High-Performance Concrete Flat-Plate Floor System

by Mike Mota, Michael W. Hopper, Michael A. Russillo, and Ramon Gilsanz

Flat-plate concrete slabs provide economical floor structures for the short spans commonly associated with mid- and high-rise residential construction. These systems typically comprise 8 in. (200 mm) thick slabs spanning up to 22 ft (6.7 m) if reinforced with deformed bars only, or up to 30 ft (9.1 m) if the slabs are also post-tensioned (PT).

The purpose of this article is to highlight technologies that allow flat-plate floor systems to economically achieve spans in the 45 to 50 ft range (13.7 to 15.2 m) commonly used in Class A office building construction. These technologies include the application of:

- ASTM A615/A615M Grade 80 steel reinforcement[1];
- Concrete mixtures with design strengths of 8000 psi (55 MPa) and higher;
- Voided slab formers; and
- PT systems in which the tendons are banded over the columns in both directions.

The use of these technologies can reduce the environmental impact of buildings. For example, the voided slab formers, which are typically produced using 100% recycled plastic, reduce the required volume of concrete in a floor slab and the associated emissions of CO_2 by as much as 20% relative to competitive solid slab systems. These formers also allow slabs to be constructed with flat soffits, thus minimizing material and labor costs associated with slab formwork.

The resulting buildings have a low floor-to-floor height, minimizing building volume, façade area, and the height of elements such as stairs, partitions, piping, and elevator runs. Coupled with minimized building volume and façade area, the thermal mass of the concrete floor slabs can influence the instantaneous load on heating and cooling systems,[2] thus allowing reductions in equipment capacity and cost as well as energy use and CO_2 emissions over the life of the building. Further, the completed buildings will satisfy the needs of owners and developers of buildings seeking economical structural solutions that are flexible to tenant modifications, such as the construction of interconnecting stairs and replacement of existing mechanical systems, without the need for major structural retrofits.

Grade 80 Reinforcing Bars

Although ASTM A615/A615M Grade 80 reinforcing bars have been available since the late 1980s, recent advancements in the metallurgy of the material have allowed them to become a popular alternative for concrete construction in nonseismic applications. In effect, Grade 80 steel is developing into the "new" Grade 60 steel, as the cost premium associated with the higher strength is compensated by the reductions in bar size and quantities allowed by the 33% increase in yield strength. While Grade 80 bars do require increased lap and development lengths, these effects can be mitigated by using higher concrete strength.

Previous studies have shown that it is advantageous to reinforce flat-plate slabs with two continuous, uniform mats: one at the bottom of the slab and the other at the top.[3] Although the continuous mats require longer splices than conventional top and bottom reinforcement, the continuous top mat has been shown to reduce long-term deflections. Also, it has been shown that both mats generally need additional bars only at the columns, simplifying bar placement and inspection. Construction is further enhanced by the continuity of the top mat, as it allows for bar and concrete placers to safely walk on top of the bars. In summary, the extra weight of having two continuous mats with longer splices is compensated by the simplicity of the installation, resulting in fewer errors and more efficient inspections.

High-Strength Concrete

In 2001, ACI Committee 363, High-Strength Concrete, defined high-strength concrete (HSC) as "concrete that has a specified compressive strength for design of 8000 psi (55 MPa) or greater."[4] Mixtures with compressive strengths of up to 17,000 psi (117 MPa) are presently used for the construction of vertical elements. Test data show that the modulus of rupture (MOR) increases with the square root of the concrete strength. The modulus of elasticity (MOE) also tends to increase with concrete strength, although this parameter is affected by the type of coarse aggregate in the mixture. ACI 363R-10[4] provides equations for the prediction of the MOE for mixtures with specified compressive strengths above 8000 psi.

