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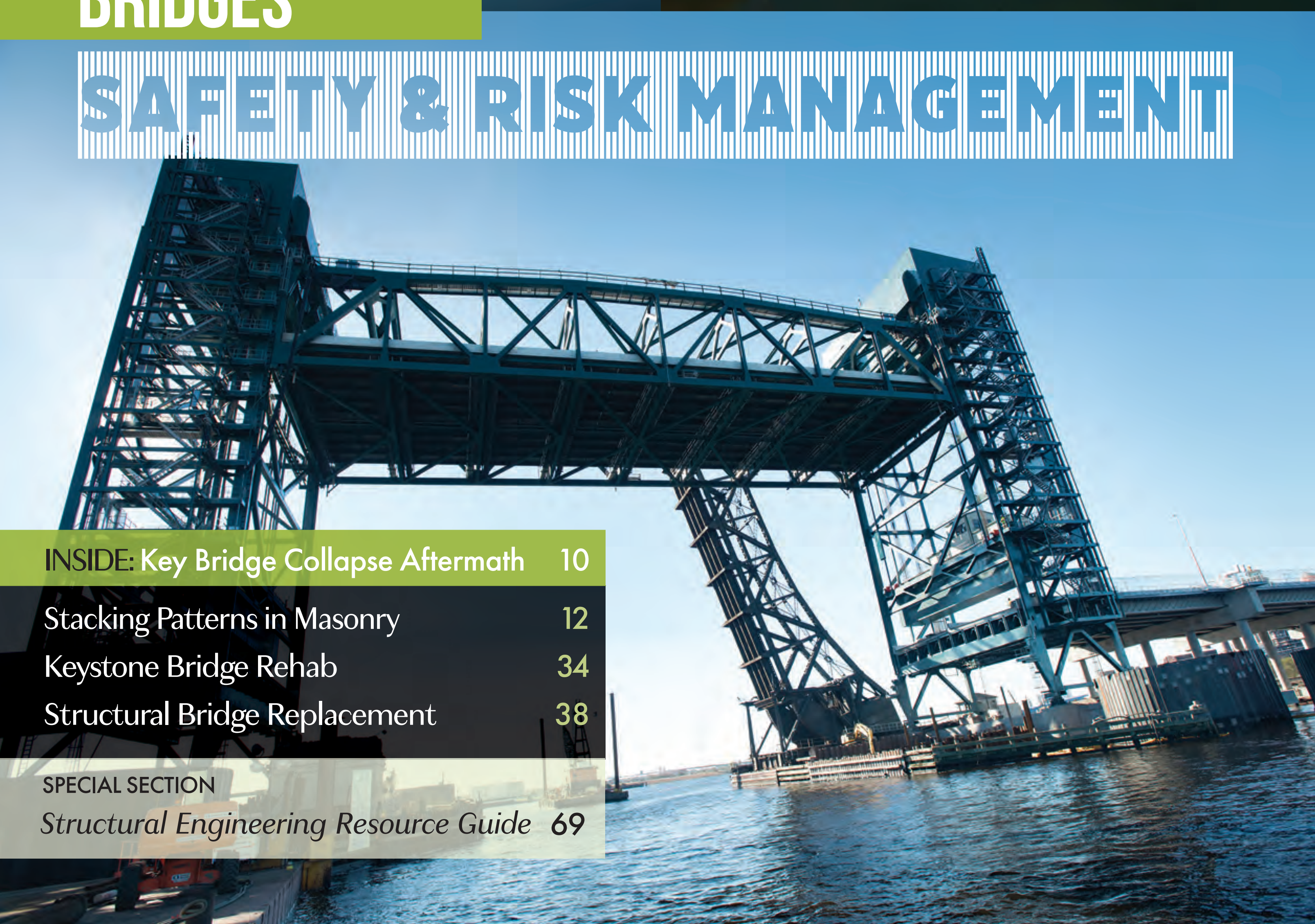

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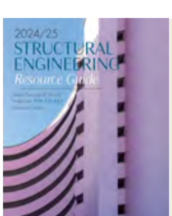

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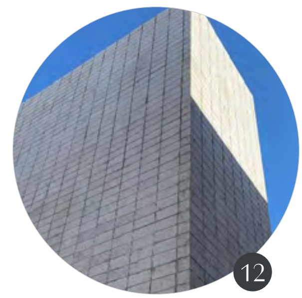

In Every Issue

Deflection and Cracking of Two-Way, Conventionally Reinforced Concrete Slabs

A measured response based on a full understanding of cracking and deflection can help engineers and owners avoid unnecessary panic and intervention.

