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POST-TENSIONED UNDERGROUND
PARKING STRUCTURES**

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RESTRAINT DESIGN OF CAST-IN-PLACE POST-TENSIONED UNDERGROUND PARKING STRUCTURES

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Post-tensioned (PT) concrete construction is popular for parking deck floor slabs. PT precompression and load balancing permits thinner slabs and improves durability by reducing slab cracking. At PT slabs in underground parking structures, however, restraint from foundation walls may reduce these benefits, impairing overall structural durability and sometimes causing structural safety issues. Restraint generally can affect structural behavior in two ways: 1) by reducing slab precompression; and 2) by creating restraint to shortening (RTS) effects, especially at long continuous structures. This paper uses the concept of slab-effective precompression to compare several approaches commonly used to reduce restraining effects from stiff walls. The effectiveness of different construction and design practices in reducing restraint is discussed. These practices include expansion joints, pour strips, slab blockouts, sliding connections, isolation controls, low slab average precompression, added bonded reinforcement, and shrinkage-compensating concrete. To minimize slab precompression loss and significantly reduce RTS problems, a combination of two or more construction practices may be necessary.

KEYWORDS

Creep; effective precompression; post-tensioned; pour strip; reinforced concrete; restraint to shortening; shrinkage; underground parking structure.

INTRODUCTION

One- and two-way post-tensioned (PT) slab systems can permit the use of thinner slabs and shallower beams than conventionally reinforced concrete (RC) structures, and slab precompression can reduce slab cracking and through-slab leaks, improving durability. At underground levels, PT framing that reduces story heights also directly reduces the costs of excavation, soil retention, foundation and retaining walls, and dewatering (at high water tables). These savings are added incentives to use PT structures. (Note that slabs propping deep basement walls against large earth pressure forces may have thicknesses determined by buckling resistance requirements.) If the PT framing monolithically connects to concrete foundation walls, however, severe restraint is introduced, which may affect the design, construction, and long-term serviceability of the framing. The potential for detrimental effects from severe restraint is considered as one of the most important reasons to discourage the use of PT systems in underground parking structures. Understanding the concerns and effectiveness of available mitigation measures is important to make a rational decision on the use of post-tensioning.

Typically, detrimental effects due to severe restraint can be sorted into two groups: those occurring during construction and those occurring after construction—or short-term effects and long-term effects. During construction, when tendons are stressed, a large portion of the PT force may be diverted away from compressing the slab cross section if slabs connect to foundation walls that are stiff in flexure and shear. As a result, slab average precompression P/A (where P is the tendon effective force and A is the slab cross section area) may be significantly lower than the expected value. In the long term after construction, floor slabs tend to shorten due to concrete shrinkage and creep, but their movement may be restrained by stiff foundation walls. The restrained concrete slabs may experience worse cracking and exposure to reinforcing bar corrosion and slab spalling than expected for a PT slab. Although the behaviors

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Table 1—Relative effect of volume changes on structural frames⁵

Volume change type	Structural system		
	Cast-in-place nonprestressed concrete	Precast pretensioned concrete	Cast-in-place PT concrete
Elastic shortening	None	None	Full
Shrinkage	Partial [†]	Partial [†]	Full
Creep	None [‡]	Partial	Full
Temperature change	Partial [†]	Full [§]	Full

[†]Cracks in concrete slabs and beams absorb a significant amount of movement, resulting in reduction of volume change effects on structural frame.

[‡]Shrinkage of topping placed over precast elements primarily results in cracking of topping over joints in precast elements.

[§]Primary effect of weep is increased deflection of beams or slabs which may affect drainage. Creep can also affect precast and post-tensioned member deflection.

[§]May be partial under some conditions, with connection details absorbing part of volume change movement.

described previously occur for all PT structures, above-grade structures with central lateral-load-resisting systems are generally negligible as restraint is much less severe.

PT structures typically suffer restraint to shortening (RTS) problems much more than RC structures. Concrete shrinkage shortens floor slabs for both PT and RC structures. PT and RC structures, however, respond to floor shortening in different ways.¹⁻³ As concrete shrinkage takes place, numerous well-distributed, closely spaced narrow cracks typically occur in RC structures as an extensive grid of mild steel reinforcing bars is bonded to concrete. As a result, concrete floors become "soft" but exhibit minimal horizontal movement. In contrast, PT structures with unbonded tendons have much less bonded reinforcement and concrete floor shortening usually results in fewer widely spaced cracks. Once tendons are stressed, precompression in concrete tends to close most cracks, directly causing PT slabs to shorten overall. If RTS problems are not adequately addressed in design and construction, floor shortening can be a major source of cracking and distress for both structural and nonstructural elements of PT structures.⁴

As shown in Table 1, for cast-in-place RC structures, concrete shrinkage and temperature contraction are primary contributors to volume change. For cast-in-place PT structures, however, contributing factors to volume change include elastic shortening and creep, as well as shrinkage and temperature contraction. This directly translates into more floor movement and, thus, more severe RTS problems in PT structures than in RC structures.

ACI 318-08, Section 18.12.4,⁶ requires a minimum average effective prestress of 125 psi (0.86 MPa) across the PT slab section. For parking structures, however, a minimum prestress level is specified as 150 psi (1.03 MPa) for structures in Zone I and 200 psi (1.38 MPa) for

structures in all other zones to ensure crack control and address durability considerations.⁵ A higher P/A requirement will certainly lead to more slab shortening, and thus more severe RTS problems.

Some engineers estimate that RTS problems are less severe for underground structures than for above-grade structures for two reasons: temperature and relative humidity. Structures usually experience smaller temperature changes and higher relative humidity underground, which directly corresponds to lower thermal and shrinkage strains and, thus, less concrete floor shortening. In truth, however, RTS problems are much more severe for underground structures than for structures above ground when stiff basement walls are rigidly connected to slabs and beams—stealing a significant amount of precompression force during tendon stressing.

Underground PT parking structures within perimeter basement walls pose design and construction challenges whether the floor system is a one-way or a two-way PT system. Analytical models created in this paper demonstrate slab axial precompression losses resulting when slabs are connected to stiff walls, and study the effectiveness of different construction and design practices that are frequently used to relieve severe restraint. The study findings are summarized as conclusions and recommendations herein.

