Guidelines for the Design of Post-Tensioned Floors

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This article presents a set of guidelines intended to assist designers in routine post-tensioning design, beginning with a discussion of the initial decisions that must be made to design post-tensioned floor members. We then provide a set of recommendations, derived from industry practice, which have yielded economical designs with good in-service performance. Where applicable, we based the guidelines on ACI 318-02[1] and IBC 2000.[2]

For the purpose of this article, we have assumed that the design engineer is familiar with the concept and application of post-tensioning. There are a number of good references on the topic of post-tensioning.[3-5] We have further assumed that the design engineer knows both the geometry of the structure and the loading; this article discusses the design process that follows the determination of the structure's geometry and loading.

GUIDELINES

The guidelines presented in this article result from more than 20 years of extensive and varied design experience in post-tensioning, including considerable review of designs by other engineers. Based on the observed performance of structures built in accordance with these guidelines, we know the guidelines lead to safe structures with good in-service performance. We hope that the guidelines will assist design engineers in the selection of the various design parameters. Choosing appropriate values for the various design parameters is particularly important for engineers using the Finite Element Method (FEM) in their designs because the current FEM technology requires that the engineer lay out the tendons, including the shape and force of each tendon, before a solution can be obtained.

These guidelines apply to typical buildings and parking structures. Special loading conditions or unique geometries may require values other than those specified in this article. In addition, local practice, availability of material, or the contractor's equipment and skill may sometimes make other alternatives more economical or efficient.

Decisions required for the preliminary design of a floor system that are not discussed in this article, but are covered in other literature, include establishing slab and beam dimensions and concrete cover. The Post-Tensioning Institute (PTI) Design Manual[6] gives recommended span-to-thickness ratios for slabs and span-to-depth ratios for beams.

Cover is determined from the requirements for corrosion protection, fire protection, and wear. ACI 362[7] and ACI 423.6[8] give recommendations and requirements for post-tensioning systems intended for use in aggressive (corrosive) environments. The IBC, ACI 318-02, and ACI 423.3[9] provide information on cover requirements for corrosion and fire protection. Additional cover for wear is discretionary; it is sometimes specified for structures such as parking garages where abrasion may result in excessive wear.

POST-TENSIONING SYSTEMS

In the U.S. and Canada, post-tensioned buildings and parking garages are typically constructed with seven-wire, 0.5-in.-diameter (12.7 mm), unbonded single-strand (monostrand) tendons. These tendons, with a typical strength of 270 ksi (1860 MPa), are also greased and sheathed. One reason for the widespread use of the 0.5-in.-diameter strand is the Code requirement that the tendon spacing not be greater than eight times the slab thickness. The use of 0.5-in.-diameter, 270 ksi (1860 MPa) strand permits 4.5- and 5-in.- thick (110 and 125 mm) slabs to meet both the minimum 125 psi (0.85 MPa) average precompression and the maximum tendon spacing requirement. In addition, the tendons and stressing equipment are light enough for workers to handle them efficiently on site. Larger diameter (0.6 in. [15.3 mm]) strands are primarily used in pretensioning and bridge construction. Higher strength steels and smaller diameter strands are also available but are not commonly used for new construction.

STRUCTURAL MODELING

In both one- and two-way systems, specifying the structural model includes defining the design strips, irrespective of whether an FEM or Equivalent Frame Method of analysis is used.[10] The distinction between one- and two-way systems is important because the design requirements in ACI 318-02 are different for the two systems. Column-supported floors generally qualify as two-way systems; beam- and wall-supported slabs and beams generally qualify as one-way systems. For a detailed discussion of one- versus two-way systems, refer to Aalami.[11]

The fixity of the connections must also be specified. In some instances, such as corner columns in flat slabs, and strong beam/weak column connections at the upper levels of one-way slab and beam construction, the assumption of full fixity does not yield a satisfactory design. For structural analysis, such connections may be assigned partial fixity or may be assumed as hinged connections (releases). Connections that are assumed to be hinged must be detailed in the construction documents to allow rotation, while retaining the integrity of the joint by limiting crack width and transfer of axial and shear forces through the joint. Another instance where a hinge connection may be beneficial is for short gravity columns at split levels in parking structures, which have a ramp on one side and a level floor on the other side.

