Technical NOTES

From PTI DC-20: Building Design Committee Issue 22 • October 2023

Dual-Banded Post-Tensioning Tendon Layout

1. INTRODUCTION

Traditional unbonded post-tensioned (PT) tendon layouts consisting of tendons “banded” together in one direction and uniformly distributed in the orthogonal direction are suitable, constructible, and well-established for many two-way slab designs. However, there are certain conditions that would greatly benefit from a more flexible tendon layout, such as extended spacing of the uniform tendons, or a fully banded tendon layout in both directions at the column strip region without any uniformly distributed tendons. This dual-banded layout is currently not explicitly addressed by ACI 318-19.[1] However, a dual-banded tendon distribution could be accomplished under the mandate of the 2021 International Building Code (IBC), Section 104.11,[2] or ACI 318-19, Section 1.10.[1] The implications of adopting a dual-banded layout will be the basis of this document. This Post-Tensioning Institute (PTI) Technical Note focuses on the tendon distribution being fully banded at the column strip region in both orthogonal directions, which constitutes the most extreme tendon distribution. Ideally, the intent is to relieve the current code requirements on spacing of tendons in the uniform direction such that the tendons can be placed anywhere from fully banded to any suitable distribution.

2. BACKGROUND

Early tendon layouts for two-way PT slabs in the United States (1950s to mid-1970s) consisted of uniformly distributed tendons in both orthogonal directions (often referred to as a “basket-weave” layout), as shown in Fig. 2.1. The tendon distribution in this type of layout varied from 60 to 75% of the tendons in the column strips and 40 to 25% in the middle strips. Common practice was to keep the average effective precompression stress (*P*/*A*) levels between 200 and 250 psi (1379 and 1724 kN/m^2)[3]; these parameters were experimentally verified.[4] While this type of construction was viable and popular with designers, it was difficult to detail and install in the field because the tendons had to be carefully sequenced and woven for proper placement. This was even more complex in irregular structural layouts.

The idea of combining or grouping the tendons in one direction to form a banded distribution came into being by accident. It is reported[5] that in 1968, the design team on the Washington, DC, Watergate Apartments project had run out of alternate design options and the distributed-banded layout was the only feasible tendon distribution possible. The layout of tendons allowed for a feasible load path with an irregular column arrangement. This project is reported to be the first known distributed-banded flat plate constructed in the United States.

The first series of tests to study the feasibility of the distributed-banded tendon layout were conducted in the early 1970s by researchers at The University of Texas at Austin.[6-9] The testing consisted of a series of multi-panel tests; two nine-panel slabs and one four-panel slab were tested. The overall goal of these tests was to study the behavior and strength of two-way slabs with different tendon arrangements from the elastic through the inelastic range and up to ultimate failure. The nine-panel slabs were designated as Slab I and II (Fig. 2.2 and 2.3, respectively), and the single four-panel slab was designated as Slab III, as shown in Fig. 2.4. Slab I was a one-third-scale model consisting of a 70/30 column-to-middle strip tendon distribution. Slab II was a half-scale model with nine panels and Slab III was a half-scale but with four panels aimed at investigating exterior panel behavior. Details of the testing can be found in the listed references.

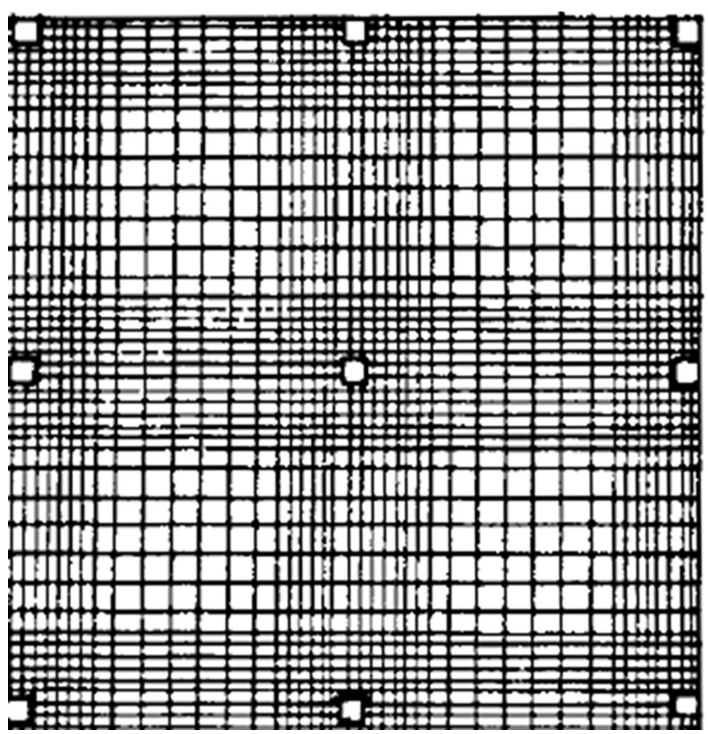

Fig. 2.1—Early tendon layout for post-tensioned slabs in the United States (“basket-weave layout”).

The conclusions from the testing and tests by others[10] showed that the use of the distributed-banded tendon layout was feasible. The improved layout provided equivalent or increased flexural and shear strength. Improved serviceability behavior at a lower average effective precompression stress of 135 psi (930 kN/m²) in Slab II was observed compared to the 200 to 250 psi (1379 to 1724 kN/m²) range, which was considered standard practice at the time. The higher average effective precompression stress was based on recommendations in the Joint ACI-ASCE Committee 423 report "Tentative Recommendations for Prestressed Concrete Flat Plates."[3] One of the observations from the Slab II tests[9] was that the slab panels in the direction of the banded tendons performed better than the corresponding panels in the uniform tendon direction. The Burns et al. research resulted in various design recommendations regarding detailing criteria of bonded nonprestressed reinforcement over columns, a minimum average effective precompression stress level of 125 psi (862 kN/m²) in two-way slabs, and the requirement for a minimum of two tendons passing through the column in both directions, among other considerations.

The distributed-banded tendon layout was first introduced in ACI 318-83. Since its introduction in ACI 318, millions of square feet of two-way PT slabs using the distributed-banded tendon layout are being successfully constructed in the United States every year.

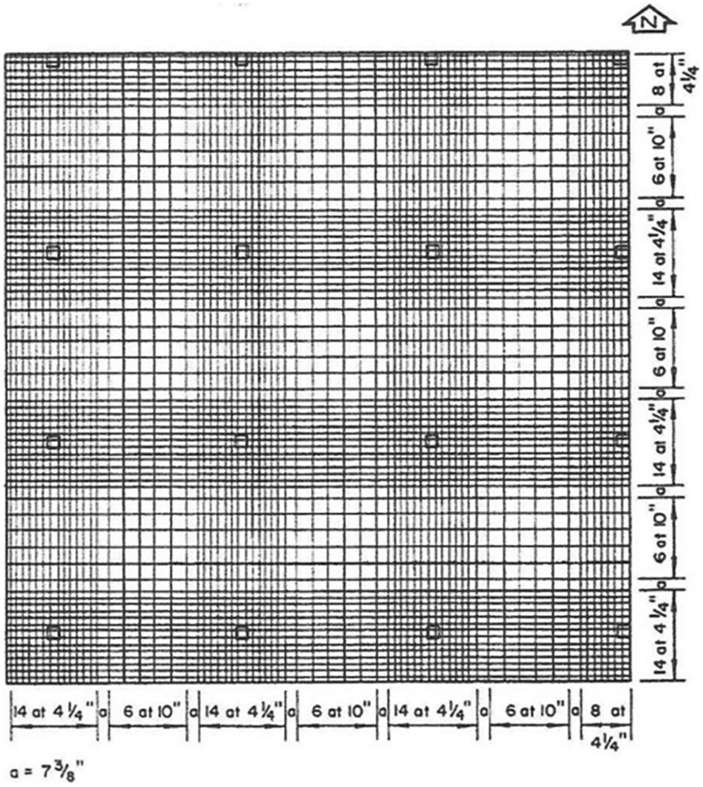

Fig. 2.2—Tendon layout in Slab I. Burns and Hemakom tests, 1974.[9]

