Tips for Post-Tensioning—Part II

Design of two-way slabs in buildings

by Donald Kline

Dan Falconer’s “Tips for Post-Tensioning,” was first published in the February 1988 issue of Concrete International, and its guidance is still relevant today. Since those tips were printed, however, there have been changes in the ACI 318 Code, advancements have been made in the software programs used for design, and additional experience has been gained with the performance of post-tensioned (PT) structures. In the current article, I provide additional tips that reflect some of these developments. In addition, the current article broadens the scope of the tips from the first article’s focus on parking structures to include two-way slabs that are typically found in buildings. For completeness, Falconer’s article is reprinted in this edition. As a tribute to Falconer and his contributions to the post-tensioning industry, my hope is that the two articles will help maintain the status of post-tensioned concrete buildings as systems that offer economical and efficient use of materials and exceptional serviceability and durability.

Use Encapsulated Tendons for All Buildings

Encapsulated tendons should be specified on all PT buildings. ACI 318-14 references ACI 423.7-14, “Specification for Single Strand Unbonded Tendon Materials,” which requires that encapsulated tendons be used for all applications. An encapsulated tendon is defined as a tendon that is completely enclosed in a watertight covering from end to end, including anchorages, sheathing, post-tensioning coating, sleeves, and an encapsulation cap over the strand tail at each end. Even if the local building code governing your project does not yet reference ACI 318-14, I recommend specifying encapsulated tendons in anticipation of this change. The added cost is negligible relative to the overall cost of the structure, and so it is good practice to ensure this high level of quality. PT slabs-on-ground, which are common in some areas of the country, are not covered by ACI 318-14 and are therefore exempt from this requirement.

Use Load Balancing as a Design Tool

The load balancing method of analysis is perhaps the most powerful tool at the disposal of an engineer who designs prestressed structures—not because he or she will use the method for routine designs, but because the method provides a simple way of checking prestressed members using hand calculations (refer to the sidebar).

Since the concept of load balancing was first introduced by T.Y. Lin, the method has been recognized as elegant in that it is intuitive and easy to understand, but powerful in that it can be used to design complex systems. Fundamentally, this method seeks to remove the prestressing strands from the structural member and replace them with a set of equivalent forces that act on the member. In a traditional design, the equivalent forces act in a direction that is opposite the applied loading on the member; hence, it is possible to “balance” a portion of the applied loads with the equivalent prestress forces, sometimes referred to as the “balanced load” (Fig. 1).

There is no specific code requirement on the percentage of load that should be balanced with post-tensioning, and I do not recommend using a prescribed percentage as design criterion. However, experienced engineers do recommend checking the balanced dead load percentage during design of a member because this can provide insight into the efficiency and reliability of the design. Balanced loads exceeding 100% dead load are often acceptable and even desirable, as long as the design is serviceable and code-compliant. However, I have seen instances where designers have attempted to balance more than 300% of the dead load in some spans—this is a sure bet for failure during stressing. For transfer members such as transfer girders, transfer plates, and podium slabs, it is not unusual to have balanced loads that exceed 150% of the dead load. These cases can be complex and it is vital that the engineering team pay close attention to initial stresses, service load stresses, initial and long-term deflections, and detailing of reinforcing steel. In many transfer members, it is necessary
to stage stress (that is, stress the member at successive intervals as load is being added to the member).

Just as overbalancing may be an indicator that the slab or beam does not have adequate thickness or depth, under-balancing may be an indicator that the member depth is overly conservative. Again, checking the percentage of dead load that is balanced is an important tool that is used to refine and verify the design.

For typical slabs in buildings, I recommend using the values in Table 1.

**Rules for Average Prestress**

Average prestress is defined as $P/A$, where $P$ is the final effective prestress force after losses and $A$ is the cross-sectional area of the member (or design strip for two-way slabs). It is important to maintain $P/A$ within certain defined limits. Some limits are code imposed and some are based on design experience. Minimum $P/A$ for two-way slabs is 125 psi (0.875 MPa) as mandated by ACI 318-14, Section 8.6.2.1. Maximum $P/A$ is not code mandated; rather, it is a function of what is achievable from a practical standpoint. Too much prestress can lead to congestion and challenges fitting anchorages and anchorage zone reinforcement in the member. Too much prestress will also increase long-term prestress losses. In my opinion, however, the biggest challenge with too much $P/A$ is increased shortening of the slab, which can lead to other challenges such as cracking due to restraint to shortening (RTS). I have developed the set of guidelines for $P/A$ listed in Table 2.