INITIAL DECISIONS

There is a major difference between the design of a post-tensioned member and the design of a conventionally reinforced concrete member. Once the geometry, loading, support conditions, and material properties of a conventionally reinforced member (Fig. 1(a)) are established, a unique solution of the required area of reinforcement, A_s, is given by a formula. For a post-tensioned member (Fig. 1(b)), however, there are a number of acceptable reinforcement designs because there are several additional parameters that must be specified by the engineer. These parameters may be grouped as follows:

- Average precompression (prestressing force);
- Percentage of load to balance (uplift due to tendon drape); and
- Tendon profile (shape and drape).

From the many possible design solutions for a post-tensioned member, the one that meets the Code requirements for serviceability and strength and is the least expensive to build is usually the preferred solution. Generally, for a given slab dimension, loading, and construction method, less material means a more economical design. There is a unique value for the design moment, M_u, for the conventionally reinforced beam shown in Fig. 1(a), which leads to a unique value for the required area of steel, A_s. For the post-tensioned alternative shown in Fig. 1(b), the design moment includes secondary (hyperstatic) effects and is thus a function of the post-tensioning. Values for the three parameters listed previously must be established before the required amount of post-tensioning can be determined. The amount of supplemental reinforcement, A_s, required for strength design of the post-tensioning member is determined by the amount of the post-tensioning reinforcement and the reinforcement profile.

Average precompression

The average precompression is the total post-tensioning force divided by the gross cross-sectional area normal to the force. ACI 318-02 requires a minimum of 125 psi (0.85 MPa) effective precompression (precompression after all prestress losses).

In general, 125 psi (0.85 MPa) should be used for the initial average precompression. For roofs and parking structures, use 150 to 200 psi (1.0 to 1.4 MPa) if watertightness or cracking is a concern. Bear in mind, however, that an increase in precompression does not guarantee watertightness and may not completely eliminate cracking. To avoid leakage, the increased post-tensioning must be supplemented by other measures, such as a membrane overlay. In stemmed structures, such as one-way slab and beam construction, the entire cross-sectional area of the member should be used when computing the average precompression.

Figure 2(a) shows the tributary for axial loading. This is further explained in the section on anchor locations. (In one-way slab and beam construction, the member is defined as the beam and its tributary slab area.) Maximum precompression should be 275 psi (2.0 MPa) for slabs and 350 psi (2.50 MPa) for beams; although the Code's limit of maximum compressive stress is much higher, values higher than these typically mean the design will be less economical.

Percentage of load to balance

Post-tensioning is typically thought of as a system of loads that counteracts the dead load of the structure. This is expressed as the ratio (percentage) of the dead load that is balanced. For slabs, it is customary to balance between 60 and 80% of the dead load. For beams, this is usually increased to between 80 and 110%.

One reason for higher balanced loading for the beams is that beam deflection is more critical to service performance of a floor system. To determine the required post-tensioning force, start with the critical span—generally, this is the longest span (in Fig. 3, this would be the first span). Using the maximum permissible tendon drape in this span as one limiting criterion, and the minimum precompression as the other, determine a post-tensioning force to balance the desired percentage of the dead load.

For the spans adjacent to the critical span, a lower percentage of the dead load should generally be balanced because less upward force in an adjacent span helps to reduce the design values of the critical span. The preferred means of accomplishing this is to keep the tendon profile at its maximum drape and reduce the force because this reduces the amount of post-tensioning required. If it is not practical to reduce the tendon force, the tendon drape should be reduced. For the beam shown in Fig. 3, an economical design was obtained by balancing 60% of the dead load in the first span and reducing the post-tensioning to balance only 50% of the dead load in the second span. The tendon is straight (it has no curvature) in the third span so it does not balance any of the dead load. The design could actually have been improved by a tendon profile that exerted a downward force in the third span because the dead load of the structure tends to lift this span. In summary, balancing all the spans of a continuous member to the same percentage of dead load is not always economical.

In practice, tendon profiles are reversed parabolas; two such examples are shown in Fig. 4. Tendons thus exert both upward and downward forces in the same span. In such cases and for the purpose of design, the percentage of dead load balanced is considered as the sum of the upward forces divided by the total dead load (DL) on the span. For the design shown in Fig. 4, this becomes:

% of DL balanced = 100[(W2+W3)/DL]

Tendon profile: shape

For beam tendons and slab tendons in the distributed direction, a reversed parabola tendon profile with inflection points at one-tenth of the span length (Fig. 5) is typically used. For the banded direction, a partial parabola (Fig. 6) with a straight length of approximately 4 ft (1.2 m) over the supports is more practical for the tendon profile. This matches how the banded tendons will be placed over the columns; the tendons have a fairly flat profile over the top bars in the orthogonal direction.