ANALYSIS MODEL

A PT underground parking project with a one-way slab and beam floor system is selected to demonstrate the effects of perimeter walls on slab precompression loss. As shown in Fig. 1, the structure has a dimension of 125 ft (38.1 m) in the beam direction and 450 ft (137.2 m) in the one-way slab direction. The slab thickness is 7.5 in. (190 mm) with a concrete strength

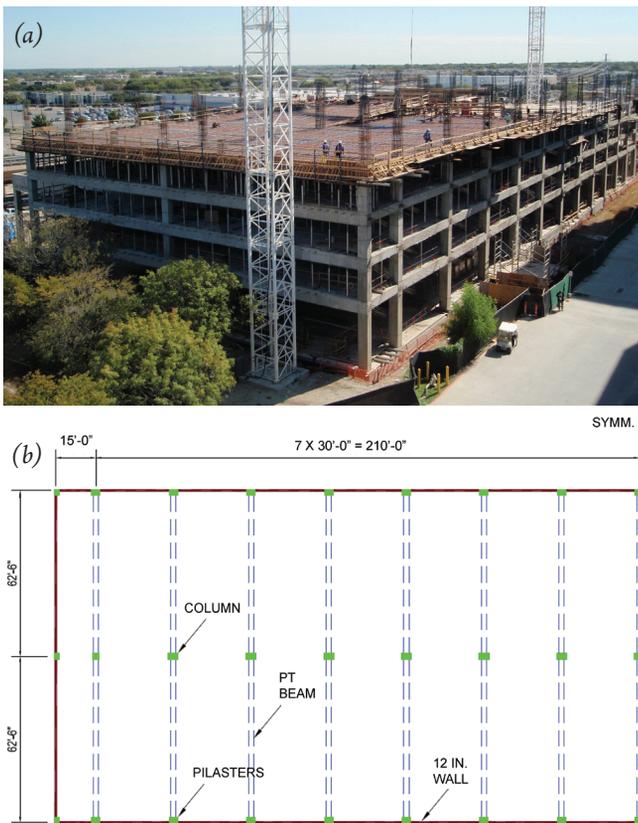


Fig. 1—Parking structure with footprint of 125 x 450 ft (38.1 x 137.2 m): a) view of the above ground portion under construction; and b) one-way slab and beam post-tensioned underground parking: framing plan. Slab spans numbered sequentially from 1 at left to 8 at right. (Note: 1 in. = 25.4 mm; 1 ft = 0.3048 m.)

of 5000 psi (35 MPa). The column sizes are 48 x 30 in. (1220 x 760 mm) for interior columns, 24 x 30 in. (610 x 760 mm) for corner pilasters, and 40 x 30 in. (1020 x 760 mm) for perimeter pilasters, as may occur under a multistory parking structure. The PT beams are 24 in. (610 mm) wide and 30 in. (760 mm) deep, spanning 62.5 ft (19 m) between perimeter walls and interior columns. The three-dimensional (3D) computer analysis software ETABS is used for the analyses.

For one-way slab and beam PT structures, tendons are typically provided in three locations: multi-strand tendon groups within the PT beams, uniformly spaced tendons in the one-way slab spanning direction, and distributed crack control temperature tendons within slabs in the direction parallel to PT beams. This study focuses on slab precompression loss in the one-way slab direction due to foundation walls, so the effect of foundation walls on the design of PT beams and temperature tendons will not be considered herein. The effective precompression force (present after considering

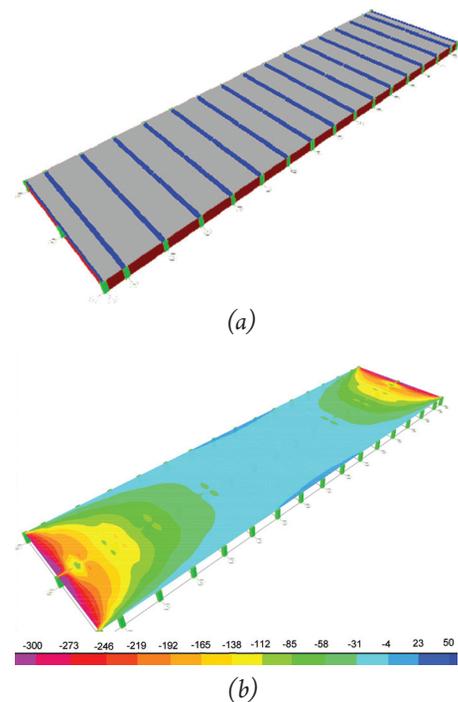


Fig. 2—Model A with slabs, beams, columns, and perimeter walls: (a) ETABS model; and (b) axial stress in psi. (Note: 1 psi = 0.0068 MPa.)

tendon force losses) to be provided by uniform slab tendons for the one-way slab is found to be 20 k/ft (290 kN/m) as determined by the post-tensioning program PTData. The equivalent P/A is approximately 222 psi (1.53 MPa) on the overall slab cross section.

Restraint provided by interior columns considers column foundation rotational stiffness as calculated using procedures outlined in the *PCI Handbook*.⁷ A partially-fixed boundary condition is simulated in ETABS using the point spring feature. The calculated foundation rotational stiffness is approximately 43,000,000 k-in./rad (4,860,000 kNm/rad) for all interior columns. Continuous footings are considered to occur under walls in both longitudinal and transverse directions. For walls parallel to the uniform tendon direction, a fixed boundary condition is assumed due to the use of continuous footings, which is close to reality. The walls in the transverse direction are modeled as a series of 5 ft (1.5 m) wide columns spaced 5 ft (1.5 m) on center, with each column having a 36,000,000 k-in./rad (4,068,000 kNm/rad) base spring. In the paper, a one-story PT structure is used to demonstrate the effects of restraint forces from stiff supports because the primary volume change problem with any PT parking structure, below or above grade, is the restraint caused by the foundations as the first elevated floor shortens. Restraint

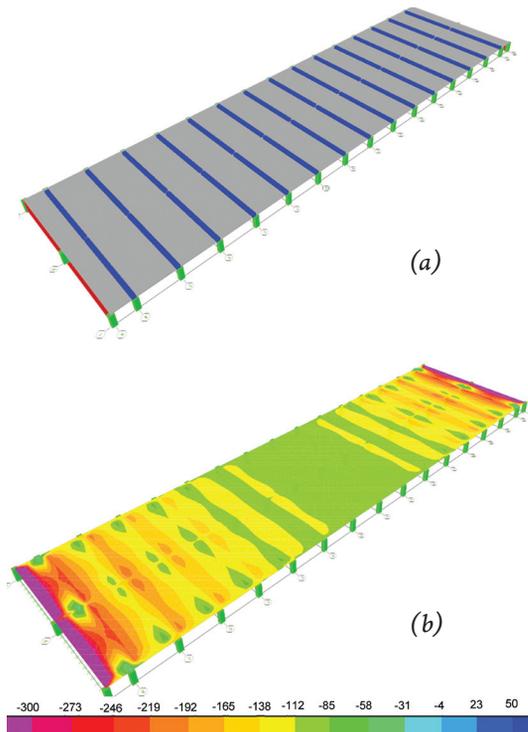


Fig. 3—Model B with slabs, beams, columns, and walls in short direction: (a) ETABS model; and (b) axial stress in psi. (Note: 1 psi = 0.0068 MPa.)

