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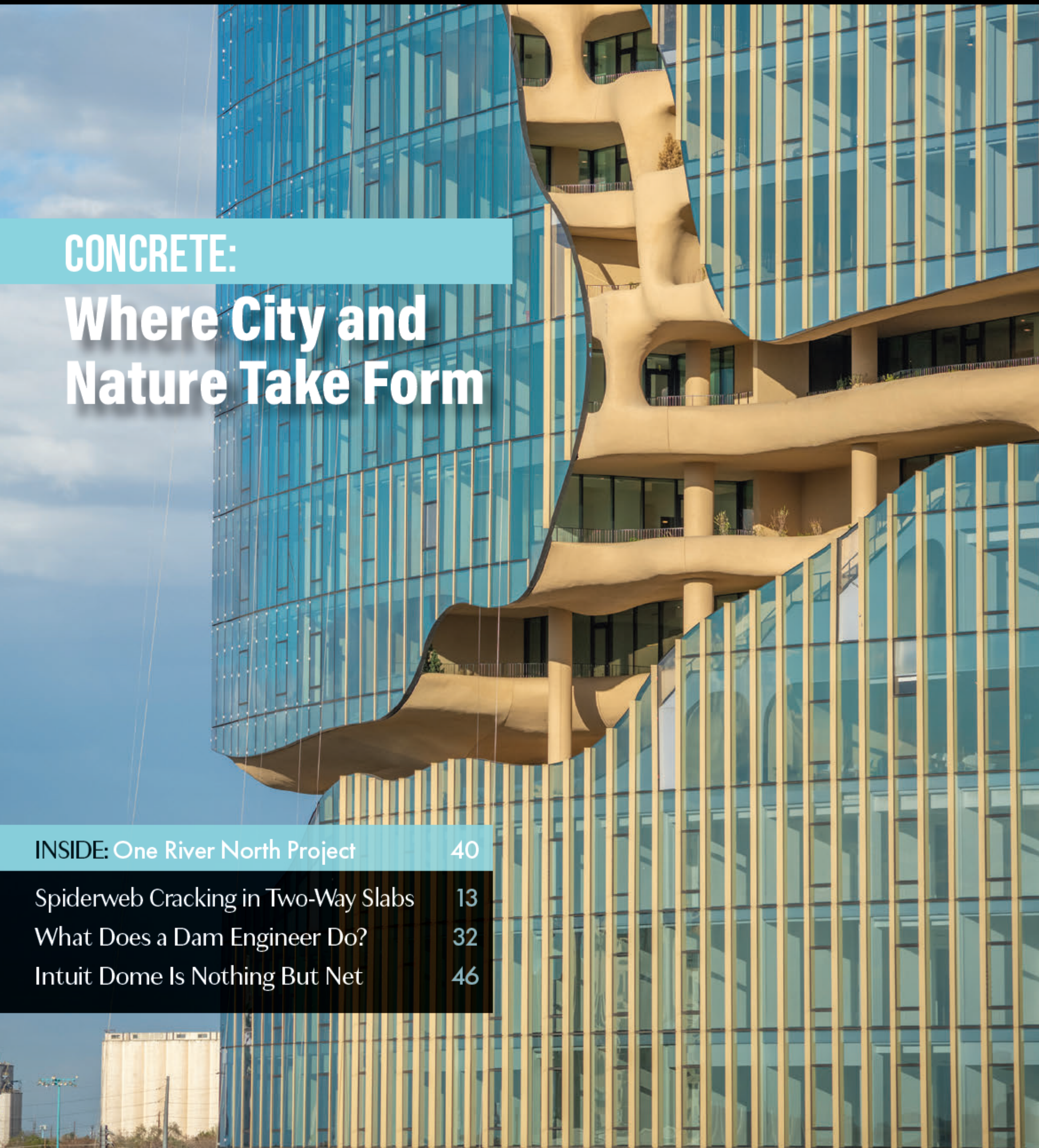

CONCRETE:

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In Every Issue

The Underlying Cause of Radial and Spiderweb Cracking in Two-Way Slabs

This article explores the subject of radial and spiderweb cracking in reinforced concrete two-way flat plates and flat slabs (herein referred to as "two-way slabs") and the underlying reasons for it. Proper investigation of radial and spiderweb cracking will be addressed in a following issue of STRUCTURE.

