand meets the minimum effective tendon force.

Concrete strength at stressing. Prior to transfer of prestress, concrete shall reach a minimum compressive strength of $f' = 3000$ psi. Minimum concrete strength shall be established by breaking concrete test cylinders. The stressing shall not commence until concrete reaches the specified strength; however, tendons shall be stressed within 72 hours after concrete reaches the minimum specified strength to mitigate early-age concrete cracking. This may not apply to stage stressing of transfer floor or mat foundations.
Calibration. The ram and attendant gauge used shall have been calibrated within sixty (60) days of use.

Tendon stressing. The stressing operation shall be done by jacking under the immediate control of a person experienced in this type of work. Continuous inspection and recording of elongations are required during all stressing operations.

Stressing sequence. In general, uniformly distributed tendons shall be stressed before concentrated beam strip (banded) tendons, and slab tendons shall be stressed before beam tendons. Additional stressing sequence requirements shall be as specified below.

### Two-Way Slab Sequence
1. Stress continuous distributed tendons
2. Stress continuous banded tendons
3. Stress added distributed tendons
4. Stress added distributed tendons
5. Stress added slab tendons

### One-Way Slab and Beam Sequence
1. Stress temperature tendons
2. Stress continuous slab tendons
3. Stress beam tendons
4. Stress transfer girder tendons
5. Stress added slab tendons

Elongation. Individual tendon field readings of elongations and/or stressing forces shall not vary by more than ±7% from the calculated required values shown on the shop drawings. If the measured elongations vary from calculated values by more than ±7%, the contractor shall provide friction calculations and/or other justification, to the satisfaction of the engineer, for the discrepancies.

Member forces. The post-tensioned force provided in the field for each structural member shall not be less than the values noted on the structural drawings. In this context, structural members are beams or slabs, whether with banded or distributed tendons, each serving its respective tributary area.

Tendon ends. Do not burn off tendon ends until the entire floor system has been satisfactorily stressed and the engineer’s approval is obtained.

Anchor protection. The stressing end anchors and wedges shall be spray-painted with rust-inhibiting paint or a similar coating for corrosion protection prior to grouting of recess pockets. Install grease caps within 24 hours after cutting tendon tails.

Grouting of stressing pockets. Stressing pockets shall be filled with nonshrink grout after stressing, tendon end cutting, painting, and grease capping to stop moisture access to the strand.

Deshoring. Slabs or beams may be deshored when all tendons have been satisfactorily stressed and the engineer’s approval is obtained, unless shoring is required to carry floors of multiple levels (reshoring). In areas supporting a partial span, such as near a pour strip or construction joint, the shoring in the partial span and immediate back span shall stay in place until the remaining section of the span has been poured and stressed or cured.

Inspection for prestressing steel. Continuous special inspection shall be provided during placement of reinforcing steel, tendon supports, and prestressing steel. Tendon location and integrity of the protective wrapping for post-tensioned tendons shall be inspected prior to placement of concrete. During stressing of post-tensioned tendons, the special inspection shall include recording of field-measured elongation and jacking force for each tendon.

Admixtures. No admixtures shall be added to the concrete mix without the approval of the engineer, unless noted otherwise. Admixtures concrete containing chlorides shall not be used in post-tensioned slabs.

Special notes to the owner. Under normal conditions, and for conventional buildings, reinforced concrete as well as post-tensioned concrete develops cracks. The cracks are due to inherent shrinkage of concrete, creep, and the restraining effects of walls and other structural elements to which the beams/slabs are tied. The early-age concrete cracks that may develop are usually of a cosmetic nature. The slab typically retains its serviceability and strength capability. Due to special features of unbonded post-tensioning, it is possible that a number of hair cracks, which would normally spread over a wide area, will integrate into a single crack with a width exceeding 0.01 in. It is emphasized that, although special efforts are made to reduce the potential causes and number of such cracks, it is not practical to provide total articulation between...
the floor system and its supports and thereby achieve complete inhibition of all cracks. Most early-age cracks develop during the first two (2) years after construction of the floor system is complete. Cracks that are wider than 0.01 in. may have to be pressure epoxied. Refer to the notes under the Material Allowances section. The objective of providing joints is to allow movement. Movements due to creep and shrinkage may be noticeable at joints for up to two (2) years after construction, beyond which movements due to variations in temperature will persist. In aggressive environments, cracks should be repaired at the time they are first noticed.

12.2.1.6 Material Allowances
The contractor shall include in the project budget material allowance for the engineer to use at the engineer’s discretion during construction to address unforeseen conflicts. Any materials not used by the engineer shall be credited back to the individual (owner, developer) funding such allowances.

Reinforcement allowance. The contractor shall provide an amount of reinforcement as specified by the engineer of record for the engineer to use at the engineer’s discretion during construction. (Example: The contractor shall provide 2000 lb plus 0.05 lb per square foot of elevated concrete slab of reinforcement for the engineer to use at the engineer’s discretion during construction.)

Post-tensioning allowance. The contractor shall provide an amount of post-tensioning material as specified by the engineer of record for the engineer to use at the engineer’s discretion during construction. (Example: The contractor shall provide 1000 lb plus 0.02 lb per square foot of elevated concrete slab of post-tensioning material for the engineer to use at the engineer’s discretion during construction.)

Pressure epoxy allowance. The contractor shall include an amount for pressure epoxy injection of cracks that may develop in the structure during the first two (2) years. (Example: The contractor shall include the cost of $0.10 per square foot of elevated concrete slab for pressure epoxy injection of cracks that may develop in the structure during the first 2 years.)

12.2.2 Standard Details
In accordance with standard industry procedures for most construction-related work, details for unbonded post-tensioned members are first developed by the design engineer or architect. The details typically show the member geometry, reinforcing layout (location of tendons and mild reinforcing), and other embeddings. After the construction contract is awarded, the post-tensioning supplier commonly prepares more project-specific drawings, called shop drawings. The shop drawings for post-tensioning materials are normally prepared in much more detail than the design drawings. Typically, they are submitted for review and approval to the design engineer or agency before fabrication of the tendons is initiated. It is essential that details of the post-tensioning tendons, nonprestressed reinforcement, ducting for electrical or mechanical service, and other embedding items be reviewed and coordinated during the detailing stage. It is not uncommon for final details for different material trades to be shown on different shop drawings, indicating incompatible or conflicting layout. In most cases, details can be rather easily adjusted at the shop-drawing stage to accommodate all embedded items. When conflicts do arise during the development of shop drawings or during construction, the tendon layout should govern over other elements or embodiments conflicts. Many specialized structural details have been developed for the construction of unbonded post-tensioned members. The following selected details illustrate typical design and detailing practices for most common applications of unbonded post-tensioning in building construction.

12.2.2.1 Tendon Anchorage Zone
The anchorage zone, probably the most critical concrete region, has to retain the tension force of unbonded tendons during the service life of the post-tensioned structure. Figure 12.4 shows typical details of stressing and dead ends. Unless otherwise detailed on the design or post-tensioning installation drawings, banded tendon anchorage zones in normal weight concrete for groups of six or more 1/2-in.-diameter single-strand tendons with anchor spacing of 12 in. or less should be reinforced in accordance
with Figure 12.4b. For restriction of anchorage zone embedments, see Figure 12.14. The flaring of tendon bundles near anchorage zones, in the horizontal plane of the concrete member, and fixed-end tendon staggering requirements are suggested in Figure 12.5.

12.2.2.2 Two-Way Slab Tendons over Column Supports

The congested mild-reinforcing arrangement and tendon layout of banded and uniform tendons over column supports must be detailed so the field personnel can understand the various layers of top reinforcement and their support system. Figure 12.6 and Figure 12.7 indicate a typical two-way slab tendon layout over interior and exterior columns. The layout of tendon groups is arranged so, except for the bundle of uniform tendons (minimum two tendons) directly above the supporting column, all tendons in both directions have essentially the same eccentricity within the proposed slab section in the negative moment region. A detailed account of all layers can be found in Figure 12.8.

12.2.2.3 Beams

A number of field problems can be eliminated if simple installation recommendations are considered during installation of the beam reinforcement. Figure 12.9 and Figure 12.10 show typical beam–column joints and beam sections with detailed information on tendon and mild reinforcement layout. In addition to showing a detailed bar layout for mild reinforcing, the tendon support system is very critical. The
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Tendon support bars must be stable and properly secured to ensure a firm tendon profile during the concrete pour. Also, large tendon bundles, such as multiple bundles of six tendons, that are not properly spaced and layered may result in tendons bunching up at locations of curvature (high and low points) and developing splitting forces in the concrete beam. The use of tendon support bars, which guide the installation crew in the appropriate spacing of tendon bundles, has successfully addressed this concern (Figure 12.11).