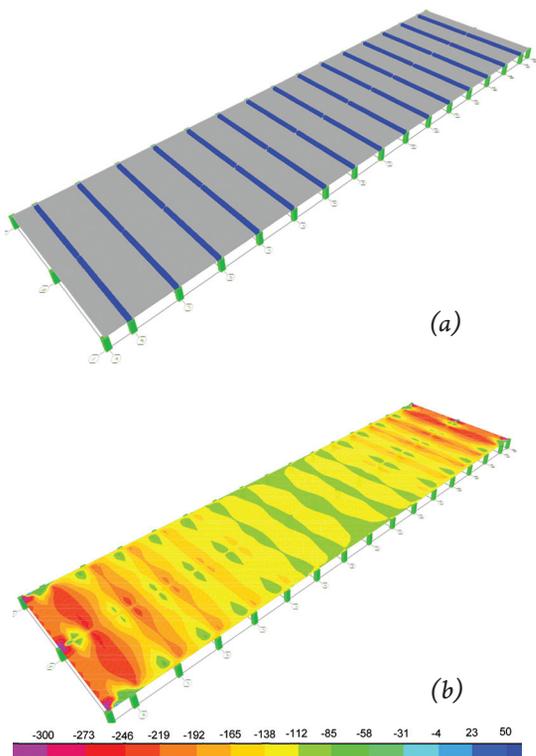


Fig. 4—Model C with slabs, beams, and columns: (a) ETABS model; and (b) axial stress in psi. (Note: 1 psi = 0.0068 MPa.)

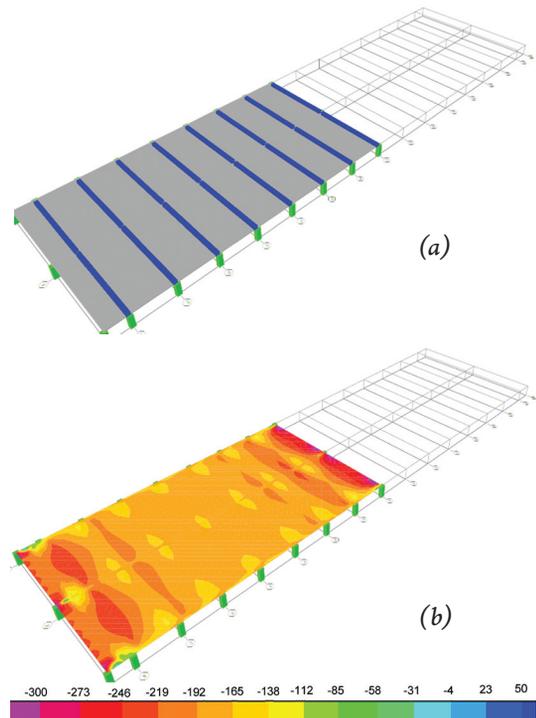


Fig. 5—Model D with slabs, beams, and columns—half of the building: (a) ETABS model; and (b) axial stress in psi. (Note: 1 psi = 0.0068 MPa.)

effects are generally much smaller for upper floors as adjacent floors shorten similarly and do not restrain each other.

All the models described in the following have 20 k/ft (290 kN/m) tendon effective force applied horizontally at both ends of the building. Four analysis cases included in the study are as follows:

1. Model A, the original model, includes slabs in grey, beams in blue, columns in green, and perimeter walls in brown, as shown in Fig. 2(a).

2. Model B includes slabs, beams, and columns, as well as walls in the transverse direction (perpendicular to uniform tendon direction), as shown in Fig. 3(a). Parallel walls are omitted from this model to determine the restraining effects of transverse walls on longitudinal slab precompression. Perimeter ex-pilasters are treated as free-standing columns assumed fixed at the base by the wall footing. This assumption also applies to both Models C and D.

3. Model C includes slabs, beams, and columns, as shown in Fig. 4(a). All perimeter walls are omitted.

4. Model D includes slabs, beams, and columns, but only half of the building is present, as shown in Fig. 5(a). This case is selected to demonstrate the effect of introducing an expansion joint or pour strip at the building center.

5. Model E includes all members as shown in Model A, but with 30 in. (760 mm) wide side slab blockouts between slabs and adjacent longitudinal walls, as shown in Fig. 6(a). The PT beams, however, are rigidly connected to pilasters.

Models A through D are used to demonstrate the restraining effects of stiff walls on slab precompression from post-tensioning in the long dimension of the building. The framing layout shown in Model E is included in the study because it is sometimes used by engineers attempting to reduce effects due to stiff walls.

A one-story-deep basement and single framed PT ground floor level is studied by the aforementioned models because it occurs quite commonly at plazas or podiums with parking below, as well as at multistory buildings. Typically, for multistory buildings, the largest RTS adverse effects occur at the first elevated concrete floors above the foundation. Depending on the nature of any superstructure framing above, final slab precompression (P/A) at the first framed floor may differ from the slab precompression obtained in this study. A multistory PT building study demonstrated that a portion of post-tensioning forces applied to upper floors is redirected to induce axial compression forces in floors below.⁸ The amount of compressive force redirected into the lowest elevated slab, however, is not likely to offset a large slab precompression loss. The effects of story-by-story post-tensioning on slab precompression could be determined through a nonlinear staged construction type analysis, but as a practical matter, the effects of redirected PT forces during realistic, staged construction are most significant at the first framed floor at floors with extra-tall columns and at PT roof slabs.

In this paper, a slab-effective precompression concept is introduced to simplify comparisons of slab precompression among different models when the same tendon stressing forces are applied. Slab-effective precompression is the average stress at the middle of each span, as determined through the section cut feature in ETABS. If slabs are completely free to move, slab effective precompression is the same as slab P/A calculated based on the tendon effective force. When stiff walls cause severe restraint, slab effective precompression can be significantly smaller than the P/A of 222 psi (1.53 MPa) from the tendon effective force.

ANALYSIS RESULTS AND DISCUSSIONS

The results of each of the previous models are discussed and compared to demonstrate the restraining effects of basement walls. The slab axial stress contour

