DESIGN CONSIDERATIONS FOR

UNBONDED CONCRETE TOPPING SLABS IN PLAZA DECK SYSTEMS SUBJECTED TO VEHICULAR TRAFFIC

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Concrete topping slabs are overlays applied on top of structural floors to provide a finished floor surface for multiple purposes, such as providing a wearing course to support traffic loads in parking facilities and bus terminals, providing a level surface for interior floors, and to resurface worn or damaged floors.

The authors are not aware of existing design guidelines or recommendations for topping slabs, particularly for unbonded applications, and where the topping slab is subjected to vehicular traffic and exposure to the weather. Design of topping slabs is not formally treated in engineering literature. The purpose of this article is to address the issues associated with the performance and behavior of topping slabs in plaza deck systems subjected to vehicular traffic.

UNBONDED TOPPING SLABS

In unbonded systems, the topping slab is not mechanically adhered or otherwise bonded to the underlying structural floor. Unbonded systems are provided when it is desired that the two slab courses move independently or to permit easy replacement of the topping slab at a later period. To prevent the bond between the topping and base slabs, plastic sheeting, roofing felt, or other similar bond-breaking materials can be used. Very often, an intermediate layer of waterproofing membrane is provided in applications where there is occupied space below. These systems are often referred to as "plaza deck systems" and will be the focus of the study presented in this article.

ISSUES WITH TOPPING SLABS

The customary engineering practice has been to treat topping slabs as nonstructural without performing any rigorous analysis to determine reinforcement and thickness requirements. Topping slabs are typically designed using the engineer's experience and reinforcement is provided for crack control due to shrinkage and temperature effects. A common flaw or misconception is that the topping slab is considered a "nonstructural" element by most engineers and is merely seen as a medium to transfer the loads to the "real" structural deck or slab below the topping. This way of thinking is true in the sense that failure of the topping will not jeopardize the structure or pose a life safety issue. However, extensive cracking and spalling of the topping slab can lead to a significant reduction of its service life and may compromise the waterproofing characteristics to occupied spaces below. For most owners, this condition will be unacceptable. Some cases of serviceability failures of topping slabs have been observed because of inadequate design and specifications for construction of these slabs.

Topping slabs have many of the same issues that slabs-on-ground and structural concrete slabs have. Concrete practices related to crack control, shrinkage and temperature control, concrete jointing, concrete mixture design, and concrete curing for elevated slabs and slabs-on-ground are also applicable to topping slabs. Improper concrete practices can lead to poor performance of topping slabs. Several American Concrete Institute (ACI) documents[1-6] offer guidance for proper design considerations and construction practices for concrete slab construction.

PLAZA DECK SYSTEMS

Plaza deck systems typically consist of a structural slab, waterproofing membrane, protection board, insulation/drainage layer, and a topping slab (wearing surface). Figure 1 illustrates the typical components of a plaza deck system. These systems are often used to provide waterproofing to occupied spaces located below driving surfaces or landscaped areas. Plaza deck systems generally occur in parking garages, airport terminals, bus terminals, and commercial properties such as hotels, condominiums, and office complexes. These systems are popular among owners because the topping slab provides protection to the waterproofing membrane with the anticipation that the need of maintenance or replacement of the membrane will be eliminated.

However, the presence of a waterproofing system that is sandwiched between the base structural floor and the topping slab can cause serviceability problems to the topping slab. The waterproofing membrane and protection board are more compressible than both the base structural and topping slabs. When subjected to loads, the waterproofing system that is sandwiched between the two more rigid slabs gets compressed or shortens. When the topping slab is resting on this soft, compressible surface, it will experience larger deformations and stresses than when it rests on a more rigid surface. The topping slab behavior can be visualized as a slab supported on spring supports or a slab on an elastic foundation for analytical purposes. The magnitude of the stresses in the topping slab will depend on the compressibility of the waterproofing system (that is, the stiffness of the spring supports), and the relative stiffness between the topping slab, waterproofing system, and base structural slab.

Plaza deck systems have been observed where the concrete topping slab experienced severe cracking and spalling because the effect of the intermediate waterproofing layer on the topping behavior may not have been considered (Fig. 2). In many cases, topping slab deterioration is initiated by improper concrete practices and detailing that leads to the origination of shrinkage cracks. The presence of shrinkage cracks can be very detrimental to unbonded toppings resting on compressible membrane systems when subjected to continuous or heavy vehicular traffic. Shrinkage cracks, which are initially narrow, will tend to widen and grow as the service loads continue to be applied by vehicles in conjunction with the dynamic effects of such loads. As the cracking progresses, the portions of concrete bounded by cracks will eventually debond and spall because of the lack of bond to the base structural floor (Fig. 3).