By Gwenyth Searer, PE, SE, Terrence Paret, Hayley Proctor, PE, and Prateek Shah, Ph.D.

Two-way, conventionally reinforced concrete slabs (herein referred to as "two-way slabs") behave in ways that many engineers and owners may not fully anticipate (see the September issue of *STRUCTURE* for a detailed description of system behavior). Two-way slabs have a predictable propensity to crack and deflect. Failure to provide a measured response to the cracking and deflection can result in misunderstandings regarding the objective physical evidence and can result in unnecessary structural intervention. This article is intended to help guide engineers in their investigations and to help avoid unnecessary panic on the part of the engineer, the owner, and the public.

Radial Cracking and Spiderweb Cracking of Two-Way Slabs

It is critical to recognize that both radial cracking, where cracks radiate outward from the columns, and spiderweb cracking, where the cracking looks like a spiderweb on the surface of the slab with both radial cracks and cracks interconnecting the radial cracks, are extremely common on the top surface of two-way slabs. Figure 1 shows typical radial cracking in two-way slabs; Figure 2 shows typical spiderweb cracking in two-way slabs. Such cracking typically goes unnoticed, and the structures continue to function as intended.

As described in the September issue of *STRUCTURE,* radial and spiderweb crack patterns are characteristic of flexural behavior. However, it is not uncommon for engineers investigating existing two-way slabs to conflate the radial and spiderweb cracks with punching shear failures—sometimes reported as imminent and even sometimes reported as having already occurred. Indeed, a recent article by Tepke et al. in *Concrete International* stated, "Cracks in elevated floor slabs that radiate outward from columns combined with cracks encircling the column are likely to be an indication of a condition that could result in punching shear failure...crack patterns that indicate the possibility of punching shear failure should be regarded as an eminent [sic] risk of catastrophic failure." This dramatic claim is contradicted by research dating as far back as the 1950s by Elstner and Hognestad, which notes that the punching shear failure surface appeared to be "completely independent of the cracks formed beforehand." Potential punching shear failures have long been recognized to be problematic precisely because they do <u>not</u> manifest visible precursors prior to failure. While spiderweb cracking might be construed to encircle columns, spiderweb cracking should not be confused with imminent punching shear failure. Both radial cracking and spiderweb cracking are extremely common in two-way slabs: if these crack patterns actually represented imminent or actual failures, two-way slabs ought to be experiencing catastrophic collapses on a regular basis. The fact that they are not is consistent with research indicating that punching shear failures are unrelated to either radial or spiderweb cracking.

Deflection of Two-Way Slabs

Designers of two-way slabs have a choice of two different compliance methods related to deflection. In ACI 318-19, designers can comply with the minimum thickness requirements provided in Table 8.3.1.1, or