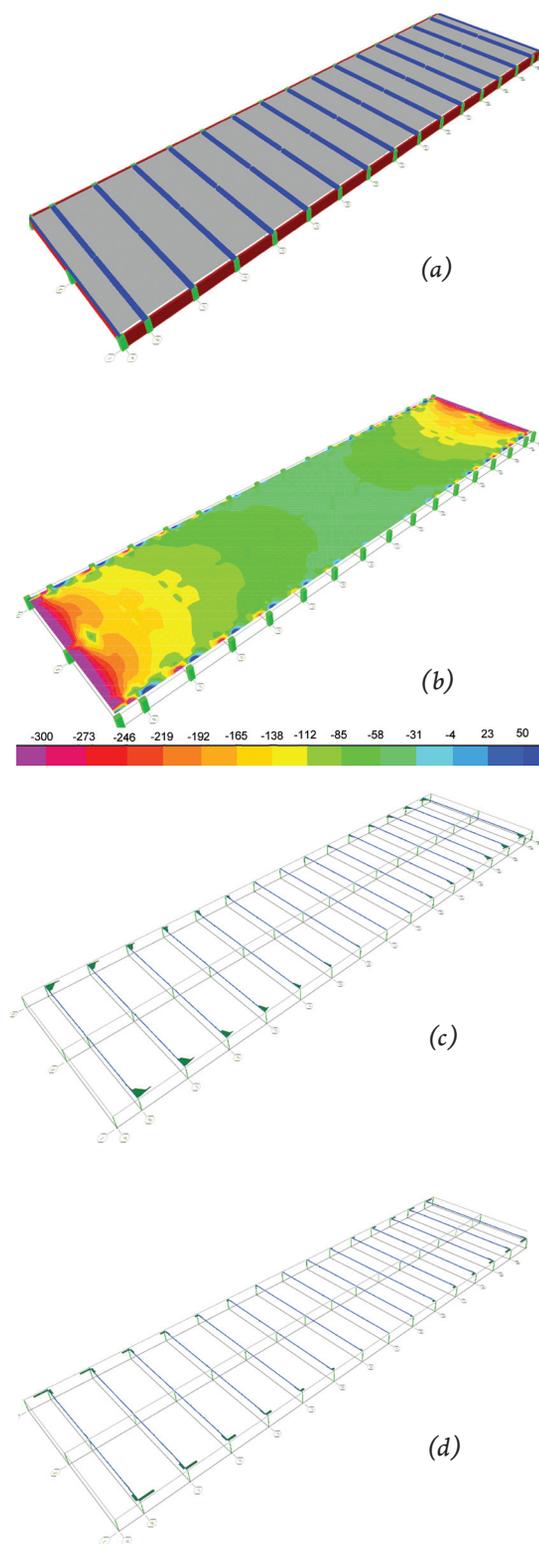


Fig. 6—Model E with columns, beams, and longitudinal walls with 30 in. (762 mm) slab blockouts: (a) ETABS model; (b) axial stress in psi; (c) beam moment diagram in weak direction; and (d) beam shear diagram in weak direction. (Note: 1 psi = 0.0068 MPa.)

Table 2—Slab effective precompression in psi (MPa) at each span

Span	1	2	3	4	5	6	7	8
Model A	185 (1.28)	132 (0.91)	82 (0.57)	50 (0.34)	30 (0.21)	18 (0.12)	12 (0.08)	9 (0.06)
Model B	189 (1.3)	166 (1.14)	147 (1.01)	132 (0.91)	120 (0.83)	112 (0.77)	106 (0.73)	103 (0.71)
Model C	203 (1.4)	179 (1.23)	159 (1.1)	142 (0.98)	130 (0.90)	121 (0.83)	115 (0.79)	112 (0.77)
Model D	206 (1.42)	189 (1.3)	178 (1.23)	172 (1.19)	172 (1.19)	177 (1.22)	187 (1.29)	203 (1.40)
Model E	187 (1.29)	144 (0.99)	113 (0.78)	90 (0.62)	73 (0.50)	61 (0.42)	53 (0.37)	50 (0.34)

plots from stressed tendons are shown in Fig. 2 through 6 for Models A through E.

All spans are numbered from the end to midspan, with the first span as the end span and the eighth span as the midspan. Table 2 summarizes slab average effective precompression at midspan for each span in each model.

Original model

As shown in Fig. 2(a), all perimeter walls are included in Model A. Figure 2(b) slab stress contours and Table 2 show that slab average effective precompression is 185 psi (1.28 MPa) at the end bay. It decreases rapidly from 132 psi (0.91 MPa) at the second span to 30 psi (0.21 MPa) at the fifth span. The rest of the spans have values below 20 psi (0.14 MPa), less than 10% of the expected value of 222 psi (1.53 MPa). It clearly shows that when stiff foundation walls parallel to PT tendons are present, a major portion of the compression force applied by PT tendons is redirected to compressing, bending, and shearing perimeter foundation walls rather than compressing the concrete slab. Restraints due to stiff walls decrease slab effective precompression stress but do not reduce upward balancing loads from draped PT tendons.

As previously mentioned, where upper floors are also PT, some additional precompression would be redirected to act on this slab. It would most likely do little to increase the small amount of slab precompression, however, as shown in Table 2 for Model A, as most of the redirected force would enter the stiff walls rather than the slab.

Original model without longitudinal walls

Figure 3(a) shows Model B with walls only in the transverse direction. Figure 3(b) shows slab axial compression stress contours when tendons are stressed. It assumes that either the longitudinal walls will be cast after the PT slabs are cast and tendons are

stressed, or that vertical joints are provided between longitudinal walls and the slab and pilasters until tendons are stressed. As shown in Table 2, slab average effective precompression in the end span is 189 psi (1.30 MPa), approximately 85% of the expected value of 222 psi (1.53 MPa). Both the second and third spans show slab average effective precompression over 145 psi (1 MPa), at least 65% of the expected value. Then, slab effective precompression decreases from 132 psi (0.91 MPa) in the fourth span to 103 psi (0.71 MPa) in the eighth span. Compared with Model A, the elimination of longitudinal walls improves slab precompression significantly, especially for the spans in the middle. Precompression, however, is no more than 75% of the expected value for all spans except the two end spans, and only 47% of the expected value in the eighth span. The slab effective precompression values shown in Table 2 for Model B demonstrate that the building length and the presence of fixed perimeter pilasters contribute to redirecting PT force to supports below.

If upper PT floors were present, some additional precompression would be redirected to act at this level, shared between slab compression and column shear. The portion acting on the slab would replace only a small fraction of the loss in slab precompression found at inner spans.

Original model without walls

Figure 4(a) shows Model C without any perimeter walls. As shown in Fig. 4(b) for slab axial compression stress contours and Table 2, the three end spans have slab-effective precompression over 155 psi (1.07 MPa), 70% of the expected value. The remaining spans show values less than 145 psi (1 MPa). Compared with Model B, Model C shows that the elimination of transverse walls increases slab effective precompression by approximately 14 psi (0.10 MPa) in the end span and 9 psi (0.06 MPa)

in the eighth span. Engagement of transverse walls has a marginal effect on slab-effective precompression in the longitudinal direction. As the engagement of transverse walls will reduce precompression from PT beams and temperature tendons parallel to those walls, the condition is worthy of attention, but is outside the scope of this paper.

Half of original model without walls

Figure 5(a) shows Model D with only half of the slab length and support framing and without perimeter walls present. As shown in Fig. 5(b) and Table 2, all spans show slab-effective precompression above 172 psi (1.19 MPa), or 77% of the expected value of 222 psi (1.53 MPa). In multistory PT structures, the effective precompression will be even higher. As demonstrated in the study by Fintel and Ghosh,⁸ in a multistory PT structure, additional precompression at this slab will occur as portions of post-tensioning forces applied at upper levels are redirected downward based on relative stiffness. With forces redirected from upper slabs, the first framed slab-effective precompression will end up between the values shown herein and the expected value of 222 psi (1.53 MPa).

Trends from models

From Models A to D, as the restraints provided by vertical supports are reduced, the slab-effective precompression values increase and approach the expected value of 222 psi (1.53 MPa).

From Models A to C, though slab effective precompression increases, the maximum slab precompression loss in Model C is still close to 50%, which most likely means slab precompression will be less than intended—even in a multistory basement where some of the upper level PT force tends to be redirected to this level. The previous simulation results demonstrate the importance of separating perimeter walls and elevated slabs, at least until PT tendons are stressed, and the benefit of providing either an expansion joint or a pour strip breaking long slabs into shorter segments to maintain slab-effective precompression values close to the expected value.

