YIELD-LINE ANALYSIS FOR FLAT-PLATE FLOORS

On behalf of the Post-Tensioning Institute (PTI), I enthusiastically congratulate the authors of “Design of Flat-Plate Floors for Progressive Collapse Using Yield-Line Analysis,” (July 2010, pp. 37-44) for their valuable contribution to the understanding of yield-line theory applied to the design and analysis of concrete flat plates. As the authors state, yield-line theory is a powerful, but underused, tool for accurately predicting the strength and behavior of all types of concrete members with minimal computational effort.

The authors’ work focuses on flat plates with nonprestressed reinforcement. However, yield-line theory is equally applicable to post-tensioned flat plates,1,2 which offer unique advantages in constructibility and resistance to progressive collapse.3 Post-tensioned flat plates (two-way solid thickness slabs with or without shear caps) reinforced with unbonded tendons are extensively used in the U.S. and elsewhere. Based upon tonnage statistics reported to PTI since 1972 and estimated for prior years, there are roughly 2.4 billion ft² of two-way unbonded post-tensioned slabs in service in the U.S. alone, representing some 24,000 individual buildings. Because PTI member companies pay dues on their reported tonnage, it is unlikely to be overstated.

The unique advantages offered by two-way post-tensioned slabs with unbonded tendons include:

- Proof testing—Every unbonded tendon in normally proportioned two-way slabs resists a load at the time of stressing that is greater than that required to develop the full flexural capacity of the slab. No other type of construction offers this type of proof testing prior to the application of any superimposed loads, meaning that undetected defects in concrete and reinforcement are unlikely to exist when the slab is in service.
- Catenary capacity—The majority of the primary reinforcement in post-tensioned slabs is continuous from one end of the slab to the other with no splices or discontinuities. This offers obvious advantages in preventing progressive collapse should the slab suffer the loss of one or more column supports. Further, the only way to increase the stress in an unbonded tendon is to increase its length between anchorages. Thus, local strains caused by large local deformations are distributed throughout the entire length of the tendon and do not result in high local tendon stresses. Tests have shown that slabs with unbonded tendons possess catenary capacities three to four times the demand loading at factored load.4

- Constructibility—The usable steel stress at nominal strength in unbonded tendons used in two-way slabs is roughly 3.5 times higher than the yield stress in nonprestressed reinforcement. Thus, there is much less steel required in post-tensioned slabs to perform the same structural function—reducing congestion; allowing for easier placement of plumbing, conduit, and all other embedded items; and resulting in much more constructible slab in every respect.

The loss of an unbonded tendon in one span of a multispans continuous slab affects all other spans. Designers have developed effective measures for mitigating this condition in all types of concrete members with unbonded tendons. In one-way beams and slabs, a load path independent of the tendons can be economically provided with the addition of a nominal amount of nonprestressed reinforcement designed to resist applied loads in the event of a catastrophic event resulting in the loss of prestressing force.5

Two-way slabs prestressed with unbonded tendons are highly redundant and intrinsically provide alternate load paths in the event of a catastrophic event resulting in significant loss of tendons. In a test of a nine-panel, two-way post-tensioned slab performed at the University of Texas in 1973, all tendons in the central bay in each direction were detensioned, simulating the loss of the entire panel and resulting in a loss of all of the prestressing force in one direction in the four adjacent edge panels.6

The surrounding edge and corner panels were then loaded to full service load, which they resisted with no significant distress. Many designers also provide a nominal grid of nonprestressed reinforcing steel in two-way prestressed slabs to provide an additional level of redundancy.

In summary, we applaud the author’s valuable work and respectfully wish to emphasize that it is equally applicable to both prestressed and nonprestressed slabs.

Kenneth B. Bondy, President, Post-Tensioning Institute

References

1. ACI Committee 423, “Recommendations for Concrete Members Prestressed with Unbonded Tendons (ACI 423.3R-05),” American Concrete Institute, Farmington Hills, MI, p. 8.
Letters

Unfortunately, Fig. 10 of “Design of Flat-Plate Floors for Progressive Collapse Using Yield Line Analysis” is incorrect. The flexural punching mechanism giving the lowest upper bound can be seen in Fig. 1 of my ACI Journal paper. It is appropriate for rectangular and square columns, and the expressions for punching strength are applicable to both isotropic and orthotropic slabs. A mechanism for circular cross-section columns is shown in Fig. 2 of the same paper.

The authors might also note that arching action in slabs, which has been observed in short-term laboratory tests, may not occur in the real world where shrinkage and creep are likely to lead to snap-through. Catenary action becomes problematical with low reinforcement ratios.

Hans Gesund, University of Kentucky

Reference

Authors’ response
We thank Ken Bondy for his letter. While our experience with analysis of post-tensioned flat plates is not extensive, we agree that applying the same principles for post-tensioned construction is possible and should be researched further.

We appreciate Hans Gesund’s comments. We agree that the local mechanism around the column, shown in the paper, is applicable to round columns and a somewhat different mechanism with fan-shaped yield line pattern would be applicable for square and rectangular columns. Our intent was to qualitatively show the nature of the mechanism. Interested readers should refer to Gesund’s paper as well as Reference 11 (Park et al.) of the paper for more detail of such local mechanisms.

We also agree that catenary action and arching action, while observed in some laboratory testing, cannot at this point be reliably applied to design of flat-plate structures. In addition to creep and shrinkage, mentioned by Gesund, our own analysis indicates that catenary action and arching action in the slabs is highly dependent on the stiffness at the yield-line mechanism boundaries. Many real world structures (especially those with irregular geometries) cannot provide sufficient stiffness for those mechanisms to develop. It is therefore our recommendation to ignore the beneficial effects of catenary action and arching action for the design of flat-plate structures until this issue is further researched.

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Fig. 1: Flexural collapse mechanisms

Fig. 2: Flexural collapse mechanism for circular columns