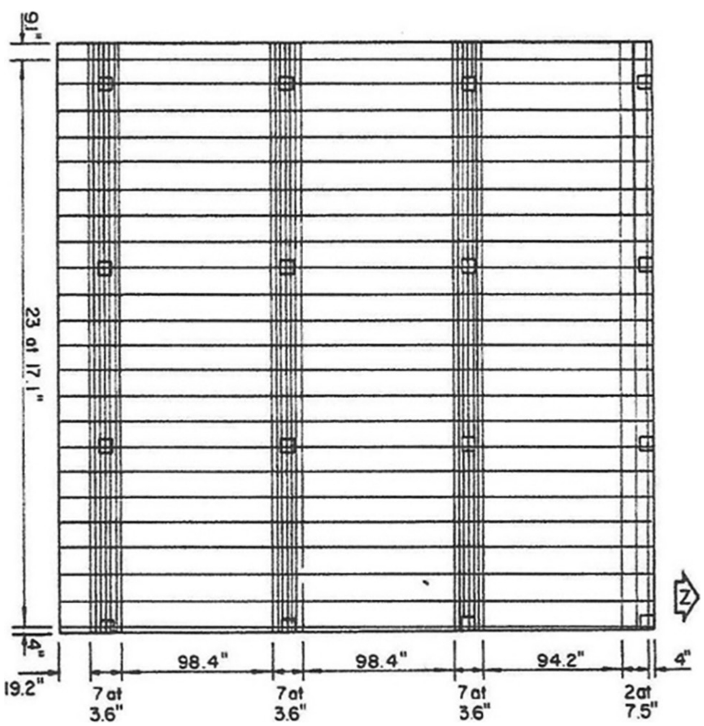

Fig. 2.3—Tendon layout in Slab II. Burns and Hemakom tests, 1975.[9]

3. PRACTICAL ADVANTAGES OF DUAL-BANDED TENDON LAYOUT

Traditionally, PT tendon placement has followed a distributed-banded layout, as previously discussed. The dual-banded layout is intended to provide the design community with an alternative layout scheme for several reasons. In the distributed-banded layout, tendons are banded along the support lines in one direction, and uniformly distributed in the orthogonal direction. The uniform spacing of the tendons is limited to the larger of 5 ft (1.5 m) and eight times the slab thickness per ACI 318-19.[1] In a dual-banded layout, the tendons are banded in both directions along the support lines, with the center of the panels being potentially free from any tendons.

Each layout scheme has its advantages and disadvantages; the choice of which layout to use depends on the requirements

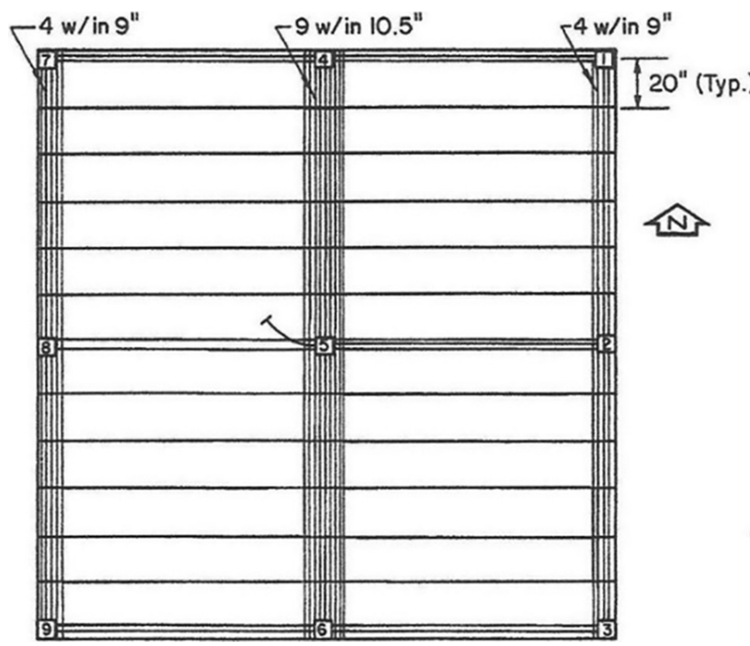

Fig. 2.4—Tendon layout in Slab III. Burns and Hemakom tests, 1976.[9]

specific to the project. Some of the advantages of the dual-banded tendon scheme are as follows:

- **Flexibility of accommodating future floor openings:** Because the center of the bays may remain clear of tendons, future penetrations can be easily post-installed without the risk of cutting tendons. This is important in applications requiring flexibility in future slab penetrations like laboratories, office buildings, health care, industrial facilities, and in cases where large openings are required for potential retrofitting purposes such as future stairs.
- **Speed of construction:** Placing the tendons is simplified, as crisscrossing between uniform and banded tendons is minimized, thus leading to reduced issues on site from clashes and weaving. Switching the tendons from a uniform scheme in one direction to a dual-banded layout reduces the profile placement extents for chairs and support bars. The support steel is concentrated on the column strip region only in lieu of being continuous across the slab area in one direction to support the distributed tendons. Furthermore, this tendon scheme reduces the time required for the layout of the tendons as the location of formwork markings becomes more concentrated.
- **Less interference with other trades:** Coordination of tendons with penetrations or embedded items is required only at banded lines and not throughout the entirety of the slab. It is important to note, however, that more thorough coordination for the placement of penetrations or embeds over the columns will be required due to the higher concentrations of tendons. Furthermore, because the tendons now only occur at the column strip region, the center of panels becomes free from potential clash issues with other disciplines. At the slab edges, the absence of anchorages corresponding to the uniform tendons allows embeds for façade elements to be placed with minimal disruption.
- **Reduction in tendon support material:** Tendon chairs and support bars will be concentrated in the regions of the banded tendons instead of the entire slab. This will allow for lower quantities of support hardware when compared to a traditional distributed-banded distribution.
- **Efficient use of voided slabs or waffle slabs:** In such applications, placing uniform tendons can be very challenging and requires that the tendons in the uniform direction be placed between the voids or waffles. The layout becomes similar to joist construction and more comparable to a one-way or ribbed slab system as opposed to a dual-slab system. This can lead to a longer construction period with less-efficient and non-economical designs. Having the tendons concentrated in bands over the columns in both directions allows the designer freedom to place the voids or waffles as practically and economically as possible.

The dual-banded tendon configuration provides additional design freedom and economics in specific scenarios, as described previously, when compared to the current standard distributed-banded layout.

4. SIMILARITIES OF DUAL-BANDED TO DISTRIBUTED-BANDED TENDON DISTRIBUTION

The behavior of a dual-banded system and a distributed-banded system are very comparable. Experience with the distributed-banded configuration has shown that banding in one direction provides extremely successful and proven performance. The dual-banded layout evolves the tendon configuration to provide banded tendon groups in two nominally orthogonal directions while also concentrating PT forces along the column strip regions, which are the regions of highest flexural demand.

With the uniform distribution of tendons, balanced forces from post-tensioning are applied at regular spacing across the design width. A banded distribution provides the same total magnitude of balanced loading, but these loads now obviously become concentrated at the column strip region. As discussed later in this document, the maximum service demand stresses occur at the column strip region. Therefore, banding tendons at these locations represents the most rational arrangement in terms of concentrating balanced loads in the regions of highest demand.

The strength level calculation of a full-width cross section is independent of the distribution of tendons, but rather depends on the area of prestressing steel provided by the tendons in a given cross section. ACI 318-11, Commentary Section R18.12.2,[11] states that "tests indicate that the moment and shear strength of prestressed slabs is controlled by total prestressing steel strength and by the amount and location of nonprestressed reinforcement, rather than by tendon distribution." Design cross sections are represented by the sum of half-distances to the adjacent support and are not broken up into column and middle strips, unlike in conventionally reinforced two-way slabs. The dual-banded system does not alter the theoretical strength capacity in flexure compared to the distributed-banded scheme as the magnitude of cross-sectional prestressing steel area does not change between systems because the design cross sections remain the same. The distribution of tendons within the cross-section width is the only changing reinforcing aspect. Strength considerations are discussed in more detail in Section 6.