By Terrence Paret, Hayley Proctor, PE, and Gwenyth Searer, PE, SE, and Prateek Shah, PhD

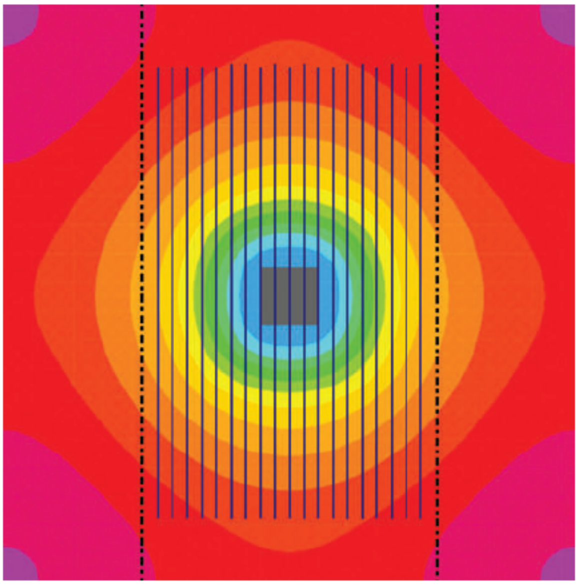
Over the years, the writers have observed radial (sometimes called "starburst" or "sunburst") and spiderweb cracking in dozens of two-way slab structures. These slabs were constructed in different regions of the country, were designed by different engineers in different decades using different editions of ACI-318, support different occupancy types, and were constructed by different contractors. Many of these slabs were found to exhibit radial and spiderweb cracking during construction, i.e., before the addition of finishes and before being put into service, but others were only reported to have radial and spiderweb cracking after years of continuous occupancy, sometimes only discovered after the removal of floor finishes during routine maintenance or remodeling. The relatively common occurrence of such cracking across a breadth of circumstances warrants a technically accurate understanding of its causes and structural significance.

While radial and spiderweb cracking sometimes are interpreted to be symptoms of elevated punching shear stress, and therefore are mistakenly interpreted to signify high risk conditions, analysis and research both demonstrate that these crack patterns are actually characteristic of flexural behavior that typically manifests at loads significantly below ultimate punching shear capacity, as documented by Elstner and Hognestad as well as Paret et al. This cracking largely results from a fundamental disparity between the explicit averaging of flexural demands across column strip widths in the ACI 318 strip method of design and the quantifiable distribution of bending moment in real slabs. Before delving into supporting analyses, it is helpful to explore the conceptual behavior of two-way slabs.

Conceptual Flexural Behavior of Two-Way Slabs

When subjected to service-level gravity load, multi-span, two-way slabs with larger span-to-thickness ratios are generally expected to experience larger midspan deflections, and therefore larger curvatures near the columns, than slabs with smaller span-to-thickness ratios, all other things being equal. These differences can be idealized in three dimensions by thinking of the relatively flatter deformed shape in slabs with smaller span-to-thickness ratios as "doming" and the amplified curvatures in slabs with larger span-to-thickness ratios as "tentpoling" (Fig. 1). Both behaviors are flexural as they are associated with curvature. The larger curvatures associated with larger span-to-thickness ratio slabs necessarily increase the propensity for cracking and local yielding of negative flexural reinforcement close to the columns, both of which would further amplify deflection and tentpoling.

Figure 2 overlays a typical layout of column strip reinforcement onto a plan view of the deformed shape for a typical bay extracted from the tentpoling illustration in Figure 1. Because curvatures vary across the width of the column strip, the distribution of negative moment across the width of the column strips also must vary, with the highest negative moment located near the centerline of the column strip (close to the columns) and significantly diminished negative moment near



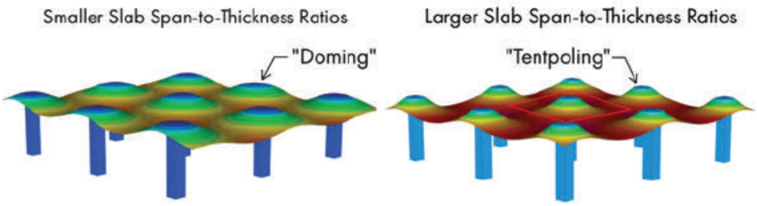


Fig. 1. (Above) Notional deformed shape comparison of slabs with varying span-to-thickness ratios. The area outlined in red is shown in plan view in Figure 2.