Profile low points are typically set at midspan for both interior and exterior spans because this makes tendon layout easier for the placing crew. In terms of post-tensioning force efficiency, however, it is preferable if the low point in the exterior spans is closer to the

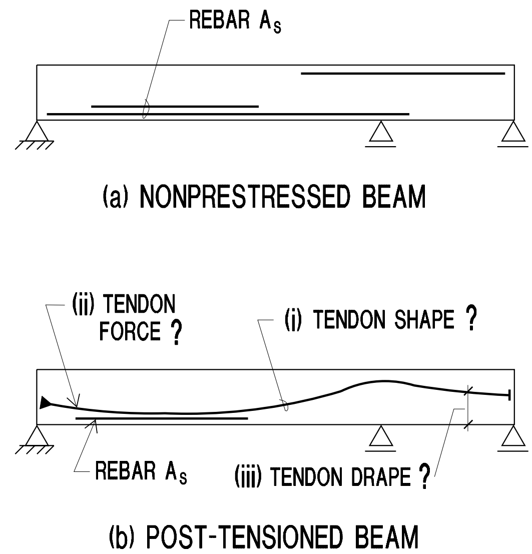

Fig.1: Schematic comparing a conventially reinforced concrete member to a post-tensioned membaer. Notice the assumptions required for the post-tensioned design

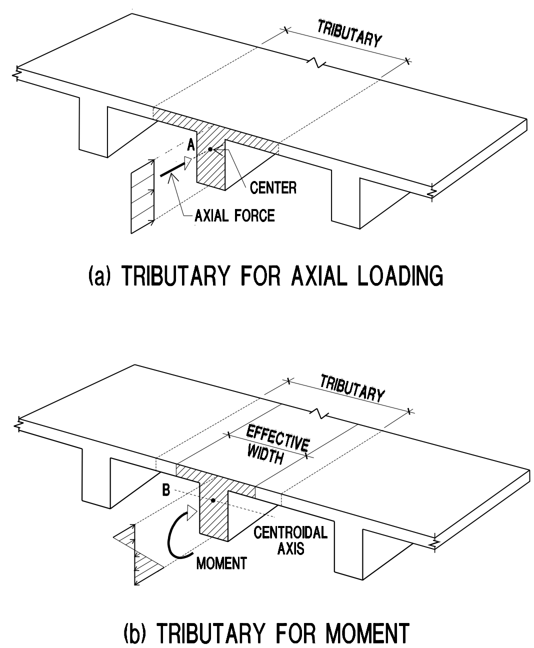

Fig.2: Tributaries used when computing average precompression stress for stemmed members.

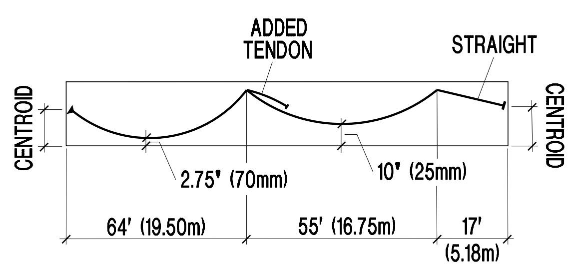

Fig.3: An example of a post-tensioning tendon profile for a member with unequal span lengths.

exterior of the building (approximately 40% of the span length [0.4L]). This is because, for an exterior span, the tendon is at the middepth of the slab at the slab edge and at its high point (typically somewhat higher than middepth) at the other end. Moving the tendon low-point to 0.4L results in a more uniform uplift over the exterior span, but the difference is usually small.

Tendon profile: drape

The high point of the tendon profile should be as close to the top surface of the member as practical, allowing for clearance and reinforcement in the orthogonal direction, if necessary. At the low point of the profile, it is best to place the tendons as close to the soffit of the member as allowable, to take full advantage of the uplift and contribution to strength that the tendon can provide. This arrangement is possible for the critical spans in a continuous member, but may need to be adjusted for other spans. As suggested previously, if using the maximum drape results in excessive uplift in a span other than the critical span, the first choice should be to reduce the prestressing force. If this is not practical, raise the tendon at midspan to reduce the drape (second span of Fig. 3). When selecting tendon heights, use intervals of 0.25 in. (5 mm) for construction purposes. Keeping the tendon high point fixed conforms with the placement of nonprestressed reinforcement at the maximum height over the supports.