5. SERVICE CONSIDERATIONS

5.1 Analytical model parameters

This section describes and compares the behavior of distributed-banded and dual-banded tendon distributions. The analytical models are representative of a uniform-thickness, two-way flat-plate floor slab with uniform applied loading. The span-depth ratios in the examples are slightly less than 45 with a square column grid and slab panel configuration. The examples in this section are for illustrative purposes and design execution of a dual-banded system should be performed by a licensed design professional (LDP).

5.2 Initial flexural stresses

When PT tendons are stressed, mostly favorable forces that counteract the gravity forces are introduced into the two-way slab system. However, at the application time of prestress, if the stresses introduced by post-tensioning significantly exceed the opposing stresses due to self-weight and the construction loading, then detrimental effects may result. ACI 318-19, Section 24.5.3.2,[1] provides tensile stress limits immediately after the transfer of prestress. When these tensile stress limits are exceeded, additional bonded reinforcement must be provided in the tension zone to resist the total tensile force assuming an uncracked section. The application of PT forces to a floor can introduce tension stresses on the top of the slab near midspan and on the bottom of the slab near the supports. The graphical representation of bottom stresses, at the transfer of prestress for a typical distributed-banded layout (with typical concrete strength), is shown in Fig. 5.1.

In contrast, the bottom stress distribution at the transfer of prestress for a typical dual-banded layout (with the same typical concrete strength) is shown in Fig. 5.2.

The peak tensile stresses at service loads tend to occur over the supports on the top of the slab. While the dual-banded layout does a better job of counteracting these service load gravity stresses, it can also create higher tensile stresses when prestressing is applied. These initial bottom tensile stresses are shown in Fig. 5.1 and 5.2 over the supports, while initial top tensile stresses may exist near midspan of the column strip region. Regardless of tendon configuration, attention should always be given to initial tensile stresses with additional reinforcement provided as needed in localized regions of high demand.

5.3 Precompression stress behavior

Per ACI 318-19,[1] a minimum average effective precompression stress of 125 psi (860 kN/m^2) is required in both directions to address the punching shear behavior of slab sections with light reinforcement. The Code requirement is based on actual prestressing forces implemented from Burns and Hemakom's banded-distributed tendon testing in 1985.[9] Furthermore, a banded tendon configuration introduces a triangular region of slab between supports at the perimeter that does not receive the average amount of precompression stress in a cross section due to shear lag effects of prestressing forces. The triangular region typically resides outside of the critical punching shear section that requires the minimum of 125 psi (860 kN/m^2) of average effective precompression stress. In many instances, experience has shown that no additional reinforcement in this area provides satisfactory performance. However, there could be instances such as long end spans and thicker slabs that will need the LDP's attention. There are some LDPs who reinforce this triangular area based on the requirements of one-way slabs per ACI 318-19.[1] Figure 5.3 illustrates the shear lag behavior of precompression stresses along the banded tendon direction. A dual-banded configuration will demonstrate the same shear lag response as a distributed-banded layout, except the behavior becomes present in both orthogonal directions in lieu of one.

5.4 Flexural bottom tensile stresses

Tension stresses at service level often control design as these slab sections must remain uncracked at service load level demands. Both positive and negative moment flexural stresses are limited to a maximum of $6\sqrt{f_c'}$ tensile stress as prescribed by ACI 318-19[1] for two-way slabs. Bonded reinforcement is not required in positive flexure if the maximum tensile stress is less than $2\sqrt{f_c'}$. An investigation of bottom stresses from concrete self-weight only with no PT effects shows regions of the highest demand tensile stresses occur along the column strip regions and not in the center of the bays, as demonstrated in Fig. 5.4.

Placing the tendons in a banded configuration along the column strip region provides balanced loading forces at the regions of highest self-weight demand. The dual-banded

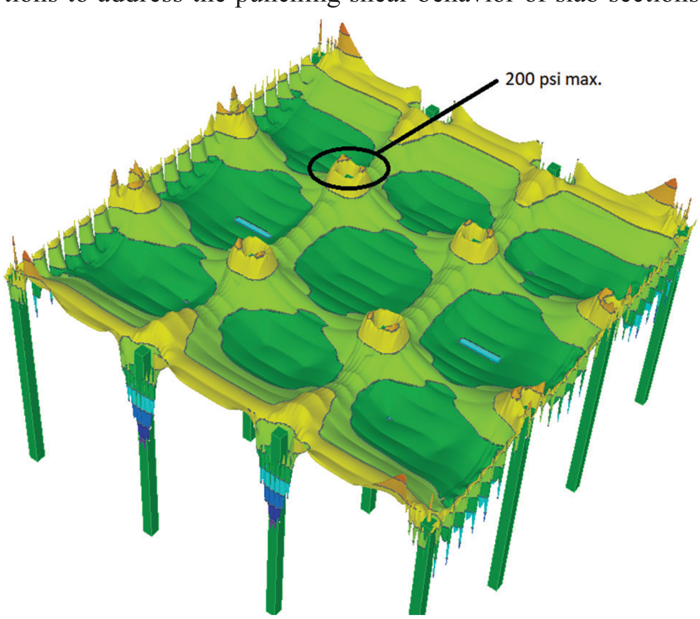

Fig. 5.1—Bottom stress at application of prestress force for distributed-banded tendon layout.

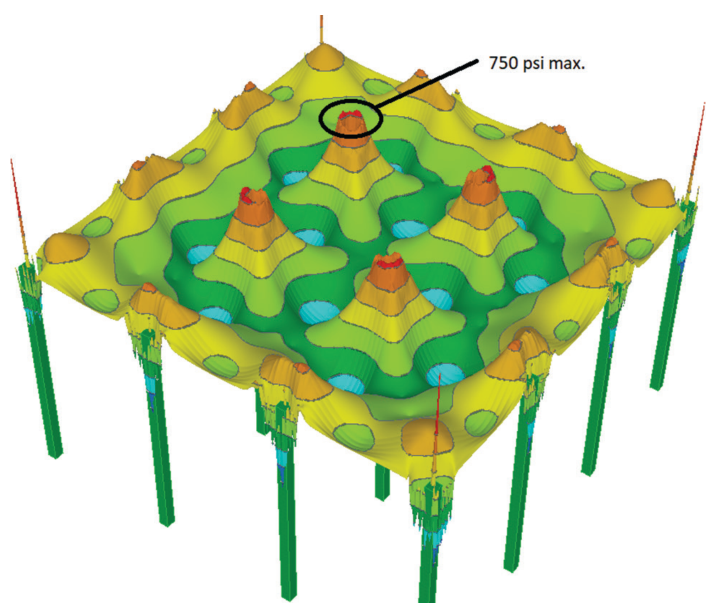

Fig. 5.2—Bottom stress at application of prestress force for dual-banded tendon layout.

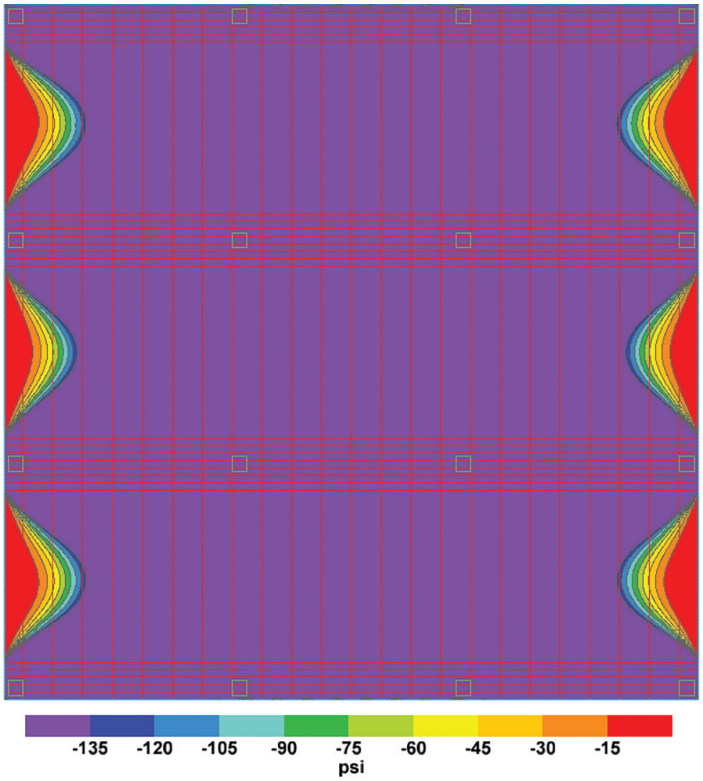

Fig. 5.3—Precompression shear lag contours with banded tendons.

