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INTRODUCTION

Two-way post-tensioned slabs have been an extremely popular floor-framing system in American building construction. The vast majority of post-tensioning tendons used in these slabs have been unbonded. In the United States alone, it is estimated that there are 2.5 billion ft^2 of two-way post-tensioned slabs with unbonded tendons in service.[1] Major research programs have been executed on two-way post-tensioned slabs with unbonded tendons at prominent American universities[2]; based on both performance and research, the ACI Building Code (ACI 318-11)[3] has developed comprehensive requirements for their use. While not prohibited by ACI 318-11,[3] the use of bonded tendons in two-way slabs built in the United States is extremely rare.

However, two-way slabs with bonded tendons are widely used in other parts of the world—notably, Asia, Europe, and Australia. While there is a dearth of published research available describing the behavior of two-way slabs with bonded tendons, the author has received reports by personal communication that their behavior in existing buildings is adequate and is unaware of reports to the contrary.

While various aspects of the behavior of two-way slabs with both bonded and unbonded tendons are discussed in this paper, the focus will be on code requirements and standard practices for minimum amounts of bonded reinforcement used for crack distribution and ductility in the highly stressed negative moment areas over columns. The need for crack control over columns in two-way slabs is not limited to slabs with unbonded tendons. High local stresses in negative-moment areas exist, regardless of whether the tendons are bonded or unbonded.

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Requirements for providing a minimum amount of bonded reinforcement to resist this cracking in two-way slabs with bonded tendons appear in codes and recommendations governing their design in other countries. However, ACI 318-11[3] has no requirements whatsoever for minimum amounts of bonded reinforcement—prestressed or non-prestressed—in any location in two-way slabs with bonded tendons.

This paper will address the ACI 318-11[3] deficiencies regarding two-way slabs with bonded tendons and make recommendations to remedy them.

SURVEY OF CODE REQUIREMENTS FOR BONDED TWO-WAY SLABS

Because two-way slabs with bonded tendons are rarely used in the United States and research on their behavior is substantially nonexistent, ACI 318-11[3] contains virtually no requirements governing their design. These would include minimum amounts of bonded prestressed and/or non-prestressed reinforcement and requirements for locating tendons over supports (integrity steel). For example, ACI 318-11, Section 18.9.3.3,[3] requires a minimum amount of bonded reinforcement over the tops of columns in two-way post-tensioned slabs with *unbonded* tendons. The purpose of this reinforcement is, in part, to increase ductility and distribute negative-moment cracking caused by high local flexural tensile stresses at the top of the slab in this area of peak negative moments. The amount of reinforcing required was based on testing of two-way unbonded slabs at the University of Texas in the 1970s (ACI 318-11, References 18.14 and 18.15[3]). However, these requirements apply only to slabs with *unbonded* tendons; similar requirements for minimum bonded reinforcement in two-way slabs with *bonded* tendons do not exist in ACI 318-11.[3]

AS3600-2009, Section 9.4.2,[4] requires no minimum amount of bonded reinforcement—prestressed or non-prestressed—when flexural tensile stresses under service loads are less than or equal to $0.25\sqrt{f_c'}$, where f_c' is in MPa, for slabs with bonded tendons. This is equivalent to $3.0\sqrt{f_c'}$, where f_c' is in psi. This stress can be exceeded—up to $0.6\sqrt{f_c'}$ MPa ($7.2\sqrt{f_c'}$ psi)—by providing "…reinforcement or bonded tendons, or both, near the tensile face…" and limiting the incremental stress in the bonded tendons and non-prestressed reinforcement to certain values, as shown in Table 9.4.2.[4] The incremental stress increase in the reinforcement is that which occurs "…as the load increases from its value when the extreme concrete tensile fibre is at zero stress to the short-term service load value." The incremental stress increase in the reinforcement is, of course, a function of the cross-sectional area of the reinforcement provided—the more reinforcement, the smaller the stress increase. This indirect, somewhat complex, method for determining the required amount of bonded reinforcement does not offer a direct comparison to the minimum reinforcement requirements for unbonded slabs specified in ACI 318-11,[3] which are simply based on a percentage of the concrete cross-sectional area. It should be emphasized, however, that if service-load flexural tensile stresses exceed $3.0\sqrt{f_c'}$ (f_c' in psi), a minimum amount of bonded reinforcement—prestressed or non-prestressed—is required by AS3600-2009.[4]

