Effect of Post-Tensioning on Tolerances

Who is responsible for slab movements that produce tolerance issues?

by Bruce A. Suprenant and Ward R. Malisch
Post-tensioned, cast-in-place concrete buildings are becoming a dominant building type due to the benefits of using prestressing to balance a portion of the slab dead and live loads. One consequence of post-tensioning, however, is movement of the building frame as the slab and beams shorten under the post-tensioning forces. The magnitude of the movement depends on such factors as the structural design; the geometry of the building; and the locations of openings, walls, columns, and perimeter elements.

Based on conversations with contractors and measurements of four buildings that moved significantly after post-tensioning, the following typical movement magnitudes could be expected: horizontal movement of perimeter slab edges and exterior columns—about 3/4 in. (19 mm); vertical movement of slab surfaces—about 1/2 in. (13 mm); and vertical movement of balcony edges—about 3/8 in. (10 mm).

Because these movements occur days after the members have been placed, some interesting questions are raised:

- Does post-tensioning produce enough movement to cause a structure originally built within tolerances to be out of tolerance after the post-tensioning force is applied?
- Do current tolerance specifications include, or were they written to include, allowances for movements due to post-tensioning?
- Should compliance with tolerance specifications be established before post-tensioning? and
- If the final locations of building elements are found to be out of tolerance after post-tensioning, who is responsible?

**SLAB EDGE LOCATION**

In 1995, the Concrete Reinforcing Steel Institute (CRSI) addressed the issue of slab movements due to post-tensioning as follows:

The use of post-tensioning sometimes compounds the problems of trying to keep the edge of the building within acceptable tolerance...[Fig. 1] The usual procedure would be to cast the first lift columns, then cast the floor slab. Before tensioning the floor beams and slabs, it is likely that the 2nd lift of columns has been cast. The tensioning operation compresses the concrete and tends to pull the edges of the building toward the center or other stable location. The result may be the movement of the slab by as much as 3/4 in. (19 mm), pulling the first floor columns out of plumb and moving the 2nd lift of columns laterally by this amount. The casting of the 2nd slab and the 3rd lift of columns followed by the tensioning of the 2nd floor system moves the top of the 2nd lift of columns an additional 3/4 in. (19 mm) inward for a total movement of 1-1/2 in. (38 mm). As the building progresses, the offsets progress. A 10-story building could be off by as much as 7-1/2 in. (190 mm) unless corrective measures were taken. The common remedy is to anticipate the movement and lean the columns outward and build the slab edge beyond its desired location. Unfortunately, the movement does not always occur due to the level of the post-tensioning force or constraints in the building geometry. This is a condition where the Architect/Engineer should advise the Contractor of the anticipated movement so the Contractor can act accordingly.

The movement caused by post-tensioning can create serious problems during the installation of the exterior building envelope—particularly for curtain walls attached to the edges or spanning between floors, or for stucco finishes applied over masonry infill walls or concrete wall-columns (Fig. 2). If the building envelope subcontractor must perform remedial work, responsibility for the cost of the fix will be disputed.

A few concrete contractors who have had to pay for remedial work now lean the columns outward and also

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adjust the slab edges so they protrude beyond the building line. Based on their experience, they typically lean 10 ft (3 m) tall exterior columns about 1/2 in. (13 mm) toward the outside, then set forms for the slab edge about 1/2 in. (13 mm) outside the building line. After the slab is post-tensioned, the tops of the columns and the slab edges move toward the inside of the building enough to align vertically in the finished structure.

Some contractors, however, won't assume the risk involved in estimating slab edge and column positioning prior to stressing the post-tensioning strands. They don't have the structural design background needed for such an estimate, so they submit a request-for-information asking the structural engineer to determine this information. As stated by the CRSI report, the post-tensioning movement at each level depends on the design, building geometry, and layout of walls and columns. If estimated movements were included on the drawings, concrete contractors could better anticipate the care required to properly set the forms for columns and slab edges when bidding the project.

ACI 117-06, “Specifications for Tolerances for Concrete Construction and Materials and Commentary,” sets the slab edge location tolerance at ±1 in. (±25 mm). Post-tensioned exterior slab edge movements that approach the typical 3/4 in. (19 mm) magnitude mentioned previously can overwhelm the tolerance stated in ACI 117. This can leave the contractor only a small tolerance in one direction for a combination of field layout and edge form location.