Increased MOR can result in reduced slab cracking that, coupled with a higher MOE, results in smaller deflections at a given load. HSC can also allow reductions in the thickness of slabs as well as elimination of the need for drop panels. Thus, the cost premium for HSC can be balanced by savings in the amount of concrete as well as reduced loads on formwork, columns, and foundations. The use of HSC combined with 80 ksi (550 MPa) bars results in additional economies.[3] Furthermore, the use of HSC and Grade 80 bars allows reinforced concrete columns to be of similar size as fireproofed steel columns.

Voided Slab Systems

Voided slab systems are two-way slabs with internal voids placed in zones where the shear demand is low. Flat-plate voided slab systems comprising normalweight and lightweight concrete have been used for many years in Europe.[5] Now, designers throughout the world are increasingly recognizing the many inherent benefits of these systems, including reduced weight; longer spans; reduced floor-to-floor heights; and smaller columns, foundations, and seismic forces.

The void formers in these systems are usually hollow spheres or ellipsoids formed of injection-molded recycled polymer. Multiple void formers are positioned within prefabricated wire support cages to create modular grids (cage modules) that are locked between the upper and lower reinforcement layers in the concrete slab (Fig. 1). The concrete placement can be completed in one or two steps. In the single-step process, the voids are anchored to the formwork to avoid floating and the slab is constructed using a single placement of concrete. In the two-step process, only the lower wire grid is encased by an initial placement of concrete. One to 3 hours after this placement, after the initial concrete placement has set, the floor slab is completed using a second concrete placement. Self-consolidating concrete is not required with either approach.

A slab containing void formers is around 35% lighter than a solid slab of the same thickness, and this reduction in load makes longer spans feasible. Tests on flat-plate voided concrete slab systems as thin as 8 in. have resulted in a 2-hour fire rating with 3/4 in. (19 mm) cover on the bottom reinforcing bars. These tests were based on ASTM E119-16a requirements,[6] and they were conducted at NGC Testing Services, Buffalo, NY, USA, in 2017.[7]

Openings in slabs are accommodated by omitting void formers and placing additional reinforcing bars at the perimeters of openings. Void formers are also omitted near supports to achieve full punching shear capacity. The voids in the remainder of the slab result in reduced dead load, potentially allowing the elimination of drop panels and/or shear reinforcement in the slab.

Designers account for the voids by using a reduced section modulus. Typically, the stiffness is about 10 to 15% lower than the stiffness of a solid slab of the same thickness. Also, for the design of two way-slabs with low percentages of deformed bar reinforcement and no post-tensioning tendons, an MOR of $4\sqrt{f'_c}$ may be needed to account for cracking associated with restrained shrinkage.[8,9]

Fig. 1: Voided concrete slab system *(illustrations courtesy of CobiaxUSA, Inc.)*

Dual Banding of Tendons

PT slabs are commonly designed with a uniform tendon layout in one direction and a banded tendon layout (tendons concentrated on the column lines) in the orthogonal direction. A banded-banded tendon layout, with the tendons concentrated on the column lines in both directions, is an attractive alternative for Class A office construction. Although this system is less efficient structurally because about 1/2 in. (12 mm) of the tendon drape is lost at the high point over the columns, it offers greater flexibility in the use of floor space in an office structure because it results in floor slabs with no tendons in the middle of each bay. Thus, the tendon system allows for the construction of openings in the slab at the intersection of the middle strips in the slab without affecting the performance of the slab. Openings in these locations are commonly used in office buildings to facilitate efficient access between floors without requiring the use of the main building elevators.

Engineers generally design the middle slab area as conventionally reinforced, without prestressing effects, even though the area is precompressed. Several structures have been constructed in the United States using this method. The Post-Tensioning Institute (PTI) is also testing slabs with banded-banded tendon layouts, and we understand that the results thus far are positive.

Voids in PT Slabs

Although voided slab and banded-banded PT technologies offer significant improvements in the design of flat slabs, more benefits can be realized when they are combined to provide economical and environmentally friendly concrete designs. This was done for the design of a new building at the Columbia University Irving Medical Center (CUIMC), New York, NY, USA, where two-way banded and bonded PT tendons were used in combination with void formers (Fig. 2 through 4).