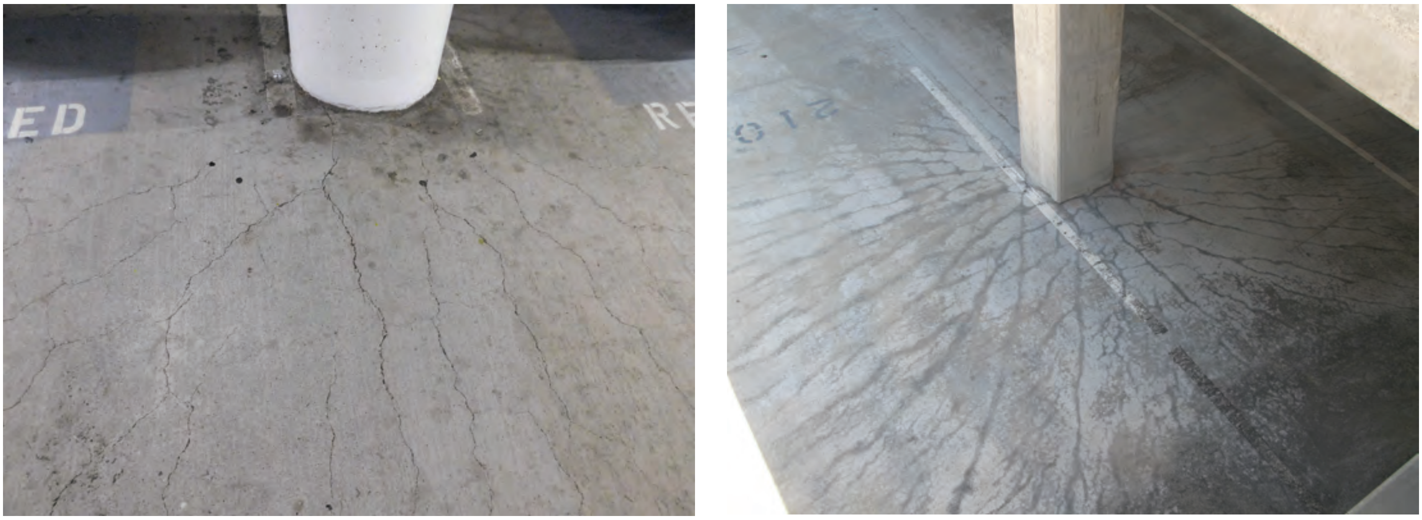

Fig. 1. Radial cracking appears in the two-way floor slabs of a garage built circa 1985 (left) and a garage built circa 2008 (right). Both structures are still in service.

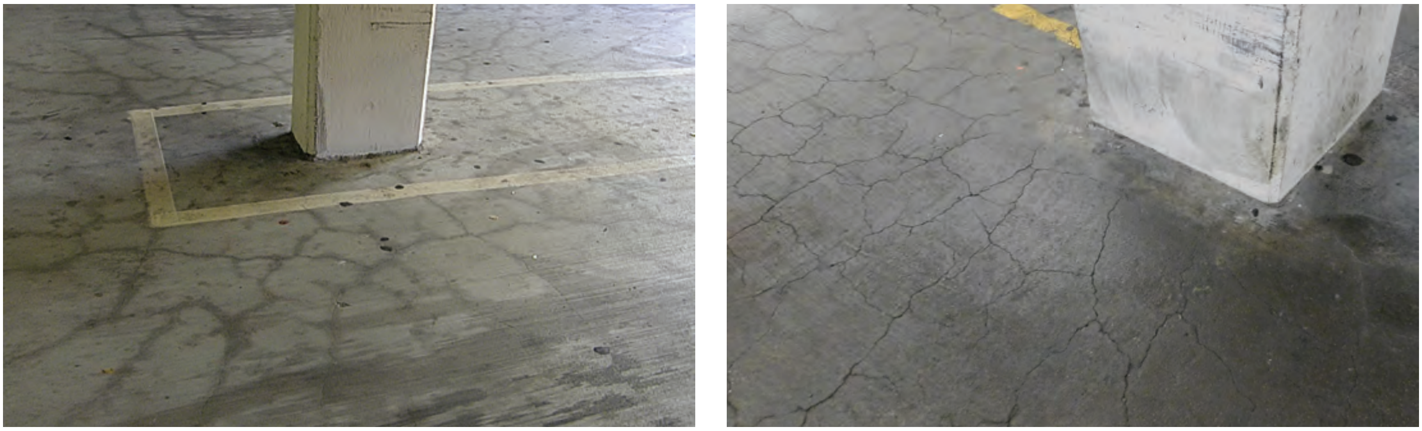

Fig. 2. Spiderweb cracking appears in the two-way slabs of a garage built circa 1991 (left) and a garage built circa 1987 (right). Both structures continue to function without issue more than three decades after they were built.

they can meet the requirements of Section 8.3.2, which limits maximum calculated deflections according to Table 24.2.2. Neither option is ideal from the perspective of understanding how the slab is likely to perform in real life. Complying with the minimum thickness requirements relieves the designer from having to calculate deflection and seems like an "easy out," but this approach can be problematic because it fails to consider important variables that affect both initial deflection and long-term, creep-related deflection such as the concrete mix design; the age and strength of the concrete at the time of formwork removal; construction sequencing loads; and restraint against shrinkage, all of which have the potential to increase the out-of-levelness of a slab.

Designers who rely on the calculated deflections of their slabs and compare these deflections to the limits in Section 8.3.2 in lieu of relying on minimum thickness may be doing so to arrive at a more economical design. Slabs designed using the calculated deflection limits in Section 8.3.2 are likely to be thinner and may deflect even more than slabs designed using the minimum prescriptive thickness limits.

Although there are four rows of requirements, two of the deflection limits in Table 24.2.2 govern many designs:

1) Where floors do not support nonstructural elements that are likely to be damaged by large deflections, the immediate deflection due to live load shall not exceed $\ell/360$.

2) Where floors support nonstructural elements that are not likely to be damaged by large deflections, the deflection that occurs after attachment of nonstructural elements plus immediate deflection due to live load shall not exceed $\ell/240$.

First note that "ℓ" is defined as the "span length of beam or one-way slab," which leaves room for interpretation when the limits are applied to two-way slabs. Although a detailed analysis of this subject is beyond the scope of this article, it could be argued that ℓ should be the larger of the length and the width of the bay; that ℓ should be the diagonal distance across the bay; or that permissible deflection should be calculated for both the long span and the short span and then added together, similar to what might be done for a steel structure with decking, beams, and girders that frame a bay, where the permissible deflections of these elements are additive. The Commentary in ACI 318 is silent in this regard.

