

**EFFECTS OF TENDON LAYOUT ON SERVICE  
LOAD PERFORMANCE OF POST-TENSIONED  
TWO-WAY SLAB SYSTEMS**

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# EFFECTS OF TENDON LAYOUT ON SERVICE LOAD PERFORMANCE OF POST-TENSIONED TWO-WAY SLAB SYSTEMS

By A. Scanlon, A. J. Schokker, and S. C. Lee

*This paper presents the results of an analytical study based on finite element analysis to evaluate the effects of different arrangements of tendons on the performance of post-tensioned cast-in-place concrete two-way slab systems. Various arrangements from uniform cable layouts to closely banded arrangements adjacent to column centerlines are considered. The slab is modeled using plate-bending elements in the software package SAP 2000.*

*Equivalent loads based on cable profiles are applied to the slab according to the tendon layout. Moment fields and deflected shapes are compared for the various tendon patterns. Gravity loads are applied in the usual way and superimposed on the results from the equivalent tendon loads to determine net moments and deflections at service load levels. In addition to a study of tendon layouts, the finite element model is compared with experimental results.*

## KEYWORDS

Post-tensioning; prestressing; service load level; slabs.

## INTRODUCTION

Post-tensioned flat plate slabs provide an economical alternative to traditional reinforced concrete slabs due to their relatively reduced thickness. The load-balancing technique is typically used in the design of these systems. A portion of the service load is balanced by the prestressing. Typically, all of the dead load and sometimes a portion of the live load will be balanced. Various tendon arrangements may be used to provide this balancing. The two extremes of tendon spacing vary from uniformly spaced to a fully banded arrangement, where tendons are concentrated along column lines. A slab containing uniform tendons in one direction and

banded tendons in the perpendicular direction would behave similarly to a one-way slab system supported on beams. A pattern between the two extremes is sometimes used, providing tendons across the entire slab with a concentration of tendons nearer to the column lines. There does not appear to have been a systematic analytical study of the effects of various tendon arrangements on the distribution of moments and deflections in two-way post-tensioned slabs. This paper presents results of an analytical study of the effects of tendon layouts on behavior at service load levels. The validity of the modeling techniques used is verified through comparisons with available experimental results.

## FINITE ELEMENT MODELING OF POST-TENSIONED FLAT PLATE

The general purpose computer program SAP2000 was used to perform plate bending analyses of flat plates subjected to gravity loads and transverse loads due to post-tensioning. Rectangular flat shell elements were used to determine deflections and internal moments in the flat plate under the prescribed loading assuming elastic response of an uncracked slab. Equivalent vertical loads due to parabolic tendon profiles were applied to the slab as uniformly distributed loads, depending on the tendon force and curvature.<sup>1</sup>

## COMPARISON WITH EXPERIMENTAL RESULTS

The analysis procedure was applied to experimental test results reported by Burns and Hemakom.<sup>2</sup> Figure 1 shows the experimental test slab dimensions and layout and the points where deflections were monitored during testing. Figure 2 shows the tendon layout. The test slab was subjected to a uniformly distributed applied load of 74 lb/ft<sup>2</sup>. Prestressing consisted of 23.5 in. diameter, 270 ksi tendons in the uniformly spaced direction and a total of 24.5 in. diameter, 270 ksi tendons in the banded direction. The tendons produced an average uniform  $P/A$  stress of 135 psi in each direction. The finite