The Eurocode (EC2)[5] has a minimum requirement for bonded reinforcement in two-way slabs with bonded tendons where the service load flexural tensile stress exceeds the concrete modulus of rupture. It is expressed as a complex equation (Section 7.3.2, Eq. (7.1)) and is a function of the yield strength and spacing of the reinforcement and the modulus of rupture of the concrete. It can be shown that the EC2[5] requirement for minimum bonded reinforcement is reasonably similar to the ACI 318-11, Section 18.9.3.3, Eq. (18-6),[3] requirement for minimum bonded reinforcement in unbonded two-way slabs.

The Concrete Society in England publishes a design handbook[6] for post-tensioned concrete floors that includes recommendations for two-way slabs with both bonded and unbonded tendons. For slabs with both bonded and unbonded tendons, this handbook recommends exactly the same minimum amount of bonded reinforcement over columns (Section 5.8.8) as ACI 318-11, Section 18.9.3.3,[3] for unbonded slabs. No minimum amount of bottom bonded reinforcement is required in positive-moment areas. It should be noted that these are recommendations, not code requirements.

Standard practices for two-way slabs with bonded tendons in Hong Kong require a minimum area of non-prestressed bonded reinforcement (f_y = 460 MPa [67 ksi]) equal to 0.13% of the gross concrete area located at the tension faces.[7] This is actually much larger than the ACI 318-11[3] requirement for minimum bonded reinforcement in two-way slabs with unbonded tendons and approaches the required amount of shrinkage and temperature reinforcement in ACI 318-11, Section 7.12.2.1(b).[3]

BONDED VERSUS UNBONDED TENDONS

The decision to use bonded tendons in two-way post-tensioned slabs must be made very carefully, particularly when the slab design is governed by ACI 318-11.[3] Virtually all American experience—both in the field and the laboratory—has been with unbonded tendons. Unbonded tendons offer unique structural advantages not found in bonded tendons, and these advantages should be recognized and carefully considered in the decision between unbonded and bonded tendons in two-way slabs.

The most significant of these advantages is post-flexural catenary capacity. The only way to significantly increase the stress in an unbonded tendon is to increase its length between anchorages. Thus, local strains caused by large local deformations, such as those encountered at columns in two-way slabs, are distributed throughout the entire length of the tendon and do not result in high local tendon stresses. It is virtually impossible to fail an unbonded tendon in tension due to applied load. This factor offers obvious advantages under severe overload or in preventing progressive collapse should the member suffer punching shear failure or the loss of one or more column supports due to some catastrophic event. Tests[8] have shown that slabs with unbonded tendons possess catenary capacities three to four times the demand at factored load.

On the other hand, in a properly bonded tendon, high local strains, such as those found in negative-moment areas at columns of two-way slabs under factored loads, can develop local stresses higher than the strand tensile strength, resulting in tensile failure. For example, using ACI 318-11[3] terminology, in an 8 in. thick normalweight slab with bonded tendons where f_c' = 5000 psi, d_p = 7 in., f_{pc} = 150 psi, f_{se} = 176 ksi, and A_{ps} = 0.082 in.^{2}/ft, the steel strain when the extreme concrete strain reaches 0.003 in./in. (the crushing strain) is 0.044 in./in.—substantially greater than the ASTM A416 breaking strain of 0.035 in./in. Thus, in this rather typical case, the bonded steel will fail in tension before the concrete crushes and the catenary capacity will be lost. In the same example, if the tendons were unbonded, the steel would *not* fail in tension at the point of concrete crushing; in fact, it would not fail at a load three to four times higher,[8] with catenary capacity available throughout that entire range.