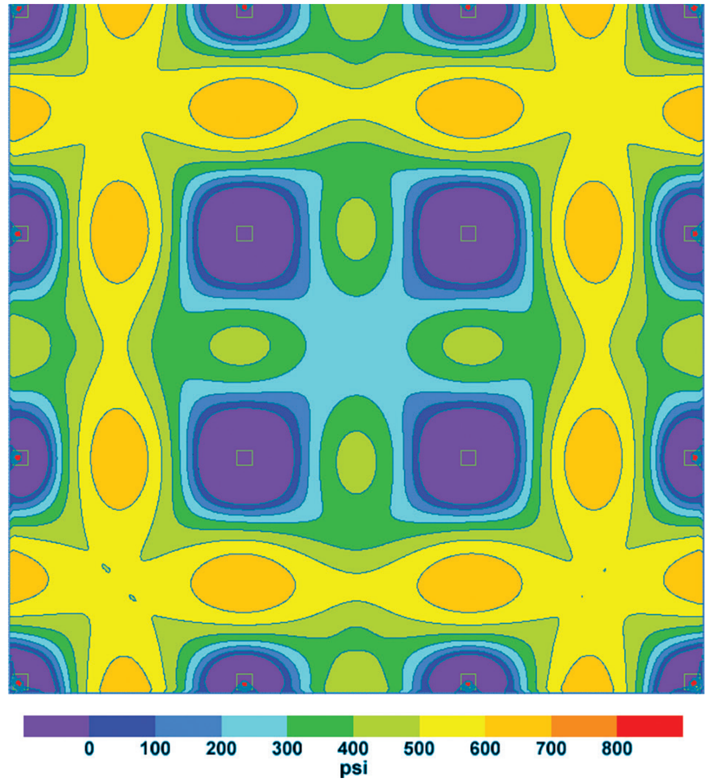

Fig. 5.4—Bottom tensile stress contours from concrete self-weight only.

configuration then demonstrates a shift of the peak stresses from the column line to the center of the bays, shown in Fig. 5.5. Although a full-width design cross section may have average stresses below code limits, there exists a possibility of tensile rupture near the midspan of a bay. The tensile rupture stresses may become further problematic if an unforeseen extreme-localized force becomes present at midspan. Section 7 describes a minimum ratio of bonded integrity reinforcement to further assist in collapse prevention during extreme events.

5.5 Flexural top tensile stresses

In slabs with continuous spans, maximum flexural demands are often induced by the negative moments over the interior supports. ACI 318-19[1] requires a minimum amount of bonded reinforcement in negative moment regions, regardless of the magnitude of demand flexure. The reinforcement provides crack control at strength level and additionally acts as a form of energy dissipation and ductility for large lateral events. Concentrating tendons in two orthogonal directions over a column head significantly and favorably reduces the top tensile stress at service-level loading. As tensile stresses exceeding code limits at the column head can often control a design, the dual-banded system directly reduces these tensile stresses, allowing for an improved design.

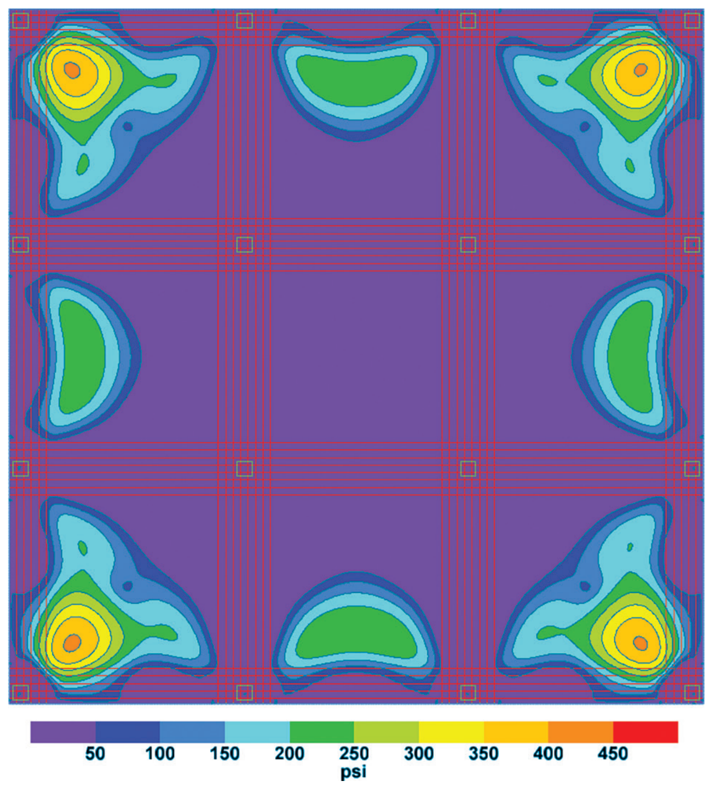

Fig. 5.5—Bottom tensile stress contours at full service loading with dual-banded tendon layout.

5.6 Deflection considerations

PT flat plates provide many advantages over mild-reinforced designs, especially with respect to increased span-depth ratios. However, with shallower sections, deflections sometimes become a controlling design parameter. Many modern structures are designed to tighten deflection limits to accommodate the building's facade and/or brittle elements such as masonry or architectural precast concrete. It is recommended that deflections should always be coordinated between architects, engineers, owners, and material suppliers during the early phases of design to minimize potential issues in the future.

Deflections in mild-reinforced and prestressed concrete members are generally challenging to estimate, and often accuracy is defined with approximately a 30% tolerance due to consideration of long-term behavior caused by creep and shrinkage. Magnitudes of sustained load and time of load application become noteworthy when investigating long-term effects. Concrete modulus of elasticity, methods of initial curing, restraint, and ambient conditions have a significant impact on long-term deflection.

As previously discussed, the highest flexural demands are generally along the column strip regions; thus, concentrating tendons at these locations has the potential to result in reduced overall deflections. Figures 5.6 and 5.7 demonstrate the improvement of instantaneous deflections for a traditional distributed-banded configuration compared to a dual-banded layout, respectively. Localized overbalancing along column strip regions at the perimeter should be investigated to ensure that cambering is not occurring or that it is being accounted for when specifying vertical movement allowances for the perimeter façade attachment.

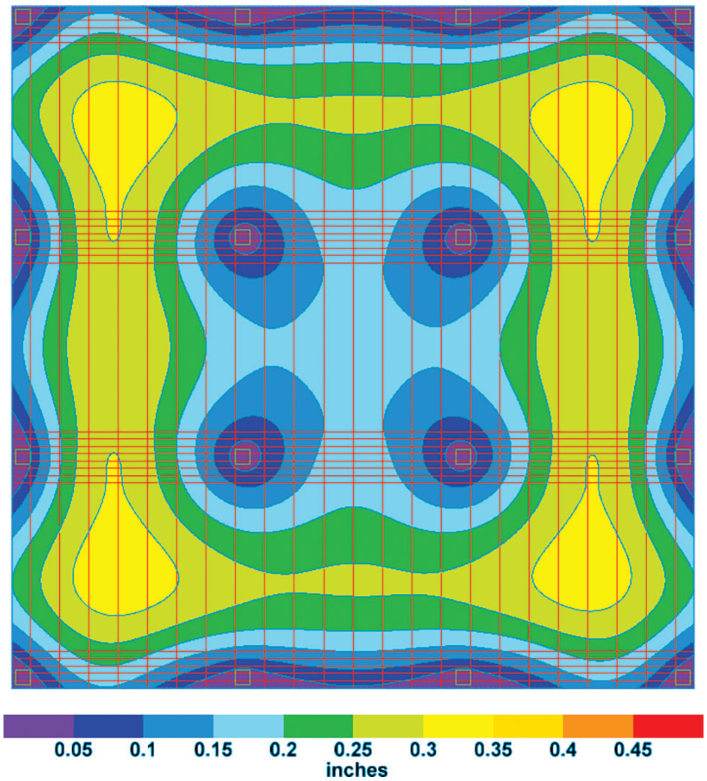

Fig. 5.6—Instantaneous elastic deflection contours of distributed-banded tendon distribution.