FIGURE 12.5 Flaring of tendon bundles and fixed-end tendon staggering: (a) flaring of banded tendons at the slab edge in a corrosive environment, and (b) placement of added tendons.
Section 12.3 discusses in detail the types and optimum locations for joints to mitigate the restraint effects of post-tensioned members. In addition to restraint considerations, joints may have to be located to limit concrete pour size (Figure 12.12a) or allow for intermediate stressing (Figure 12.12b). The selection of pour-strip location and duration of pour-strip opening shall be based on a numerical shortening evaluation of the structure. A sample reinforcing layout for a typical interior stressing blockout and a 3-foot-wide...
The preceding discussion emphasizes that the successful performance of an unbonded post-tensioned structure is directly related to the understanding and extent of detailing of specific performance considerations.

### 12.2.3 Typical Field Shortcomings: Problems and Solutions

#### 12.2.3.1 Preventing the Most Frequent Problems

Prior to placing the concrete, the post-tensioning installation should be checked for the following.

- The area behind the anchors (18 in. behind the anchor at 45° angles on each side, as shown in Figure 12.14) should be free of sleeves, blockouts, large conduit, or any other voids or congestion that could affect tendon alignment.

**Note:** A minimum of two tendons shall be placed in each direction directly over column.

![Diagram](image)

- Rebar to be placed within dimensions shown.
- The distributed tendons under banded tendons @ column per.
- Banded tendons @ column per.
- Concrete column.
- 2 #7 support bars typ. @ col. supports.
- Drop cap if applicable.
- 4 #4 × 9'-0" each way.
- Place distributed tendons that fall within the lengths of top rebars below the uppermost layer of rebar.

**Note:** A minimum of two tendons shall be placed in each direction directly over column.

**FIGURE 12.7** Typical two-way slab tendon layout: (a) typical interior column, and (b) typical drop-panel section.

Pour strip is shown in Figure 12.13. The preceding discussion emphasizes that the successful performance of an unbonded post-tensioned structure is directly related to the understanding and extent of detailing of specific performance considerations.

### 12.2.3 Typical Field Shortcomings: Problems and Solutions

#### 12.2.3.1 Preventing the Most Frequent Problems

Prior to placing the concrete, the post-tensioning installation should be checked for the following. The area behind the anchors (18 in. behind the anchor at 45° angles on each side, as shown in Figure 12.14) should be free of sleeves, blockouts, large conduit, or any other voids or congestion that could
FIGURE 12.8 Layers in typical two-way slab tendon layout: (a) section through banded tendon at column, and (b) section through distributed tendon at column.

FIGURE 12.9 Typical column–beam joints: (a) typical column-beam section; (b) exterior beam–column connection.

allow the concrete to crush or form a void in this high-stress zone. If penetrations must be positioned within the 45° region, steel pipe inserts must be used as specified by the engineer. Frequently, the electrical, mechanical, and plumbing contractors place their sleeves just before the pour, after the
FIGURE 12.10 Typical beam sections: (a) placement of tendons in beam, and (b) placement of reinforcement in beams.

(a) Slab thickness 1–1/2" clr.
Continuous top bar
Stirrups or PT tendons @ low point
Cont. bottom bar
3/4" chamfer typical

Note:
Keep tendon groups uniformly spaced throughout the length of beam.

(b) Slab thickness 1–1/2" clr.
Beam width (T)

Note:
At conditions where there are two types of added bars (top or bottom), the longer bars shall be placed first.

FIGURE 12.11 Tendon support bar.

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tendon-placement inspection. While checking the anchor zones, make sure a sufficient strand tail extension is protruding through the edge form. It is typically much easier to adjust the tendon by a few inches prior to placing the concrete than it is to use splices and special equipment to stress a short tendon later.

For an encapsulated system, the sheathing should be connected to the anchor according to the manufacturer’s recommendation to ensure that there will be no exposed strand and to provide continuous protection. In normal environments, however, because there is no connection between the anchor and the sheathing, special care should be taken to minimize the length of greased strand behind the anchor. The maximum length of greased strand should not exceed 1 in. If concrete is cast against unsheathed strand, the rifling pattern of the strand will be cast in the concrete, forming spiral grooves that twist the strand when stressed. The spiraling of the strand will cause the stressing jack to spin at the end of the stressing cycle and could injure the person operating the stressing equipment or break the hydraulic supply hoses on the jack. Even if no one is harmed, the twisting motion of the strand through the jack grippers causes premature wear. It is important to tape wrap exposed strands before the concrete pour, as the fix is costly once the concrete has hardened.

FIGURE 12.12 Joint locations: (a) construction joint with no intermediate stressing, and (b) construction joint with intermediate stressing in a corrosive environment.
If more than 1 in. is exposed, repair the sheathing right up to the back of the anchors. If this area is difficult to access due to bursting steel or other obstructions, make a circular cut on the sheathing 18 to 24 in. back from the anchor, slide the sheathing forward until it touches the anchor, and then repair the bare spot at a location away from the congestion. The second option has the advantage of leaving the most critical area (that zone 12 in. behind the anchor) covered with good sheathing.

The quality of the installation can be jeopardized by people walking on the placed cable before a pour. The pocket former must be held tight against the anchors so concrete slurry does not leak into the anchor cavity. This can happen if the concrete vibrator bounces the edge form and separates the pocket former from the anchors. There is no substitute for having the anchors tightly attached. If a small amount of post-tensioning coating is applied to the tip of the pocket former before inserting it in the anchor cavity, it will make a seal between the two pieces that will keep concrete slurry out even if a small gap develops.
12.2.3.2 Slipping Strand and Jack Hang-Up

When wedges fail to hold the strand, the most common cause is concrete slurry in the wedge seat of the anchor cavity. If a separation between the pocket former and the anchor occurs, concrete slurry can flow into the anchor cavity and set up in the form of a ring around the strand at the back of the anchor. This will stop the wedges from penetrating into the anchor the proper distance and result in strand slippage. If the elongation requires more than one cycle of the stressing equipment, it can cause the jack to become locked onto the tendon. On the first cycle, the wedges usually hold because they do not have to be fully seated and the pressure is low. On the second cycle, the wedges bottom out on the concrete slurry and the strand will be free to slide back into the concrete, stripping the teeth on the wedges and hanging up the jack. Several different methods can be used to detension the tendon, thereby releasing the jack, depending on individual site conditions as follows. A second jack should not be used on the back of the one that is hung up to detension it. Once the jack is hung up, a troubleshooting split anchor (Figure 12.15) must be inserted behind the nosepiece of the jack bearing on the anchor cast in the concrete but in front of the gripper block of the jack to free up the jack.

Notes:
1. Penetrations with dimensions greater than 12" require trim reinforcement.
2. Sweat PT tendons (where possible) to avoid conflict between PT anchors and openings.

FIGURE 12.14 Openings at post-tensioning anchorage.

FIGURE 12.15 Split troubleshooting anchor.

12.2.3.2 Slipping Strand and Jack Hang-Up

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FIGURE 12.14 Openings at post-tensioning anchorage.

FIGURE 12.15 Split troubleshooting anchor.
During this procedure, do not exceed the recommended gauge stressing pressure. Open the jack just enough to insert the troubleshooting split anchor on the strand. Insert the wedges in the troubleshooting anchor and slowly release the pressure on the jack until the stress in the strand is taken up by the troubleshooting anchor. Continue closing the jack until the jack grippers in the jack gripper block are released from strand. Extend the jack fully and then retract the jack approximately 2 in. Engage the jack grippers and extend the jack to stress the strand again and release the wedges in the troubleshooting anchor. (Applying a thin coat of Never-Seez® or a similar product on the back of the wedges will make them easier to remove during this step.) Slowly release the pressure in the jack and let the strand slide back into the concrete slab until fully relaxed. (If the jack bottoms out before the strand is relaxed, simply repeat all the steps of the sequence.) When the jack is fully released, remove it and the wedges from the anchor in the slab. It is not uncommon to find that the wedge seating was either restricted by a small film of concrete slurry around the tapered sides of the anchor cavity or a ring of concrete formed around the strand at the back of the anchor. If necessary, remove the debris by scraping or chipping the slurry out of the anchor. Because the area is very congested, a small screwdriver may be the proper tool for this procedure. After removal of all debris, clean the wedge seat of loose materials and dust using compressed air. Insert a new pair of wedges and stress the tendon.