Fig. 2. (Right) Plan view of overlay of distribution of negative moment reinforcing steel (solid blue lines) and deformed shape (see Figure 1). The edges of the column strip are shown with black, dashed lines. The corners of the plan coincide with the centers of the surrounding bays.

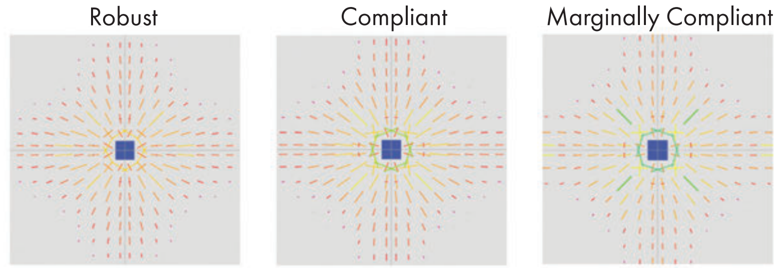


Fig. 3. Similar crack patterns are predicted by ETABS for each model. Maximum predicted crack widths increase from 38 to 45 to 53 mils as the robustness of the slab decreases.

the edges of the column strip. This distribution, whether for the larger or smaller span-to-thickness ratio slabs, is at odds with the ACI 318 strip method of design which assumes an averaged, uniform distribution of moment across the column strip width, thereby leading to designs in which negative moment reinforcement is uniformly distributed across the column strip width.

For typical span-to-thickness ratio slabs, even when the total quantity of column strip reinforcement is adequate to carry the total column strip moment, the concentration of negative bending stresses very close to the column results in a mismatch when compared to the more uniform distribution of steel in the column strip. This mismatch is indicative of what the writers refer to as a "nonuniform utilization" of the negative moment reinforcement: closer to the column, the stresses in the column strip reinforcement are necessarily higher than they are farther away from the column. Intuitively, the greater the degree of nonuniform utilization of the reinforcing steel, the greater the likelihood of developing relatively wide concrete cracking and yielding of reinforcing steel. However, this mismatch must be quantified to objectively assess the consequences of the mismatch.

Quantifying Nonuniform Utilization

Finite element software packages commonly used in structural design can readily quantify the severity of any nonuniform utilization, provide insight as to whether this nonuniformity is sufficient to lead to radial and spiderweb cracking and yielding of reinforcement, and predict the midspan deflection and crack pattern that results. Using ETABS, the writers developed three models of an idealized multi-span parking garage slab to isolate and study the influence of span-to-thickness ratio on performance (Table 1). The analyses, described below, demonstrate that characteristic tentpoling behavior due to nonuniform utilization of negative moment reinforcement, including radial and spiderweb cracking and yielding of reinforcement close to columns, predictably occurs even in code-compliant slabs under service loading.

The three models were identical in every respect (e.g., span length, column size, and loading) except for slab thickness, which was used to alter the span-to-thickness ratio. As tabulated, the slabs in all models were compliant in two-way shear (i.e., punching shear), though to different degrees since the slab thickness varied. Models characterized as "Robust" and "Compliant" had 12-inch-thick and 10-inch-thick slabs, respectively; each satisfied the minimum thickness requirements and the deflection limits set forth in ACI 318-19 Table 8.3.1.1 and Table 24.2.2. The third model, which had a 9-inch-thick slab, did not meet ACI 318's minimum slab thickness requirements but was also ACI-318-compliant because it satisfied the calculated deflection limits. The 9-inch-thick slab model was characterized as "Marginally Compliant" – despite being compliant with the letter of the code – to distinguish it from the "Compliant" model, which met the minimum slab thickness requirements, while the marginally compliant model did not. The flexural reinforcement in all three models was "designed" by ETABS to comply with the ACI 318 strip method.

For parking garages, which typically have few, if any, deflection-sensitive finishes, the controlling criterion for immediate live load midspan deflection per ACI 318 Table 24.2.2 is $\ell/360$, or 1 inch in the case of a 30-foot span. Table 1 shows the predicted immediate live load deflections; all are less than 1 inch, indicating that the designs are code compliant, though notably, the predicted midspan deflection of the "Compliant" and Marginally Compliant" slabs are roughly five and eight times, respectively, the predicted deflection of the "Robust" slab. These values represent the deflection increment due to short-term live load on a slab that may have already experienced some cracking due to dead load.