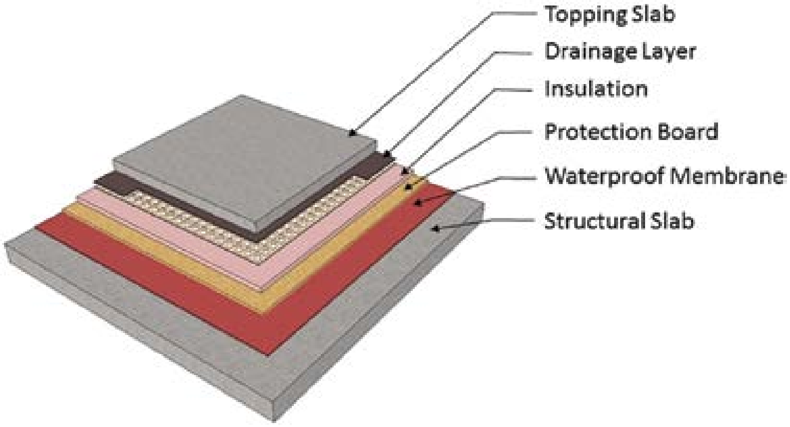


Fig. 1: Typical components of a plaza deck system

Fig. 2: Cracking and concrete spalling of topping slab (plaza deck system)

Fig. 3: Lack of bond at waterproofing membrane caused delamination and spalling of concrete segments in topping slab between cracks

ANALYSIS OF UNBONDED TOPPINGS

To analyze unbonded topping slabs, a limited parametric study based on an elastic analysis of a topping slab supported on spring supports above a structural floor was performed using commercially available structural software. The characteristics of the prototype system used in the analytical study are summarized in Fig. 4. The analytical model consisted of two concrete shell elements (one above the other) representing the base concrete structural slab and the topping slab supported by a structural steel frame. Links were provided between the base structural concrete slab supported by the structural steel frame and the concrete topping slab above (Fig. 5). The objective of the analysis was to study the effect of the link properties (that is, stiffness) on the behavior of the upper concrete topping slab when subjected to uniform and concentrated loads. The stiffness of the link element represents the compressibility of the sandwiched membrane system. The compressibility of the sandwiched system is often referred to in the literature as "foundation modulus" (compressive stress per unit deflection) and it is usually expressed in units of psi/in. or lb/in.^{3} (pounds per cubic inch). The effects of stiffening or softening of the supporting structural slab or steel structure were not investigated. Slab

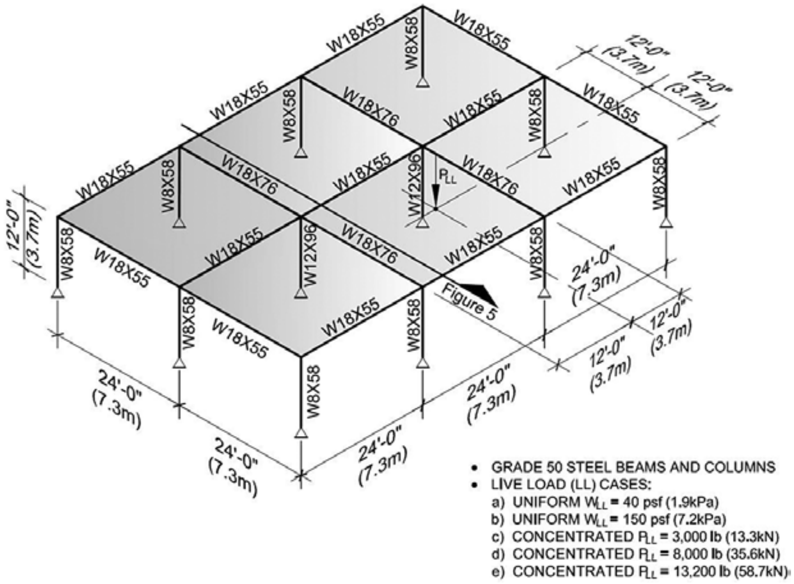


Fig. 4: Three-dimensional view of analytical model of topping slab supported on structural slab and steel framing