12.2.3.3 Honeycomb in Concrete

Rock pockets, sand pockets, or voids should be repaired prior to the stressing operation. Remove all loose material and dust prior to repair. Wet the concrete surface before repair. When patching, use a high-strength, nonshrink concrete grout mix with an epoxy binder. Grout strength should equal or exceed specified concrete strength. *Do not* use grout that contains calcium chloride or other materials containing chloride. When the patch has attained proper strength, the stressing operation may proceed. It is essential to repair honeycomb in anchorage zones to avoid blowouts. After detensioning of tendons, all loose material and dust should be removed until sound concrete surfaces are encountered. Stress tendons after the repaired area reaches the minimum concrete compressive strength specified. Prior to stressing, check the quality of the patch by tapping it with a hammer to sound for voids. A hollow sound indicates a poor patch that is not suitable for stressing.

12.2.3.4 Splicing Tendons

Tendons are sometimes too short to reach an edge form because of misplacement or misfabrication. If the tendon is in one pour only and not continuous, every effort should be made to replace the short tendon with a tendon of proper length instead of using couplers. If tendons are continuous from another pour, thus making tendon couplers necessary, the engineer of record and the post-tensioning material supplier should be notified. The coupler location should be determined by the post-tensioning material supplier such that the coupler is centered in the member and not at a point of tendon curvature. Couplers should not be located side by side. If more than one tendon requires splicing, couplers should be staggered at half-bay increments per tendon group.

A PVC pipe of sufficient inside diameter to hold the coupler and of sufficient length to allow for subsequent elongation movement should be used. Also, an additional piece of sheathed strand of sufficient length to reach the edge form is required, along with two pocket formers. Post-tensioning coating should be used to fill the void in the PVC pipe. The tapered tip of the pocket former that normally fits inside the anchor cavity can be cut off when being used for splicing, thereby reducing the length of the PVC pipe needed. The original strand is first cut with a saw or abrasive plate at the coupler location, and one pocket former is placed on the strand. The strand should be marked before coupling to make certain that the proper length of strand has been fully inserted into the coupler. The coupler is then coupled to the original strand. The PVC pipe is placed over the coupler. The second pocket former is placed over the new strand (the strand is marked) and inserted into the coupler. A pocket former is taped to one end of the PVC pipe, which is then packed tightly with post-tensioning coating, allowing no air voids. The second pocket former is affixed to the PVC pipe, completing a tightly sealed coupler.
The tendon coupler’s location within the PVC pipe must permit the coupler to move the required elongation amount in the direction of stressing. Allowance for movement in both directions must be provided when the tendon is to be stressed from both ends. Conservatively, a minimum of 1.5 times the total expected elongation at the splice location should be allowed for. A dark crayon or paint mark on the deck will facilitate locating the coupler after the pour, should that become necessary if the above procedure was not properly followed.

12.2.3.5 Tendons Too Short to Stress Using Normal Stressing Procedure

Short tendons can result from an incorrect tendon-fabrication cutting list, misfabrication, misplacement, or a job-site mistake such as cutting tendons off prior to stressing. During stressing, most conditions may be addressed with special equipment that can be obtained from the post-tensioning material supplier. If a tendon is too short to be stressed using a standard jack, in some cases a short tendon can be stressed by simply removing the nose piece and using jack feet. When using jack feet, care should be taken to center the jack with the tendon before applying pressure. If the tendon is stressed without being centered on the anchor, it will rub on the side of the anchor, and inserting one of the wedges may be impossible. This will cause the other wedge to be drawn all the way to the back of the anchor cavity, breaking or damaging the strand. Without the hydraulic-seating attachment, the wedges will have to be inserted and seated using a hand-seating tool and a hammer. Tendons that are too short for the above procedure will have to be stressed using a coupler with a short piece of strand fixed on one end of the coupler. Tendons that were cut with a torch prior to stressing have lost some of the temper in the steel due to the heat. If the jack grips or the coupler grip near the previously heated area, the tendon may slip at a very low pressure. If this condition exists, make the first pull as short as possible (so the stressing pressure is kept low), install the wedges in the anchor, and regrip the tendon farther away from the end that was heated.

12.2.3.6 Lift-Off Procedures

The purpose of a lift-off is to verify the force of a tendon after it has been stressed. A lift-off may be required when the recorded elongation is out of code-recommended tolerance. Project specification may call for a selected force verification using the lift-off method. A lift-off test may be conducted by use of the standard hydraulic stressing jack on previously stressed and anchored monostrand post-tensioning tendons to determine the residual effective force in the tendon at the anchorage. The lift-off test is preferable and most easily done before the stressing tails of the tendons have been cut off. While it may be possible to conduct a lift-off test after the stressing tails have been cut off, this possibility is determined by the length of tendon protruding beyond the wedges in the stressing pocket as well as the possibility of connecting the hydraulic jack to this length of tendon (this may be dangerous). When the tendon is initially stressed and anchored, the wedge seating that occurs develops a mechanical-friction force between the strand, wedges, and anchorage casting. During the lift-off test, it is necessary to stress the tendon in excess of the residual effective tendon force at the anchorage by an amount equivalent to this mechanical-friction force to break the wedges loose and determine the force remaining in the tendon. This process will be reflected during the lift-off test by stressing to a level (reflected on the gauge attached to the ram) sufficient to break the wedges loose and a subsequent reduction in the gauge pressure to reflect the residual force in the tendon. It should be understood that the lift-off test determines the residual force in the tendon at the anchorage. Determination of the force level in the tendon at other locations requires detailed consideration of friction and wedge-seating effects.

12.2.3.7 Cracked Wedges

Hairline cracks may appear in the case-hardened surface of wedges due to deformation of the wedges around the strand at the time of seating. These cracks do not affect the integrity of the post-tensioning system.

12.2.3.8 Shooting Power-Driven Fasteners

The structural designer of an unbonded post-tensioned member should offer detailed information regarding the limited application of power-driven fasteners that may be used on a particular project.
member. Frequently, developers are concerned about damage to tendons if future plumbing penetrations are added. This problem can be solved for structures in which changes are anticipated. The dye-transfer technique relies on the dye color marked on the forms to transfer to the concrete soffit after the member is poured. Alternatively, markers may be installed to visually mark the location of each band and tendon bundle.

12.2.3.9 “Hazardous” Statement

The procedures described in this part of Section 12.2.3 may be hazardous. Only qualified experienced personnel, with a minimum of 5 years of specialized experience in the installation and repair of unbonded post-tensioned systems, should attempt these procedures.

12.3 Evaluation and Rehabilitation of Building Structures

12.3.1 Evaluation

Even though concrete is considered to be one of the most durable construction materials, building structures must be evaluated during their useful life for various reasons. Some of the more common reasons may include deterioration (serviceability shortcomings, loss of strength), change in loading of a structure, building modification, overloading (disaster), or simply as an assurance evaluation. The evaluation of an existing unbonded post-tensioned elevated floor system may be divided into three principal activities: (1) examination of the existing floor system and structure (conditional survey), (2) diagnosis, and (3) prognosis or findings. All three steps are necessary before a repair or retrofit can be outlined. The level of evaluation may vary from simple nondestructive examinations and preliminary calculations for initial reporting to rigorous destructive testing with detailed analytical diagnosis of the structure.

12.3.1.1 Examination of an Existing Unbonded Post-Tensioned Floor System

As part of the structural assessment, the engineer should initially complete a detailed survey of the structural floor framing system, geometry, and the "as-is" condition of the structure, including environmental impact. This stage includes the collection of existing information about the structure, surveying the floor system for signs of distress, and establishing a listing of proposed nondestructive and destructive testing based on the distress observed and information gathered. To establish as-built data, the examination should consider the material properties and the detailed survey of the condition of each material and the material configuration or quantity.

The physical testing of concrete may include verification of the concrete compressive strength, material uniformity, mix properties, permeability, and aggregate type. In addition, chemical testing may be performed to establish the concrete constituents, which are used in the evaluation of concrete reactivity or concrete resistivity. The tests should determine the amount of chloride, sulfate, or other materials that may result in a chemical attack on the concrete section of concern. Properties such as the tensile strength of the mild steel and post-tensioning strands may be of interest. Should the tendon anchorage zones be of concern, it may be necessary to test individual elements of the anchorage system.

The material-condition survey of the examination may focus on locations of primary distress but should extend to the comparative performance of the entire structure. Concrete voids (consolidation), delamination, spalling, discolored concrete, chemical attack, excessive air voids, and cracking should be investigated to determine the extent, formation, and amount of concrete damage within the distressed concrete area. In addition to selectively locating the position and amount of reinforcing steel and post-tensioning, the level of deterioration, as a result of corrosion, should be assessed. Specifically, post-tensioned slab edges should be surveyed for exiting tendons or loose grout plugs at stressing ends. The removal of grout plugs at tendon-stressing ends may allow visual assessment of the anchorage zone. Along the tendon length, removal of the tendon sheathing may be necessary to view the condition of the high-strength strand wires at high and low points.
In addition to the factual material-condition review of structural members, the survey should include a performance survey. Besides the typical serviceability considerations, this would include the performance review of joints, hinges, attachments, locations of movement, and locations of restraint. As part of the material-condition survey, each distress location should be assessed using time as one of the evaluating parameters.

