2 Post-Tensioned Two-Way Slab

Introduction

The Filigree beam system creates a thin lightweight floor system that leaves plenty of open plenum space for mechanical and electrical equipment. However, the beams divide the plenum space into channels, reducing the overall utility. In addition, the system is designed by Filigree Incorporated, making it a black box for the engineer of record. A preliminary investigation showed that a conventional two-way slab system can provide slabs that are just as thin, and bring the design back into the hands of the engineer of record. It may be possible to achieve even thinner slabs by introducing pre-stressing or post-tensioning to the system.

Solution Overview

Proprietary systems have costs and benefits in addition to those assumed by conventional systems. In this case a conventional two-way slab provides a nearly identical product to the proprietary Filigree system. Considering that the two-way slab does not have the additional costs of using a proprietary system, it appears to provide a better value. This value can be improved by using pre-stressing or post-tensioning to reduce the overall slab depth, thus increasing the usable space. Therefore, a pre-stressed two-way slab may be a very effective alternative to the proprietary Filigree beam system. In addition to creating more usable space, the two-way slab system will also eliminate the channeling of the plenum and allow the free placement of lateral resisting systems.

Design Criteria

The following questions must be addressed regarding the effectiveness of the two-way slab:

- Can the two-way slab meet code?
- Can the two-way slab be constructed at no greater cost?
- Will the two-way slab introduce more problems than it corrects?

The code governing the design of the two-way slab will be IBC 2003. The cost analysis will be based on data provided by RS Means. The last question will be addressed by comparing the benefits and disadvantages of the two-way slab to the Filigree beam system. For the two-way slab to be considered, the first question must be answered in the affirmative. The remaining two questions should also be answered in the affirmative if the two-way slab is optimal. If the two-way slab is not optimal, then the relative success and failure compared to the Filigree system will determine the final decision on whether or not the two-way slab is a reasonable alternative.

Load Analysis

When considering two-way slabs in a post-tensioned system, it is important to perform an advanced analysis of the loads and their effects at different locations in the building. For the Medical Office Building, there were three locations considered to determine the worst case loading for a two-way slab system; the longest interior span, an exterior span with edge beams, and an exterior span without edge beams (Figure 2-1). Each of these areas has a different set of design criteria based on code, and has to be evaluated to ensure the safety of the slab at all locations. In order to simplify the construction of the design, modification of the design to respond specifically to each support was forgone in favor of evaluating only the maximum condition in each of the three slab areas and applying the resultant design to all similar locations.

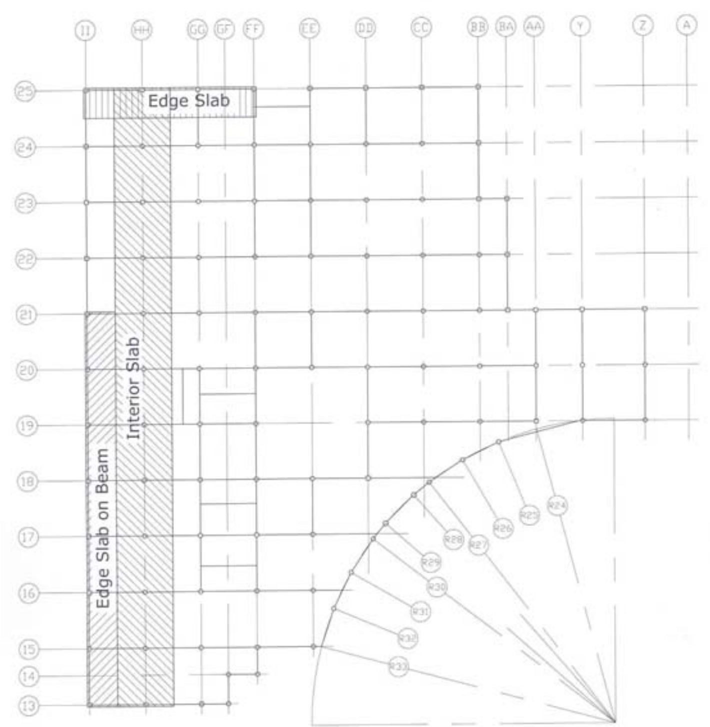

Figure 2-1 Typical floor plan highlighting the three areas of the slab evaluated for design

In order to determine the requisite loads for the slab an initial guess at the slab thickness was taken as 1/36th the clear span of the slab, which is 25'-10". The resulting slab depth of 9" leads to a dead load for normal wiehgt concrete of 112.5 psf, an additional 15 psf was added for mechanical electrical and plumbing (MEP) equipment, and an additional 10 psf was added for the combined raised floor and hung ceiling weights. The live load for a typical office building is 80 psf according to ASCE 7-02, but this value was increased to 100 psf to account for additional loads related to open planning, such as movable partitions and corridors.