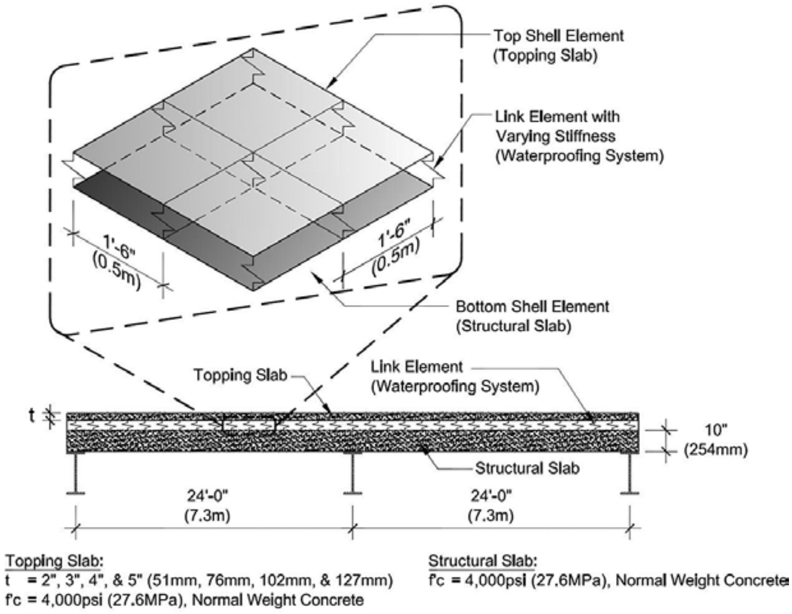


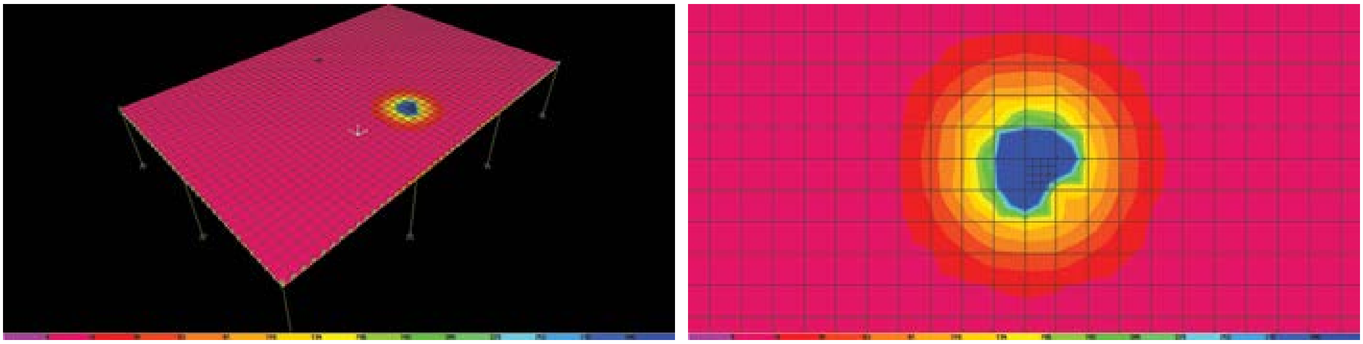
Fig. 5: Cross section of analytical model of topping slab supported on structural slab and steel framing

joints (contraction and isolation joints) were not modeled in the shell elements for simplicity and to limit the number of variables.

Five live load cases were studied: a) uniform load of 40 lb/ft^2 (1.9 kPa); b) uniform load of 150 lb/ft^2 (7.2 kPa); c) concentrated load of 3000 lb (13.3 kN); d) concentrated load of 8000 lb (35.6 kN); and e) concentrated load of 13,200 lb (58.7 kN). Concentrated loads of 3000 and 8000 lb (13.3 and 35.6 kN) acting on an area of 4.5 x 4.5 in. (114 x 114 mm) are prescribed in ASCE/SEI 7-10[7] for parking garages subjected to passenger vehicles, and for driveways subjected to truck loads, respectively. The same standard prescribes a uniform load of 40 lb/ft^2 (1.9 kPa) for parking garages. The 13,200 lb (58.7 kN) load applied over a 12 x 20 in. (305 x 508 mm) area represents the wheel load of a typical airport terminal shuttle bus (a 13,200 lb [58.7 kN] load over a 13.5 x 18 in. [343 x 457 mm] area was used in the analysis to fit the size of the shell elements). An arbitrary uniform live load of 150 lb/ft^2 (7.2 kPa) was used to represent medium to heavy vehicular traffic loads.