Tendons along and over interior walls should be laid out flat (without profile) at their high point (Fig. 7). Continuous wall support eliminates the necessity of

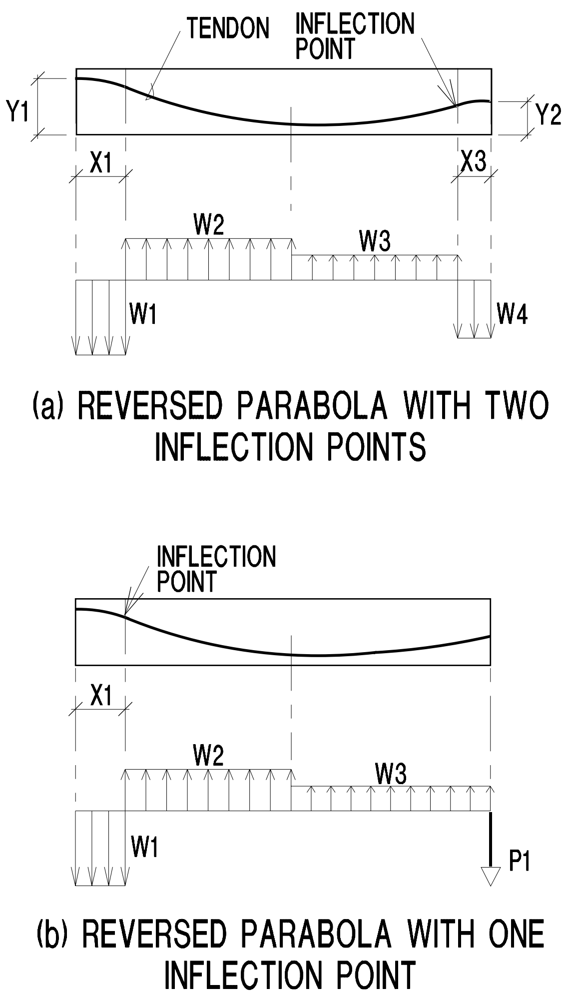

Fig.4: Two Examples of the post-tensioning tendon profile shape, a reversed parabola. With such a profile, tendons exert both an upward and a downward force in the same span

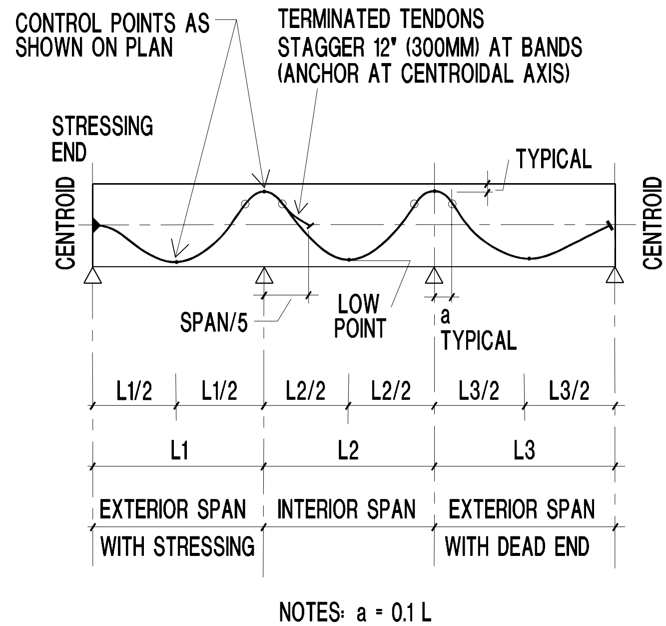

Fig.5: For tendons in the distributed direction of beams and slabs, the tendon profile is a reversed parabola with inflection points at one-tenth the span length