The evaluation of the three loads was performed using ADOSS, the full results can be found in Appendix II. A summary of the critical results for each section appears in Table 2-1.

Slab	M_{col} (ft-k)	M_{mid} (ft-k)	M_{beam} (ft-k)	v (psi)
Edge with beams	45.3 (-)	37.6 (-)	256.5 (-)	155.84
	33.0 (+)	27.4 (+)	186.9 (+)	
Edge without beams	233.3 (-)	77.8 (-)	-	330.69
	136.5 (+)	91.0 (+)		
Interior	399.3 (-)	133.1 (-)	-	328.03
	216.5 (+)	144.3 (+)		

Table 2-1 Critical Shear and Moment as calculated by ADOSS

ADOSS does not cover wide beam shear analysis, but a brief investigation reveals that the per foot strength is roughly 9.5 kips. Based on the aforementioned loads, the shear on a per foot basis is only 4.5 kips, so wide beam shear does not control.

Shearhead Investigation

The ADOSS analysis showed that the majority of cross-sections did not meet the necessary requirements for shear strength. The ACI code states this strength as:

$$\phi v_n = 0.75 * 4\sqrt{f_c^{'}} \qquad (2\text{-}1)$$

For 5000 psi concrete, this value is 212.13 psi. The code also states that the strength can be taken as:

$$\phi v_n = 0.75 * 7\sqrt{f_c^{'}} \qquad (2\text{-}2)$$

if shearheads are used. The shear strength developed on the new shear plane created by the shearheads must still meet the first strength requirement. The new capacity for shear in 5000 psi concrete is thus 371.23 psi at the standard shear plane, and 212.12 psi at the extended shear plane. The size of the shearheads required to generate the necessary secondary shear plane were determined using a program written in EES (Appendix III). The results of this program show that the exterior shearheads must extend 4’-3” from the center of the columns, and that the interior shearheads must extend 3’-9” from the center of the columns (Figure 2-2).

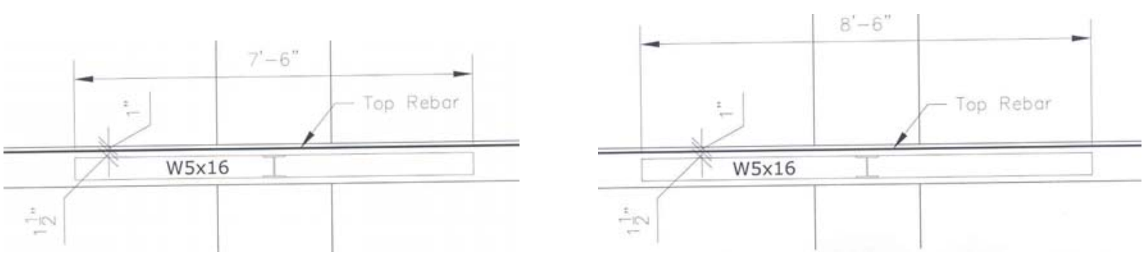

Figure 2-2 Shearhead details for interior (left) and exterior (right) columns

Post-Tension Investigation

Besides shear strength it is also important to consider the moment capacity of each of the sections. An analysis of the bulk cross section of each segment of slab is summarized in Table 2-2.

Segment		A_s (in^2)	Bars	Spacing (in)
Interior Column	Top	12.74	64 # 4's	2.55
Strip	Bot	6.66	34 # 4's	4.67
Interior Middle	Top	4.03	21 # 4's	7.30
Strip	Bot	4.38	22 # 4's	7.00
Exterior Beam	Top	1.56	8 # 4's	9.60
Column Strip	Bot	1.56	8 # 4's	9.60
Exterior Beam	Top	2.72	14 # 4's	10.50
Middle Strip	Bot	2.72	14 # 4's	10.50
Exterior Beams	Top	2.01	3 # 8's	5.00
	Bot	2.79	3 # 9's	5.00
Exterior	Top	13.60	68 # 4's	1.37
Column Strip	Bot	4.22	22 # 4's	4.00
Exterior Middle	Top	2.72	14 # 4's	10.50
Strip	Bot	2.74	14 # 4's	10.50

Table 2-2 Analysis of slab sections

From this analysis, it can be seen that the sections that will most benefit from post-tensioning are the column strips on the exterior surfaces without beams and in the interior. Tensioned reinforcement must provide the same force as the untensioned reinforcement for the design to be valid. The code limits the pressure allowed in tension cables in two ways:

$$f_{ps} = f_{pu}\left(1 - \frac{\gamma_p}{\beta}\left[\rho_p \frac{f_{pu}}{f'_c} - \frac{d}{d_p}(w - w')\right]\right) \quad (2\text{-}3)$$

$$f_{ps} = f_{se} + 10 + \frac{f'_c}{300\rho_p} \text{ ksi} \quad (2\text{-}4)$$

Using these limitations and choosing cables with an ultimate strength of 275 ksi and a yield strength of 240 ksi, an iterative design process was used to find the required area of cable and their post-tensioning force. This process found that for the interior columns, 4 in^2 of cable tensioned by 920 kips was adequate, and for exterior columns, 4 in^2 of cable tensioned by 900 kips was adequate. Both of these designs are detailed in Figure 2-3.