Figure 6 shows a plot of maximum shell stresses on a topping slab when subjected to a concentrated live load of 8000 lb (35.6 kN) when the stiffness of the link element between the deck and topping slab is 32.4 kip/in. (5.7 kN/mm). With link elements in the model spaced at 18 in. (457 mm), this is equivalent to a foundation modulus of 100 lb/in.^{3} (0.03 N/mm^3). Similar plots where produced for the stiffness of link elements ranging from 10 to 1000 kip/in. (1.75 to 175 kN/mm), equivalent to a range of foundation modulus from 30 to 3000 lb/in.^{3} (0.008 to 0.81 N/mm^3). Typical foundation modulus values for some insulation systems fall within this range.[8-10]

In Fig. 7, maximum tensile stresses in the topping slab shell element are plotted against the foundation modulus of the link element for 2 to 5 in. (51 to 127 mm) thick topping slabs when subjected to concentrated live loads of 3000 and 13,200 lb (13.3 and 58.7 kN). Figure 8 shows a similar plot for concentrated live loads of 3000 and 8000 lb (13.3 and 35.6 kN). A line showing a stress of $7.5\sqrt{f'_c}$ is



(a) isometric view of analytical model

(b) close-up of loaded area

Fig. 6: Plot of maximum shell stresses on topping slab when stiffness of link element is 100 lb/in.^{3} (0.03 N/mm^3) and it is subjected to a concentrated live load of 8000 lb (35.6 kN)

plotted in these figures as a reference. This stress level, known as modulus of rupture (f_r) as defined by ACI 318-11,[11] typically represents the tensile strength of the concrete. Clearly, as the thickness of the topping slab decreased, it experienced larger stresses for all ranges of link foundation moduli when subjected to concentrated loads. As the link foundation modulus decreased below the range of 500 to 700 lb/in.^{3} (0.14 to 0.19 N/mm^3), the stresses in the topping slab increased in a more pronounced manner. No significant changes in shell stresses were observed for link foundation moduli larger than 1000 lb/in.^{3} (0.27 N/mm^3). In this particular analysis, the 2 to 4 in. (51 to 102 mm) thick topping slabs subjected to a concentrated load of 13,200 lb (58.7 kN) (Fig. 7) experienced stresses larger than the concrete modulus of rupture for all values of link foundation modulus. The 5 in. (127 mm) thick topping subjected to a 13,200 lb (58.7 kN) concentrated load experienced stresses less than the concrete modulus of rupture except for very low values of link foundation modulus (100 lb/in.^{3} [0.03 N/mm^3] or less). Slab stresses produced by an 8000 lb (35.6 kN) concentrated load (Fig. 8) were somewhat larger but similar to those for the 13,200 lb (58.7 kN) load case (the 8000 lb load [35.6 kN] was applied on a footprint smaller than that for the 13,200 lb [58.7 kN] load). Shell stresses for 3 to 5 in. (76 to 127 mm) thick topping slabs remained below the concrete modulus of rupture when the structure was subjected to the concentrated load of 3000 lb (13.3 kN) typically specified in parking garages (except for the 3 in. [76 mm] thick topping slab supported on links having a foundation modulus of 100 lb/in.^{3} [0.03 N/mm^3] or less).

Figure 9 is a similar plot to Fig. 7 but with the addition of uniform live load cases of 40 and 150 lb/ft^2 (1.9 and 7.2 kPa). The results for the 2 in. (51 mm) topping slab subjected to 13,200 lb (58.7 kN) concentrated load were excluded from Fig. 9 for clarity. Interestingly, behavior of the topping slab when subjected to uniform loads exhibited an opposite trend as compared to when subjected to concentrated loads: The stresses increased as the foundation modulus of the link element increased. Nevertheless, the topping slab shell stresses were well below the concrete modulus of rupture when the topping slab was subjected to uniform loads of 40 and 150 lb/ft^2 (1.9 and 7.2 kPa), regardless of topping slab thickness and link foundation modulus. As can be seen in Fig. 9, the stresses experienced by different topping thicknesses were very similar for each uniform load value, although the thicker toppings experienced somewhat larger stresses than thinner toppings (a trend also opposite to that observed under concentrated loads).