Voids reduce the slab self-weight, cross-sectional area, and section modulus. The reduction in self-weight allows a proportionate reduction in PT material quantities. Further, the reduction in cross-sectional area results in increased precompression stresses (assuming the same tendon layout and stressing), and the reduction in the section modulus results in a

Fig. 2: The CUIMC Roy and Diana Vagelos Education Center *(image courtesy of Pavel Bendov/@archexplorer)*

Fig. 3: Construction of a voided slab with two-way banded and bonded tendons *(photo courtesy of LERA Consulting Structural Engineers)*

stress profile with increased bending stresses. The increase in precompression typically overcompensates for the increase in tensile bending stresses, so the net result is fewer tensile stresses in the voided slab than in the solid slab. Obviously, if the maximum stresses occur where there are no voids, this secondary benefit cannot be realized.

To demonstrate the potential scale of these benefits, consider a case study represented by an 8 in. thick one-way solid PT slab that is simply supported and spans 25 ft (7.6 m). If the slab is required to support 100 lb/ft^2 (about 20 kPa) of total service load (in addition to its self-weight), about 31 kip/ft (450 kN/m) of effective post-tensioning force is required to meet ACI Prestressed Class U criteria (see Case A in Fig. 5).[10] If a voided 8 in. slab with a weight reduction of 26 lb/ft^2 (1.3 kPa) in the voided area is used, and only the weight savings is considered in the structural design, about 24 kip/ft (350 kN/m) of effective post-tensioning force is required to meet the same criteria (see Case B in Fig. 5). Lastly, if the same voided slab is used but the modified cross-sectional area and section modulus are also accounted for in the stress calculations, an effective post-tensioning force of 22 kip/ft (320 kN/m) is required (see Case C in Fig. 5).

Design Methodology

To design a PT slab with voids, engineers must compare initial and

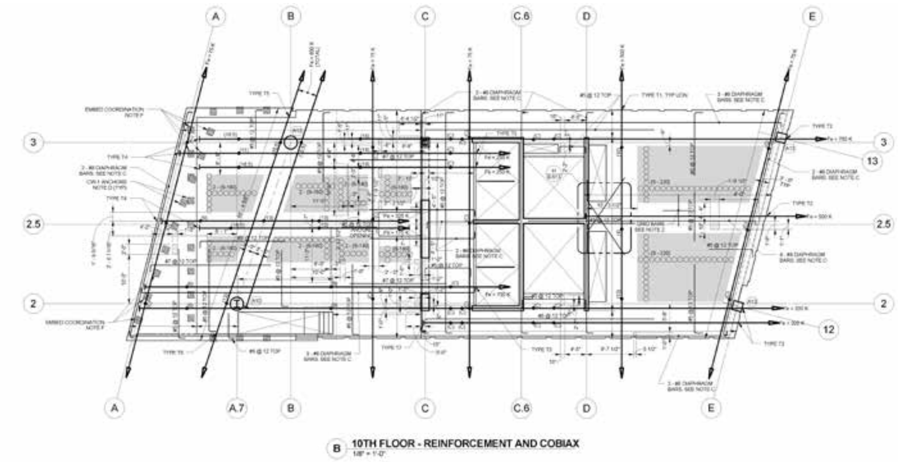


Fig. 4: Two-way banded tendon and void layout for the CUIMC Roy and Diana Vagelos Education Center *(illustration courtesy of LERA Consulting Structural Engineers)*