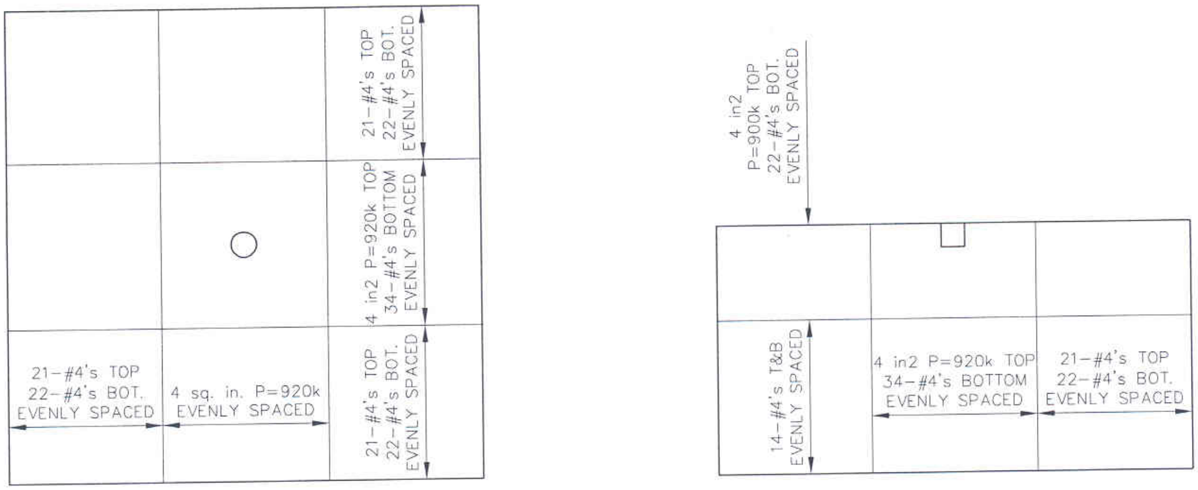

Figure 2-3 Details of the two-way slab: Interior (left), Exterior (right)

Deflection Analysis

The final consideration in the design of the two-way slabs is deflection. According to ADOSS, the interior spans due not meet the code requirements to neglect deflection. Therefore a deflection analysis was performed on the interior slab section to determine whether the slab meets the serviceability requirements. The tension in the cables generated an initial camber of 0.95" upward. This camber leads to an immediate and long-term deflection of 0.11" downward, which is less than the limits of 0.93" and 0.70" for immediate and long-term deflection respectively.

Conclusions

The two-way slab meets all the design and serviceability requirements for code. Therefore, the system can be a reasonable alternative to the Filigree beam system. A direct cost comparison is not possible between the two systems because of the proprietary nature of the Filigree system. However, comparing the cost of the post-tensioned two-way slab to a typical banded beam system (Table 2-3) should provide a reasonable comparison.

	Two-way	Banded
Slab Formwork	$457,050	$457,050
Slab Reinforcing (w/ shearheads)	$161,020	$33,083
Slab Post-tensioning	$165,000	$0
Slab Concrete and Placement	$839,237	$839,237
Beam Formwork	$0	$173,765
Beam Reinforcing	$0	$63,000
Beam Concrete & Placement	$0	$275,229
TOTAL	$1,622,307	$1,841,364

Table 2-3 Cost comparison of a two-way slab and a banded beam system

The difference in cost between the two systems is $219,000, which is nearly the cost of the concrete in the beams. In fairness to the Filigree system, less concrete is used than in cast-in-place construction. Assuming that the Filigree beams use 30% less concrete, would result in a $334,000 savings. This makes the Filigree system more favorable by $115,000. However, factory costs, transportation costs, and other fees associated with the Filigree technology, including the charges of the contractor for working with an unfamiliar system may eat up these savings. Due to these speculative expenses, it is difficult to discern which system is of better economic value. Fortunately, the economic value alone is not a deciding factor.

Although the Filigree system provides a thin floor structure, it is still twice the overall depth of the two-way slab due to the beams. The direct consequence of the deeper system is the loss of usable space in the building. The indirect consequence of the beams hanging down is that they divide the plenum space of the building into strips, which means the ceilings must be hung deeper to allow enough clearance for ductwork and wiring in areas directly beneath the beams. Because the two-way slab system is flat, there is no division of the plenum, and the hung ceiling may be hung much closer to the bottom of the slab, thus recovering even more usable space.

Despite an uncertain cost advantage, the additional benefits of a two-way slab system make it an appealing alternative, particularly because they can be used to optimize the building for Underfloor Air Distribution.