The analysis results for the structural slab underneath the topping slab are not shown in Fig. 7

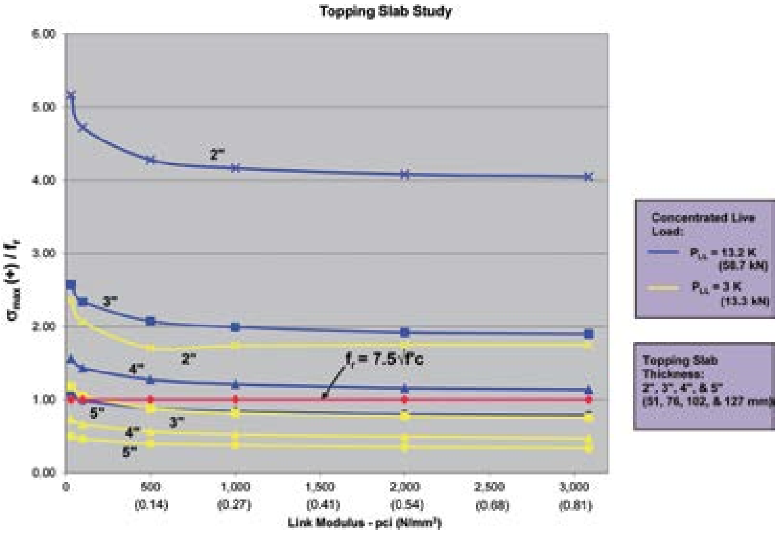


Fig. 7: Plot of maximum tensile stresses versus link modulus for topping slab with various thicknesses subjected to concentrated live loads of 3000 and 13,200 lb (13.3 and 58.7 kN)

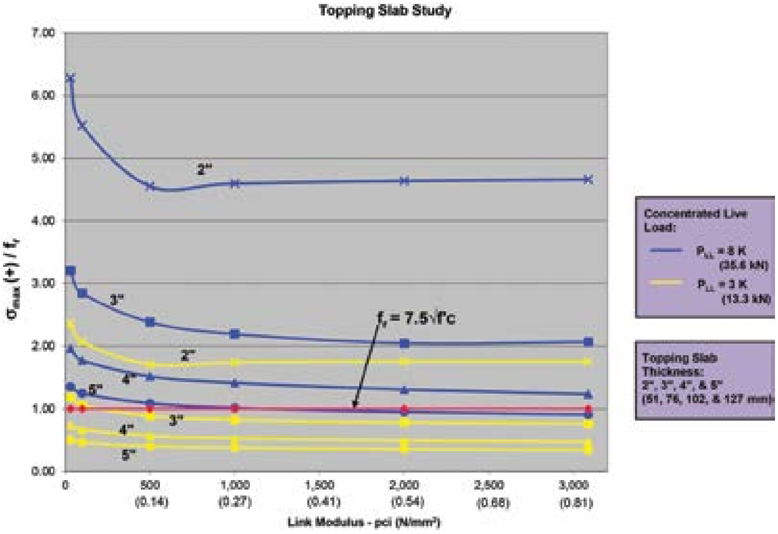


Fig. 8: Plot of maximum tensile stresses versus link modulus for topping slab with various thicknesses subjected to concentrated live loads of 3000 and 13,200 lb (13.3 and 58.7 kN)

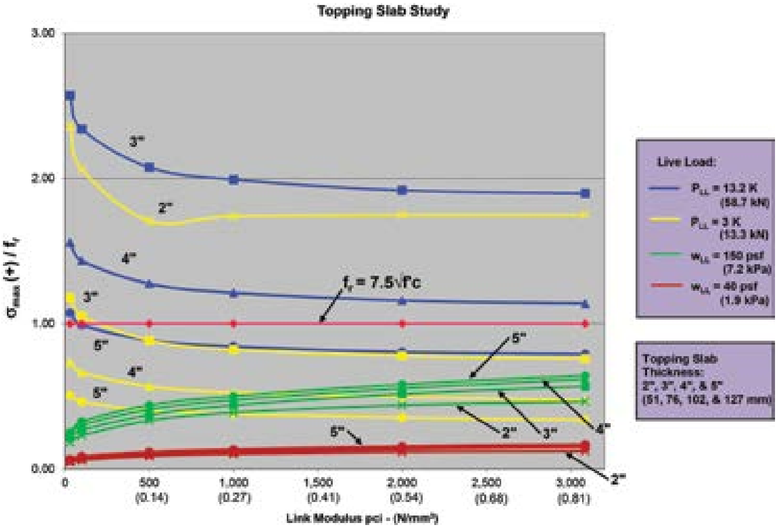


Fig. 9: Plot of maximum tensile stresses versus link modulus for topping slab with various thicknesses subjected to concentrated and uniform live loads

through 9 for clarity. The stresses in the structural slab did not seem to be affected by changes in the stiffness of the link member and remained generally constant and well below the concrete modulus of rupture for all ranges of link foundation moduli and load values.