Plan for exterior and interior column movement

As the perimeter of the slab moves inward, interior columns also move. When the lateral force-resisting system’s center of rigidity is at the center of the slab, movement of an interior column should be proportional to its distance from the center of the slab. For instance, consider a 200 ft (61 m) long slab with columns spaced at 20 ft (6.1 m). Using the CRSI estimate, the perimeter columns move in 3/4 in. (19 mm) and the interior columns adjacent to the perimeter move in (80 ft/100 ft) × 3/4 in. = 0.6 in. [(24.4 m/30.5 m) × 19 mm = 15 mm]. The next row of columns toward the center of the slab moves (60 ft/100 ft) × 3/4 in. = 0.45 in. [(18.3 m/30.5 m) × 19 mm = 11 mm], the next 0.30 in. (8 mm), and then 0.15 in. (4 mm), while the column at the center doesn’t move. Thus, if the interior columns are initially plumb, they can go out of plumb after post-tensioning. This doesn’t create the problem with curtain wall fit up that is

Fig. 2. Post-tensioned slabs (note patched pockets at tendon anchors) supported by wall-columns. Although the 2nd floor slab is reasonably flush with the 1st and 2nd floor wall-columns, the 3rd floor slab extends over the wall-column below. This is because the 1st floor wall-column, the 2nd floor slab, and the 2nd floor wall-column were all placed before the 2nd floor tendons were stressed. Once the 2nd floor slab was post-tensioned and shortened, the 3rd floor slab was laid out to plan location, creating an overhang relative to the 2nd floor wall-column. The 3rd floor wall-column is reasonably flush with the slab, however, as it was placed before the 3rd floor tendons were stressed.

Fig. 3: Two control lines on a post-tensioned slab; one was established by the concrete contractor prior to post-tensioning and the other by the general contractor after post-tensioning. Note that they are about 1/2 in. (13 mm) apart.
typical for exterior column movement, but interior partition finishes may be affected. If the interior column locations are critical to the work of other trades, the engineer should also indicate the relative positions of those columns prior to post-tensioning.

**Recheck control lines after post-tensioning**

Control lines snapped on the concrete slab to position columns for the next level will move when the slab is post-tensioned. The amount of movement depends on the post-tensioning force, the distance from the control line to stiff wall and column elements, and the distance from the control line to the center of the slab. If the concrete contractor needs to lay out new lines, the old lines must be marked out to avoid confusion about the correct column locations. In addition, other trades should not use the original control lines because they will no longer be at the correct location. Figure 3 shows two control lines that are about 1/2 in. (13 mm) apart. One control line was established by the concrete contractor during layout for the column forms. The other control line was established by the general contractor for the interior finish installers after the concrete had been post-tensioned.

**Case study**

Measurements of slab edge locations were made on the 4th floor of an eight-story building (Fig. 4). The 8 in. (200 mm) thick flat plate concrete floor slabs were post-tensioned in both directions. In the north-south direction, draped uniformly-spaced strands were spaced at 36 to 50 in. (0.91 to 1.27 m) on center. In the east-west direction, draped strands were banded at the column lines.

Both before and after post-tensioning, slab edge locations in the north-south and east-west directions were determined at the 46 points shown in Fig. 4. Treating the change in location for each direction separately, Fig. 5...
shows the frequency distribution of the absolute change in slab location. The maximum slab-edge movements were 7/8 in. (22 mm) inward and 1/2 in. (13 mm) outward. The average inward movement was 5/16 in. (8 mm), while the average outward movement was 3/16 in. (5 mm).

For this building, the maximum inward slab-edge movement is reasonably close to the 3/4 in. (19 mm) estimate included in the CRSI Engineering Data Report referenced previously. More importantly, the measurements verify that slab edge movement doesn’t always occur, as also stated in the CRSI report.

Movement will vary depending on the building geometry, design parameters, and concrete properties at the time the tendons are stressed. These factors could perhaps account for some of the apparent anomalies in the data, such as the small movement parallel to the long direction of the slab, but these factors weren’t evaluated. The contractor’s goal in collecting these data was simply to determine if slab movement was occurring and, if so, how much movement occurred.

It should also be noted that the contractor on this project set forms for slab edges at the locations indicated on the drawings. Had they attempted to compensate for anticipated shortening due to post-tensioning by setting the slab edge forms 3/4 in. (19 mm) beyond the locations shown on the drawings, the slab edges that moved outward would have been even further from the locations indicated on the drawings.

**SLAB ELEVATION**

As part of the finish work for another building, floor-to-soffit partition walls were to be installed between post-tensioned concrete slabs. The subcontractor arrived on site to install the partitions 6 months after post-tensioning was completed. When the partitions didn’t fit, the subcontractor insisted that the elevations of the slabs were out of tolerance. The construction manager hired a surveying firm to measure the concrete surface elevations and compare them to the required elevations. The conclusion was that the slab elevations were out of tolerance, but a question remained:
had the post-tensioning affected the slab elevations?