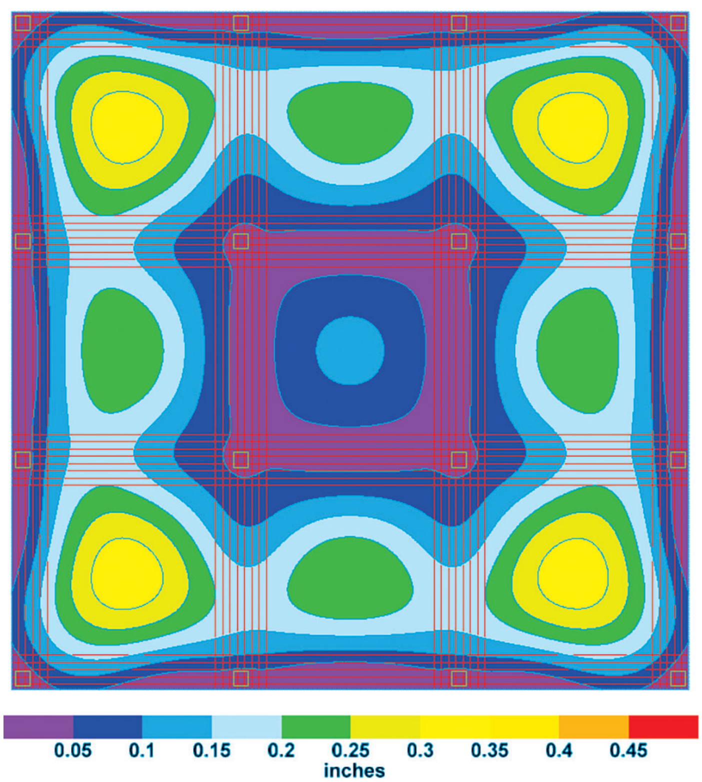

Fig. 5.7—Instantaneous elastic deflection contours of dual-banded tendon distribution.

5.7 Control of concrete cracking

Although two-way PT slabs are considered to always maintain a gross cross section, localized cracking may occur. Due to the high localized concentration of tensile stresses at support locations, tensile flexural cracks may be locally observed. These cracks are often very small and may not even be noticeable to the human eye. The Code-prescribed minimum amount of mild reinforcement (0.00075 times the larger cross-sectional area of the two orthogonal intersecting slab-beam strips per ACI 318-19)[1] at regions of negative bending assists in mitigating the widths of these cracks. Furthermore, concentrating tendons over the support in both directions will help to reduce the potential of minor cracking.

With any tendon configuration, cracking from restraint of laterally stiff vertical elements should always be considered. Proper detailing at these elements will allow the average effective precompression forces to behave as intended and will reduce the chance of any restraint-to-shortening cracking. Multiple PTI publications on PT slab design provide guidance on this issue.

6. STRENGTH CONSIDERATIONS

This section compares the strength aspects of distributed-banded layouts to dual-banded layouts.

6.1 Flexural strength

Strength calculations for both mild-reinforced and prestressed concrete members neglect the tensile strength of the concrete. The flexural strength behavior of a PT member differs significantly from that of a mild-reinforced concrete member. As load is increased, the mild-reinforced concrete section derives its strength from increasing stress in the reinforcement, with the tension force in the reinforcement balanced by a compression force in the concrete, and the lever arm remaining approximately constant. In contrast, as the load is increased on an unbonded PT section, the strength is derived from an increasing lever arm, with the tendon force only increasing slightly from the force at the transfer of prestress. During tendon stressing, two types of beneficial pre-strains

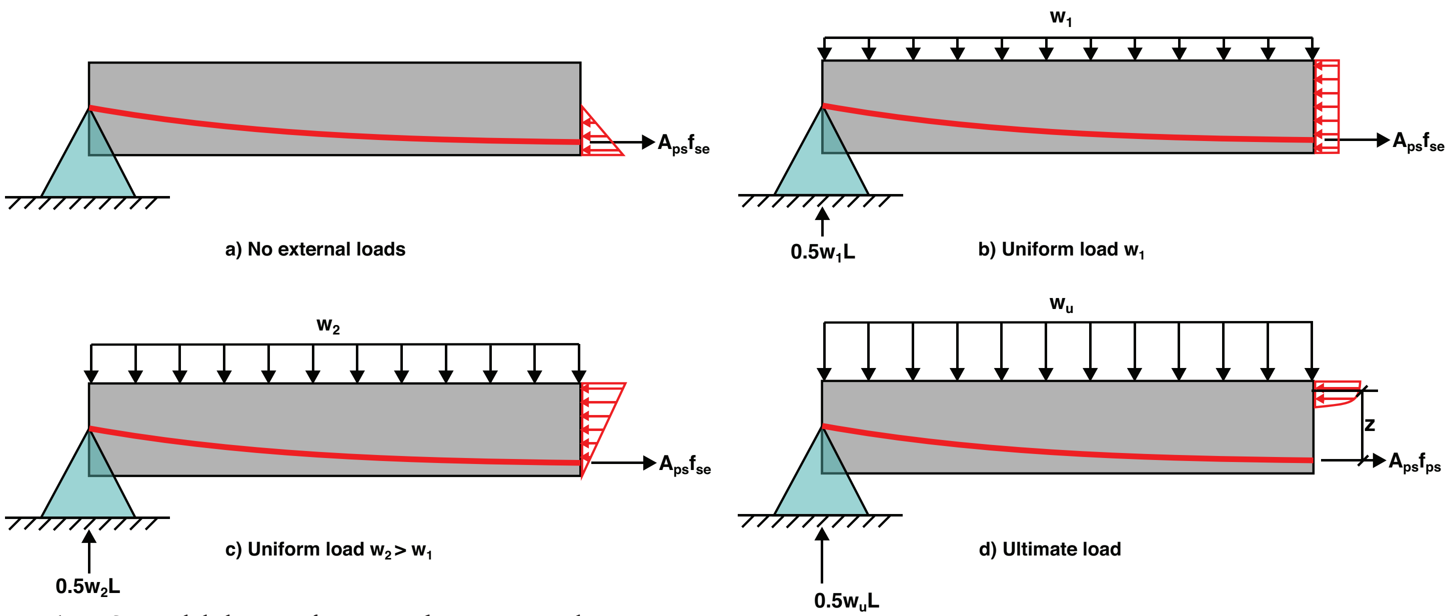

Fig. 6.1—Strength behavior of prestressed concrete members.

are introduced into the prestressed PT member: a pure axial compression strain and a flexural strain caused by the drape on the tendons and/or eccentric anchorage locations (Fig. 6.1(a)). The pure axial compression strains quickly spread into the slab from the anchorage locations and become uniform at a certain distance away from the anchorage. For this reason, away from the slab edges, this strength component is not highly affected by the exact location of the tendons. The flexural strains and resulting stresses are introduced by the vertical components of prestress caused by tendon curvature and are therefore influenced by the distribution of the tendons. In a dual-banded system, the largest benefit of these flexural pre-strains will be realized at the column strip region, but they will also be present, to a lesser extent, at midpanel. As the loading increases, the internal distribution of pre-strain shifts (Fig. 6.1(b) and 6.1(c)), causing a shift in the resultant compression force. The shift in the compression region location causes a larger lever arm between the tendon tension force and concrete compression resultant. As the member is loaded to ultimate strength (Fig. 6.1(d)), there is an increase in stress on the strand. This is caused largely by rotation of the loaded cross sections. The strength derived from the change in tendon stress is virtually identical to that of a reinforced concrete section. The increase in tendon stress causes an increase in the force in the compression block, which increases the internal force couple.