The previous simulations also demonstrate that during tendon stressing, the short-term effect of severe restraint from foundation walls is redirection of a significant amount of PT effective force as flexure and shear of support elements below rather than compression of the intended slab cross section. In the long term, as concrete floors creep and shrink over time, the tendency of surrounding elements to prevent floor shortening

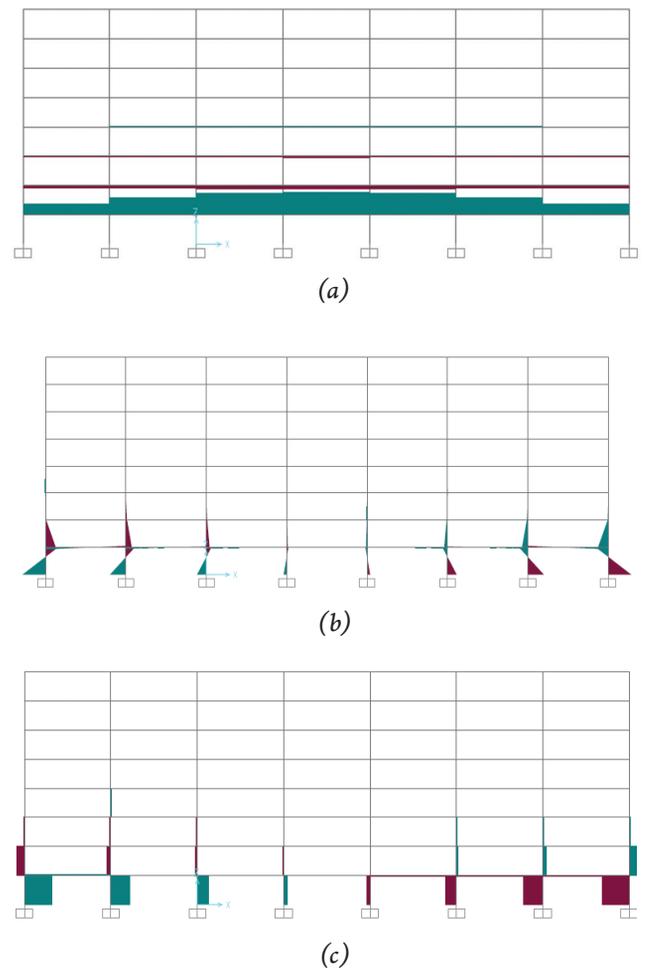


Fig. 7—Effects of floor shortening on eight-story frame: a) axial force in floor diagram; b) moment diagram; and c) shear diagram.

may create large forces in the surrounding elements and restraint to shortening effects in the slabs themselves.

For example, consider an eight-story plane frame with fixed-base columns. Even without stiff perimeter walls, creep and shrinkage strains that would tend to shorten unrestrained floor slabs induce slab tensile forces instead. Figure 7 shows the effects of restraint on the structure when floor shortening attempts to occur, as simulated by a uniform temperature decrease. To clearly exhibit RTS effects, the resulting tensile forces in Fig. 7(a) ignore any precompression from post-tensioning. Note that a large tensile force builds up in the first elevated floor slab with the largest force at midpoint—the center of overall lateral stiffness. Significant column moments and shears in Fig. 7(b) and (c) are the direct results of RTS. If RTS effects are not appropriately considered and detailed for design, considerable concrete cracking and distress in floor diaphragms, columns, and perimeter

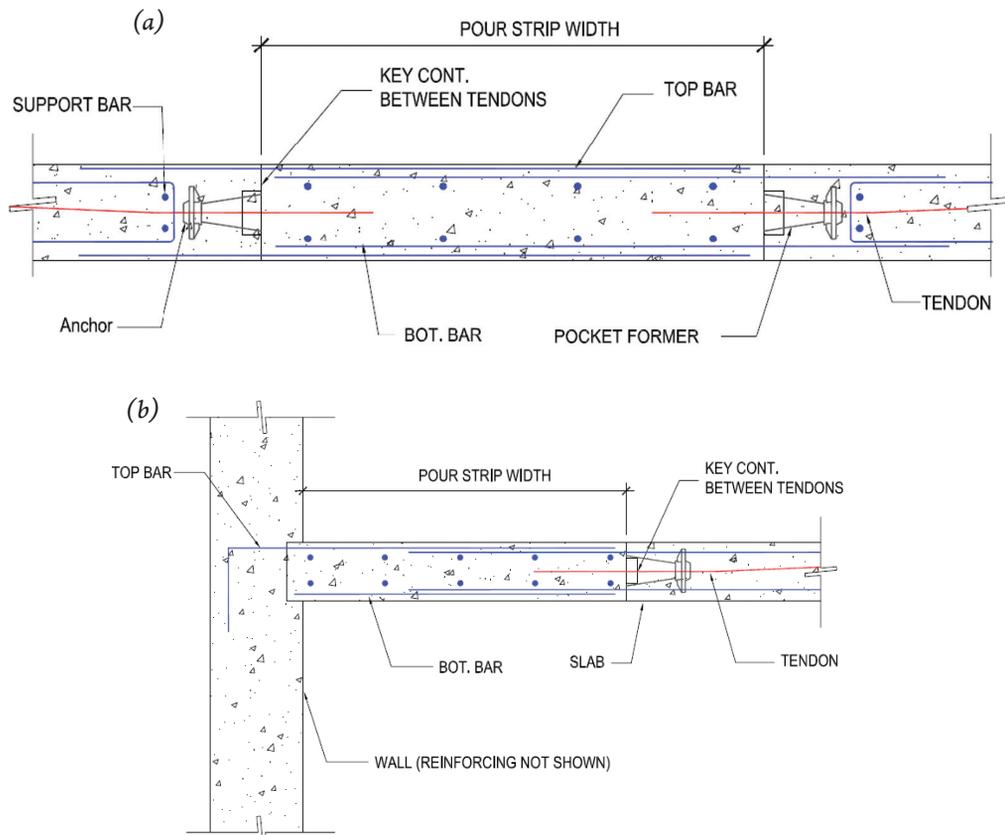


Fig. 8—Pour strip at different locations: (a) between two supports; and (b) between slabs and walls.

walls may occur.

In the sections that follow, some commonly used construction practices are discussed with regard to slab precompression and RTS and are summarized. The use of successful practices, individually or in combination, can significantly improve slab precompression and relieve RTS effects.

CONSTRUCTION PRACTICES

Expansion joints

An expansion joint is defined as an intentional gap provided between adjoining parts of a structure to allow movements tending to either close or open the gap. In concrete construction, shrinkage, elastic shortening from post-tensioning compression, and concrete creep from post-tensioning compression would all tend to open expansion joints and should be considered when locating, sizing, and specifying expansion joints for PT structures. As demonstrated by Model D, introducing an expansion joint can effectively maximize slab precompression. Reducing the building length involved in tendon stressing reduces

the movement at restraints, reducing the restraint forces generated.

