Movements That Affect Tolerance Measurements

Contractors' workmanship should be measured independently of movements

by Bruce A. Suprenant and Ward R. Malisch

Building a structure that is within tolerance is one measure of a contractor's workmanship. As-built measurements of a concrete structural member's location are used to determine if the work is in compliance with the specified tolerances. But structural members move after the concrete has been placed. The movements[1] can be a result of short- or long-term deflection, post-tensioning, drying shrinkage, thermal expansion or contraction, soil settlement or heave, or a combination of these effects. Most of these movements are time dependent and occur over a period of months or years. But when should the as-built measurements be made? In one court case involving a condominium association, variations in member locations were measured more than 15 years after the building was constructed. If these measurements indicated the members were out of tolerance, was that a reflection on the contractor's workmanship?

ACI 117-10[2] addresses some, but not all, movements that affect measured variations that are used to determine compliance with the specified tolerances. This article describes how ACI 117-10 deals with this issue for slabs and how the document could expand this approach for other movements.

Measuring Slab Surface Flatness and Levelness

Slab surface variations are measured by F-numbers or a gap under a straightedge. F-numbers measure the slab's flatness and levelness while a gap under a straightedge measures only surface flatness. Regardless of the method used, ACI 117-10, Section 4.8.4.4, requires that slab-on-ground and suspended slab surfaces "be measured and reported within 72 hours after completion of slab concrete finishing operations and before removal of any support shores." ACI 301-16,[3] Section 11.3.5.2, also includes the same time limit: "Surface flatness and levelness shall be measured within 72 hours after finishing and test results submitted to Architect/Engineer within 3 days of measurement."

Slabs-on-ground

Commentary Section R4.8.4.4 of ACI 117-10 includes one reason for this 72-hour time limit by stating that: "All slabs will shrink; joints and cracks in slabs-on-ground will curl with time, resulting in a surface that is less flat with the passage of time." ACI 302.1R-15,[4] Section 10.15.1.1, also states: "…the slab-on-ground floor surfaces change after construction as a result of shrinkage and curling." Suprenant[5] reported results of F-number surface measurements for two slabs-on-ground: one for the University of Maryland practice gym and another for

Designing for Movement

Reinforced concrete suspended slabs shored in their initial position deflect into a final position after the shoring is removed. Recognizing the effect of deflection on the serviceability of the slab, engineers sometimes specify that the initial shored position be cambered so that the desired final deflected position is obtained when the shoring is removed. This same approach can be used for other concrete elements that move after being placed in service. Engineers can specify the initial position of walls or perimeter columns for post-tensioned slabs to account for movements.

Pre-construction meetings should address how and when:

- Initial locations of key benchmarks will be measured; and
- Adjustments will be made to compensate for deflections occurring during construction.

Because calculated deflections can differ from actual deflections by as much as ±50%, contractors should provide deflection measurements to the engineer so that adjustments can be made to the initial position as the structure is constructed.

an industrial warehouse in Pennsylvania. Measurements taken 7 months apart on the University of Maryland slab showed a 10 to 20% decrease in floor flatness and a 10 to 45% decrease in floor levelness during the 7-month period. Measurements taken 12 months apart on the industrial floor slab in Pennsylvania showed a 40% decrease in floor flatness and a 50% decrease in floor levelness. Based on this data, the American Society of Concrete Contractors (ASCC) issued Position Statement #35[6] in 2010 to alert the industry to this issue.

Rather than set a movement limit, ACI 117-10 sets the 72-hour time limit based on the knowledge that very little shrinkage and curling would occur during this time. This is the ACI 117-10 tolerance that sets a time limit for measurements that assess a contractor's work product.