A sectional strength calculation completed on an entire panel width would not significantly differ due to changing the distribution of tendons. However, as noted previously, the distribution of the tendons may have some local effects. As such, when using a dual-banded layout, it is recommended that some minimum bonded bottom reinforcement be placed in the panels between the bands. This topic is covered further in Section 7.

6.2 One-way shear strength

In two-way slabs, the load path must track to the columns, which results in a concentration of shear stress near the

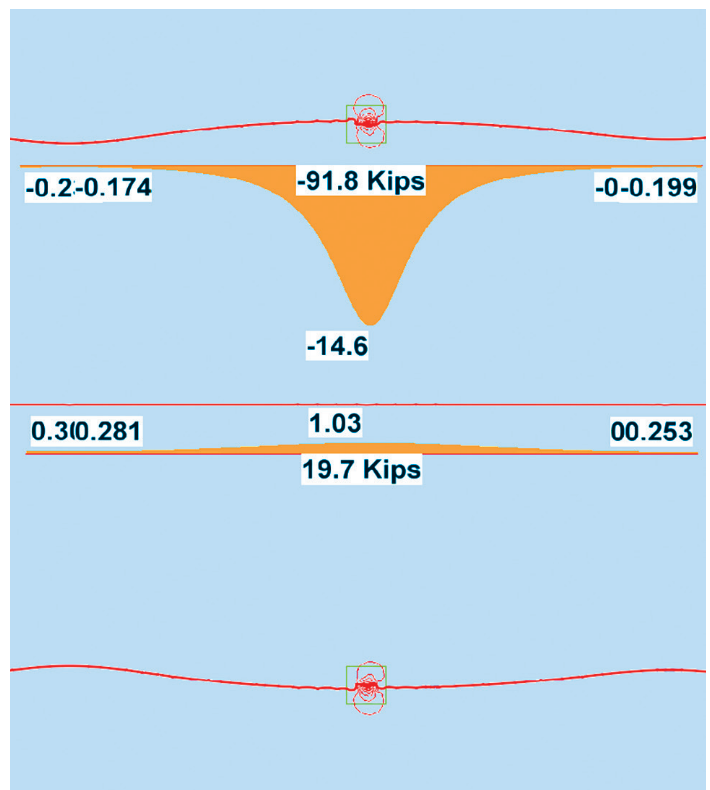

Fig. 6.2—Linear-elastic shear stress.

supports. Figure 6.2 illustrates increasing shear forces near the support location compared to midspan.

Shear in one-way PT slabs is covered by ACI 318-19, Section 22.5.8.[1] In practice with U.S. building codes, one-way shear is normally evaluated over the width of the entire design strip. Using this methodology, the transverse location of the tendons based upon a dual-banded tendon layout will have no influence on the calculated shear strength per code. Theoretically, the concentration of tendons in a dual-banded layout should only serve to increase the shear capacity. Many slabs have been successfully constructed using a distributed-banded tendon layout. The use of a dual-banded tendon layout extends this successful practice from banded tendons only in one direction to banded tendons in two orthogonal directions.

6.3 Two-way (punching) shear strength

Punching shear behavior is a complicated behavior and difficult to quantify analytically. In the case of a dual-banded layout, the presence of more tendons in the punching shear region serves to increase punching shear strength over the traditional distributed-banded layout. The favorable performance is due to the increase in compression stresses as the tendons are concentrated over the support zone in both directions, as well as the concentration of longitudinal steel.

7. MINIMUM PANEL BONDED REINFORCEMENT

Because the prestressed reinforcement in a dual-banded layout is concentrated along the lines connecting columns, it is prudent to provide a minimum amount of nonprestressed reinforcement in each direction in the slab between the banded tendons. It enhances the slab's ability to carry the applied loads back to the banded tendons and to control cracking. In most cases, this would require a bottom mat of reinforcement between the banded tendons in the interior, exterior, and corner panels, and top reinforcement as required. Although not always required analytically for strength or serviceability, this reinforcement would help ensure ductile behavior and load redistribution.

Limited analytical and experimental work based on uniformly loaded slabs with a minimum reinforcement ratio of 0.001 of gross concrete area have shown satisfactory behavior, although in some cases, a higher value may be appropriate. The LDP must carefully review slabs with large, concentrated loads; non-orthogonal layouts; or slab discontinuities to ascertain the appropriate amount of reinforcement required in these regions of the slab. A maximum reinforcement spacing of 24 in. (610 mm) is recommended. It is advisable to use smaller-size bars at a tighter spacing for better crack control. The LDP should evaluate the extent of the minimum reinforcement considering the effects of loading, slab discontinuities, and existing or future slab openings. The LDP should also evaluate the placement and extent of minimum reinforcement when using a "hybrid" dual-banded tendon layout. One example of a hybrid layout could be banded tendons in one slab direction and partially banded tendons in the opposite direction. In the partially banded direction, a portion of the tendons would be banded along the lines connecting columns, and the remaining tendons would be distributed across the slab panel with a tendon spacing greater than the historical allowable limit of 60 in. (1520 mm) or eight times the slab thickness.

8. OTHER DESIGN AND ANALYSIS CONSIDERATIONS

There are several additional considerations that should be well thought out by the designer during the analysis and detailing of slabs using the dual-banded layout. These considerations are listed, but not limited, by the discussion points that follow:

- **Identification of primary and secondary direction:** A primary and secondary direction should be identified. In a distributed-banded tendon layout, the banded tendons are often placed in the long-span direction as they are best suited for the higher demands. Following the same theory, the primary banded direction would be the column strip region with the largest spans, while the secondary direction would be in line with a traditional distributed orientation. The secondary direction will not be able to receive full drape as they will need to be placed under the primary banded tendons.
- **Congestion:** In the case of a dual-banded layout, there will be a concentration of tendons in both orthogonal directions over and around the columns. Physical items contributing to the congestion include tendons in both directions, top steel in both directions, the presence of punching shear headed-stud reinforcement, slab penetrations, and slab embeds. The region will be highly congested, and it is important that there be adequate clearance between the various elements so that concrete can flow and consolidate properly. Furthermore, it is important that reinforcement can be fully developed and that there are no unintended deviations in horizontal or vertical tendon profile due to interference between the various elements. The use of larger (0.6 in. [15 mm]) diameter strands may be considered to reduce congestion in the slab. However, larger-diameter strands are heavier to install, create larger radial stresses at tendon sweeps, and produce higher bursting stresses at the anchorage zones. These stresses must be calculated with adequate reinforcement being installed.
- **Stressing sequence:** Careful consideration should be given to the sequence of stressing for a dual-banded layout. It is important that the tendons do not crush or collapse penetrations during the stressing operation. It is recommended that the lower secondary-direction banded tendons be stressed prior to the upper primary-direction banded tendons. Consideration should be given to the percentage of tendons being stressed in each direction at each sequence. The stressing sequence should be evaluated such that the formwork is not overloaded by balancing forces.
- **Flat profiles over columns:** Providing a flattened tendon profile over the columns in the primary direction reduces interference of the perpendicular tendons with each other. The flattened profile should be provided to the extent of the secondary-tendon group's width below. This profile allows for a placing sequence of the primary tendons last, without the need to weave through the secondary-tendon groups at support locations.
- **Splitting stresses between tendon bundles:** As tendon bundles' spacing decreases significantly, detrimental stresses may occur in the concrete. The tendons provide significant downward balanced forces into the concrete at the column head. As the concrete

below the tendons is strained, it engages the concrete between the tendon groups by deformation compatibility. With a close tendon spacing, there exists the potential for splitting cracking between tendon groups. This can be further exacerbated by tendon sweeps due to penetrations near columns, which are very common in two-way slabs. The cumulative effects of these conditions should be considered by the designer. The dual-banded layout increases the chances for this behavior as the forces are now localized at the column heads in both directions. Designers should also consider supplemental reinforcement if they believe splitting cracking behavior could be applicable to the specific project. In-depth behavior of splitting cracking behavior is complex and beyond the scope of this document.