The maximum $P/A$ values in Table 2 should be general guidelines for typical building structures that will provide reasonable results. They are not meant as absolute maximum values, as there will be occasions when it is necessary and desirable to go above these values.

**Sweeping Tendons Laterally**

One of the biggest advantages of PT flat plates is the fact that they can be designed and built with an irregular arrangement of supporting columns and/or openings. Such systems can make it necessary to sweep tendons laterally to catch all of the columns and to get around slab openings. Tendons with lateral curvature at low points have a tendency to blow out the bottom of the slab—either immediately upon stressing or many years later. It is vital that the designers recognize this risk and ensure that hairpin reinforcing is installed at these locations. The PTI Manual, Sixth Edition,6 provides instructions for proper detailing at these locations (refer to Fig. 2).

**Check Tendon Profiles at Slab Folds**

Slab folds occur any time there is a change in the top-of-slab elevation. Often, it is desirable to run post-tensioning tendons continuously through the fold, but it is important to check the tendon profile at critical points. It is not uncommon to see a theoretical tendon path falling outside of the slab at

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**Table 1:**

<table>
<thead>
<tr>
<th>Building type</th>
<th>Balanced load, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apartments, condominiums, and hotels (Live load = 40 lb/ft²)</td>
<td>40 to 70</td>
</tr>
<tr>
<td>Office buildings (Live load &gt; 75 lb/ft²)</td>
<td>50 to 80</td>
</tr>
</tbody>
</table>

Note: 1 lb/ft² = 0.00005 MPa

**Table 2:**

<table>
<thead>
<tr>
<th>Structure type</th>
<th>Minimum $P/A$, psi</th>
<th>Maximum $P/A$, psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parking garage slab (Zone II and III)</td>
<td>175</td>
<td>300</td>
</tr>
<tr>
<td>Parking garage slab (Zone I)</td>
<td>125</td>
<td>300</td>
</tr>
<tr>
<td>Parking garage beam (Zone II and III)</td>
<td>200</td>
<td>500</td>
</tr>
<tr>
<td>Parking garage beam (Zone I)</td>
<td>125</td>
<td>500</td>
</tr>
<tr>
<td>Building slab</td>
<td>125</td>
<td>300</td>
</tr>
<tr>
<td>Building beam†</td>
<td>125</td>
<td>500</td>
</tr>
<tr>
<td>Building transfer girder†</td>
<td>200</td>
<td>700</td>
</tr>
</tbody>
</table>

†Refer to Reference 5 for definitions of Zones I, II, and III

†When calculating $P/A$ for beams and girders, the cross-sectional area is based on the effective flange width chosen by the designer

Note: 1 psi = 0.007 MPa
the fold—clearly, a situation to be avoided (refer to Fig. 3). But, it is just as important to examine locations where reverse curvature with minimum cover could lead to blowouts during stressing. Figure 4 shows an example where a blowout occurred in a slab fold sometime after stressing. The reason for the failure was that the tendon was positioned as shown in Fig. 5(a). Where such folds occur, it is good practice to graphically lay out the tendon profile within the slab fold to determine if adjustments are required either in the tendon profile or in the concrete geometry.

Rules for Sizing Drop Panels in PT Flat Slabs

Drop panels at columns are often used to increase flexural and shear capacity in non-prestressed two-way slabs. Most engineers are familiar with the limitations on the size of drop panels in such slabs. ACI 318-14, Section 8.2.4, has the following two qualifications:

- Depth of the drop panel must be at least 1/4 of the slab thickness away from the drop panel; and
- The drop panel must extend 1/6 of the span length from center of support in each direction.

It is important to note, however, that these limitations do not apply for prestressed slabs. This allows the designer tremendous flexibility in sizing of drop panels to increase negative moment capacity and reduce non-prestressed reinforcement over the columns. For example, one need not design large drop panels that are 1/6 of the span length in each direction to take advantage of the increased section for flexure.

