Atkinson Engineering, Inc.

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One of the problems in underpinning a typical post-tensioned foundation is support for the slab part that spans between the stiffening beams. An example of how to support even minimum loads on the slab component shows why more support than just the stiffening beams may be required.

The lightest dead load would be the weight of the typical 4-inch slab itself. Assuming that the concrete and reinforcement weighs 150 pounds per cubic foot (pcf), then the slab dead load would be 50 pounds per square foot (psf). In an open living area other than a sleeping area, Table 1607.1 of the 2012 IBC specifies designing for a minimum uniform live load of 40 psf. The minimum total unfactored load would be 90 psf.

Supporting even these light loads can be problematic for post-tensioned foundations. This is because if these slabs were designed according to requirements of the Post-Tensioning Institute (PTI), then they have only unbonded reinforcement. Lifting the foundation off the soil and supporting it with pilings, however, makes the foundation structural concrete with flexural members, for which the building code requires bonded reinforcement in addition to the unbonded prestressing tendons; bonded reinforcement that was not included in the original slab-on-ground design and construction.

Beginning with the 2000 International Building Code, Chapter 19, Concrete, defers largely to the American Concrete Institute Model Code, ACI 318. In the analysis to follow, I will refer to the 2008 edition of ACI 318.

Article 18.9.2 tells how much that minimum amount of bonded reinforcement is for a flexural member. [Two-way slabs have similar requirements. It will be shown that the requirement for bonded reinforcement in a two-way slab is essentially equivalent.] It reads, "Except as provided in 18.9.3, minimum area of bonded reinforcement shall be computed by

AS = 0.004Act (ACI 318-08,18-6)

where Act is area of that part of cross section between flexural tension face and center of gravity of gross section, in.2"

Now Bonded Reinforcement is a prestressing tendon, a deformed reinforcing bar, or welded wire fabric, that is bonded to concrete either directly or through grouting. But PTI slabs have none.

The exception to Article 18.9.2, Article 18.9.3, applies only to two-way slabs. Article 18.9.3.1 states that in positive moment areas, bonded reinforcement is not needed if the extreme fiber stress in tension, ft, in the precompressed zone at service loads does not exceed twice the square root of the concrete compressive strength. For 3000-psi concrete in typical residential construction, that would require that ft be less than 110 psi.

In negative moment areas, however, the requirement for bonded reinforcement is mandatory regardless of the tensile stresses. At column supports (that is, where underpinning pilings are placed beneath the stiffening beams), Article 18.9.3.3 states, ". . . the minimum area of bonded reinforcement As in the top of the slab in each direction shall be computed by

As = 0.00075Acf (ACI 318-08, 18-8)

where Acf is the larger gross cross-sectional area of the slab-beam strips in two orthogonal equivalent frames intersecting at a column in a two-way slab."

Accordingly, because neither the beam nor the slab parts of an unbonded post-tensioned slab-on-ground foundation contain bonded reinforcement, ACI 318 requires that the concrete be treated as plain concrete. Plain Concrete is defined by ACI 318 as "Structural concrete with no reinforcement or with less reinforcement than the minimum amount specified for reinforced concrete."

Plain concrete design requirements are given in ACI 318-08 in Chapter 22, Structural Plain Concrete.

The use of structural plain concrete is restricted. ACI 318-08, Article 22.2.1 states, "Use of structural plain concrete shall be limited to (a) members that are continuously supported by soil or supported by other structural members capable of providing continuous vertical support, (b) members for which arch action provides compression under all conditions of loading, or (c) walls and pedestals." If the foundation is supported atop underpinning piers, then it is not continuously supported by soil or other structural member capable of providing continuous vertical support, arch action does not provide compression under all conditions of loading, and the slab is not a wall or pedestal.

A PTI foundation lacking the minimum amount of bonded reinforcement thus cannot be underpinned with point supports and be fully complaint with the Building Code. The best that can be done with point supports is to comply with the rest of the ACI requirements for plain concrete. The justification for doing so is that while no strength can be assigned to steel reinforcement that may be present, the PTI foundation does have some reinforcement; it's just not bonded. That redundancy, and the likelihood that the foundation will be lifted mere inches off the ground, are the arguments to justify violating the building code by underpinning the foundation with point supports.