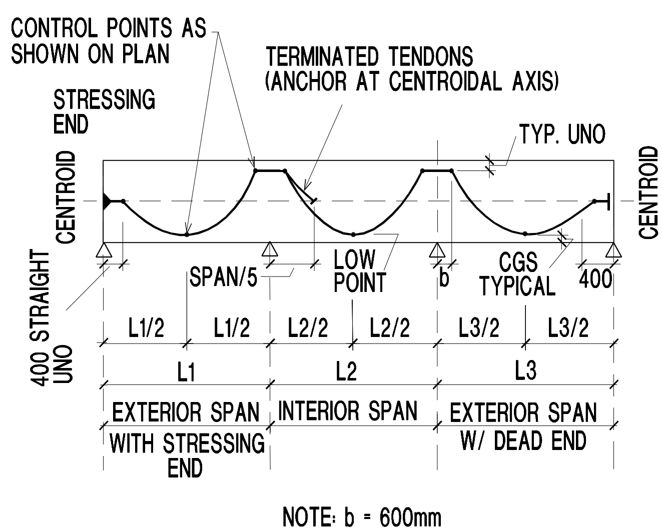

Fig.6: In the banded direction, the tendon profile is a partial parabola with a straight length of about 4 ft (1.2 m) over the supports

profiling a tendon for uplift. Placing the tendon at the high point is best suited to resist negative moments typical over wall supports.

Likewise, tendons along exterior walls should be placed flat and anchored at the centroid of the slab in the first span (shown in Fig. 8(a)). Tendons should be anchored at the centroid of the slab even if there is a transverse beam or drop cap/panel at the slab edge (Fig. 8(b)). Tendons anchored eccentric with respect to the centroid of a member result in a moment in addition to precompression. The option of eccentric anchoring should be used only if the impact of the added moment is recognized in design.

Similarly, banded tendons along an interior wall may all be placed flat and at their high point, either over or adjacent to the wall. Distributed tendons parallel to an interior wall should be placed flat and at their high point over a fraction of their tributary as indicated in Fig. 7(b). The remainder of the distributed tendons can be transitioned by gradual modification of their low point to follow the profile of adjacent design strips.

Tendons along continuous exterior walls are generally selected to provide a nominal precompression over the tributary of the exterior wall equal to that used for the rest of the slab. The function of post-tensioning in this case is to provide a precompression compatible with the rest of the floor system to improve the in-service performance of the floor system.

ANCHOR LOCATIONS

Tendons in stand-alone beams (beams not cast monolithically with the slab) should be anchored at the centroid of the beam. Tendons in flanged beams, such as in one-way slab and beam structures, should be anchored at the centroid of the combined beam stem and its tributary (Fig. 2a). As discussed in the following, however, a beam's "tributary" is not the same as its

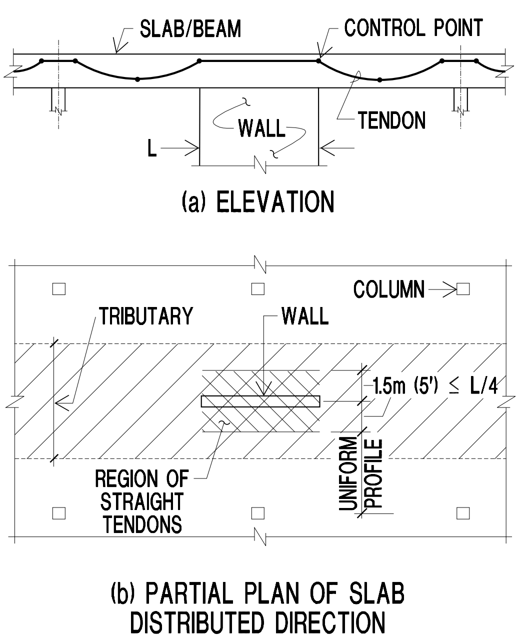

Fig.7: Tendons along or over interior walls should be laid flat (without profile) at their high point.

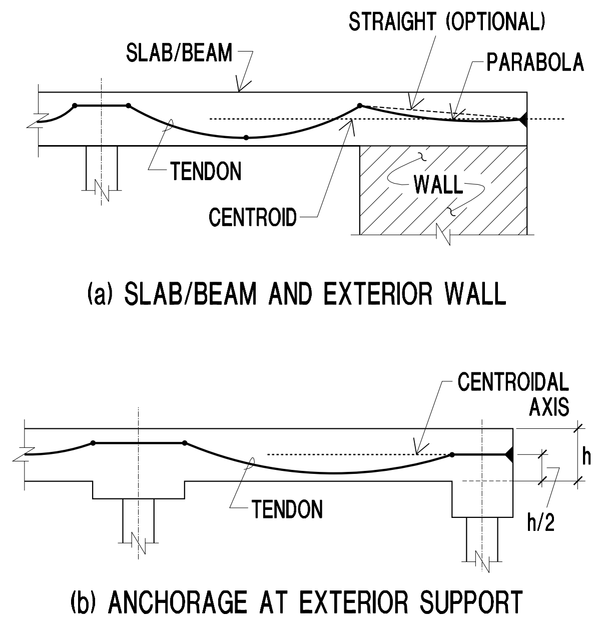

Fig.8: Tendons along exterior walls should be placed flat and anchored at the centroid of the slab in the first span