Suspended slabs

While ACI 117-10, Section 4.8.4.4, requires that surface measurements for suspended slabs also be made prior to 72 hours, it further includes an additional construction operation requirement—making the measurements "…before removal of any supporting shores." This was added because deflection affects the results of surface measurements. ACI 302.1R-15, Section 10.15.1.1, concurs by stating that "…the surfaces of suspended slabs change as a result of deflection." Malisch and Suprenant[7] reported on floor flatness changes from about 5 to 60% for initial floor flatness F_F values ranging from 25 to 50 with deflections of *L*/360, *L*/480, and *L*/960. In response to this information, ASCC issued Position Statement #36[8] to alert the industry to this issue. Because the timing of the removal of supporting shores varies, ACI 117-10 did not set a time limit but instead set the construction operation requirement before removal of any supporting shores. Thus, for assessment of the contractor's work, suspended slab surface tolerance measurements must be taken before removal of any supporting shores. This eliminates the influence of any surface movement due to deflection.

Philosophy of tolerance measurement prior to movements

The provisions in ACI 117-10 for measuring surface variations for slab-on-ground and suspended slabs have, in effect, established a philosophy of measuring surface variations due to workmanship and comparing the results with specified tolerances *before the surface is affected by any movements*. Although ACI 117-10 is silent on measuring other as-built variations, this philosophy should be extended into other areas, where movements affect tolerance measurements.

Measuring Drainage and ADA Slopes

ACI 117-10, 301-16, and 302.1R-15 all state that floor test surfaces should be measured within 72 hours and before removal of supporting shores. ASTM E1155-14, "Standard Test Method for Determining F_F Floor Flatness and F_L Floor Levelness Numbers," also states in a nonmandatory note:

"NOTE 5: When this test is used to evaluate the compliance of a new concrete floor with contract flatness and levelness specifications, the timeliness of the test vis-a-vis the date of the floor's installation is of critical importance. Since most concrete floors will change shape significantly within a few days after installation, owing to inevitable shrinkage and deflection, the American Concrete Institute (see ACI 117-90) now requires that specified concrete floor tolerances be checked within 72 h after floor installation in order to ensure that an accurate gage of the surface's 'as-built' shape is assessed."

Based on industry requirements and standard practice for measuring floor surface tolerances, it would seem a logical and necessary extension that specified slopes for drainage and slopes required by the Americans with Disabilities Act (ADA) should also be measured within 72 hours and prior to removal of any supporting shores for suspended slabs. Curling and deflection that affect surface flatness and levelness will also affect slopes for drainage and ADA surface accessibility.

Suprenant[9] reported that: "Upward curl at slab corners can be as high as 1 in. [25 mm], but is typically about 1/4 in [6 mm]." Thus, this magnitude of curling will affect slopes and drainage. ACI 318-14[10] does not set a limit on dead-load deflections, but does state that members shall be designed with adequate stiffness to limit deflections that adversely affect the serviceability of a structure. Dead-load deflection could adversely affect drainage. ACI 318-14 does set maximum permissible calculated deflection limits for live load that range from l/180 to l/480. For a span of 30 ft (9.1 m), the live load deflection could range from 3/4 to 2 in. (19 to 51 mm). Thus, this magnitude of deflection will affect slopes and drainage. Suprenant[11] has also reported the effect of deflection on balcony slopes, and hence drainage. But why are contractors sometimes held responsible for specified drainage slopes for parking structures or parking lots months or years after they are constructed?

The "2010 ADA Standards for Accessible Design"[12] states that:

- "All dimensions are subject to conventional industry tolerances";
- Dimensions will "produce an end result of strict and literal compliance with the stated requirements and eliminate enforcement difficulties and issues that might otherwise arise"; and
- "Information on specific tolerances may be available from industry or trade organizations, code groups and building officials, and published references."

Based on the ADA standards language, the ACI 117-10 and ACI 301-16 requirements for measuring surface tolerances within 72 hours should also apply to ADA accessible surfaces such as sidewalk and ramp slopes. In addition to the requirements for measuring surface variations for flatness and levelness, ACI documents should directly state that it applies to slopes for drainage and ADA work. The levelness F-number represents the slope of the floor. So why are contractors being held accountable for the slopes of ADA work *months or even years after the work is completed*?

It is not appropriate to find the contractor at fault on the basis of as-built measurements made long after a slab was built. Surface tolerance measurements for drainage and ADA slopes should be taken prior to the 72-hour time limit to assess and measure the contractor's work without influence of any surface movements.