Continuing with the slab example, ACI 318-08 Section 22.5, Strength Design, requires that design of cross sections subject to flexure be based on

$$\phi M_n \geq M_u$$

(ACI 318-08, 22-1)

where

ϕ

is the strength reduction factor, Mu is the factored moment, and Mn is the nominal moment strength computed by

$$M_n = 5\sqrt{f_c'}\,S_m$$

(ACI 319-08, 22-2)

and where Sm is the elastic section modulus.

Consider the typical four-inch thick residential floor slab. The section modulus is $S_m = \frac{bd^2}{6}$

So for a 12-inch unit width the section modulus is

$$S_m = \frac{(12)(4)(4)}{6}$$

$$S_m = 32\ in^3$$

Since for plain concrete, ACI 318-08 Article 9.3.5 says the strength reduction factor ϕ shall be 0.60, then for a four-inch thick slab of 3000-psi concrete,

$$\phi M_n = (0.60)5\sqrt{f_c'}\,S_m$$

$$\phi M_n = \frac{(0.60)(5)(54.77\,lb/in^2)(32\,in^3)}{12\,in/ft}$$

$$\phi M_n = 438\,ft - lb$$

Let's see how this factored moment fits for the typical residence. Begin with assuming the design loads and load factors as specified in ACI 318-08:

Self Weight = 50 psf

Dead Load Factor = x 1.2 = 60

Live Load = 40 psf

Live Load Factor = x 1.6 = 64

Design Factored Load, w = 124 psf

The simplest model to assume is a simply-supported, one-way slab of length L and unit width of one foot. The maximum moment Mmax will be at the center of the span and is given by $M_{max} = \frac{wL^2}{8}$

Solving for L, $L = \sqrt{\frac{8M_{max}}{w}}$

Substituting the values, $L = \sqrt{\frac{8(438\,ft - lb)}{124\ lb/ft}}$

$L = 5.31\,ft.$

Thus, assuming a simply-supported one-way slab of four-inch thick, 3000-psi concrete, the span between supports should not exceed 64 inches. (It can be shown that shear will not dominate.)

Would the allowable span increase much if we assumed that moment could be transferred at the ends? This would require that all cracks be repaired and that the slab no longer were subject to shrinkage or temperature effects that could cause deleterious cracking.

If we assume that the one-way slab is fixed at both ends, then the maximum moment will be at the ends of the slab, and is given by $M_{max} = \frac{wL^2}{12}$

Solving for L, $L = \sqrt{\dfrac{12(438\,ft - lb)}{124\ lb / ft}}$

$$L = 6.51\,ft.$$

This still makes for rather close pier spacing; any one-way slab spanning more than 6'-6" between stiffening beams needs interior slab support.

What if we design the underpinning by assuming two-way slab action? ACI 318-08 Section 13.6 provides design criteria assuming that the slab moments cross the stiffening beams. We can make a worst-case calculation by assuming the subject slab is a square with sides of length L, located such that the slab has beam support on all sides. From the table in Section 13.6.3.3, the total factored static moment MO is distributed 70% in interior negative moment and 57% in positive moment, so that the negative moment condition would rule. The two-way maximum design moment is given by $M_{2\text{-way}} = \dfrac{M_O}{0.70}$

Again solving for L, $L = \sqrt{\dfrac{8(438\,ft - lb)}{(0.70)(124\ lb / ft)}}$

$$L = \sqrt{40.37\,ft^2}$$

$$L = 6.35\ ft.$$

For a square slab area, then, there is no benefit in assuming a two-way model. Considering that the PTI design method allows for beam spacing of up to 17 feet, underpinning PTI foundations often requires intermediate support for the slab panels. Note also that these calculations assumed no loads from partitions;

from other superstructural components such as ceilings, roof structure and struts, or second-story floors; or from automobiles; and that the concrete was uncracked.

A similar calculation is needed to determine how far apart to provide support for the exterior and interior beams.

Finally, it can be shown that underpinning only the perimeter of a typical slab-on-ground foundation on expansive soil will violate the Building Code. [See Atkinson, Gardner D., "The Myth of Residential Foundation Repair by Perimeter Underpinning," Proceedings of the Fall Meeting of the Texas Section of the American Society of Civil Engineers, El Paso, Texas (October 2010).] This is because the interior slab and beam portions would span too far without support if the interior soil shrinks or subsides.