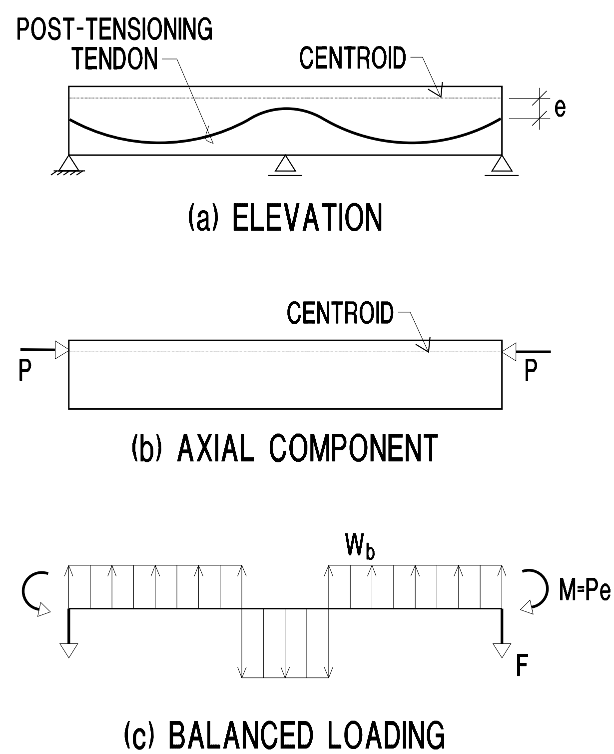

Fig.9: Flanged beam under uniform precompression from an axial force *P* and balanced loading from other force components causing bending of the member.

"effective width for bending." Consider the flanged beam shown in Fig. 9(a). In the traditional load-balancing analysis used by most designers, the force in the tendons, generally considered constant, is represented by an axial force, *P*, at a location that results in "uniform precompression" (Fig. 9(b) and Fig. 2(a)) and other force components that cause bending of the member (Fig. 9(c)). Regardless of the shape of a cross section, if a force is acting at the centroid of a member, it will disperse into a uniform compression at a distance "sufficiently far" from the point of application of the force (in this case, the ends of the member). Flanged beams are no exception to this phenomenon.

For dimensions typically used in building construction, for example, a one-way slab and beam parking structures, the dispersion of the tendon force into a uniform compression across the member's entire tributary occurs at a distance approximately equal to the beam spacing (the force disperses at approximately a 45 degree angle) (Fig. 10). Therefore, at a distance of one beam spacing away from the beam end, the force across the entire tributary is uniform. In other words, tendons placed in the beam stem create a uniform force across the entire beam-slab cross section. In the upper portion of Fig. 10, the precompression is shown at two sections—one next to the beam end (high peaks) and one at midspan. The distribution at midspan is uniform. The lower half of the figure shows the contour of precompression in the direction of the beams. The dispersion of precompression into a uniform distribution is evidenced by the single contour region at the interior of the slab.

Another noteworthy observation of Fig. 9 is that the axial component and its impact (uniform precompression) are independent of tendon profile and position of anchors at the beam ends. It is the balanced loading (Fig. 9(c)), and consequently the bending effects, that depend on the tendon profile and position of its anchors.

Note that the previous discussion does not apply to precast pretensioned beams with topping slabs. In pretensioned beams, the entire force is locked into the beam stem. The small diffusion of prestressing into the slab due to creep is not treated in this article.