When introducing an expansion joint, first consider locating it near the middle of the building, or midway between two stiff restraints (if present). A joint framed with double columns maintains support regardless of joint movement and provides maximum flexibility in construction scheduling and sequencing at some cost in materials and occupied space. In contrast, an expansion joint relying on sliding pads bearing on ledges or brackets requires extra care in planning and should be used only if worst-case movements are allowed for and the construction sequence is considered. Expansion joint width and design travel distance must consider long-term shortening behavior, slab expansion, and contraction within a specified temperature range, deflection of the building segments on either side of the joint due to lateral load, construction tolerances, and detail requirements of the joint cover or seal, if any. A comprehensive approach was proposed by Chowchuech and Gee⁹ to consider additional factors such as elastic shortening and concrete creep due to

post-tensioning, concrete long-term shrinkage, and the time and temperature when expansion joint hardware is installed. A spreadsheet was developed to calculate the appropriate as-formed width of the expansion joint at the time of slab casting and at the time the expansion joint hardware is installed. To avoid segment collisions under extreme conditions, however, the design engineer must also check that the specified expansion joint width and joint cover free movement allowance when closing is at least the width required for deflection of building segments due to lateral loads. This governing condition may occur before long-term shortening occurs. The designer must also check that both the joint cover and the bracket slide bearing, if used, have a sufficient free opening movement allowance for the sum of long-term shortening and building segment deflections due to lateral loads to avoid cover damage or loss of bearing support.

Pour strips

A pour strip, or delayed pour strip, is a section of slab left open during the initial concrete placement, creating a complete break through the structure that is filled in at a later date. Pour strips are widely used in PT structures, as they simultaneously provide room for performing tendon stressing, reduce RTS problems by allowing some shortening to occur before engaging stiff elements, and help retain maximum precompression in the PT slab by applying PT forces before engaging stiff elements.

As demonstrated in Reference 10, the effectiveness of a pour strip largely depends on its open period. The longer the open period, the more volume change can occur before two adjacent concrete slab sections are connected together. In a 25-story PT frame building, the two basement levels with a plan dimension of 663 x 646 ft (200 x 195 m) were constructed with two pour strips in each direction.¹¹ To reduce the future potential for cracking from RTS effects, concrete at pour strip locations was not placed until the roof structure was topped out. It was estimated that at least 60% of the concrete shrinkage and creep had taken place by the time the pour strips were filled.

Figure 8(a) shows a pour strip detail within a span between two vertical supports. The pour strip can be located either at the middle of the span or at a quarter point of the span. The midspan pour strip, however, is strongly favored due to constructability issues.¹⁰ Bonded reinforcement through the pour strip must be designed to resist all tensile, shear, and flexural forces alone, as post-tensioning is interrupted. As shown in Fig. 8(a), all bonded reinforcement, including shear, flexural, drag,

and chord bars, must be lap spliced within the width of the pour strip, rather than extending into concrete on the other side of the strip. Pour strip concrete is not placed until it is anticipated that an acceptable portion of shortening has occurred, helping to relieve potential RTS problems. Detailed information regarding pour strip locations, design, and open period are provided in Reference 11.

Figure 8(b) shows a typical pour strip detail between one-way slabs and structural walls. It is drawn as if occurring in the study model, where slab-primary PT tendons meet a transverse direction end wall. The pour strip provides room for stressing PT tendons.

Slab blackout

A slab blackout refers to a delayed-pour region that does not create a complete break through a structure. The most common condition is a local pocket formed in a slab to permit stressing PT tendons that end at that location. Study Model E, however, considers blockouts with a different function: reducing precompression loss. A series of long narrow slab openings, located between transverse beams, temporarily separates the one-way slab from foundation walls in the longitudinal direction (parallel to the uniform tendon direction). The blockouts are similar to a pour strip in detail, allowing room for tensioning perpendicular temperature PT tendons and using lapped conventional reinforcing bar across the gap, but usually with a shorter specified open period than for pour strips. The slab blackout width may be 2 ft (50 mm) or more. The primary intent of creating these long blackout slots is to reduce redirection of PT compression forces from the slab to parallel stiff shear walls. Unfortunately, slab blockouts provide little or no help to reduce RTS problems in the long term, due to their short open period. They are also relatively ineffective at reducing PT force redirection because the PT beams that are present between the slots still provide considerable restraint.

Figure 6(a) shows Model E with all perimeter walls, but with 30 in. (760 mm) wide temporary slab blockouts between slabs and longitudinal walls. Rigid connections between PT beams and wall pilasters are still present. As shown in Fig. 6(b) and Table 2, slab-effective precompression values are between those for Models A and B, which indicates that restraint has not been significantly reduced. The slab-effective precompression decreases rapidly from 144 psi (0.99 MPa) in the second span to approximately 50 psi (0.34 MPa) in the eighth span. More than 66% of PT tendon effective force between the fifth and eighth

span has been redirected out of the slab due to high restraint—even with blockouts. It is apparent that, while blockouts allow slabs to move relative to the parallel walls to some degree, beams framing to pilasters integral with foundation walls still resist transverse movements and restraint slab-free movement.

For Models A through D, PT beams deform together with slabs and, therefore, no significant moments in the beam weak direction are observed. In Model A, the restraining effects from shear walls are mainly provided through shear connections from slabs to perimeter walls. In Model E, however, there is a gap between slabs and walls, so restraining effects from stiff walls are concentrated and transferred only through pilasters and PT beams. As a result, PT beams experience significant weak way shear and bending forces near their ends. As shown in Fig. 6(c), beam sections adjacent to the slab blockouts experience maximum weak way beam moments as large as 300 k-ft (405 kNm) near building ends and approaching zero near building midpoint. Figure 6(d) shows that PT beams have weak way shears that vary from 190 kips (845 kN) at the endmost beams to zero for the beam in the middle. The further a PT beam is from the center of zero movement (the stiffness center), the higher the moments and shears due to the horizontal movement. If those moments and shears are not properly considered and detailed in design, serious cracking and strength problems could occur.

If there are PT slabs above, for the breakout slot approach, redirection of force to this slab will be minimal. Upper slab forces redirected through weak way restraint from their own beams simply enter the foundation wall.

Only the upper slab forces redirected through inner column shear will help compress the bottom framed slab. This is a small fraction of the redirected force. Any additional PT force that does reach the lower slab will further increase slab shortening and thus the resulting beam weak way shear and moment forces.

Therefore, it is apparent that the slab edge breakout approach is both ineffective in improving slab precompression values and risky, potentially causing damage to beam ends. So, the slab edge breakout approach should generally be avoided.

Sliding connections/movement details

Sliding connections or movement details can be provided between slabs and walls through the use of slip materials such as bond breakers, polyethylene sheets, and smooth-faced high-density plastic shims, or low shear stiffness neoprene pads at the interface of walls and slabs. In areas where PT buildings are common and both engineers and contractors understand the importance of RTS effects, sliding connections are frequently used to reduce RTS effects due to perimeter walls. Where perimeter walls are not being relied on for diaphragm shear transfer and frame lateral stability, sliding connections can be permanent. But it is more common, especially where lateral loads in the floor diaphragm must be transferred to walls for shear resistance, that temporary movement details are active only during and shortly after the application of PT forces to the slab. After sufficient floor shortening has occurred to reduce RTS effects to an acceptable level, slabs are tied to perimeter walls using dowels for shear transfer. A typical temporary movement detail is shown in Fig. 9. As shown in Fig. 9, PT slabs are free to move relative to stiff walls during tendon stressing. Once the walls above are poured, PT slabs are rigidly connected to walls through U-shaped dowels. More examples of movement details can be found in References 2, 4, and 12.