A common criticism of unbonded tendons is that a failure at one point results in the loss of prestress force for the full length of the tendon. A failure at one point in a fully bonded tendon results in the loss of prestress force for only a development length on either side of the failure point—a total distance of 6 to 7 ft for a 0.5 in. diameter, 270 ksi strand. However, two-way slabs prestressed with unbonded tendons are highly redundant and intrinsically provide alternate load paths in the event of a catastrophic event, which results in significant loss of tendons. In a test of a nine-panel, two-way, unbonded post-tensioned slab performed at the University of Texas in 1973 (Reference 2 in the Freyermuth paper[9]), 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. The surrounding edge and corner panels were then loaded to full service load, which they resisted with no significant distress. In two-way prestressed slabs, many designers also provide a nominal grid of non-prestressed reinforcing steel (typically No. 4 at 36 in. on center each way) throughout the entire slab to provide an additional level of redundancy.

Two-way post-tensioned slabs with unbonded tendons offer further advantages in the prevention of local or progressive punching shear collapse. If a primary punching shear failure occurs at a column due to overloading or some catastrophic event, the slab outside the critical shear section will start to slide down the column; however, the tendons passing over the column will engage it, as will the first group of orthogonal tendons they pass below adjacent to the column. Because it is impossible to fail the tendons in tension by this behavior (the high local strains are distributed over the full length of the tendon), the tendon system will form an interlocked mechanical catenary capable of supporting the entire slab weight without further movement. This behavior is shown graphically in Fig. 1,[9] where the tendons have been added in red. In the case shown, the slab has moved down 2.5 in. and is restrained from further movement by tendons passing through the column and under the first group of two orthogonal tendons.

This behavior is not just theoretical; the author has seen this event happen in several actual instances in his career. In one case, a catastrophic overload (the plaza-level slab above collapsed onto the post-tensioned slab below due to the unanticipated weight of a large statue placed

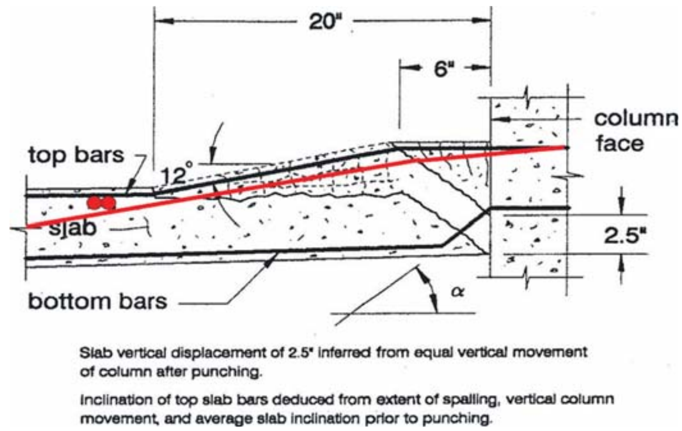

Fig. 1—Post-punching shear failure behavior.

adjacent to a corbel in the slab at an expansion joint. The corbel failed in shear and caused the entire weight of the plaza-level slab, the statue, and the landscaping to fall onto the slab below where the four shear failures occurred. The expansion joint did not exist on the lower slab) in one panel of a two-way slab produced primary punching shear failures at the four columns bounding the panel, and the slab slid down each column approximately 3 to 4 in. until the movement was engaged and restrained by the tendons passing over the column and under the first group of orthogonal tendons near the column. The entire 30 x 30 ft panel was supported, without further failure or additional movement, by the two unbonded tendons passing through each of the four columns in both directions. It is unlikely that this same highly beneficial behavior would have existed had the tendons been properly bonded; if they had performed as predicted for bonded tendons, the high local strains at the columns would have been sufficient to fail the tendons in tension.