12.3.1.2 Diagnosis

After all project documents have been collected and reviewed and after detailed inspection and testing of the floor system of the structure have been performed, the formal process of analytically assessing the existing unbonded post-tensioned floor member takes place. First, the floor framing system should be checked for adequate strength. The selected modeling must accurately represent the actual geometry and boundary conditions using the two-dimensional simple beam frame or the equivalent frame slab strip for a two-way slab. The calculated elastic factored-load moments may be increased by the code-permissible plastification, commonly referred to as redistribution of moments. The elastic support moments may be raised or lowered to the maximum percent of the code-permissible redistribution for each respective support. This band of the factored-load moment demand yields a range of acceptable solutions.

After establishing the band of acceptable moment-demand solutions, determine the capacity of the existing structure at critical points. Select a redistribution based on the capacities of the existing structure and the permissible percentages computed, and, finally, establish whether or not the redistribution made on the basis of the existing capacities falls within the permissible range. The demand-vs.-capacity check should include consideration of possible strength loss due to distressed member cross-sections. For conditions where the demand design strength exceeds the capacity of the member, refer to Section 12.3.3, below. For unbonded post-tensioned slabs in particular, extensive destructive testing should be conducted to confirm that calculated member capacity is based on the observed quality and quantity of the tendon.

Serviceability of the unbonded floor system should then be reviewed. Sectional stress checks at critical locations and immediate and long-term deflections should be calculated. The observed distress may reveal a direct relationship to the original design, material sections, construction, or applied loads and maintenance. In most cases, serviceability limitations, such as durability or deferred maintenance shortcomings, initiate concerns that are typically answered by evaluations. The more common serviceability shortcomings include corrosion of strands and anchorage zones, as well as broken strand wires and tendon concrete cover at high and low points.

12.3.1.3 Findings

Assessing a post-tensioned member, particularly one showing signs of distress, is not simply a matter of conservatively selecting the desired material properties and load flow path, as is the case for a newly designed member. After an analytical model representing the unbonded post-tensioned member has been developed, it should be used to perform a detailed review. The objective is to explore the consequences of variation in tested material properties, assumed loading and load distribution, boundary conditions, extent of distress, and rate of material deterioration. As part of a member evaluation process, it is common to apply various modeling techniques in the process of understanding how the structure behaves and where hidden strength reserves may be available. After the diagnosis of the structural element is completed, the engineer should have developed a clear understanding of how the structure behaves and be clear on the causation of distress, including future behavior, considering time and site-specific adverse environmental conditions as additional dimensions. Based on the preceding description, it is obvious that the prognosis is based on a multitude of variables that may only be understood by a reviewer with extensive experience in the evaluation of unbonded post-tensioned concrete structures. In closing, it should be noted that the review or evaluation of an existing post-tensioned member requires the highest degree of professional expertise, knowledge, and integrity from the assessing engineer.
12.3.2 Repair

Unbonded post-tensioned concrete members are considered one of the more difficult structural members to assess for repair or retrofit. It is not uncommon for engineers who are not experienced with unbonded post-tensioning to misinterpret the distress observed. The author frequently encounters assessment reports of crack development that conclude that cracks may have developed as a result of member strength deficiency, where, in fact, the cracks may have developed as a result of reverse tendon-profile curvature or restraint member effects. Even if the assessing engineer correctly found the cause of concrete cracking of the post-tensioned member, the effects that the distress has on the structure and its repair may be grossly misjudged. For this reason, it is not uncommon for proposal requests for evaluation and repair to require the contractors to have a minimum of 5 years of specialized experience in designing, analyzing, and repairing unbonded post-tensioned members. This is a fundamental consideration before assessing the repair of a member. The common repairs outlined below may be used to address distress resulting from poor detailing or construction execution and deterioration of the materials.

12.3.2.1 Blowout

The sudden exiting of a tendon at the slab edge or at tendon profile high or low points, during or after stressing, is typically referred to as tendon blowout. In contrast, if the concentrated precompression force behind tendon anchors or the reverse tendon-profile curve causes the sudden disintegration of a localized concrete pocket, it is typically referred to as concrete blowout.

12.3.2.1.1 Typical Examples of Tendon Blowout

Tendon blowouts are typically recorded either at the slab edge or on the slab surface or soffit. During the installation of mechanical, electrical, or structural elements, should the contractor partially rupture or cut the unbonded tendon, the tendon tail may eject from the slab edge. The amount of existing slab edge is primarily related to the type of sheathing that was supplied. Extruded tendon should typically result in minimal tendon exiting (up to 3 ft) at slab edges (Figure 12.16). If unbonded tendons are used with a stuffed or heat-sealed sheathing application, the tendon exiting during a sudden release of stored energy may be unpredictable. The minimal void between the sheathing and the creased strand (of stuffed or heat-sealed tendons) limits the internal friction, allowing the stored energy to travel past the existing location. During a sudden release of the entire tendon force, the strand may exit vertically (also known as vertical tendon blowout) at locations of minimal concrete cover, typically the high and low points of

FIGURE 12.16 Tendon exiting at slab edges.
profiled tendons, due to the vertical component of the draped profile. The seven-wire strand may exit, resulting in a 1- to 3-ft vertical strand loop (Figure 12.17). Conditions noted above may be a result of the accidental cutting of a strand or due to deterioration of the member. **Horizontal tendon blowouts** are typically found where horizontal tendon curves around openings are not detailed and executed correctly. Tendons are typically installed side by side in groups of two to four unbonded tendons. The tension force allows the strands to ride on each other in the horizontal radial plane, creating a splitting force that can result in a tendon blowout (Figure 12.18). Tendon groups should be reduced and limited to groups of two maximum over the length of the horizontal curvature. In addition, adequate reinforcing steel (U-pins) should be added to account for and tie back the centrifugal forces.

**FIGURE 12.17** Vertical loop resulting from exit of seven-wire strand.

**FIGURE 12.18** Tendon blowout resulting from strands riding on each other.
12.3.2.1.2 Typical Examples of Concrete Blowout

Concrete blowouts are most frequently recognized during the tendon-stressing operation. The anchoring of tendon forces tests the compressive strength of the concrete pocket immediately behind the tendon anchorage. A simple void, rock pocket, low concrete strength, or lack of reinforcing behind the tendon anchor may cause the concrete to pulverize, resulting in a concrete blowout. Figure 12.19 and Figure 12.20 show pulverized concrete behind the tendon anchor due to low concrete strength and voids, respectively. Most concrete blowouts are recognized during the stressing operation or within several months of stressing the tendons. In addition, tendons that are stretched over a longer distance near the concrete surface (i.e., with minimal concrete cover) and that have a reverse tendon-profile curvature may split the concrete section over the distance of reverse curvature to allow the tendon to straighten. This may take place during the stressing operation or at a later date if the concrete section experiences additional concrete stresses due to loading.
12.3.2.1.3 How to Repair Concrete Blowout

Depending on the location and severity of the blowout, adjacent tendons may have to be detensioned before concrete removal can begin. After detensioning (as necessary), the damaged concrete is removed in sufficient amounts to expose any damaged strands and allow the resetting of the anchorages. In some cases, it may be necessary to use couplers in the repair to increase tendon length due to strand damage. It is important that the back side of the opening be cut square and perpendicular to the tendon to avoid slippage of the concrete patch during stressing. Remove all loose debris and clean the surface of dust. Make sure all the anchor zone reinforcements have been replaced, and fill the area to be repaired with a high-strength, nonshrink concrete grout mix. Do not use grout that contains calcium chloride or other materials containing chlorides. Stress the tendons only after the grout patch has attained the required design strength as approved by the engineer of record.

12.3.2.2 Tendon Rupture

Tendons may rupture partially if only one wire is damaged or totally when several wires are damaged, causing the remaining wires to fail under sustained tension load. The cause of tendon rupture for tendons should be determined. One of the most critical actions for unbonded post-tensioned structures is to immediately determine the extent of damage. If corrosion is the leading cause of the damage, several tendons should be spot checked to establish the extent of damage to each tendon and the slab area or beams in which damage has been recorded. If preliminary calculation indicates that the loss of the ruptured tendons affects the strength of the unbonded post-tensioned member, the member should immediately be shored. Destructive testing to recover representative strand samples should be considered to record the tendon location, wire condition at the location of rupture, concrete cover, type of sheathing, condition of the crease, remaining cross-sectional area of the seven-wire strand, and other project-specific conditions. When the extent of damage and type of tendon sheathing have been identified, strand replacement or splicing of tendons may be considered.