I recommend that the depth of the drop below the slab soffit be at least 4 in. (100 mm), which is the nominal depth of a 2 x 4 plus 3/4 in. (19 mm) plywood sheathing (plyform). The depth of the drop should be increased if required to increase punching shear capacity. I further recommend using a minimum drop panel size of 4 x 4 ft (1.2 x 1.2 m) in plan. The size of the drop should be increased if necessary to increase flexural or punching shear capacity and fit shear reinforcement within the dimensions of the drop.

Use Caution with Finite Element Design Software

Finite element (FE) design software can be incredibly useful in the design of PT concrete structures, particularly for...
complicated slabs. But be aware that overreliance on FE software could result in bad designs and poor quality drawings. Also be aware that too much post-tensioning can be just as detrimental as not enough post-tensioning. Design of prestressed members is unique in that it involves an iterative procedure between design and analysis that requires interaction between the designer and design software to converge on an acceptable solution. As should always be the case, but particularly when using software options that produce a structural framing plan with post-tensioning and reinforcing steel called out, have an experienced designer review all results and drawings.

Mitigate RTS

Although this topic was also covered in Falconer’s article, I believe it should be repeated here. RTS is the source of the majority of the problems—both aesthetic and structural—that arise in new PT concrete buildings. Stiff vertical elements such as columns and walls have a tendency to restrain shortening caused by short term (elastic) and long-term (creep) responses to compression stress as well as drying shrinkage. RTS can have two potentially detrimental effects on a structure:

1. The fundamental assumption that the member is in a state of compression due to the prestress force ($P/A$) may be negated. This effect (sometimes referred to as hyperstatic tension\(^8\)) can have a significant effect on the service load stresses in the member and should be accounted for in the design; and
2. Tensile stresses in the member can lead to cracking. If the prestressing steel is unbonded (the vast majority of buildings use unbonded tendons), then any crack that forms will tend to be large in terms of crack width.

It is critical to evaluate the design in terms of potential for restraint and include measures to mitigate such effects. While strategies for mitigating RTS are beyond the scope of this article, the reader is encouraged to review the guidance provided in References 9 and 10.

**Practical Hand Calculations for Post-Tensioning**

While reliance on computer software for design of prestressed concrete members is nearly universal, it is possible to design these members using hand calculations. After all, this is how buildings were designed before the proliferation of computers. It is important for the design engineer to be able to perform hand calculations to check a design or even to make a last minute tendon adjustment in the field before a placement. So how is this possible? The answer lies in the load balancing method together with Eq. (1).

\[
\text{w}_{\text{pre}} = \frac{8P}{l^2} \alpha
\]

where $\text{w}_{\text{pre}}$ is the balanced load due to prestress, kip/ft (kN/m); $P$ is prestress force, kip (kN); $l$ is span length, ft (m); and $\alpha$ is tendon drape defined in the figure, ft (m).

Note: 1 in. = 25 mm; 1 ft = 0.3 m; 1 kip = 4.45 kN; 1 kip/ft = 14.6 kN/m

Equation 1 provides a simple and elegant way to perform preliminary design or to check a design to ensure that it is reasonable. Clearly, once the tendon force and profile are established, the design must be checked against all of the serviceability and strength requirements in the Code. But it can be shown that for members that are sized using customary span-depth ratios and that are subjected to typical superimposed dead and live loads, Eq. (1) will provide a reasonable solution. Be advised, however, that this equation does not apply for cantilevers or for spans with harped tendons. Also, it is not advisable to use Eq. (1) for designing transfer members, including podium slabs. As can be seen in the previous example, Eq. (1) is one of the most useful tools at the disposal of an engineer designing PT concrete.
Summary

The “tips” presented in this article are those I consider most useful for designers (whether novice or experienced) of PT concrete buildings using unbonded tendons. The tips provided in Dan Falconer’s article covered PT parking structures and are still relevant to designers today. The tips provided in the current article are focused primarily on two-way slabs that are typically found in buildings. Although mastering these topics in design of prestressed concrete will go a long way toward ensuring a successful project, this article cannot and does not provide a complete checklist of things to watch out for in design. It is therefore crucial that all designs be overseen by a licensed design professional who has significant experience in design of PT concrete structures.

References
2. ACI Committee 318, “Building Code Requirements for Structural Concrete (ACI 318-14) and Commentary (ACI 318R-14),” American Concrete Institute, Farmington Hills, MI, 2014, 519 pp.

Selected for reader interest by the editors.

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