ACI 318-11, Eq. (18-1),[3] permits a substantially higher tendon stress at nominal strength f_{ps} in bonded tendons than in unbonded tendons (ACI 318-11, Eq. (18-2) and (18-3)[3]). This means that a member with bonded tendons will have a larger nominal strength than a member with the same number of unbonded tendons (all other things being equal in both members). This is often cited as an advantage of bonded tendons. However, the flexural capacity of unbonded tendons can be supplemented with non-prestressed reinforcement. The cost of the supplemental non-prestressed reinforcement required in the unbonded member to increase its capacity to that of the bonded member with the same number of tendons is generally less than the cost of grouting the tendons. Therefore, there is no economic advantage in favor of bonded tendons, resulting from the fact that they develop a larger nominal tendon stress. Further, it is the author's opinion that the incremental flexural strength is more reliably achieved with non-prestressed reinforcement, which can be visually inspected, than with grouting, which cannot be visually inspected.

Finally, it should be mentioned that two-way slabs with bonded tendons must satisfy ACI 318-11, Section 18.8.2.[3] This section requires that members with bonded tendons contain sufficient prestressed and non-prestressed reinforcement to develop a flexural capacity at every section of at least $1.2M_{cr}$, where M_{cr} is the moment that produces first cracking at the section (based on a modulus of rupture of $7.5\lambda\sqrt{f_c'}$). This requirement is waived for unbonded members because the type of undesirable behavior addressed (sudden transfer of tensile force from concrete to reinforcement at first cracking) does not occur in unbonded tendons. In many typically proportioned and loaded two-way slabs with bonded tendons, this code section will require more *total* bonded reinforcement than that required for two-way slabs with unbonded tendons in ACI 318-11, Section 18.9.3.3.[3]

However, the reinforcement required by ACI 318-11, Section 18.8.2,[3] cannot be directly compared to that required by Section 18.9.3.3 for ductility and crack distribution for the following reasons:

- The reinforcement required by Section 18.8.2 for negative moment can be located anywhere horizontally in the slab. There is no requirement that it be concentrated over the column, as opposed to Section 18.9.3.3, which requires that the reinforcement be concentrated in a narrow width straddling the column; and
- There are many two-way slab configurations (for example, lightly loaded, relatively thin slabs with low concrete strengths and densities) in which the *total* bonded reinforcement required by Section 18.8.2 is substantially *less* than that required by Section 18.9.3.3.

Clearly, the $1.2M_{cr}$ requirement in Section 18.8.2 in itself does not adequately address the problem of minimum reinforcement in two-way slabs with bonded tendons.

The primary purpose of this paper is not to dwell on the virtues of unbonded tendons in two-way slabs, but to emphasize what the author considers to be ACI 318-11[3] deficiencies in the use of bonded tendons. Nonetheless, the author feels that the previous discussion of bonded and unbonded tendon behavior is important in evaluating the significance of these code deficiencies.

QUANTITATIVE EXAMPLE

Consider a two-way slab post-tensioned with unbonded tendons with a 30 x 30 ft bay size, 8 in. slab thickness, and 24 in. square columns. A section of the slab at the column is shown (perpendicular to the span) in Fig. 2.

ACI 318-11, Section 18.12.6,[3] requires a minimum of two 0.5 in. diameter seven-wire strands to pass directly over the column in each direction. A minimum area of bonded reinforcement is also required between lines that are $1.5h$ ($1.5 \times 8 = 12$ in.) outside opposite column faces (Section 18.9.3.3). Thus, in this case, the added bonded reinforcement is required within a distance of $24 + 2 \times 12 = 48$ in. centered on the column, and the amount of bonded reinforcement required in this distance is

$$A_s = 0.00075A_{cf} = 0.00075 \times 8 \times 30 \times 12 = 2.16 \text{ in.}^2$$

Thus, in addition to the two tendons (A_{ps} = 0.312 in.^{2}) required directly over the columns, the code would require an additional seven No. 5 bars within lines that are 12 in. outside each column face (a 48 in. total dimension centered on the column).