Measuring Slab Surface Elevation

ACI 117-10 accounts for slab surface variations due to curling and deflection when considering flatness and levelness for both slabs-on-ground and suspended slabs. That is not true, however, for *elevation* of slabs-on-ground and suspended slabs. Because movements—curling and deflection—affect flatness and levelness, they will also affect surface elevations for both slabs-on-ground and suspended slabs.

ACI 117-10, Section 4.8.4.4, requires that elevation variations be measured "before removal of supporting shores" for suspended slabs, thus acknowledging the effect of deflection on elevation measurements. This is consistent with the requirement for measuring flatness and levelness for suspended slabs. There is not a time limit, however, for measuring slab-on-ground elevations. Thus, slab-on-ground elevation measurements could be affected by curling. We recommend that slab-on-ground elevations also be measured within 72 hours so that workmanship is measured and not the effects of curling. This would be consistent with the ACI requirement for measuring flatness and levelness within 72 hours.

Other Movements That Affect Tolerance Measurements

Although there are many different movements that can take place in a building, we will focus on movements in: (a) walls due to backfill operations; (b) columns and slab edges due to post-tensioning; and (c) columns and expansion joints due to thermal changes.

Backfill

Retaining walls are designed to resist pressures resulting from the backfill and any loads superimposed on the backfill. These forces are transferred down the wall and into the foundation. The most economical retaining walls are those designed for active backfill pressure, but to achieve this pressure, the wall must move. The top of the wall rotates and translates due to the foundation rotation and wall deflection.

The movement of a retaining wall and the final wall location is usually not a concern. But architects sometimes support curtain walls or other architectural or structural elements on retaining walls. In this case, the location of the wall can be important. After the backfilling operation, the retaining wall will move—changing the location of the top of the wall and the vertical alignment (plumb) of the wall face. Figure 1 shows measured movements for a 16 ft (4.9 m) high concrete cantilever retaining wall.[13] After backfill was placed, the top of the wall had moved horizontally about 5/8 in. (16 mm). Because of this movement, retaining wall tolerance measurements should be taken prior to any backfilling operation. If taken after backfilling, the tolerance measurements will not represent the concrete contractor's workmanship of the as-constructed wall.

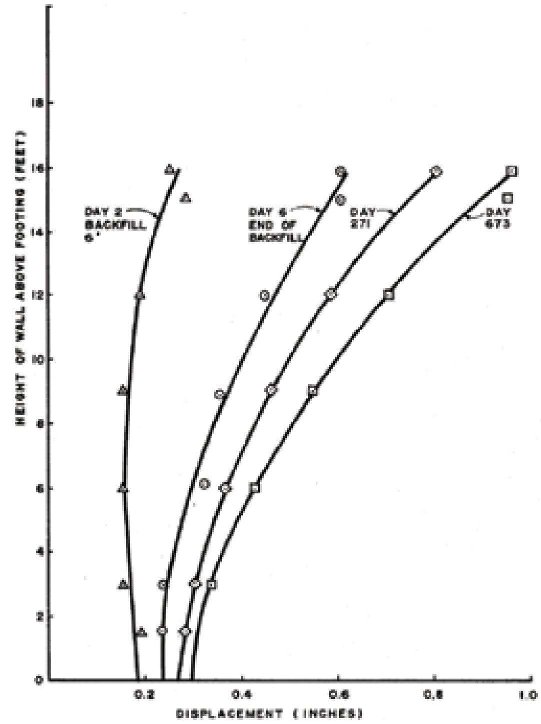

Fig. 1: Measured movements at the top of a 16 ft (4.9 m) cantilever retaining wall illustrates the movement due to backfill operations.[13] The measured movements were the combination of a horizontal movement at the foundation and the deflection of the wall. Tolerance measurements that represent the concrete contractor's workmanship should be taken prior to any backfill operation (Note: 1 in. = 25.4 mm; 1 ft = 0.3 m)

Post-tensioning

Post-tensioned slabs shorten, which means that columns and walls move toward the center of rigidity of the structural system.[14,15] The most common estimate for the amount of shortening is 1 in. per 100 ft (25 mm per 30.5 m) of length.[16-18] Kelley and Barth[19] provide details for calculating the amount of shortening for a particular project. Figure 2 illustrates the movement of perimeter columns due to post-tensioning for a four-story building.