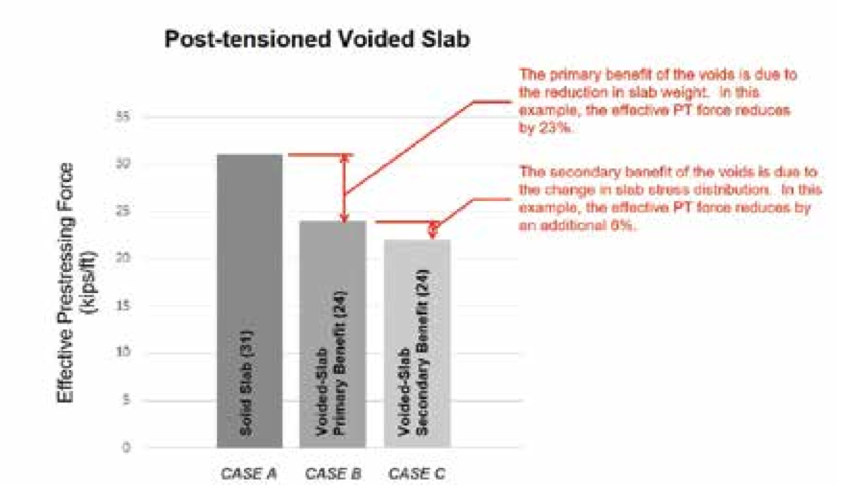


Fig. 5: Effective post-tensioning force required for an 8 in. thick one-way slab spanning 25 ft (7.6 m). Case A is a solid slab designed to meet ACI Class U prestressed slab criteria; Case B is a voided slab, designed by considering the weight savings provided by the voids; and Case C is a voided slab, designed by considering the weight savings, reduced cross-sectional area, and reduced section modulus associated with the voids (Note: 1 kip/ft = 14.6 kN/m)

service level stresses to ACI 318 limits.[10] This requires that they account for the reduced cross-sectional area and section modulus resulting from the insertion of the voids. At critical locations, which are often at the high and low points of the tendon profile, manual calculations can be performed to consider the effects of both the reduced section modulus and the reduced cross-sectional area, using the following equation:

$$\sigma = -\frac{P}{A_{mod}} \pm \frac{Py}{S_{mod}} \pm \frac{M}{S_{mod}}$$

where σ is the extreme fiber tensile or compressive stress; P is the prestressed force, initial or service; y is the tendon drape (distance from prestressing steel centroid to concrete centroid); A_{mod} is the modified cross-sectional area, equal to the gross cross-sectional concrete area minus the area of the void; S_{mod} is the modified section modulus, equal to the section modulus of the concrete including the voided zone; and M is the service moments, initial or service, including void former weight-savings effects.

Designers must also confirm that slab stresses between the high and low points of the tendon profile do not exceed the Code-allowable stress limits. Although commercially available software can account for the change in stiffness and weight for the voided slabs, we don't know of any commercial software that can directly account for the voids in the calculation of stresses. Manual calculation of stresses between the critical locations can be tedious. However, the following method has been used for the design of PT slabs with voids.

Commercially available software can be efficiently used by first modifying the inputs to adjust for the reduced slab weight and stiffness at sections with voids. Next, stresses at sections with voids can be compared to tensile or compressive stress limits based on Code values that have been reduced by factors that account for reductions in the section modulus or cross-sectional area for tensile stress limits or compression stress limits, respectively, using the following equation:

$$\sigma_{t\ or\ c} \times \left(S_{factor} \text{ or } A_{factor}\right) \geq -\frac{P}{A} \pm \frac{Py}{S} \pm \frac{M}{S}$$

where $\sigma_{t\ or\ c}$ is the extreme fiber tensile or compressive stress Code limit; S_{factor} is the voided slab section modulus reduction factor, used to compare tensile stress limits; A_{factor} is the voided slab cross-sectional area reduction factor, used to compare compressive stress limits; A is the cross-sectional area of the solid slab; S is the section modulus of the solid slab; and M is the service moment, initial or service, including the weight-savings effects of the void formers. Adjustments to weight, stiffness, and limits on stresses are not required at sections where voids have been omitted (for example, near column connections).