Column isolation

Columns are necessary to carry structural framing gravity loads, but to maximize slab precompression and minimize RTS, they should be isolated from stiff walls for as long as possible. There are three different approaches to column isolation: (a) perimeter columns (isolated pilasters) built separately from bypassing perimeter walls; (b) permanent joints to each side of each pilaster, creating short interrupted wall segments; and (c) columns or pilasters built first to allow for concrete elastic, creep, and shrinkage shortening, with infill walls constructed at a later date.

Approach (a) is strongly favored by engineers, as

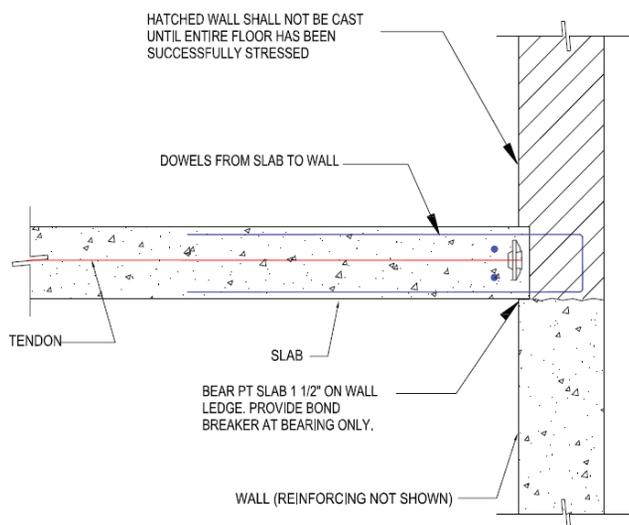


Fig. 9—Temporary movement connection. (Note: 1 in. = 25.4 mm.)

columns totally separate from perimeter walls can flex with slabs to improve slab precompression and reduce RTS problems. These stand-alone columns project into usable space, however, which may be undesirable for architectural or functional reasons.

Approach (b) is commonly used at shallow basements above the water table because this approach is a compromise that meets the requirements of both engineers and architects. As the perimeter foundation walls become alternating wall panels separated from embedded columns/pilasters by sealed joints, it is clear that close attention to joint details is essential to simultaneously allow for adequate movement and keep joints watertight. As recommended by Falconer,¹² a generous joint width between pilasters and walls should be provided to allow for irreversible effects of elastic shortening, creep, and shrinkage, as well as cyclical movement due to temperature changes. Typically, 1 in. (25 mm) thick compressible joint filler material on both sides of columns is specified between walls and pilasters. For the joint to accept long-term movements, a formed groove at the face of the joint should be sized and detailed to work with the anticipated deformations and the movement capacity of the sealant material. For joints to work, slabs do not connect to wall panels, so lateral load resistance must be provided elsewhere. If slabs are needed to prop foundation walls against soil pressure, a slip pad can be provided in the vertical joint between slab and wall.

Approach (c) is strongly discouraged by most contractors because constructing walls at a later date will typically delay the construction schedule or interfere with construction on upper floors.

As stated in ACI 362.1R-97,⁵ if isolation joints exist between a structural frame and stiff elements, the resulting frame shall be designed and detailed for necessary lateral stability and all required loads and deformations, especially for PT structures.

Low slab precompression (P/A)

According to recommendations of ACI 362.1R-97,⁵ parking structures typically require a slightly higher slab precompression P/A than do nonparking slabs: a minimum of 150 psi (1.03 MPa) in Zone I and 200 psi (1.38 MPa) in all other zones. A higher precompression P/A generally results in greater concrete floor shortening effects.

According to ACI 318-08, Section 18.3.3,⁶ three classes are specified for prestressed flexural members: Class U, T, and C based on extreme fiber tensile stress at service loads. Flexural members are classified as

Class U for tensile stress no more than $7.5\sqrt{f'_c}$ ($0.62\sqrt{f'_c}$), as Class C for tensile stress more than $12\sqrt{f'_c}$ ($1.0\sqrt{f'_c}$), and as Class T for stress between $7.5\sqrt{f'_c}$ ($0.62\sqrt{f'_c}$) and $12\sqrt{f'_c}$ ($1.0\sqrt{f'_c}$). ACI 318-08 specifies that two-way slab systems to be designed as Class U have a maximum tensile stress of $6\sqrt{f'_c}$ ($0.5\sqrt{f'_c}$). For one-way slab systems, it is recommended that parking structures be designed the same way as well.^{3,12} According to ACI 318-08, Section 18.9.3.1,⁶ for two-way flat slab systems, bonded reinforcement is not required in positive moment areas where computed concrete tensile stress at service load (after allowance for all prestress losses) does not exceed $2\sqrt{f'_c}$ ($0.17\sqrt{f'_c}$). Thus, engineers frequently design slabs with tensile stress less than $2\sqrt{f'_c}$ ($0.17\sqrt{f'_c}$) so that no bonded reinforcement is required in positive moment regions. This approach may facilitate construction due to the elimination of bottom bars, but PT quantity may increase significantly. This approach might be acceptable for elevated slabs with restraints that are low to moderate: saving in bonded reinforcement and labor may balance out the increase in post-tensioning without introducing serious RTS problems. For underground structures with perimeter walls, however, increasing the prestress level may worsen RTS problems. In addition, reducing the bonded bars that can effectively control and minimize cracks may lead to more undesirable crack patterns and behaviors. Thus, as long as some flexural cracking is tolerable for serviceability, a lower P/A or partially prestressed system such as Class T or Class C is more desirable for structures with severe restraint, such as PT slabs tied to foundation walls, than for those with little restraint.

A strategy of low precompression along with a fine-tuned concrete mixture to reduce drying shrinkage was successfully used to mitigate the slab's natural shortening tendencies in PT parking for Seattle's first LEED Silver and "Built Green" Condominium Mosler Lofts.¹³

For underground parking with severe restraint, however, if a lower P/A is desirable, other measures or their combinations recommended by ACI 362.1R-97⁵ could be taken to make parking structures durable. At the same time, if members are designed as Class T or C, ACI 318-08, Section 7.7.6.2,⁶ specifies that concrete cover be increased by 50%. This requirement can be waived if the precompressed tensile zone is not in tension under sustained loads.

The previous discussions of slab precompression ignore potentially helpful compression in slabs used to prop basement walls against soil pressure. This effect is minor in shallow basements but may be significant at lower levels of multistory basements.

Shrinkage compensating concrete

Concrete drying shrinkage is the biggest contributor to slab total shortening. Other contributors include elastic shortening, concrete creep, and temperature change. It is reported that the contribution of concrete shrinkage to slab total shortening is approximately 66% for a PT parking structure in southern California² and 60% for a PT parking structure in Ottawa, ON, Canada.¹⁴ Thus, the use of shrinkage compensating concrete could significantly reduce total slab shortening and improve RTS behaviors. For example, Li and Sha¹⁵ reported that an eight-story PT building with a length of 534 ft (160 m) was successfully built without the introduction of an expansion joint. This was attributed to the use of two middle pour strips and shrinkage-compensating concrete, where the ultimate concrete shrinkage was reduced roughly by half.