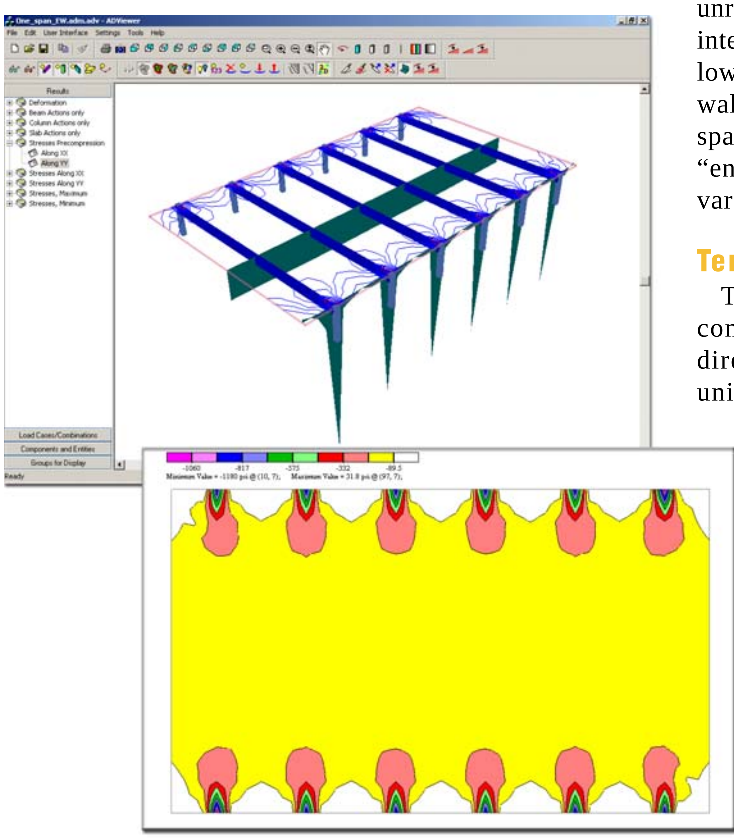

Fig.10: A computer model shows, in a one-way slab and beam configuration, the dispersion of the tendon force into unifrom compression across the member's tributary at a distance equal to the beam spacing

ADDITIONAL CONSIDERATIONS

Cover for fire resistance

When determining fire ratings, designers typically consider the end spans in column-supported structures unrestrained. To achieve fire resistance equal to that of interior spans, provide a larger cover for tendons at the low point of exterior spans unless the end support is a wall or transverse edge beam. Only the first and last spans of tendons along a slab edge are considered as "end spans." IBC gives the minimum cover for the various fire ratings.[2]

Tendon layout

The preferred tendon layout for two-way slabs is to concentrate the tendons over the supports in one direction (the banded tendons) and distribute them uniformly in the other direction (the distributed tendons).[6, 12, 13] Typically, banded tendons should be placed in the long direction of the slab. This minimizes the number of wedge-shaped regions between the bands where additional reinforcement will be necessary due to insufficient precompression. If the supports in the short direction do not line up, however, place the banded tendons in the short direction. Place the distributed tendons in the orthogonal direction, parallel to one another, making sure that a minimum of two tendons pass over each support as required by ACI 318-02.

Tendon stressing

Most engineers in North America design with final effective forces—the post-tensioning forces after all prestress losses. The post-tensioning supplier determines the number of tendons required to provide the force shown on the structural drawings, based on the effective force of a tendon. The effective force of a tendon is a function of a number of parameters, including the tendon profile, certain properties of the concrete, and the environment. For typical designs, however, a constant force of 27 kips (120 kN) may be assumed for 0.5 in. (12.7 mm) unbonded tendons, provided the following stressing conditions are met:

- Tendon length (length between anchorages) is less than 240 ft (72 m);
- Tendons less than 120 ft (36 m) long are stressed at one end; and
- Tendons longer than 120 ft but less than 240 ft are stressed at both ends.

Tendons that do not meet these conditions may be used, as long as the assumed effective force is lowered to account for the higher friction losses.

Selection of nonprestressed reinforcing bar size

To take full advantage of the maximum lever arm for reinforcement in both directions, the top bar diameters should match those of the adjacent tendons. Thus, it is reasonable to use No. 5 (16 mm) bars over the supports—a sheathed 0.5 in. -diameter (12.7 mm) strand is slightly larger than a No. 5 (16 mm) bar. For bottom bars, it is better to use smaller bars, such as No. 4 (12 mm) bars, for the distributed tendon direction because these are distributed uniformly among the tendons, and larger bars for the banded tendons because bars for the banded direction are normally grouped together and placed within the band width.

CONCLUDING REMARKS

For a given member geometry, support conditions, and loading, the design of a post-tensioned member depends on three parameters which need to be established by the design engineer: the average precompression, the percentage of load to balance, and the tendon profile. This article presents a set of guidelines to assist the design engineer in selecting values for these parameters. The guidelines reflect industry practice for economical designs and based on observed performance, lead to safe structures with good in-service performance.

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