The results of this limited study clearly suggest that the thickness of the topping slab and type of loading are the most significant factors affecting the behavior of a plaza deck system. Concentrated loads had more significant effect on the behavior of the topping slab as compared to uniform loads. Thicker topping slabs experienced lower tensile stresses when subjected to concentrated loads. For a particular topping slab thickness, a link member with larger foundation modulus resulted in lower tensile stresses in the topping slab when subjected to concentrated loads. This means that in a plaza deck system with the topping slab reinforced for shrinkage and temperature control only, a thicker topping slab should be selected and installed to reduce the tensile stresses in the topping slab. Selecting a waterproofing membrane (link member in the model) with low compressibility (high foundation modulus or stiffness) would be the second most important consideration after the topping slab thickness.

Figures 7 and 8 show that for certain combinations of topping slab thickness and magnitude of concentrated load, changes in the link foundation modulus resulted in shell stresses being above or below the concrete modulus of rupture. For these cases, the compressibility of the combined waterproofing membrane and protection board may need to be considered in the structural design of an unbonded topping slab to reduce the stresses below the concrete modulus of rupture. The designer would need to obtain the compressibility of the waterproofing system from the manufacturer and perform analyses of the topping slab similar to the ones presented in this study. Unfortunately, foundation modulus properties of waterproofing systems may be difficult to obtain from manufacturers because of the lack of test results. The engineer needs to work collaboratively with the waterproofing manufacturer to specify minimum compressive strength and subgrade modulus values for the sandwiched waterproofing system. If such information is lacking with the manufacturer, then tests may need to be performed to get the required properties for design.

When performing the recommended analysis, if tensile stresses in the topping slab are higher than the modulus of rupture of normalweight concrete ($7.5\sqrt{f'_c}$), steel reinforcement should be designed to reinforce the topping slab for bending moments produced by traffic loads, considering the effects of the waterproofing system and the topping slab behavior. Providing reinforcement for shrinkage and temperature alone, as is normally done in topping slabs, will not be adequate, particularly for applications with heavy traffic loads subjected to truck or bus loads (that is, a concentrated load of 8000 to 13,200 lb [35.6 to 58.7 kN]).[7]

CONCLUSIONS

Based on this parametric study of various topping slab thicknesses, and a range of the stiffness of the sandwiched waterproofing membrane that could be normally encountered in practice, the following conclusions can be drawn:

1. An analysis of the structural slab plus topping slab, taking into consideration the compressibility of the waterproofing membrane plus protection board system and including the stiffness of the supporting structural frame, is recommended to evaluate the required thickness and reinforcement in the topping slab for the anticipated concentrated and uniform live loads that will be applied to the plaza deck system.
2. Where a plaza deck system is to be used, consider the largest possible topping slab thickness to minimize tensile stresses and cracking of the topping slab. For applications with light traffic (concentrated load of 3000 lb [13.3 kN]), a topping slab with a minimum thickness of 3 in. (76 mm) is preferred. This is also the minimum thickness in which steel reinforcement can be placed with adequate cover for exterior exposure as defined by ACI 318.[11] For applications with heavy traffic (concentrated load of 8000 to 13,200 lb [35.6 to 58.7 kN]), a minimum unbonded topping slab thickness of 5 in. (127 mm) will provide a better serviceable life.
3. In certain cases, a waterproofing membrane system (membrane plus protection board) with foundation modulus higher than 300 lb/in.^{3} (0.08 N/mm^3) may help minimize the magnitude of tensile stresses and, consequently, reduce the amount of cracking in the topping slab. The foundation modulus needs to be obtained from the membrane manufacturer. If this information is not available, material tests to obtain the required properties may be needed.
4. It is important that, in addition to determining the appropriate topping slab thickness and reinforcement for the anticipated loads, proper construction practices for topping slabs should be followed.

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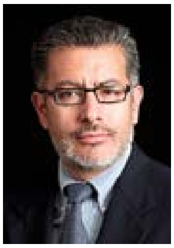

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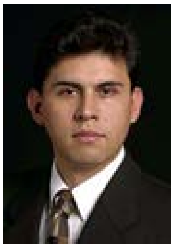

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