We recommend that designers use $S_{factor} = 0.9$ and $A_{factor} = 0.5$ for a two-way slab with void forms. Thus, to account for the voids in the software's stress calculations, tensile stresses calculated based on solid slab section properties are compared to the Code tensile stress limit for two-way prestressed slabs multiplied by 0.9. This conservatively neglects the benefits of increased precompression at the voids. Similarly for compressive stresses, calculated solid slab compression stresses are compared to the Code compression stress limits multiplied by 0.5. This compares compressive stresses using the cross-sectional reduction factor for both the precompression $(-\frac{P}{A})$ and the flexural stresses $\pm\frac{Py}{S} \pm \frac{M}{S}$, which is conservative for the flexural stresses, as the compression stresses increase by a factor of only 1/0.9 rather than the factor of 1/0.5 we recommended in the previous discussion. Engineers can use this approach to efficiently confirm that stresses between critical locations (the tendon high and low points) do not exceed the Code allowable stress limits.

Design for Seismic and Wind Loads

In most cases of voided slab construction, the slab elements are not included in the structure's lateral force-resisting system; however, they are designed to act as diaphragms when subjected to wind and seismic loads. When proportioning the required diaphragm reinforcement in the depth of the slab, it is recommended that the voided zone be ignored, and the diaphragm reinforcement be placed above and/or below the void formers. The structural drawings should clearly show where the diaphragm reinforcement is to be placed, and they should state the slab depth that was assumed in the diaphragm design.

In addition to proportioning the voided slabs for forces from lateral loads, it is recommended that engineers also consider the impacts that lateral displacements have on the slab-column joints. Lateral displacements of the structure result in rotations of the slab-column joints, which can lead to increased unbalanced moments that should be considered in the punching shear design of the voided slab. As with a flat slab with drop panels, engineers should check the required extents of the solid slab at supports to determine where the first rows of voids can be placed.

Furthermore, ACI 318, Section 18.14.5, requires that the gravity load must be supported at the critical section during lateral displacements resulting from an earthquake to prevent slab punching shear failure. When voided slabs are used as part of the lateral load force-resisting system and/or there are unbalanced moments, the voids can be placed at least a distance twice the slab thickness away from the critical perimeter to conservatively ensure this section is not compromised.

Conclusions

The combined benefits of Grade 80 bars, voided slabs, and dual-banded post-tensioning will allow flat-plate construction to be employed as an economical and environmentally friendly solution for the construction of Class A office buildings. Savings realized by the application of these technologies go beyond lowered slab costs, however, as the system also provides the building owner opportunities to safely modify the floor slab after construction.

Acknowledgments

We thank Borys Hayda, DeSimone Consulting Engineers, for reviewing the manuscript and providing valuable advice and Sebastian Delgado, Gilsanz Murray Steficek, for his significant contribution.

References

1. ASTM A615/A615M-20, "Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement," ASTM International, West Conshohocken, PA, 2020, 8 pp.

2. Childs, K.W.; Courville, G.E.; and Bales, E.L., *Thermal Mass Assessment*, Oak Ridge National Laboratory, Oak Ridge, TN, Sept. 1983, 86 pp.

3. Huang, C.I.-C.; Hoy, D.E.; Lan, Y.J.; de Romémont, C.; and Gilsanz, R.E., "Deflection of Flat-Plate Slabs," *Concrete International*, V. 42, No. 8, Aug. 2020, pp. 36-41.

4. ACI Committee 363, "Report on High-Strength Concrete (ACI 363R-10)," American Concrete Institute, Farmington Hills, MI, 2010, 69 pp.

5. Mota, M., "Voided Slabs," *Concrete International*, V. 32, No. 10, Oct. 2010, pp. 41-45.

6. ASTM E119-16a, "Standard Test Method for Fire Tests of Building Construction and Materials," ASTM International, West Conshohocken, PA, 2016, 36 pp.

7. Fanella, D.A.; Mota, M.; and Trygestad, A., "Fire Resistance of Flat Plate Voided Concrete Floor Systems," *Structure Magazine*, Jan. 2018, pp. 12-14.