The dominant slab cracking patterns predicted by ETABS for the three slabs are distinctly radial and concentrated close to the columns (Fig. 3), which is consistent with expectations for the flexural doming and tentpoling behavior illustrated in Figure 1. Although the mesh-size dependency of these predictions makes them more reliable as qualitative points of comparison than as explicit predictions of in-field performance, the ETABS prediction that even the "Robust" slab will crack radially suggests that this behavior is inherent to two-way slabs regardless of level of safety and that engineers should not be surprised to see such cracking in buildings they design, even when the slabs are code-compliant in all ways, including punching shear.

The ETABS analyses also illustrate that the underlying mechanics of the radial cracking issue derive from nonuniform utilization of the uniformly distributed negative moment slab reinforcement. Figure 4 graphically depicts the nonuniform utilization from the ETABS analysis for the "Compliant"/10-inch-thick slab. Since the negative moment demand across the width of the column strip is not uniformly distributed while the negative moment reinforcement is, the local moment demand close to either side of the column significantly exceeds the reinforcement provided per the ACI 318 strip method. At the same time, near the outer margins of the column strip width, the reinforcement is more than adequate to resist the local moment

Table 1. Numerical Study Summary

Model	Interior Span (ft)	Exterior Span (ft.)	Column Size (in.)	Slab Thickness (in.)	Two-way Shear DCR	Complies With ACI 318 Min. Thickness Limits?	Complies With ACI 318 Deflection LImits?	Calculated Live Load Midspan Deflection (in.)
Robust	30	27	30x30	12	~0.7	Yes	Yes	0.1 in.
Compliant	30	27	30x30	10	~0.8	Yes	Yes	0.5 in.
Marginally Compliant	30	27	30x30	9	~1.0	No	Yes	0.8 in.

demand. Said another way, while the ACI 318 strip method provides adequate capacity to resist the total column strip moment, the demand significantly exceeds the slab capacity over the portion of the column strip width nearest the column, which leads to radial and spiderweb cracking and yielding within that portion of the column strip. In a true nonlinear analysis package that explicitly accounts for yielding and redistribution, the lateral extent of the overstress would spread farther from the column.

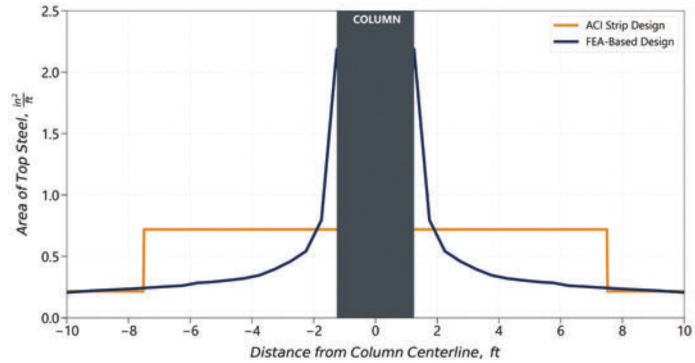


Fig. 4. Area of reinforcing steel required to satisfy the actual negative moment demand (blue) versus the ACI 318 strip method requirement (orange) for the "Compliant" (10-inch-thick) slab.

Consequences of Nonuniform Utilization

Radial and spiderweb cracking and yielding of reinforcement that results from the described nonuniform utilization may not negatively impact the ability of the slab to support design loads, but it can impact how the slab performance is perceived, and – if exposed to water and chlorides – the slab's long-term performance. In addition to the possibility that some owners and occupants may consider the cracking to be objectionable and may express alarm due to the presence of radial cracking, tentpoling behavior can lead to a potentially significant increment of deflection that might not always be considered during design especially if it is not relevant to the ACI deflection criteria for that structure; that increment can also impact owner and occupant perception of performance even if it does not impact safety. For example, for the design of parking garage slabs for which immediate live load deflection is the only relevant codified calculated deflection criterion, dead load deflection and incremental dead load deflection due to tentpoling would normally be ignored, even though those together may be several times greater than the immediate live load deflection. In the writers' experience, when tentpoling and out-of-levelness of two-way slabs become readily visible, the users' experience and owner satisfaction regarding those slabs may be reported as being diminished (Fig. 5).