- **Building code acceptance:** Currently, ACI does not explicitly recognize a dual-banded tendon layout as an acceptable design. Designers considering this layout should have great knowledge, background, and experience with PT design. Furthermore, local code officials should be notified and in agreement with the proposed system prior to detailed design. The designer should be able to demonstrate performance that is equal to or better when compared to a distributed-banded distribution. This performance-based design should only be attempted with the full competency of the design team until ACI officially recognizes a dual-banded configuration.

At a minimum, the aforementioned considerations should be considered when designing a dual-banded slab system until further research is conducted.

9. RELATED PROJECT EXAMPLES

The following project examples are provided to document previous building design and construction efforts aimed at attaining the advantages of a dual-banded PT tendon layout. They are not literal two-way PT flat slabs with dual-banded tendons as previously defined and analyzed in this technical note. As shown, they represent examples where designers sought and achieved pseudo-dual-banded solutions while still constrained by the previous and current provisions set forth in ACI 318. Their inclusion here is for historical reference purposes only, and they are neither endorsed by PTI nor is there any implied warranty provided by PTI in relation to these project examples.

Other technical publications such as the International Federation for Structural Concrete *fib* Bulletin No. 31, "Post-Tensioning in Buildings,"[12] identify the dual-banded layout as an advantageous system and provide additional project examples.

9.1 Example: office project

The example project is a four-story office building located in Fort Lauderdale, FL, that was constructed starting in 2007 using a dual-banded tendon layout. The structure consists primarily of an 8 in. (205 mm) thick slab using 17 in. (430 mm) thickened "bands" along the column strip regions. These thickenings are often referred to as "band beams" or "wide-shallow drops." The theory behind this system is to maintain two-way bending stiffness by not making the drops thick enough to create primary one-way slab behavior as would be experienced in a beam and slab system. By keeping the drops shallow, the two-way behavior of the slab can be preserved; thus, these systems are normally designed using the two-way slab provisions of ACI 318-19.[1]

The typical panels in the building are 30 x 33 ft (9.1 x 10.1 m), which would normally require approximately a 9 in. (230 mm) thick PT flat-plate slab. Using the band beam system allows for more drape on the PT cables and adds additional stiffness to the system, which increases its efficiency and results in a thinner slab. In this case, band beams were provided in both directions of the building with banded tendons provided in each beam line. A representation of the designed post-tensioning and reinforcing bars for a typical panel is shown in Fig. 9.1.

The average effective precompression stress throughout most of the structure was in the 75 to 125 psi (520 to 860 kN/m^2) range. However, more nonprestressed reinforcement than is typically required for a two-way PT slab was used.

The nonprestressed reinforcement in a typical panel consists of a bottom mesh with a reinforcement ratio of approximately 0.003. Top reinforcement is also provided in the slabs over and perpendicular to the band beams with a reinforcement ratio of approximately 0.004.

A performance-based analysis of the design shows that the floor has adequate strength and serviceability, while the structure has not experienced any performance issues during its approximate 16-year service period. While the mild-reinforcement quantities are slightly larger than the 0.0018 reinforcement ratio recommendation in this document, this structure demonstrates that a dual-banded tendon layout can perform satisfactorily in an in-service building.

9.2 Example: Commercial project subject to heavy loads

The project built in the late 1990s is a food storage facility with large spans in both directions and is still in full operation. It was designed as an unbonded two-way PT slab with tapered

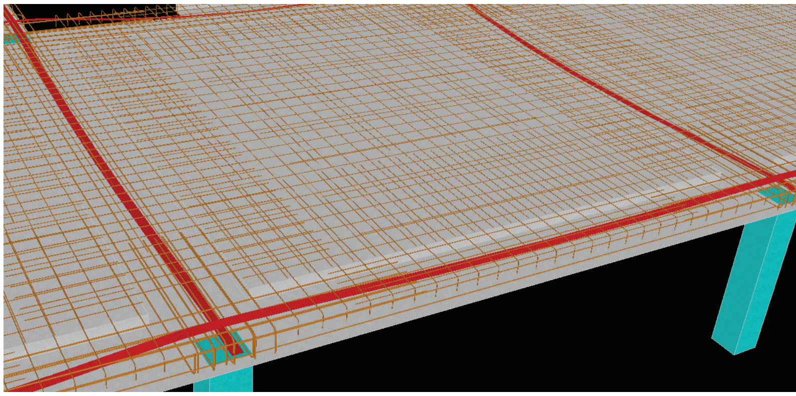

Fig. 9.1—Computer rendering of dual-banded office case study reinforcement distribution.

drop panels and expected to carry heavy superimposed dead loads and live loads. To enable installation of future openings, the project team opted for an unconventional tendon layout.

The established layout was a hybrid dual-banded scheme where, in the y-direction, the tendons followed a typical banded configuration (all tendons are fully centered at the column), and in the x-direction, the tendons followed a hybrid banded layout mostly concentrated at the column strip region, except for a small group of tendons distributed at every 5 ft (1.5 m) outside of the banded regions as temperature tendons. In the least tendon layout concentration scenario, 20 tendons were concentrated at the column and only four tendons were distributed outside the column band, yielding average effective precompression stress values of 173 psi (1190 kN/m^2).

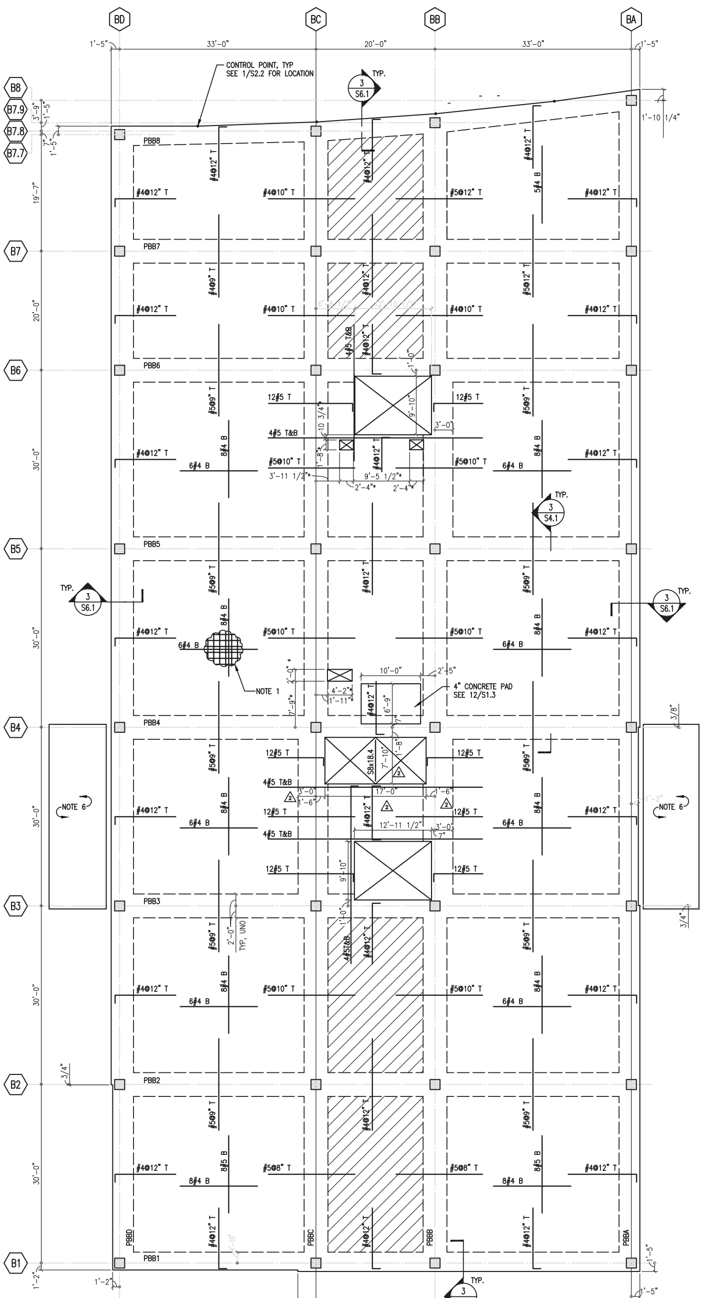

Fig. 9.2—Office example project plan view of framing and reinforcement.