The shortening due to post-tensioning does not occur instantly but takes time—about 40% occurs in 1 month, about 60% in 3 months, and about 80% in 12 months.[15] Thus, column location and plumb and slab edge locations continuously change. As an example, Fig. 3 illustrates two control lines on a post-tensioned concrete slab that are about 1/2 in. (13 mm) apart—one control line was established by the concrete contractor prior to post-tensioning and the other control line was established by the general contractor for the finish trades sometime after post-tensioning.[15]

Figure 4 shows how perimeter and interior columns move toward the center of rigidity. In this example, it is estimated that a 200 ft (61 m) long building will ultimately shorten by 2 in. (51 mm). In this case, the perimeter columns move toward the center by 1 in. and the other columns move toward the center in proportion to the distance away from the center. If the building structural layout is symmetrical, the center of movement is at the center of the building. If the structural layout varies, however, movement will be toward the center of rigidity, which must be calculated based on the stiffness of the structural elements. The center or rigidity can vary from floor to floor as the structural layout varies.

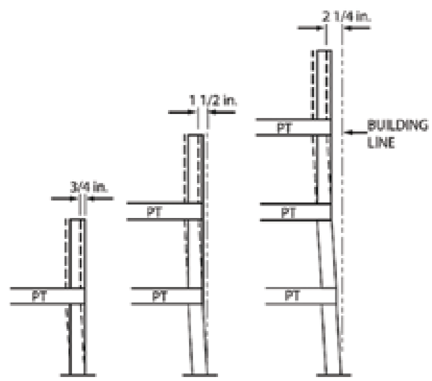

Fig. 2: Post-tensioned slabs shorten, causing the perimeter columns to move toward the center of the building.[14] Tolerance measurements representing the concrete contractor's workmanship should be taken prior to post-tensioning (Note: 1 in. = 25.4 mm)

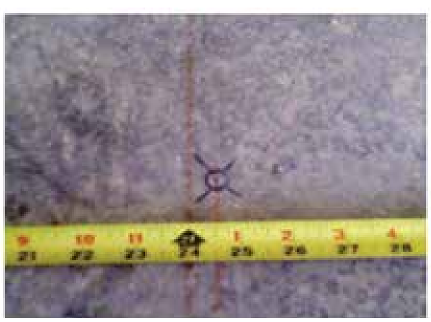

Fig. 3: Two control lines on a post-tensioned concrete slab are about 1/2 in. (13 mm) apart: one control line was established by the concrete contractor prior to post-tensioning and the other control line was established by the general contractor for the finish trades sometime after post-tensioning[15]

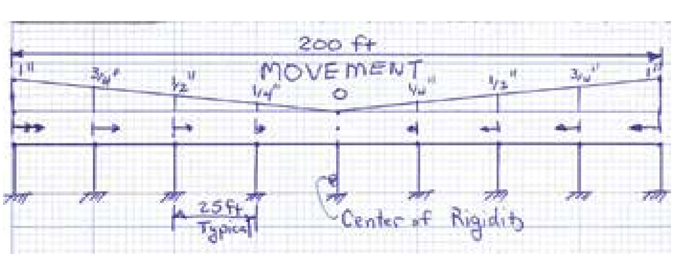

Fig. 4: Example illustrating column movements estimated to be 2 in. (51 mm) for a 200 ft (61 m) long building. The perimeter columns move toward the center by 1 in. (25.4 mm) and the other columns move toward the center in proportion to the distance away from the center (Note: 1 ft = 0.3 m)

Because of the inherent difficulties in calculating the amount of shortening, the shortening that occurs with time, and the center of rigidity, tolerance measurements should be taken prior to post-tensioning.

Temperature changes

AISC 303-10[20] includes temperature changes as a necessary consideration in design and construction. For example, the American Institute of Steel Construction (AISC) advises the steel erector when plumbing columns to apply a temperature adjustment at a rate of 1/8 in. per 100 ft for each change of 15°F (2 mm per 10,000 mm for each change of 15°C) between the temperature at the time of erection and the working temperature (Fig. 5). Thus, tolerance measurements need to be adjusted due to temperature; otherwise, columns could be out of plumb at 100°F (38°C), but be plumb at 70°F (21°C).