Strand rupture or breakage can also occur from misalignment of wedges, the anchor to the strand not being perpendicular, overstressing, or internal damage to the tendon. Misalignment of wedges occurs when the two or three parts of the wedges are offset prior to stressing. The wedges can pinch one or more wires due to different circumstances. Internal damage to the tendon could be caused by nicks in the strand or heating of the strand due to torch cutting of adjacent objects prior to concrete placement. Damage can be caused after concrete placement by drilling, saw cutting, or shooting power-actuated studs into the concrete.

If a strand does not hold, remove the wedges, clean the cavity, install new wedges, and restress. Overstressing of a tendon can occur by misreading the pressure gauge or using a jack and gauge that are out of calibration or that are not a matched set. The strand may either break or be stressed beyond yield. If the strand breaks, the engineer of record will determine how the structure is affected and whether replacement is necessary. If the wedges hold and the strand does not break, it is usually preferable to leave the tendon in the overstressed condition. Attempts to detension the tendon may damage tendon or break it necessitating replacement of the strand.

Prior to replacement of existing strands, adjacent strands may have to be detensioned. After exposing stressing and dead ends, it may be advantageous to weld a 1/4-in. wire rope to the existing damaged strand tail, allowing repulling of the new strand. If the existing strand is ruptured, not allowing the rethreading of a wire, the new strand may have to be pushed into the sheathing void by hand. Strand replacement can be effectively executed for unbonded monostrand tendons with heat-sealed or stuffed sheathing. The slightly oversized sheathing typically can accommodate new strands. For long tendons or tendons with extruded sheathing, a smaller size strand, such as 7/16- or 3/8-in.-diameter strands, may be selected. Strand replacement for tendons with paper-wrapped sheathing is nearly impossible. For all strand replacement, adequate creasing application should take place as part of the strand installation procedure.

The substitution of the original 1/2-in.-diameter strand with a smaller strand may be acceptable for the following reasons. Most older structures used stress-relieved type strands that are typically replaced by new low-relaxation strands. Strain tempering is very effective in improving the stress–strain characteristics and has the additional advantage of substantially reducing time-dependent losses due to
relaxation of the strand. Stress-relieved type strands may experience over 10% more loss in stresses due to relaxation than do low-relaxation strands. The stress loss due to concrete shortening may not have to be compensated for.

12.3.2.3 Cracking of Concrete Members

12.3.2.3.1 Crack Development

The most frequent crack development is typically due to restraint of adjoining members. This phenomenon is extensively covered in Chapter 35 of this book. Crack development due to the incorrect installation of the tendon profile or anchors and overbalancing of the member self-weight is in most cases misinterpreted. The incorrect placement of an unbonded tendon profile high point near the quarter span of a beam instead of over the column support has resulted in notable beam cracking approximately two beam depths away from the support (Figure 12.21). In this case, even though the inspection reports and survey of the installation crew confirmed correct placement of the tendons, destructive testing revealed the misaligned tendon profile (Figure 12.22). A simple realignment of the tendon profile reconditioned the beam for its intended life cycle. The layout of unbonded tendons should incorporate appropriate locations for the dead ends and stressing ends of the tendon. The localized concrete zone surrounding groups of added tendons may be subjected to high-tension stresses, which, if combined with flexural stresses, may result in crack development. Figure 12.23 illustrates a significant crack that developed in a post-tensioned beam at the location of added tendon dead ends. The dead ends were not staggered, allowing a load distribution as called for in the standard details.

12.3.2.3.2 Repair of Cracks

The objectives of crack repair on structures with cracks caused by restraint effects tendon profiles or for cracks in anchorage zones, which were surveyed by the author, served the following purposes:

- In most cases, repair was conducted as a precautionary measure to eliminate the exposure of reinforcements and post-tensioning to weather and moisture. In some cases, it was performed to stop leakage.
- It was rarely necessary to carry out repairs to restore structural strength.
- Occasionally, repairs were conducted for aesthetic reasons.

Which cracks should be repaired? Cracks that are determined to be of structural significance should be repaired regardless of width and location. Most such cracks are due to poor design, deficient detailing, or bad workmanship. Cracks that affect the serviceability of a structure, such as deflection and local distress,
may be left unrepaired if the diminished serviceability is acceptable and the repair is not cost effective. Under normal conditions of service, shortcomings due to deterioration may be encountered if cracks exceed 0.01 in. in width. Such cracks should be sealed to prevent intrusion of moisture and possible oxidization, loss of steel area, and possible spalling. Cracks in structures exposed to especially adverse conditions should be sealed, even if they are less than 0.01 in. in width. Also, cracks that show rust stain should be sealed.

When should cracks be repaired? Restraint cracks are best repaired after the shrinkage and creep shortenings are essentially complete. Generally, a lapse of approximately 2 years after construction is adequate, after which cracks may be repaired. A time delay in sealing of cracks is only justifiable if corrosion considerations permit. Cracks caused by reverse tendon profile should not be repaired until the reverse profile is relieved, neutralizing the cause of cracking.

How should cracks be repaired? Among the numerous reports on methods for sealing cracks in prestressed concrete structures, the most common and effective procedure is the injection of an epoxy resin compound under pressure into the cracks to fill in the crack voids. For details, consult the

FIGURE 12.22 Misaligned tendon revealed by destructive testing.

FIGURE 12.23 Crack in a post-tensioned beam where tendon dead ends were added.
manufacturer’s literature. For cracks that are nonworking (that is, they no longer move), the best sealing method is to inject the cracks with an epoxy resin of low viscosity. This is done in such a manner that the cracks filled with the resin and the concrete on each side of the cracks are reunited by the gluing action of the resin. Another method is to rout a groove along the crack throughout its entire length and fill the groove with an epoxy compound. The latter scheme is not recommended in highly corrosive environments. Cracks that are working (that is, they open and close as a result of loads, temperature, etc.) cannot normally be successfully sealed with epoxy compounds but must be sealed with flexible sealant that can withstand the movements to which the cracks are subjected.

12.3.3 Retrofitting Concrete Structures Using Unbonded Post-Tensioning

From the mid-1980s to the mid-1990s, a series of natural disasters tested the performance of existing structures on the west and east coasts of the United States. As a result, building-code revisions addressed improved strength and serviceability considerations. The perception of building performance during recent disasters, the ever-changing building codes, and the gradual deterioration of existing structures have sparked increased public interest in the retrofitting of structures. The objective of retrofitting a structure is to modify or improve the strength and serviceability of the existing member. The options of strengthening an existing concrete floor system for gravity loads include the following:

- Adding drop caps, drop panels, or beams at the slab soffit
- Slab overlay that supports the existing slab dead load
- Increase in or jacketing of existing beams, girders, and columns
- Adding columns or remove and replace existing columns
- Adding a gridwork of beams at the slab soffit
- Attaching externally applied metal plates to the existing concrete slab
- External prostrating

The options outlined in the following sections are limited to members being retrofitted with unbonded post-tensioning. It is understood that other elements or connections may have to be strengthened (columns, walls, and foundations and their connections) within the structure as a result of the external tendon retrofit application. The application of external prestressing for nonprestressed or prestressed floors is a widely used retrofit option for gravity-load strengthening and serviceability. The following section differentiates between gravity-load strengthening and serviceability considerations.

12.3.3.1 External Prestressing for Gravity-Load Strengthening

A strength requirement ensures that all elements of the building provide an adequate factor of safety against injury or material damage in the event of a code-specified overload. Slabs with inadequate strength or slabs that are subject to overload initially exhibit significant crack formation in tandem with noticeable deflections. If a thorough evaluation indicates inadequate member capacity for code-predicted factored load demand, the member should be subject to strength retrofit. Using an external unbonded post-tensioning retrofit scheme, the author has used two principal approaches to compensate for the strength shortfall of the existing structure—namely, direct-member strengthening (for one-way slabs and beams) and indirect-member strengthening (for two-way slabs).

Direct-member strengthening is typically used for one-way members such as one-way slabs and beams. First, the engineer should establish the capacity of the existing member and scale the strength shortfall by comparing the established capacity with the load demand. The strength-shortfall compensation may be readily supplied by attaching externally stressed unbonded tendons on each side of a beam. The tendons should be profiled (typically, harped with one or two deviators) so as to uplift or unload the beam equal to or more than the amount of load that the existing capacity cannot safely sustain. The external tendons are only intended to supplement the existing capacity. It may be difficult to establish the capacity of damaged structures or members with highly deteriorated reinforcing. In such cases, the
external post-tensioning may be considered to take all loads. Where anchors are attached to columns or beams, the applied load is retained in the form of precompression in the existing member. The installation of deviators (deflector saddles) or anchors should miss all main member reinforcing.