Tendon concentrations over the column strip region did not lead to delamination issues even with PT forces exceeding 870 kip (3870 kN) in each direction. However, due to the heavy applied loads, the slab thickness was higher than what is typically used in buildings.

The following lists the parameters of design:

- Two-way slab with grid: 29.7 x 29.7 ft (9.1 x 9.1 m)
- Slab thickness: 14 in. (360 mm) with drop panel having a footprint of 10 x 10 ft (3.1 x 3.1 m) and tapered depth with a maximum of 31 in. (790 mm) at column
- Columns: 3 x 3 ft (0.9 x 0.9 m)
- SDL: varied from 40 to 95 lb/ft^2 (1.9 to 4.6 kN/m^2)
- LL: varied from 100 to 600 lb/ft^2 (4.8 to 28.7 kN/m^2)
- Unbonded 0.6 in. (15 mm) low-lax strands
- Precompression stress: 24 x 0.6 in. (15 mm) cables per typical bay; approximately 173 psi (1190 kN/m^2)
- Layout configuration: banded in both directions, with temperature tendons mid-bays in one direction
- Profile: partial parabola
- Reinforcing bar: bottom mesh of No. 3 at 6 in. (150 mm) on center; top bar at columns per code requirements; no top mesh[7]

10. RESEARCH TESTING PROGRAM

A research testing program was conducted at Virginia Polytechnic Institute and State University, where several one-third-scale specimens of a prototype PT flat plate were cast and then tested for serviceability and strength, and some of the specimens were loaded to failure. The specimens were subjected to uniform dead and live loading conditions. The prototype slab is based on a 9 in. (225 mm) thick, two-way PT flat slab comprised of three bays in one direction, and three bays with a cantilever in the other direction, like the test slab shown in Fig. 2.2 and 2.3. Each bay is 30 x 30 ft (9.1 x 9.1 m), which is a span length typically found in high-rise construction, and the cantilever is 7.5 ft (2.3 m).

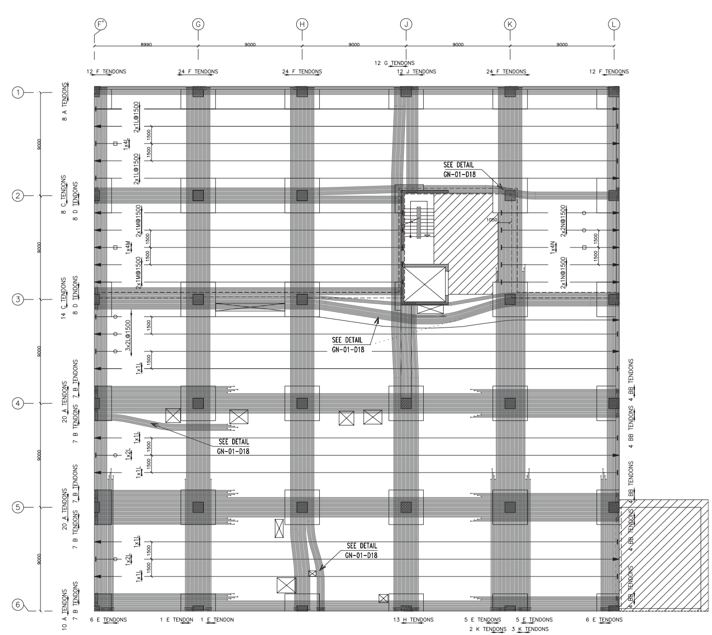

Fig. 9.3—Heavy loads example—project plan view of tendon distribution.

The research involved testing the behavior of otherwise analogous specimens using different tendon layouts and types of reinforcement. To validate the performance and determine if and how the tendon layout influences the behavior of the slab, one-third-scale specimens with a distributed-banded tendon layout (control specimen) were compared to like specimens with a banded-banded (dual-banded) tendon layout.

The details and results of the research are published in a separate report and are not included in this document. The testing was very successful and showed that the performance of the PT slabs with either tendon configuration was very comparable. The slabs met the serviceability and strength criteria, and the load at failure far exceeded the design factored load. The experimental results were also in agreement with the analytical models, which is important for the correlation between design and actual expected behavior.

Comparisons were made, both analytically and experimentally, between the banded-distributed and banded-banded layout, and the analytical and experimental results were very similar in behavior. Because both extremes were studied and tested, it is reasonable to expect that any variation of tendon spacing in between should also yield comparable results.

11. SUMMARY

The traditional distributed-banded tendon layout has been successfully implemented for over 40 years. However, there are considerable design and construction-related advantages that can be realized using a dual-banded scheme. Freedom of tendon group spacing, thus also allowing additional flexibility in slab penetrations, will expose post-tensioned (PT) concrete to additional markets and may increase the efficiency of current slab systems. Analysis has shown that a dual-banded tendon configuration is viable and efficient. This investigation has revealed favorable service stresses with minimal change to strength level capacity compared to a distributed-banded layout. Until further research is performed, adding a small amount of nonprestressed reinforcement in the middle region of the panels is prudent to ensure a quality system. Additional analytical and scale-model laboratory tests are required so that future ACI 318 provisions may explicitly specify a dual-banded tendon configuration in design. A very strong and promising future is shown for concrete slab systems reinforced with a dual-banded tendon configuration.

12. REFERENCES

1. ACI Committee 318, "Building Code Requirements for Structural Concrete (ACI 318-19) and Commentary (ACI 318R-19) (Reapproved 2022)," American Concrete Institute, Farmington Hills, MI, 2019, 624 pp.
2. International Code Council, "2021 International Building Code (IBC)," ICC, Country Club Hills, IL, 2021.
3. Joint ACI-ASCE Committee 423, "Tentative Recommendations for Prestressed Concrete Flat Plates," *ACI Journal Proceedings*, V. 71, No. 2, Feb. 1974, pp. 61-71.
4. Burns, N. H., and Hemakom, R., "Test of Scale Model Post-Tensioned Flat Plate," *Journal of the Structural Division*, ASCE, V. 103, No. 6, June 1977, pp. 1237-1255.
5. Bondy, K., "Banded Tendons in Flat Plates," Seminar Proceedings, Structural Engineers Association of Southern California, North Hollywood, CA, 1985.
6. Hemakom, R., "Strength and Behavior of Post-Tensioned Flat Plates with Unbonded Tendons," PhD dissertation, The University of Texas at Austin, Austin, TX, 1975.
7. Hemakom, R., "Behavior of Post-Tensioned Concrete Flat Slabs with Unbonded Reinforcement," MS thesis, The University of Texas at Austin, Austin, TX, 1970.
8. Winter, V. C., "Test of Four Panel Post-Tensioned Flat Plate with Unbonded Tendons," research paper, The University of Texas at Austin, Austin, TX, 1977.
9. Burns, N. H., and Hemakom, R., "Test of Post-Tensioned Flat Plate with Banded Tendons," *Journal of Structural Engineering*, ASCE, V. 111, No. 9, Sept. 1985, pp. 1899-1915.
10. PTI Committee DC-20, "Design of Post-Tensioned Slabs Using Unbonded Tendons (PTI DC20.8-04)," Post-Tensioning Institute, Farmington Hills, MI, 2004, 82 pp.
11. ACI Committee 318, "Building Code Requirements for Structural Concrete (ACI 318-11) and Commentary (ACI 318R-11)," American Concrete Institute, Farmington Hills, MI, 2011, 503 pp.
12. *fib* Bulletin No. 31, "Post-Tensioning in Buildings," International Federation for Structural Concrete, Lausanne, Switzerland, 2005, pp. 43-48.

POST-TENSIONING INSTITUTE
Strength in Concrete

38800 Country Club Drive,
Farmington Hills, MI 48331

www.post-tensioning.org

+1 (248) 848-3180

technical.inquiries@post-tensioning.org