Three of the primary considerations often involved in structural design of two-way slabs are code-compliance, structural safety, and serviceability. In part due to the nonuniform utilization of negative reinforcement, all code-compliant two-way slab designs do not attain comparable degrees of safety and serviceability. Given that ACI 318 provides no guidance on this subject, it might be assumed that a design that exactly satisfies minimum code requirements would attain comparable degrees of safety and serviceability. This assumption, however, does not withstand scrutiny. Not only will common design software predict tentpoling behavior, including cracking and amplified deflections, in code-compliant designs, but slabs that are code-compliant also commonly exhibit such behavior in the field. This phenomenon has sometimes resulted in design engineers, third-party engineers, developers, owners, and occupants characterizing normal predictable radial cracking and measured elevation differences in slabs that exceed code design limits as objectionable or even as safety risks. As such, an objective understanding of two-way slab behavior is urgently needed by the profession.

Fig. 5. This parking garage slab is exhibiting tentpoling behavior. Larger curvatures can be seen near the column.

To assist in developing the needed understanding and perspective, Figure 6 sets forth conceptual "scales" of code compliance, structural safety, and serviceability notionally achieved by any given slab design. The scales depict ranges of possible design outcomes from "increasing non-compliance" (solid red) to "marginally compliant" (dashed red to dashed blue) to "increasing robustness" (solid blue) relative to code-compliance; from "decreasing safety" (solid red) to "increasing safety" (solid blue) with intermediate degrees of safety (dashed red to dashed blue); and from "unsatisfactory for most owners" (solid red) to "unsatisfactory for some owners" (dashed red to dashed blue) to "satisfactory to most owners" (solid blue) relative to serviceability. The scales are intended to be read in accordance with their vertical alignment, e.g., reading vertically along Line 1, the dashed red and blue "marginally compliant" portion of the code-compliance scale aligns with the solid blue of the structural safety scale because "marginally compliant" designs are likely to still be structurally safe, but may well perform unsatisfactorily for some owners; this may represent a design that meets only the minimum strength and deflection requirements of ACI 318. At the lower end of "marginal compliance" (i.e., Line 2), structural safety is still likely but is less assured while serviceability tends toward "unsatisfactory for most owners." At the higher end of "marginal compliance" (Line 3), structural safety becomes more assured while serviceability tends toward "satisfactory for most owners."

Conclusion

While the ACI 318 strip method of design has proven to be a reliable method for achieving safe two-way slab designs, the mechanics of two-way slab behavior result in nonuniform curvature—and therefore nonuniform utilization of the negative reinforcement—across the width of the column strip in slabs designed by the strip