PCI MNL 135-00[21] does not stipulate a temperature for tolerance measurements but does acknowledge the effect temperature can have by stating: "The effects of differential temperature from one side of a member to another can cause the member to bow or camber. Similarly in long members the effect of lengthening and shortening due to wide extremes of temperatures can be important to the overall length tolerance of members."

ACI 117-10 has no provision to account for the effect of temperature changes on tolerance measurements. Thus, measured variations from design values that might be in tolerance at 70°F could be out of tolerance at 100 or 40°F (38 or 4°C).

Iqbal[22] provided recommendations for computing thermal movements. His recommendations are based on monitoring expansion joint movements for 10 Chicago, IL, area concrete parking structures. Six structures were of precast/prestressed construction and four were post-tensioned. The precast/prestressed structures were of untopped precast double-T

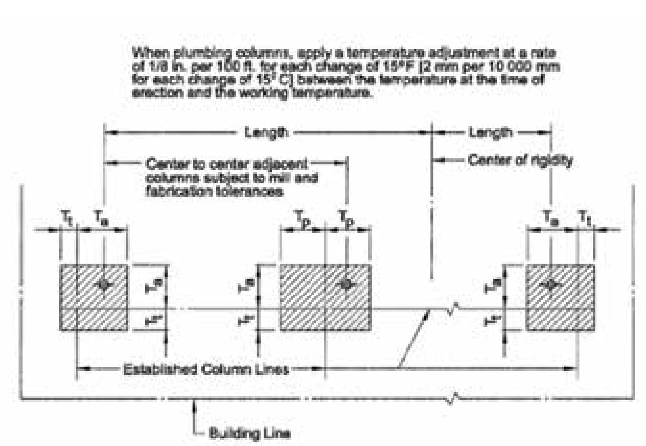

Fig. 5: AISC 303-10[20] directs steel erectors to adjust for temperature changes when plumbing columns during erection. Note that the temperature adjustment is applied based on the length the column is from the center of rigidity

construction, and the post-tensioned structures had one-way post-tensioned slab-beam systems. The ages of the precast facilities ranged from 2 to 5 years and the ages of post-tensioned structures ranged from 5 to 20 years. The monitoring consisted of field measurements for horizontal movements spread over a 2-year period and included temperature ranges from −6 to 73°F (−21 to 23°C).

Iqbal evaluated thermal expansion and contraction by measuring changes in the gaps between pairs of parallel lines drawn on either side of expansion joints in adjoining parking structures (Fig. 6). The initial distances between the line pairs ranged from 3 to 8 in. (76 to 203 mm). The distances between the centers of rigidity of the adjacent structures ranged from 135 to 197 ft (41 to 60 m).

The general expression to calculate expansion or contraction due to a thermal change is $\Delta L = e_{th} L \Delta T M_{th}$ where e_{th} is coefficient of thermal expansion; L is length subjected to thermal change; ΔT is temperature change, and M_{th} represents movement factor equal to 0.0 for fully restrained and 1.0 for unrestrained (free).

Based on his measurements, Iqbal[22] recommends using a coefficient of thermal expansion of 7.5×10^{-6} in./in./°F (13.5×10^{-6} mm/mm/°C) and a movement factor of 0.8 for post-tensioned structures and 0.6 for precast structures. AISC adjusts their temperature correction based on a free unrestrained structure or a movement factor of 1.0.

Correcting for movements caused by temperature changes in a cast-in-place concrete building under construction is likely to be difficult. The most practical recommendation might be to make tolerance measurements only when the temperature is between 60 and 80°F (16 and 27°C). This minimizes the effect of temperature movements on tolerance measurements. However, this may not be possible. At the very least, the concrete and air temperature should be recorded whenever tolerance measurements are taken so the effect of temperature on the tolerance measurements can be assessed.