Now, consider the same two-way slab, except with bonded tendons. A cross section through this slab, taken in the same location as Fig. 2, is shown in Fig. 3.

For two-way slabs with bonded tendons, ACI 318-11[3] has no *minimum* requirements for bonded reinforcement—prestressed or non-prestressed—anywhere in the slab, including the critical area in the immediate vicinity of the column. This slab would satisfy ACI 318-11[3] with no reinforcement of any kind in the shaded area of Fig. 3. Note that Section 18.12.6, which requires a minimum of two 0.5 in. diameter seven-wire strands directly over the column, applies only to slabs with unbonded tendons and that Section 18.9.3.3, which requires a minimum amount of bonded reinforcement in the shaded area, also applies only to slabs with unbonded tendons. This does not seem rational.

Figure 4 presents the author's recommendations for minimum amounts of bonded reinforcement in two-way slabs with bonded tendons. Similar to slabs with unbonded tendons, the author proposes that a minimum of one bonded tendon with at least two 0.5 in. diameter seven-wire strands be required directly over the column in both directions. If some physical condition makes it impossible to pass tendons directly over the column (as in a lift slab), the minimum amount of bottom integrity reinforcement required for unbonded slabs in ACI 318-11, Section

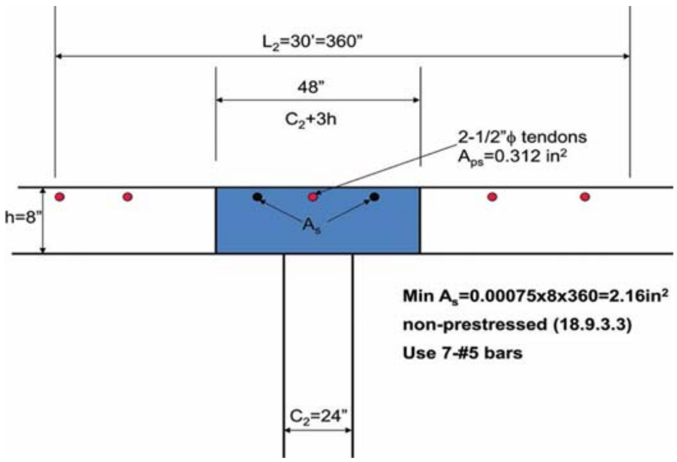

Fig. 2—Two-way slab with unbonded tendons (ACI 318-11).

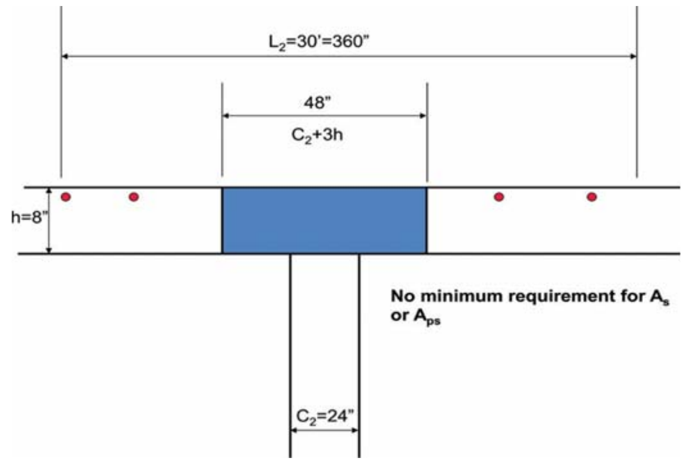

Fig. 3—Two-way slab with bonded tendons (ACI 318-11).