Indirect-member strengthening, typically used for two-way slabs, takes advantage of the possibility of alternate load passes by using the capacity of the existing structure. Initially, a two-way member may be examined, using code-factored loading, to establish the as-is failure mechanism and locations of hinge formation. The objective is to search for and select an alternative failure mechanism that is capable of safely sustaining the factored loading. Through the addition of external applied post-tensioning upward forces, the failure mechanism may be altered to accomplish this objective. External prestressing, if used to supplement the strength of the member, should be encased in fire-retardant material that meets the fire-resistivity or rating requirements for the particular application.

12.3.3.2 External Prestressing for Serviceability

Serviceability describes the in-service functionality of a building for its users. Excessive out-of-level floors, inadequate drainage, perceived vibration, perceived sagging of ceiling lines, exposure of reinforcement to corrosive elements due to excessive crack widths, and unsightly cracks are the primary serviceability considerations. Serviceability may be influenced by original design, material selection, construction, applied loads, and maintenance. When a structure reflects signs of serviceability shortcomings, such as excessive deflections or cracking, external prestressing has been effective as a corrective retrofit. For example, the installation of tendons at the underside of a slab or at each side of a beam, profiled to result in upward forces where desired, may be an effective and economical retrofit solution. For cracks or deterioration of members, additional work may be required beyond the application of external post-tensioning. The retrofitting of nonprestressed members, using external forces to counteract excessive elastic deflection and plastic deformation, may have to be analyzed using specialized software to model the time-dependent creep deformation. If the application of external tendons is used solely for the purpose of improving serviceability shortcomings in a structure with adequate strength to sustain the code-predicted factored loading, then the tendons may not require corrosion protection if they are aesthetically acceptable.

12.3.3.3 Retrofit Application of External Unbonded Post-Tensioning

The principal considerations for the selection of a retrofit scheme are performance, durability, economy, and appearance. The performance records of external prestressing on hundreds of retrofitted structures across the United States and its versatile and economical application have resulted in today's frequent use of this system. External tendons may be threaded through existing concrete members (such as walls or beams), directly attached to existing elements, or routed over deflector supports. When selecting a particular tendon layout support system, access, available space, fire protection requirements, and aesthetics must be considered. The following section is intended to offer selected examples of the external prestressing installation application. The information on member selection and connections, shown in the details, offers project-specific design information prepared by the author which may not be applicable to other retrofit projects.

12.3.3.3.1 Beam Retrofit

During the course of evaluating the nonprestressed beams of a private parking structure in Woodland Hills, California, excessive post-elastic deformation and concrete cracking were recorded. The use of bundled unbonded tendons on each side of the beam, with one deviator at midspan, was selected to utilize the upward force component to instantly neutralize elastic deflection and to remove the postconstruction plastic deformation (creep) to near zero within a 10-year period after the retrofit was successfully installed. A time-dependent analysis was performed to establish the deformation of the nonprestressed beams during their predicted useful life. A typical elevation and details of tendon attachments are shown in Figure 12.24 and Figure 12.25. An alternative connection of external unbonded tendons is shown in Figure 12.26.
12.3.3.2 Slab Retrofit

During the final construction stages of a hybrid structure (a three-story residential wood framing over a one-story concrete garage) located in Glendale, California, excessive deflection and cracking of the elevated concrete slab were recorded. An initial document review revealed that inadequate reinforcement was specified in the original design. The non prestressed cast-in-place concrete slab was supported on an array of orthogonally spaced concrete columns. The first-mode failure mechanism of parallel hinge line formation was altered by the introduction of external upward forces along said hinge line (Figure 12.27).
The upward force was calculated, utilizing the existing slab's capacity, allowing for an alternative failure mechanism with a significantly higher capacity limit. Three principal external tendon layout support systems were proposed.

**FIGURE 12.26** Alternative connection of external unbonded tendons.

**FIGURE 12.27** Simplified failure mechanisms of column-supported slabs: (a) failure mechanism as constructed, and (b) new failure mechanism after retrofitting the slab.
The first system consists of simple steel tube deviator or saddle supports anchored at each end of the structure (Figure 12.28 and Figure 12.29). The fabrication and application of this externally applied system can be readily installed around utility pipes and other obstructions. This layout should be considered if adequate headroom is available, allowing for large harped-profile shapes; however, short spans may result in large tendon angular changes over the deviator, which may result in localized damage to the tendons. Aesthetics considerations may be difficult to satisfy, especially if the entire system requires fire-protection coating (Figure 12.30).
The second option may allow for using more tendons with a less vertically harped profile and tendons anchored in added drop panels at columns (Figure 12.31). The advantage of this option is that tendons may be discontinued at column lines for localized application, and it may be installed in areas with limited headroom. The concrete for the added column capitals may have to be poured through access holes from above the slab. A fire-protective coating must be applied if external tendons are required to supplement strength shortcomings.

FIGURE 12.30 Fire-protection coating.

FIGURE 12.31 Schematic of external tendon at column line: (a) typical elevation, and (b) typical tendon deviator detail.
The third option was added to address fire protection and aesthetic considerations. The objective of this option is to install additional unbonded tendons without the structure retrofitting becoming visible. The tendons are installed within a reinforcing cage reflecting the intended vertical profile (Figure 12.32 to Figure 12.34). A concrete beam is poured at each column grid line to encase the tendons, offering fire protection and concealing the retrofit approach in concrete, hiding the afterthought even to a trained eye. Enough tendons must be selected to balance the dead load of the added concrete beam in addition to achieving the required upward force. The beams are isolated from the existing slab with contact at midspan for upward load transfer. The concrete for the added beams may have to be poured through access holes from above the slab. As this option addresses the durability and aesthetics of the retrofit effectively, the economic penalty of adding a grid of concrete beams may not be of great significance.

12.4 Demolition of Post-Tensioned Structures

12.4.1 Introduction

The purpose of this section is to address the concerns of the industry, primarily contractors and engineers, regarding the unique properties of prestressed concrete that must be addressed to safely demolish structures that contain unbonded prestressing systems and devices. The scope of this section is limited to the structural engineering considerations that must be made to properly evaluate prestressed structures for demolition and not for the purpose of mandating regulatory requirements.
The reader is advised to refer to those publications prepared by OSHA (promulgates rules and regulations regarding health and safety in the workplace) and the American National Standards Institute (provides standards for safety during construction and demolition operations). In addition, the National Association of Demolition Contractors’ publication *Demolition Safety Manual* covers the use of demolition equipment and safety procedures to be followed for all forms of structures to be demolished including precast and prestressed concrete structures. The recommendations are presented for the guidance and information of professional engineers, who must add their engineering judgment to the application of these recommendations.

**FIGURE 12.33** Details of retrofit using external tendons: (a) plan, (b) section 1-1, and (c) post-tensioning anchor orientation.

**FIGURE 12.34** Tendons installed within a reinforcing cage.
12.4.2 Structural Evaluation

The demolition of an unbonded post-tensioned structure should be carefully evaluated by an engineer to ensure safety during all phases of the demolition operation. Shoring that is to be used to support the structure during all phases of demolition, including tendon destressing, should be designed to accommodate vertical loads and horizontal loads, including any associated structural deflections. It is important to account for the loss of strength in multiple spans (over the tendon length) when detensioning unbonded tendons. It is important to secure the slab edge, as the release of energy stored in each tendon can result in sudden exiting of the strand at stressing ends.

12.4.2.1 Material Considerations

Wood and steel structures allow the demolition contractor to stage the demolition sequence and procedures based on the member strength and configuration. Concrete structures have inherent uncertainties with regard to the location, size, splice, prestressing force, and quantity of tensile reinforcing beyond the information provided by original construction documents. The layout and amount of mild and prestressed reinforcing in the continuous beams of frames must be reviewed, accounting for the altered modeling of a span by a span-demolition sequence.

12.4.2.2 Identification of Structural System Used

It is necessary to review available records relating to the design and construction of the building or structure to be demolished. These include design drawings, shop drawings, project specifications, field reports, repair records, job photographs, and correspondence. These records should be retained by the building owner; they may also be available from the engineer or architect of record or the contractor and should be on file with the local building department.

12.4.2.3 Condition Survey of Building or Structure

Prior to demolition operations, an engineering condition survey of the premises should be performed to determine the type and condition of the structural elements to prevent a collapse of any portion of the structure. This survey should include adjacent structures, overhead and underground utilities, and sidewalk vaults that may be affected by the demolition operations. All necessary permits and notices to adjacent owners and utilities should be obtained. The condition survey should include intrusive probes of the slab, girder, and column connections of critical elements to verify both their presence and their condition.