**As-built data for post-tensioning effects on slab elevations**

Concrete surface elevations were measured before and after post-tensioning for a building constructed using column-hung forms with no shores. The contractor measured elevations of the finished concrete surface at 70 points for the 4th through 9th floors before and after post-tensioning. Table 1 shows the difference between the measured surface elevation before and after post-tensioning. Because the elevations of some points moved up and other elevations moved down, the average for the entire floor was about zero. The average standard deviation of the elevation readings was 0.195 in. (5 mm). Assuming a normal distribution, 99.7% of the slab elevation changes for this building after post-tensioning should be within ± three standard deviations or about ±9/16 in. (±14 mm). After post-tensioning, the maximum upward movement was 7/8 in. (22 mm), whereas the maximum downward movement was 1-1/4 in. (32 mm).

Table 2 shows the surface elevation differences before and after post-tensioning for a building that was conventionally shored and formed. The average standard deviation for the elevation change, weighted by the number of data points, was 0.152 in. (3.9 mm). For a three-standard-deviation tolerance envelope, the expected range in movement for floors in this building after post-tensioning would be about ±7/16 in. (±11 mm). After post-tensioning, the maximum upward and downward movements measured were both 1/2 in. (13 mm).

Changes in slab elevation during post-tensioning are related to design choices such as locations of the anchorages and the drape of the strands. Because of this, we believe the concrete contractor

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<th>Floor</th>
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<th>Minimum elevation difference, in. (mm)</th>
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<th>Standard deviation, in. (mm)</th>
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Fig. 6: Plan view showing balcony locations for a post-tensioned building (1 in. = 25.4 mm, 1 ft = 0.3 m)
should not be held responsible for elevations that are out of tolerances after the slabs and beams have been post-tensioned.

Engineers should communicate the possibility of elevation changes to other members of the design team, the construction manager, and the concrete contractor. ACI 117-06 requires elevation measurements to be taken before removal of supporting shores. Normally, post-tensioning raises the slab off of the supporting shores, so it would be preferable for ACI 117 to state that slab elevation measurements are to be taken before post-tensioning or the removal of supporting shores.

**As-built data for post-tensioning effects on balcony edges**

The elevation of balcony edges can also be affected by post-tensioning and is of special concern because of the effect on balcony drainage. The slab shown in Fig. 6 is part of an eight-story concrete-framed structure with 7 in. (180 mm) thick slabs post-tensioned in both directions and wide beams in the short direction at the column lines. To allow drainage while keeping the form elevation constant, the balcony slab thickness was decreased from 7 in. (180 mm) at the face of the building to 6 in. (150 mm) at the end of the 8 ft (2.4 m) wide balconies. This provided a slope of 1/8 in./ft (12.5 mm/m).

The contractor measured balcony slab elevations before and after post-tensioning, typically taking two measurements at each balcony slab edge. There were 67 measurements taken over the 4th, 5th, 6th, and 7th floors. Of these, 34 measurements indicated upward movement, 22 indicated downward movement, and 11 indicated no movement. The average change in elevation after post-tensioning was 3/8 in. (9.5 mm), with a maximum upward movement of 1.5 in. (38 mm). Figure 7 shows the frequency distribution for the absolute change in balcony edge elevation after post-tensioning.

Upward movement of balcony edges caused by post-tensioning has resulted in slabs that drain poorly or even direct water toward the building. Designers typically locate the tendon anchors at middepth of the slab. Anchors located above middepth tend to deflect the edge upward, whereas anchors located below middepth deflect the edge downward. ACI 117-06 sets a vertical tolerance of ±1/4 in. (±6 mm) for pre-stressing strands in slabs 8 in. (203 mm) thick or less and ±3/8 in. (±10 mm) for slab thicknesses between 8 and 24 in. (203 and 600 mm). With strands placed within these tolerances, the balcony edge could move either up or down after the strands are stressed.

Designers should consider that a 1/8 in./ft (12.5 mm/m) slope may not be enough to overcome the effects of post-tensioning on balcony drainage. A structural analysis might be needed to evaluate the degree to which strand placement is critical. Any such analysis should also include the effect of construction tolerances. The designer may decide to locate the anchor below middepth of the slab to help ensure that the balcony drains water away from the building, but long-term effects will be of concern.

**RESPONSIBILITY**

This article is intended to make design professionals, general contractors, construction managers, and concrete contractors aware that post-tensioning can cause significant
building frame movements. Concrete contractors who have set forms in accordance with project drawings are often held responsible for the consequences of out-of-tolerance conditions that may be a result of building frame responses to post-tensioning forces. Thus, we believe concrete contractors should be responsible only for meeting construction tolerances prior to post-tensioning.

This places responsibility for movements after post-tensioning on the structural engineer. Data in this article is insufficient to permit structural engineers to estimate expected movements due to post-tensioning. Many variables are involved, and more data on the effects of these variables may be needed to aid in making reasonable estimates. The effect of post-tensioning on building frame movements should also be considered when detailing finishes, especially when the finishes require tight tolerances for the frame.

**References**

2. ACI Committee 117, “Specifications for Tolerances for Concrete Construction and Materials (ACI 117-06) and Commentary,” American Concrete Institute, Farmington Hills, MI, 2006, 70 pp.

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