Combined movements

Figure 7[1] illustrates how a column in a parking structure deforms after it is constructed. It shows a column: (a) as constructed; (b) after post-tensioning; (c) with live load; (d) with shrinkage and creep added; and finally (e) with cold-weather thermal shortening. Note that the column changed shape after it was constructed. As the figure shows, measuring the location and plumb of the column prior to post-tensioning and before any other added loads or movements is the only condition that represents the contractor's workmanship.

Tolerance Measurements Must Be Independent of Movements

ACI 117-10 requires slab surface tolerance measurements for flatness and levelness to be independent of movements. The document also requires suspended slab elevation measurements to be independent of movements. However, ACI 117-10 does not require tolerance measurements to be independent of movements for many other cases. These need to be addressed; otherwise, as in the condominium example, tolerance measurements to evaluate the concrete contractor's workmanship might be taken years after the structure has been constructed and placed in service.

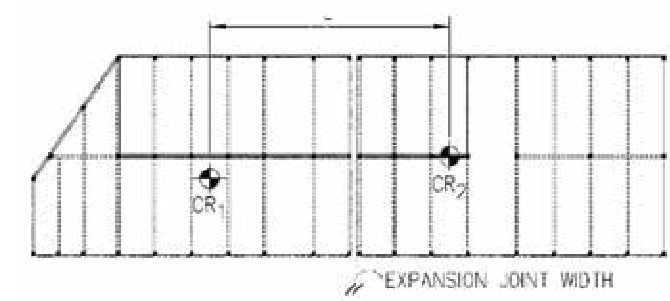

Fig. 6: Expansion joint width measurements made over a period of 2 years on 10 Chicago-area parking structures.[22] Air temperatures during this measuring period ranged from −6 to 73°F (−21 to 23°C). Calculations for the theoretical amount of joint width movement due to thermal changes are based on the length between the structures center of rigidity (CR_1 and CR_2)

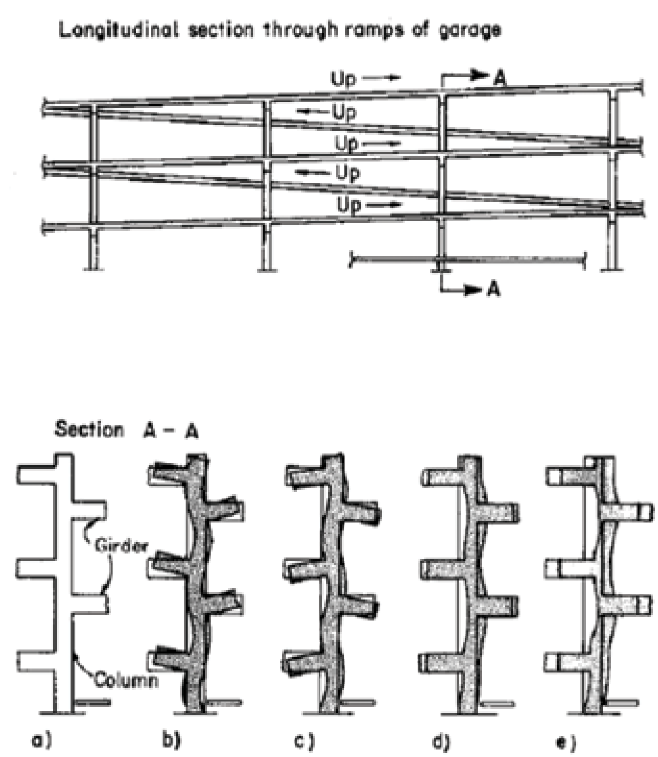

Fig. 7: The lower drawing shows a column: (a) as constructed: (b) after post-tensioning: (c) with live load; (d) with shrinkage and creep added; and finally (e) with cold-weather thermal shortening.[1] Note that the column changed shape after it was constructed. Measuring the location and plumb of the column prior to post-tensioning and before any other added loads or movements is the only condition that accurately represents the contractor's workmanship

References

1. "Building Movements and Joints," EB086, Portland Cement Association, Skokie, IL, 1982, 64 pp.