For utilitarian structures like parking structures, there tend to be few nonstructural elements that can be damaged by large deflections, so the immediate live load condition would typically be the governing deflection limit. For cases where the ℓ/240 limit is applicable, designers are permitted to ignore the immediate dead load deflection and all of the creep-related deflection that occurs after formwork is removed but before nonstructural elements are installed.

Avoid Common Investigation Pitfalls

When investigating deflections and cracking of existing two-way slabs, keep the following recommendations in mind.

Don't Be So Negative

Engineers can fall into the trap of considering only the negative aspects of as-built construction. For example, in-situ reinforcing steel in two-way slabs near the columns is often positioned lower than called for in the construction documents. However, construction tolerances permit some variation in position, and the phi-factors for flexural and shear strength are in part intended to accommodate lower strengths that may occur due to variations in construction consistent with practical limitations. As more information is determined about the actual as-built structure, the need for phi-factors is reduced, and their values should trend towards 1.0. Consequently, considering the effects of out-of-position reinforcing but still using standard phi-factors, while ignoring code-permitted tolerances, overly penalizes the structure.

Moreover, while it may be tempting to analyze the slab using measured reduced flexural steel depths and assume that the rest of the construction is exactly as specified, it is important to also recognize factors that may increase strength. Reinforcing steel that is specified as having a yield stress of 60 ksi can very easily have an actual yield stress of 68 to 72 ksi. Mill certificates from the project may contain valuable data regarding the actual yield stress of the bars. Similarly, concrete rarely falls below the minimum specified strength because concrete suppliers aim above the minimum, and because concrete tends to gain strength over time. Using the actual or likely strengths of the steel and concrete typically makes more sense than using the minimum strength, particularly if phi-factors are going to be used in the analysis.

The Maximum Permissible Calculated Deflections Table Is a Design Tool, NOT an Evaluation Tool

All too often, engineers measure the out-of-levelness of a slab and then compare the out-of-levelness with Table 24.2.2 from ACI 318. However, doing so is incorrect. Pure and simple, this table, which is titled, "Maximum permissible *calculated* deflections" (emphasis added), is a design tool, not an evaluation tool; it cannot predict what the actual field-measured deflections will be or should be.

Nothing in either the table or the Commentary indicates that the limits in the table are intended to be used as a measuring stick to evaluate or to predict the in-field performance of a slab. Researchers have shown that deflections related to shrinkage and creep can be double that indicated by ACI 318 Table 24.2.4.1.3, "Time-dependent factor for sustained loads," as summarized in ACI 435R-20.

Since the engineer designing the slab is not even required to use this table if minimum thickness requirements are met, comparing actual out-of-levelness of a slab with an optional table that shows calculated limits on deflection does not make sense. Thus, Table 24.2.2 can only be used as a design tool to help proportion slabs, not as a tool to evaluate slabs.

Fig. 3. Mid-bay puddles in a parking structure roof slab are due to the unavoidable deflection of the roof slab between columns. Photo courtesy of www.nearmap.com.

Beware of Compression Tests of Concrete Cores

Removing and testing concrete cores may seem like a good way to obtain the compressive strength of the in-situ concrete; however, the coring process actually damages the concrete in the core, as documented by Bartlett and MacGregor. The core may contain microcracks that occurred naturally during routine loading of the structure or due to restraint against shrinkage or due to the coring process itself; these microcracks may weaken the core in a way that would not occur either in a cast concrete cylinder or in situ where the concrete is confined, thus resulting in an apples-to-oranges comparison between results from cores and cylinders.

In addition, the core cuts through aggregate in a way that would not occur in a cast cylinder and that does not occur in the concrete slab. This process can result in lower-than-expected concrete core strengths that may not actually be representative of the concrete in the structure, and adjustment of the data to account for some level of damage may not fully address the actual effects of the damage. Arioz et al. found that this phenomenon can be particularly problematic with well-rounded river gravel. Cores taken from concrete with such gravel often seem to give compressive strengths lower than those from cylinders.

Caution is also warranted when using statistical methods to derive an equivalent compressive strength. In a recent investigation, 14 cores were removed from the slabs in an existing seven-story structure. The compressive strength of every core was greater than the 4,000-psi minimum required compressive strength shown on the drawings, with an average strength of 4,300 psi and an impressively low standard deviation of only 110 psi. Yet when the investigator used ACI 562-16 to derive an equivalent compressive strength of the concrete, the procedure yielded an equivalent design strength of only 3,670 psi, a result that does not appear appropriate when looking at the data.