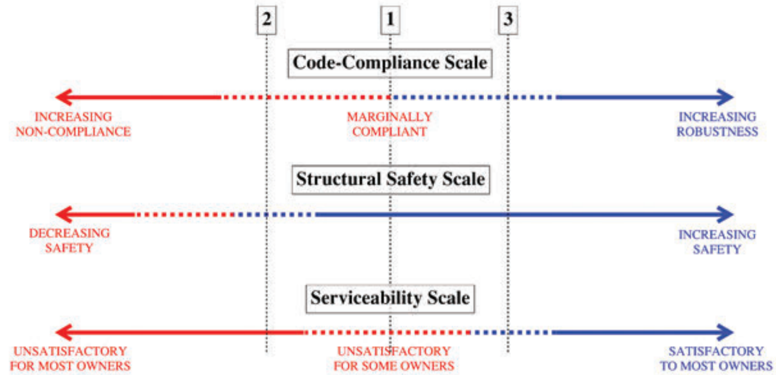
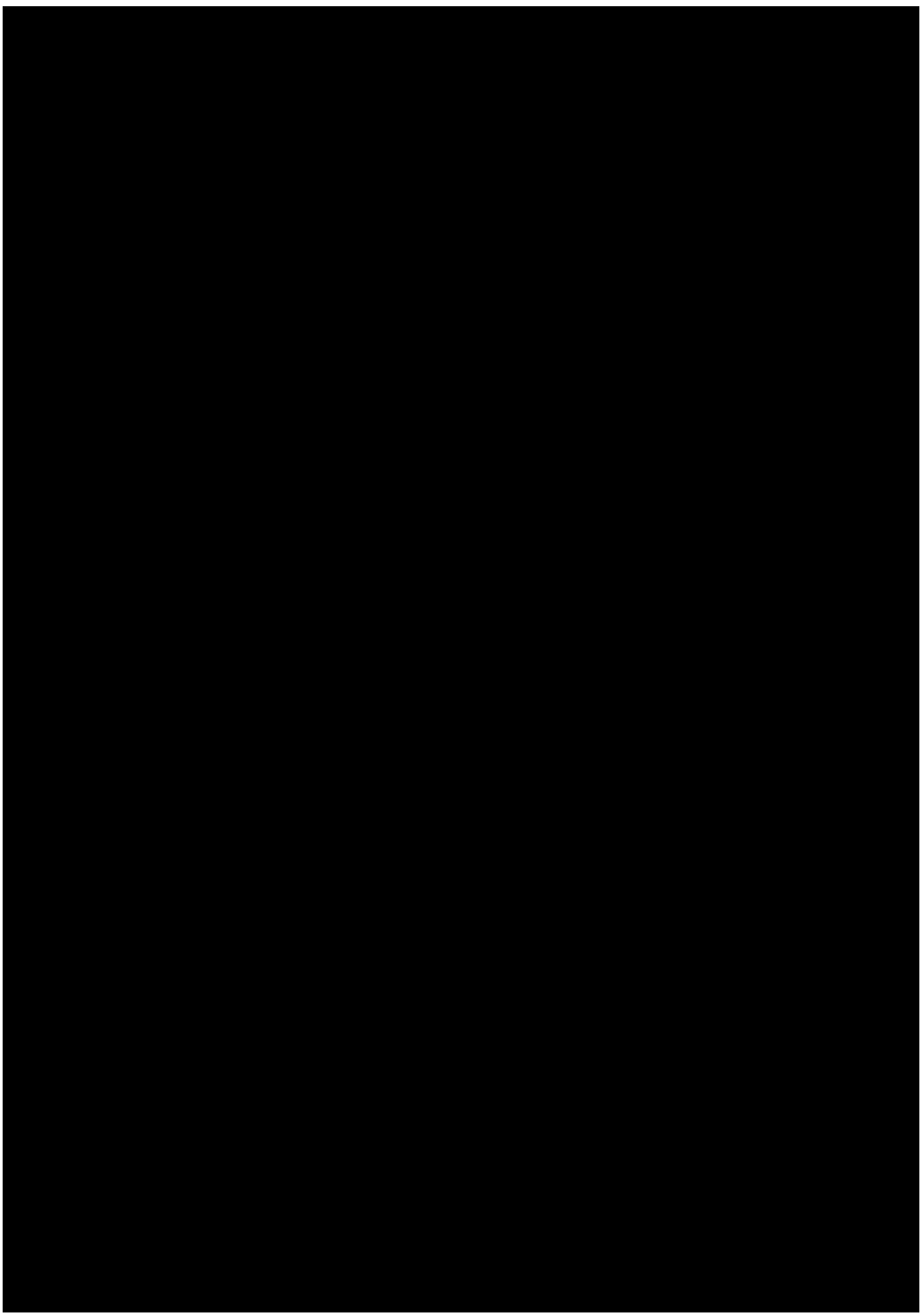


Fig. 6. Notional performance scales for two-way slabs. Numbered lines are described in the text.

method. These nonuniformities are underlying causes of commonly observed radial cracking and spiderweb cracking, which are characteristic flexural behaviors of two-way slabs and are often exhibited by code-compliant slabs. Commonly used design software can be used to demonstrate that radial and spiderweb cracking are predicted to occur in slabs that are proportioned and reinforced to just satisfy all code requirements, including for punching shear, as well as in slabs that are substantially more robust than required by code. Localized slab softening that develops in the vicinity of the supports as a result of nonuniform utilization of the negative moment reinforcement will result in greater curvature close to column supports (i.e., tentpoling), which is sometimes noticeable and necessarily amplifies midspan deflection beyond what would otherwise occur.



Engineers designing and assessing two-way slabs should anticipate this behavior, take steps to mitigate it by relying on more robust proportioning and reinforcement than is set forth by code minimum requirements, and be aware that radial and spiderweb cracking and tentpoling behavior are sometimes incorrectly construed as ramifications of punching shear or as otherwise detracting from the safety of the slabs that exhibit them. The performance of highly optimized designs will not be comparable to more robust designs with regard to these behaviors. More robust designs generally tend to experience less noticeable radial and spiderweb cracking and less noticeable tentpoling even if these behaviors will not be completely eliminated. Expectations of behaviors that may be unsatisfactory to some owners (i.e., cracking and out-of-levelness) should be clearly discussed with clients before completion of new designs to ensure that design decisions regarding slab span-to-thickness ratios are not driven entirely by code minimum requirements and cost.

Full references are included in the online version of the article at **STRUCTUREmag.org**.

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