2. ACI Committee 117, "Specification for Tolerances for Concrete Construction and Materials (ACI 117-10) and Commentary (ACI 117R-10) (Reapproved 2015)," American Concrete Institute, Farmington Hills, MI, 2010, 76 pp.

3. ACI Committee 301, "Specifications for Structural Concrete (ACI 301-16)," American Concrete Institute, Farmington Hills, MI, 2016, 64 pp.

4. ACI Committee 302, "Guide to Concrete Floor and Slab Construction (ACI 302.1R-15)," American Concrete Institute, Farmington Hills, MI, 2015, 76 pp.

5. Suprenant, B.A., "The Concrete Floor Tolerance/Floor Covering Conundrum," *Concrete International*, V. 25, No. 7, July 2003, pp. 89-94.

6. "The Effect of Curling on Floor Flatness," ASCC Position Statement #35, *Concrete International*, V. 32, No. 12, Dec. 2010, p. 76.

7. Malisch, W.R., and Suprenant, B.A., "Effect of Deflection on Flatness of Elevated Slabs," *civil + structural Engineer*, Jan. 2013 (http://cenews.com/article/9135/effect-of-deflection-on-flatness-of-elevated-slabs).

8. "The Effect of Deflection on Floor Flatness," ASCC Position Statement #36, *Concrete International*, V. 33, No. 1, Jan. 2011, p. 75.

9. Suprenant, B.A., "Why Slabs Curl," *Concrete International*, V. 24, No. 3, Mar. 2002, pp. 56-61.

10. 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.

11. Suprenant, B.A., "Understanding Balcony Drainage," *Concrete International*, V. 26, No. 1, Jan. 2004, pp. 84-87.

12. "2010 ADA Standards for Accessible Design," Department of Justice, 2010, 275 pp. (www.ada.gov/regs2010/2010ADAStandards/2010ADAStandards.pdf).

13. Wright, W.V.; Coyle, H.M.; Bartoskewitz, R.E.; and Milberger, L.J., "New Retaining Wall Design Criteria Based on Lateral Earth Pressure Measurements," *TTI-2-5-71-169-4F Report*, Texas Transportation Institute, 1975, 113 pp.

14. "Construction Tolerance Conflicts in Reinforced Concrete," *Engineering Data Report Number 40*, Concrete Reinforcing Steel Institute, Schaumburg, IL, 1995, 4 pp.

15. Suprenant, B.A., and Malisch, W.R., "Effect of Post-Tensioning on Tolerances," *Concrete International*, V. 31, No. 1, Jan. 2009, pp. 58-65.

16. Aalami, B.O., and Barth, F.G., "Restraint Cracks and Their Mitigation in Unbonded Post-Tensioned Building Structures," *Cracking in Concrete Prestressed Structures*, SP-113, G.T. Halvorsen and N.H. Burns, eds., American Concrete Institute, Farmington Hills, MI, 1989, 212 pp.

17. Allred, B., "Common Post-Tensioning & Construction Issues," *Structure*, National Council of Engineers Associations, July 2005, pp. 22-25.

18. Bondy, K.B., "Shortening Problem in Post-Tensioned Concrete Buildings," *SEAOC Seminar Proceedings—Design Review and Inspection of Prestressed Concrete Building Projects*, Jan. 1989.

19. Kelley, G.S., and Barth, F.G., *Design, Construction and Maintenance of Cast-in-Place Post-Tensioned Concrete Parking Structures*, Post-Tensioning Institute, Farmington Hills, MI, 2001, 159 pp.

20. "Code of Standard Practice for Steel Buildings and Bridges (AISC 303-10)," American Institute of Steel Construction, Chicago IL, 2010, 71 pp.

21. "Tolerance Manual for Precast and Prestressed Concrete Construction (MNL 135-00)," Precast/Prestressed Concrete Institute, Chicago, IL, 2000, 181 pp.

22. Iqbal, M., "Thermal Movements in Parking Structures," *ACI Structural Journal*, V. 104, No. 5, Sept.-Oct. 2007, pp. 542-548.

Note: Additional information on the ASTM standard discussed in this article can be found at **www.astm.org**.

Selected for reader interest by the editors.

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