12.4.2.4 Determination of the Condition of Critical Elements

All structural elements reviewed should be to ensure that sufficient load-carrying capacity and stability is maintained for each stage of demolition. Strength capacity may be affected when adjacent supports and lateral load-resisting elements such as shear walls are removed. Strength reduction may already be diminished due to previous damage from fire, corrosion, age, and improper and undocumented alterations to the structure. All structural elements reviewed should be for the controlled release of stored energy in cutting tendons, especially the unbonded tendons. The location and direction of the anchor wedge seating of the intermediate anchors and splices may be of great interest to avoid a progressive collapse in a multi-frame structure. Stability requirements for each stage of demolition should be evaluated. Locations of stair and elevator towers may be isolated from the primary structure and may require special attention. A structural analysis may be required to determine unbalanced post-tensioning thrusts on framed elements, shear forces on wall systems, cantilever construction, continuously designed floor elements, and locations of critical tensile stresses in post-tensioned concrete elements due to temporary loading and unloading conditions. The presence of wind forces and other environmental effects should be considered in the analysis, including temporary crane and equipment loads that may be supported on the structure. The prime concern to be addressed in all demolition of post-tensioned concrete buildings and prestressed elements is the sudden release of stored energy caused by either removing the adjacent concrete cover or
cutting or burning the stressed tendon strands, either intentionally or accidentally, which may cause a sudden uncontrolled collapse to occur. In addition, the possibility exists that anchors and tendons may be released suddenly, resulting in steel ejection at slab edges or blowouts along the tendon length.

12.4.2.5 Preparation of Demolition Plan
A written plan for controlled demolition operations should be prepared that includes the following:

- Identification of anchorage layout within the structure
- Site protection and barriers
- Sequence of dismantling structural elements and demolition of entire assemblies
- Location of all temporary shores and supports
- Location of all equipment loads
- Sequence of cutting strands
- Sequence of cutting partial structural elements
- Control of other site operations
- Preparation of demolition sequence and procedural drawings
- Pre demolition survey

12.4.3 Deconstruction Analysis
Mass concrete demolition prior to the mid-1980s was typically executed by positioning equipment such as the crane and impact ball outside the collapse envelope of a structure. This was considered nonengineered demolition or removal of concrete. The demolition contractor’s survey of available documents and field conditions were the primary basis for equipment selection and the removal sequence or procedure.

Engineered demolition involves the analytical evaluation of a concrete structure during all stages of demolition to verify the adequacy of its strength and stability. The deconstruction analysis is essentially the reverse process of the original construction of a structure, with revised partial framing and alternative load patterns. Engineered demolition is mandatory for post-tensioned structures if the operator is on the structure or is within the collapse envelope of the structure to be demolished. The contractor should seek experienced engineering advice. The process of engineered demolition should, at a minimum, include a thorough review of the existing condition of a structure, its proximity to other structures, any utilities above and below grade, the preparation of the demolition sequence, the procedures, the assignment of equipment to be used, an analysis of all actual altered structural models, and a stability analysis of the structure considering the member demand (all demolition-load combinations) and the member capacity (remaining concrete cross-section, tendon profile, tendon layout, and location of anchors).

Absent design guidelines for engineered demolition of concrete structures, several state agencies have agreed on minimum considerations. The following guidelines have been used on over 50 major engineered demolition projects since 1990.

The intent of the stability analysis is to confirm that the structure to be demolished has the capacity during all stages of demolition to safely support the weight of equipment or other demolition-related loading such as debris loading. The analysis is limited to a strength review only; no serviceability stress checks are considered. Strength-reduction factors are employed as recommended for new construction. Concrete configuration, reinforcing quantity, size of bars, splice locations, and prestressing forces are obtained from the as-built drawings. To calculate the demand or required strength ($U$), live loads are magnified by a load factor of 1.3 ($U = 1.0D + 1.3L$), except as noted below. The live-load factor is assumed to include an adequate increase for impact loading as the equipment live load is a well-defined load. Where supporting members show minor visual damage such as cracking at beam–column joints or questionable rebar configuration, the live-load factor is increased to 2.0. For damaged sections of the structure, shoring should be considered and installed to support the dead and live load of its respective tributary area. Minimum temporary lateral-load capacity of the structures to be demolished is defined as a horizontal...
force, applied at the center of mass of a section, equal to 2% of its own weight. Pinned joints of supporting elements may require lateral bracing during demolition. Adequacy of the structure or a member of a structure to be demolished is established when the capacity/demand ratio is equal to or exceeds 1.0.

12.4.4 Methods of Demolition

The following demolition methods may be used on prestressed concrete structures where applicable and permitted by local regulations.

12.4.4.1 Ball and Crane

The method requires the controlled swing (choking) or dropping of a steel headache ball from a crane. The chief advantage is that the workers are outside of the building collapse envelope during this work. A disadvantage is that it cannot be used on tall structures and on those structures that are close to adjacent ones or in congested urban areas.

12.4.4.2 Explosives

Explosives require experienced personnel to detonate critical building elements to effect a proper controlled collapse of the structure. The chief advantage is that this is a fast method of demolition. Disadvantages include ground and air vibration effects that may damage adjacent facilities. Users of this method should consider the stored energy effects of prestressed concrete when determining the charge levels of the explosives being used. Due to the sudden stored-energy release of unbonded tendons, explosives have limited application for purposes of demolition.

12.4.4.3 Pressure Bursting

This method utilizes hydraulic bursters, gas expansion bursters, and hydraulic jacks to break the concrete into sections. This method is not frequently used and is limited to mass concrete, areas of limited direct access, and other unique conditions.

12.4.4.4 Thermal Lance

This method uses a steel rod in conjunction with oxygen or acetylene to melt concrete aggregates to form a series of boreholes that permit further demolition by other methods such as pressure bursting or the use of hand tools.

12.4.4.5 Torch

Typically, an acetylene torch is used to cut strands by heating the strands, resulting in a yielding behavior of the steel section. This tool is also frequently used to cut reinforcement during demolition as it may interfere with demolition equipment access. Acetylene torches are an effective tool to cut steel embeds and structural steel section connected to the concrete structure.

12.4.4.6 Diamond Saws and Drills

Using diamond plate saws is an effective way to cut a large concrete slab into smaller sections that can be removed and transported. The most common application is to sever concrete to be removed from slab sections that will remain. Line drilling by using cores can be used in slabs and beams.

12.4.4.7 Hand-Held Percussion Tools

These are typically operated from a compressor and are used locally to remove concrete from tendons and reinforcing steel to permit access for torches and other saws to cut the reinforcement.

12.4.4.8 Pneumatic and Hydraulic Breakers

These are large pieces of equipment, such as excavators, special pulverizers, and shear or hammer attachments. They can extract and demolish thick floors with a maximum boom reach of up to 85 ft. Hydraulic crushers are used extensively because the pulverizer separates and processes the base materials during the demolition of a floor or wall.
12.4.4.9 Water Jetting
High-pressure water cuts and removes aggregate from concrete. Very high pressures can cut steel. The disadvantage is that large volumes of water are required during the demolition.

12.4.4.10 Other Methods
Other methods include chemical reactions, cutting by lasers, plasma-arc thermal cutting, and variations of methods previously described.

12.4.5 Other Considerations
12.4.5.1 Type of Construction
The type of original framing and erection should be investigated, as lift-slab framing or other types of unique erection require special attention. Multistory buildings must be shored to allow the dead load of the uppermost slab (slab to be removed) to be distributed to several levels below using reshoring. The deconstruction of a post-tensioned building must consider the reverse construction sequence and reverse removal of structural members of the original construction.

12.4.5.2 Proximity to Other Buildings
Adjacent buildings and structures must be protected during all phases of the demolition. Adequate dust and noise control should be addressed. Adequate limits can be selected for dust and noise and be monitored to satisfy other property owners in densely populated areas. If applicable, vibration measurements should be taken.

12.4.5.3 Accessibility of the Exterior Slab Edge and Beam Ends
Exterior wall assemblies, cladding, or other facades should be safely removed to provide access to exterior slab edge strips and beam ends.

12.4.5.4 Interior Closure Strips
These strips should be carefully opened to release tendon stresses, if applicable. Controlled cutting of one side of the closure strip at a time is required so as not to adversely affect the adjacent concrete slab area of the other side of the closure strip. Adequate shoring of both sides of the closure strip may be required before any cutting proceeds when structural drawings and shop drawings are not available.

12.4.5.5 Intermediate Stressing Joints or Construction Joints
Intermediate stressing joints can be an advantage during the deconstruction of a building. When tendons are severed, the loss of strength may be limited to an area before or after the intermediate stressing joint location. It is imperative for the engineer to understand the location and direction of the intermediate stressing anchor to confirm the direction in which the strength of the slab is retained during detensioning. (See also the description of interior closure strips in Section 12.4.5.4.)