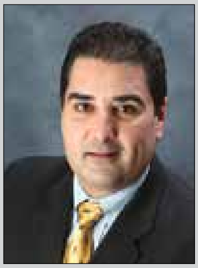
8. Fanella, D.A.; Mahamid, M; and Mota, M, "Design of Flat Plate Voided Concrete Slab Systems," *Recent Developments in Two-Way Slabs: Design, Analysis, Construction, and Evaluation*, SP-321, M. Mahamid and M.(J.) Shin, eds., American Concrete Institute, Farmington Hills, MI, Sept. 2017, pp. 12.1-12.17.

9. ACI Committee 435, "Control of Deflection in Concrete Structures (ACI 435R-95), (Reapproved 2000), Appendix B added 2003)," American Concrete Institute, Farmington Hills, MI, 1995, 77 pp.

10. ACI Committee 318, "Building Code Requirements for Structural Concrete (ACI 318-19) and Commentary (ACI 318R-19)," American Concrete Institute, Farmington Hills, MI, 2019, 623 pp.

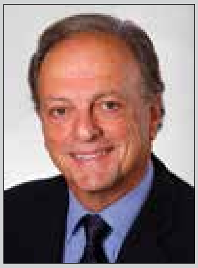
11. Beres, A.B., and Mota, M., *Design Guide for Voided Concrete Slabs*, first edition, Concrete Reinforcing Steel Institute, Schaumburg, IL, 2014, 56 pp.

Selected for reader interest by the editors.

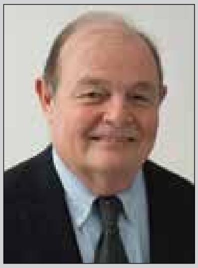


Mike Mota, FACI, is Director of Engineering and Partner at CobiaxUSA, Inc., Dedham, MA, USA. As Vice President of Engineering for the Concrete Reinforcing Steel Institute (CRSI) and Regional Engineer for the Portland Cement Association (PCA), he gained more than 20 years of experience in the best practices of using voided concrete slab systems. Mota is a Fellow of the American Society of Civil Engineers (ASCE) and the Structural Engineering Institute (SEI). He received his BS, MS, and CE from New Jersey Institute of Technology, Newark, NJ, USA, and his PhD in civil engineering from Drexel University, Philadelphia, PA, USA. He is a licensed professional engineer in five states.

ACI member **Michael W. Hopper** is an Associate Partner at LERA Consulting Structural Engineers. Since joining the firm in 2010, he has specialized in the design of concrete structures and is an expert in the use of post-tensioning. He is also a member of the Post-Tensioning Institute (PTI), where he serves on PTI Technical Committee DC-20, Building Design. He is a licensed professional engineer and teaches reinforced and prestressed concrete design at Princeton University, Princeton, NJ, USA. He received his bachelor's degree and MS in architectural engineering from Pennsylvania State University, University Park, PA, USA.



ACI member **Michael A. Russillo** is President of CobiaxUSA, Inc. Prior to the formation of CobiaxUSA, he was a Founding Partner and served as the President of Barker Post-Tensioning LLC. His lifelong experience includes working with a variety of architects, engineers, contractors, and owners/developers during the planning and completion of multiple building projects. He is a licensed professional engineer and received his BSCE from Northeastern University, Boston, MA, USA, and his MBA from Boston College, Chestnut Hill, MA, USA.



Ramon Gilsanz is Partner at Gilsanz Murray Steficek LLP. His experience ranges from new buildings, adaptive reuse, and special structures such as the tallest building in Spain, the Caja Madrid Tower, to suspending cars in the atrium of the Guggenheim Museum for the Cai Guo-Qiang exhibit. He is an active contributor to the structural engineering community and is currently helping develop new building codes. He is a Fellow of ASCE and SEI, and an Honorary Member of the American Institute of Architects' New York Chapter.