Do Not Conflate Out-of-Levelness With Deflection

Surveying the elevation of the top surface of the slab and then comparing it to the elevation of the slab at the supporting columns and walls does not yield a measure of deflection. The elevation of the top of the slab has permissible construction tolerances; variations in flatness, levelness, slab thickness, and support elevations are also permitted, as are deflections of freshly placed plastic concrete that occurs while formwork is supported on suspended slabs. Quite simply, although deflection will always contribute to out-of-levelness of a slab bay, measured out-of-levelness represents only that, and not deflection. Finally, it is always wrong to include elevation data from distant bays in the computation of out-of-levelness of a slab within a given bay.

Fig. 4. Paint from this parking stall stripe is present within and spanning across the crack, indicating that the crack was present at the time the paint was installed and that the crack has not moved substantively since.

Camber May Not Have Been Installed

Camber is often omitted during

construction, even when it is specified in structural drawings. While camber can be used to offset some of the immediate deflection that occurs upon formwork removal, it requires the contractor to create difficult-to-fabricate vertically undulating formwork, complicates layout of reinforcing, and introduces labor-intensive complications during placement and finishing operations. As a result, it is quite common for camber to get value-engineered out of the construction, for the concrete subcontractor to decide to omit the camber on their own, or for the detail to be missed by the construction team during the chaos of construction. During an investigation of a slab that was specified to have camber, it is important to recognize that the camber may not have been installed, which may partially explain why measured out-of-levelness is larger than expected.

Fig. 5. This photo shows a swath of slab that has been bead-blasted or otherwise ground down to remove a curved white line; the mechanical removal of the line resulted in the cracks that were already present in the slab becoming noticeable due rounding of their edges.

Even if camber is installed, it cannot solve all deflection issues. Engineers, architects, and owners often do not understand what camber can and cannot do. A slab that is exposed to water and that was constructed without an overall slope-to-drain will develop mid-bay puddles at the low points of the deflected shape, cambered or not. If excessive camber is specified and slab deflection does not overcome the camber, the slab will slope towards the column lines, and water will collect there. If only moderate or minimal camber is specified and slab deflection is greater than the camber, the slab will still tend to slope towards the centers of the bays, and water will collect there. Moreover, because deflection is time- and load-sensitive, slab drainage characteristics change over time. The only way to reliably avoid puddles in a two-way slab that is exposed to water is to provide sufficient overall slope in the slab that exceeds the local slope caused by deflection so that water will drain to one edge or point, or to install drains at the low point of every bay. Figure 3 shows an aerial photo of a parking structure; the presence of the puddles does not indicate that the slab is performing poorly; rather, the puddles indicate that drains should have been designed and installed in the middle of every bay but were not. Similarly, if designers do not want the water in those puddles draining through the slab, a traffic coating should be specified. The fact that water will travel through the inevitable cracks in a concrete slab should not be taken as convincing evidence that the slab is performing poorly.

Follow the Evidence

One of the most important keys to investigating existing structures, including two-way slabs, is to follow the objective physical evidence. Just because someone noticed cracking recently does not mean that the cracking occurred recently. There is often evidence that the cracking has existed in its current state for a long time and thus may be less of a cause for concern than if it just occurred. The presence of paint, soot, dirt, patching compound, prior repairs, and carpet glue within a crack all indicate that the crack was present at the time the material was applied over or accumulated in the crack. Figure 4 shows an example of paint within a crack that can be used to estimate the age of the crack.

Similarly, take care not to overestimate the width of cracks, particularly when the edges of the cracks are rounded or raveled. It is common for the edges of cracks to spall and become rounded over time when subjected to vehicular and even pedestrian traffic. Surface preparation like bead-blasting prior to installation of finishes, or to remove finishes, can also make a dramatic difference in the appearance of cracks (Fig. 5). Since the purpose of measuring crack widths is generally to understand their structural relevance, it is the crack width at-depth that is most relevant, not the crack width at the surface.

Conclusions

It is easy to get wildly off track with respect to investigation of two-way slabs. Nearly all two-way slabs have performed as designed, particularly given the many decades of documented performance as well as laboratory testing. Engineers should ensure that they do not overreact upon discovery of radial or spiderweb cracking or upon determining that the out-of-levelness of a slab is greater than ACI design limits for calculated deflection. Emergency shoring is rarely required, and expensive repairs and retrofits should generally be avoided unless there is a significant risk to life safety.

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