Bonded reinforcement

Although bonded reinforcement at commonly used reinforcing ratios does not significantly reduce concrete slab volume changes, it can be very effective in reducing RTS problems by controlling and minimizing concrete cracks when placed at locations where cracks are expected. For PT structures with severe restraints such as foundation walls, floor shortening may have a significant effect on floor diaphragms. These effects are similar to those on structures due to a temperature drop and can be evaluated by frame analysis with imposed member strains to simulate those due to elastic, creep, and shrinkage shortening phenomena. As shown in Fig. 7, for an eight-story frame subject to floor shortening, tensile force from movement restraint builds up in the first elevated floor diaphragm, with the largest force at the stiffness center. This force would counteract PT compression (not shown). The results also show that upper levels experience small tension or compression forces from movement restraint because they shorten similarly in magnitude and have little restraint relative to each other. Thus, the first elevated floor slab is more susceptible to concrete cracks than are upper levels. Therefore, providing adequate bonded bars can be a good RTS management strategy, particularly when placed in the first elevated floor and at locations most affected by restraint. One location is slab bays close to the frame stiffness center where displacement from floor shortening is a minimum. Another location is slabs near wall corners, where the concrete slab may suffer severe restraint forces due to volume changes in both orthogonal directions and, therefore, is more susceptible to cracking.

In evaluating tensile forces due to concrete floor

shortening, for typical PT structures with unbonded tendons, a length change of 1 in. (25.4 mm) per 100 ft (30.5 m) of slab length can be assumed as a reasonable estimate due to elastic, creep, shrinkage, and temperature change.¹⁴ Concrete creep and shrinkage occurs over a long period of time: for thin slabs common in PT construction, volume changes due to creep and shrinkage gradually stabilize over 3 to 5 years. Because the movements are slow, concrete creep will reduce the effective stiffness of both the PT structure and the restraints (vertical supports such as columns and walls). As a result, forces anticipated to result from the previous estimated strain are normally reduced. For example, the *PCI Handbook*⁷ divides the strains by a factor of 4.0 when determining restraint forces from concrete creep and shrinkage. Dividing by a factor of 2 is suggested by others.^{3,4}

Reinforcing bar layout and corrosion rate

For PT structures that are expected to crack, corrosion may significantly affect both structural serviceability and safety. A reinforcing bar layout permitted for PT slabs may help reduce the corrosion rate. A basic corrosion cell includes four components: an anode, a cathode, an electrolyte, and an electrical conductor. The removal of any one of these components stops corrosion. It is generally believed that the corrosion between the top and bottom mats of reinforcing bars is the primary cause of early age bridge deck deterioration.¹⁶ A similar corrosion mechanism exists for concrete floors of snow belt parking structures as road deicing salts are dropped by cars during winter months. In a concrete slab, the electrolyte is provided by moisture and concrete pore solution and any metal connecting top and bottom bars, such as bar chairs, can serve as the electrical conductor. Thus, in a corrosion cell, top and bottom bars serve as the anode and cathode, respectively. Falconer¹² pointed out that if the anode and cathode are further apart than approximately 18 in. (450 mm), the corrosion process can be greatly reduced. This can be advantageous for PT slabs. For minimum bonded reinforcement in both one- and two-way PT structures, ACI 318-08, Section 18.9.4,⁶ states that the minimum bar length is to be one-third of the clear span length in positive moment areas, and in negative moment areas, bonded bars shall extend one-sixth the clear span on each side of support. When only minimum bonded bars are required, it is strongly recommended that these lengths not be exceeded. This way there is no overlap between top and bottom bars. The distance between anode top bars and cathode bottom bars is large, greatly reducing the corrosion rate.

Summary

As presented previously, restraints due to foundation walls may affect PT structures in two ways: 1) reducing slab precompression during construction; and 2) causing severe RTS effects after construction. Different construction and design practices are discussed regarding their effectiveness in improving severe restraint situations. Table 3 summarizes the ways these practices act to improve slab precompression and reduce RTS effects. From the authors' experience, each volume change mitigation approach discussed previously may be of rather limited effectiveness. Realistically, a combination of these practices could be used to achieve the best results.

In current practice, a majority of underground PT parking structures are built with temporary movement connections between concrete frame and walls to permit the concrete frame to move relative to stiff walls, as shown in Fig. 9. After a certain period, walls are rigidly connected to the concrete frame and slabs for diaphragm shear transfer. The volume changes due to concrete creep and shrinkage that occur within the concrete frame before this connection is made greatly reduce restraint forces from perimeter walls. If the shear transfer connections can be located near midface of each perimeter wall, slabs at wall corners can be left unconnected to reduce post-connection restraint effects.

A related strategy for a recent three-story underground PT parking structure uses perimeter shear walls of shotcrete that will be cast after the whole concrete frame is finished. It is estimated that when shotcrete walls are constructed, approximately 50% of the volume changes due to concrete creep and shrinkage at the first elevated floor will have occurred.

CONCLUSIONS AND RECOMMENDATIONS

Based on the study findings presented in this paper, the following conclusions can be drawn:

1. Connecting PT slabs to stiff foundation walls in underground parking structures could redirect a large portion of PT tendon effective force to bend vertical supports below instead of compressing the slab cross section, significantly reducing the slab precompression present while leaving load balancing effects from draped tendons unaffected.

2. Slab blockouts in the longitudinal direction that are interrupted at beams rigidly connected to integral pilasters are not effective in reducing restraints to slab movement. In addition, the beam section between slab blockouts experiences large, potentially damaging weak

Table 3—Functions of different construction/design practices

Construction/design practice	Reduce precompression loss	Reduce RTS problems
Pour strip in slab	Yes	Yes*
Expansion joint in slab	Yes	Yes
Temporary sliding connection at wall	Yes	No
Permanent sliding connection at wall	Yes	Yes
Shrinkage compensating concrete	No	Yes
Through pilaster/wall joint	Yes	Yes
Low P/A	NA	Yes
Bonded reinforcement	No	Yes
Slab blockout parallel to wall, but rigid connection between beam/pilaster	Yes†	No

*Extent that pour strips can be used to reduce RTS problems depends on pour strip open time.
 †Extent is limited and severe bending and shear forces are induced in beam weak direction.
 Note: NA is not available.

way flexural and shear forces when PT tendons are stressed.

3. For the cases studied in this paper, walls in the longitudinal direction provided the greatest restraint. For slabs and columns separated from the wall, restraint increased with total building length (more columns involved). Applying both observations, eliminating rigid connections from slabs to walls, and creating short slab lengths for PT stressing could significantly improve the fraction of PT force remaining in the slab as helpful precompression.

4. Multiple construction practices can be used to relieve restraints due to stiff walls by either improving slab precompression during construction, or to reduce RTS effects after construction and to reduce corrosion rates. To achieve maximum slab precompression, significantly reduce RTS effects, and improve serviceability, typically a combination of two or more of the previous construction practices might be necessary.

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