18.12.7,[3] may be used. The bonded integrity tendons will not be as effective in preventing catastrophic failure as if they were unbonded, but they should provide some incremental benefit. In addition, the author proposes that the same minimum cross-sectional area of bonded reinforcement required for unbonded slabs be required in the same distance (the shaded area between lines 1.5*h* on either side of the column faces), and that this minimum required area of steel can include the area of all bonded tendons within the stated distance. Thus, if the minimum of two tendons is placed directly over the column (A_{ps} = 0.312 in.^{2}), the required incremental area of bonded reinforcement would be 2.16 – 0.312 = 1.848 in.^{2} or six No. 5 bars. Additional bonded tendons placed within the 48 in. wide shaded area would further reduce the incremental amount of bonded reinforcement required.

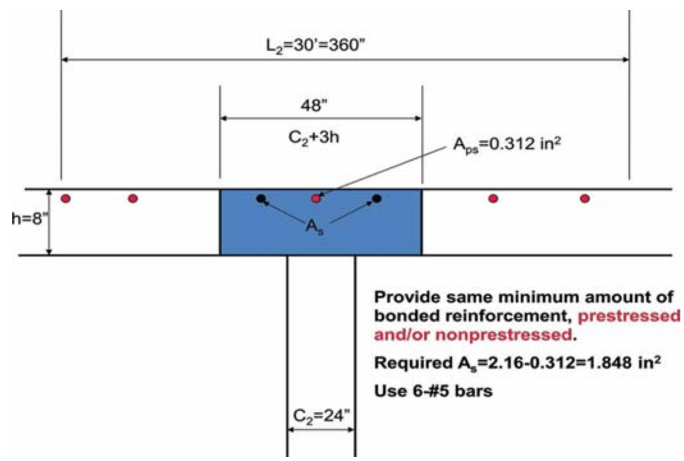

Fig. 4—Recommendations for two-way slabs with bonded tendons.

CONCLUSIONS

The author is aware of no published American research work that has been performed on two-way slabs with bonded tendons. A literature search and personal communications with those knowledgeable about the use of bonded tendons in two-way slabs outside the United States suggests that no such research exists anywhere. While the field performance of bonded slabs is reported to be adequate, field performance generally reveals little about the behavior of structures in the realm between service loading and flexural and/or shear failure; thus, no information exists about the behavior of bonded two-way slabs in this critical range.

The design of two-way slabs with bonded tendons outside the United States is primarily based on the Australian Code,[4] EC2,[5] and the British Code,[7] depending on location. The Australian Code[4] requires a minimum amount of bonded reinforcement when service-load flexural tensile stresses exceed a relatively small value. EC2[5] requires a minimum amount of bonded reinforcement over columns under certain conditions, and it is reasonably similar to the ACI 318-11[3] requirements for unbonded slabs. The British Code[7] actually requires more non-prestressed bonded reinforcement in two-way bonded slabs than ACI 318-11[3] for two-way unbonded slabs.

Lacking any research information on the actual overload behavior of two-way bonded slabs and considering how they are actually being designed outside the United States, it seems rational that ACI 318 should require the same amount of bonded reinforcement in two-way slabs with bonded tendons as is required in slabs with unbonded tendons. It should be permitted to include the cross-sectional area of the bonded tendons in the total cross-sectional area of bonded reinforcement required. If minimum reinforcement is required in two-way slabs with bonded tendons in other parts of the world, where they are actually being built, there is no reason it should not be required by ACI 318. It is anticipated that the incremental amount of bonded reinforcement required to satisfy the criteria recommended herein would be small and would present no significant economic penalty on the use of bonded tendons in two-way slabs, but it would provide a substantial benefit in performance. Finally, it is recommended that a minimum of one bonded tendon with at least two 0.5 in. diameter strands be placed directly over columns in both directions.

Perhaps testing of two-way slabs with bonded tendons will demonstrate this recommendation to be conservative, but until that testing exists, these recommendations should be followed to reasonably ensure the same level of performance and safety in bonded two-way slabs as has been demonstrated by tests and performance in slabs with unbonded tendons.

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