12.4.5.6 Height of Structure
Special consideration for high-rise construction containing prestressed elements may be necessary. Any and all interferences (e.g., power lines), adjacent buildings, and debris disposal during demolition must be carefully considered. It is not uncommon for high-rise structures to be removed in small sections, level by level, similar to a reverse sequence or operation of the original building construction. Any and all elements must be secured during the removal process to minimize the effects of falling debris.

12.4.5.7 Condition of Concrete
A strength evaluation of the in situ concrete is advisable to determine the stability of remaining elements of the structure and to determine limits of possible deterioration that has occurred within the structure.
12.4.5.8 Condition of Reinforcement
A strength evaluation of floor systems may be required where severe deterioration of reinforcement has occurred. The designer may use a load test or other methods outlined in Chapter 20 of Building Code Requirements for Structural Concrete (ACI Committee 318, 2008).

12.4.5.9 Shoring Requirements
Adequate shoring is required for all phases of demolition. The design of shoring and reshoring is one of the most critical aspects of a demolition plan. A detailed sequence of shoring installation and removal must be offered to give guidance to the contractor and to retain structural stability during all phases of demolition. The shoring plan and installation and removal sequence must be submitted to the local building officials for approval.

12.4.5.10 Protection of Personnel and Public
Adequate site supervision, sidewalk bridges, barriers, and other protective devices should be employed. It is advisable to retain a safety officer on site at all times during the demolition of a concrete structure. Due to the large potential variation between actual construction and old as-built drawings, the engineer (or designated representative) designing the deconstruction of a post-tensioned building should consider remaining on-site at all times to confirm compliance with the removal and demolition sequence. This allows the engineer to verify that as-built conditions match assumptions made on a continuous basis.

12.4.5.11 Partial Demolition
Where a structure is to undergo partial demolition to alter or maintain adjacent parts, special consideration to demolition procedures is required. Lack of consideration for impact loads and sudden stress release may damage existing concrete. The reduction of mechanical energy from pneumatic hammers in areas to be preserved may be limited to 1200 ft-lb or less so as not to fracture sound concrete unnecessarily.

12.5 Defining Terms

*Added tendons*—Tendons, usually short in length, placed in specific locations, such as end bays, to increase the structural capacity at that location without having to use full-length tendons.

*Anchor, troubleshooting*—See troubleshooting anchor.

*Anchorage*—A mechanical device comprised of all components required to anchor the prestressing steel and permanently transmit the prestressing force to the concrete.

*Anchorage, dead-end*—See dead-end anchorage.

*Anchorage, intermediate*—See intermediate anchorage.

*Anchorage, live end*—See live-end anchorage.

*Anchorage zone*—The region in the concrete adjacent to the anchorage subjected to stresses (forces) resulting from the prestressing force.

*Anchor*—For monostrand tendons, normally a ductile iron casting that houses the wedges and is used to transfer the prestressing force to the concrete.

*Back-up bars*—Reinforcing steel used to control the tensile splitting forces in the concrete resulting from the concentrated anchor force developed by the stressed tendons.

*Bearing plate*—A metal plate that bears directly against concrete and is part of an overall anchorage system.

*Blowout*—A blowout is a concrete failure that occurs during or after stressing; a blowout may be explosive in character.

*Bonded tendon*—A tendon in which the annular spaces around the prestressing steel (strands) are grouted after stressing, thereby bonding the tendon to the concrete section.

*Bulkhead*—See edge form.

*Bursting steel*—Reinforcing steel used to control the tensile bursting forces developed at the bearing side of the anchor as the concentrated anchor force from the stressed tendon spreads out in all directions.
Cantilever—Any rigid horizontal structural member projecting beyond its vertical support.
Casting—See anchor.
Chair—Hardware used to support or hold prestressing tendons in their proper position to prevent displacement before and during concrete placement.
Chuck, single-use splice—See coupler.
Coating—Material used to protect against corrosion and reduce the friction of the prestressing steel.
Coupler—A device, normally spring loaded, for connecting two strand ends together, thereby transferring the prestressing force from end to end of the tendon.
Creep—The time-dependent deformation (shortening) of prestressing steel or concrete under sustained stress (load).
Dead-end anchorage—The anchorage at the end of the tendon that is usually installed before the tendon arrives at the project site and that is not used for field stressing of the tendon.
Detensioning—A means of releasing the prestressing force from the tendon.
Edge form—Formwork used to limit the horizontal spread of fresh concrete on flat surfaces such as floors.
Effective prestress—The prestressing force at a specific location in a prestressed concrete member after all prestress losses have occurred.
Elastic shortening—The shortening of a member that occurs immediately after the application of the prestressing force.
Elongation—Increase in the length of the prestressing steel (strand) under the applied prestressing force.
Encapsulated system—A system that provides watertight connections at all stressing, intermediate, and dead ends and that has the wedge-cavity side of the anchorage covered by a watertight cap filled with a corrosion-protective coating material.
Fixed-end anchorage—See dead-end anchorage.
Friction loss—The stress (force) loss in a prestressing tendon resulting from friction created between the strand and sheathing due to the wobble or profile of the tendon during stressing.
Friction, wobble—See wobble friction.
Hand-seating tool—A small, hand-held device used to properly align (seat) the wedges in the anchor prior to attaching the jack to the strand for stressing.
Initial prestress—The stress (force) in the tendon immediately after transferring the prestressing force to the concrete. This occurs after the wedges have been seated in the anchor.
Installation drawings—Drawings furnished by the post-tensioning material supplier showing information such as the number, size, length, marking, location, elongation, and profile of each tendon to be placed.
Intermediate anchorage—An anchorage, located at any point along the tendon length, that can be used to stress a given length of tendon without the need to cut the tendon; normally used at concrete pour breaks to facilitate the early stressing and removal of formwork.
Jack—A mechanical device (normally hydraulic) used for applying force to the prestressing tendon.
Jack-gripper plates—Steel plates designed to hold the jack grippers in place in the jack.
Jack grippers—Wedges used in the jack to hold the strand during the stressing operation.
Jacking force—The maximum temporary force exerted by the jack while introducing the prestressing force into the concrete through the tendon.
Kip—One kip = 1000 lb force.
Live end—See stressing end.
Live-end anchorage—The anchorage at the end of a tendon that is used to stress the prestressing steel (strand).
Monostrand—A single strand.
Multiuse splice chuck—A coupler that uses three-piece wedges and is made of heavier material for repeated use.
Nosepiece—The front part of the jacking device that fits into the stressing pocket to align the jack with the anchor.
Split donut—See troubleshooting anchor.
Split pocket former—A temporary device used at the intermediate end during casting of concrete to provide an opening in the concrete for access by the installer and the stressing equipment to the anchorage area.

Stage stressing—Sequential stressing of tendons in separate steps or stages in lieu of stressing all the tendons during the same stressing operation.

Strand—High-strength steel wires twisted around a center wire. For unbonded tendons, seven-wire strand conforming to ASTM A 416 is used almost exclusively.

Stresses—Internal forces acting on adjacent parts of a body.
Stressing end—The end of the tendon at which the prestressing force is applied.
Stressing equipment—Consists normally of a jack, pump, hoses, and a pressure gauge.
Stressing force—See jacking force.

Tendon—A complete assembly consisting of anchorages, prestressing steel (strand), protective coating, and sheathing; the tendon imparts the prestressing force to the concrete.

Tendon, bonded—See bonded tendon.
Tendon, unbonded—See unbonded tendon.

Tensile stresses—Internal forces directed away from the part of a body on which they act.
Tension—The effect of tensile forces on a body.

Trouble-shooting anchor—A special anchor used for structural modification or repair of existing tendons. The anchor consists of a removable segment that allows it to slide onto an existing strand; the segment is then returned and tightened by a screw or bolt.

Unbonded tendon—A tendon in which the prestressing steel (strand) is prevented from bonding to the concrete and thus is free to move relative to the concrete; therefore, the prestressing force is permanently transferred to the concrete by the anchorage only.

Wedge set—The relative movement of the wedges into the anchor cavity during the transfer of the prestressing force to the anchorage, resulting in some loss of prestressing force.

Wedges—Pieces of tapered metal with teeth that bite into the prestressing steel (strand) during transfer of the prestressing force. The teeth are beveled at the front end to ensure gradual development of the tendon force over the length of the wedge. Two-piece wedges are normally used for monostrand tendons.

Wobble friction—The friction caused by the unintended horizontal deviation of the tendon.

Note: Local practices, customs, and usage may employ terminology, jargon, and nicknames different from the terms and definitions set forth in this chapter. Check with the local engineering community or other qualified person to clarify terms and definitions.

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Hibernia offshore oil platform constructed in Newfoundland. (Figure courtesy of Hoff Consulting LLC, Clinton, MS.)