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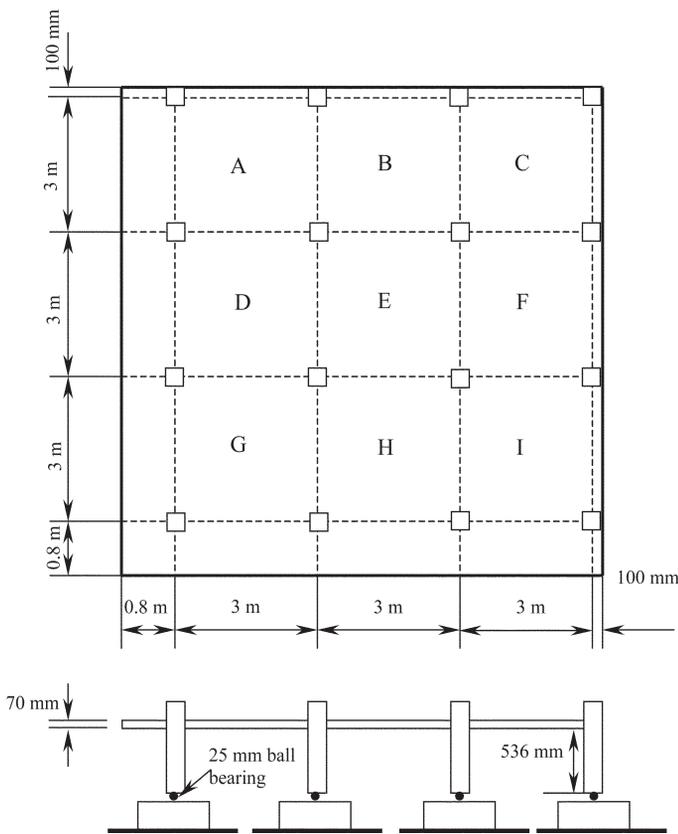


Fig. 1—Plan and elevation of test slab.

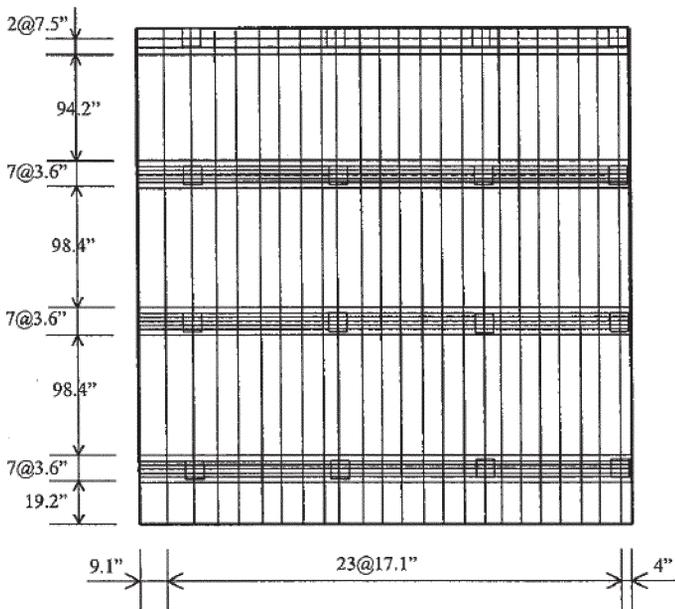


Fig. 2—Tendon layout of test slab.

element model included the slab stubs and roller supports at the base of the columns as used in the test. Variations in tendon force along the tendon due to friction and wobble losses were

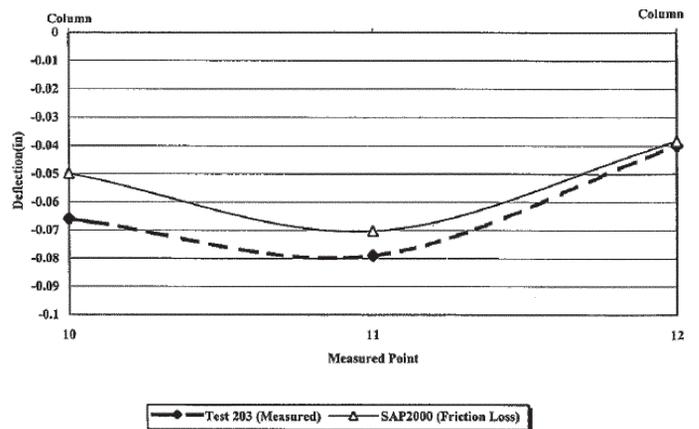


Fig. 3—Computed and experimental results for deflections in Panel C.

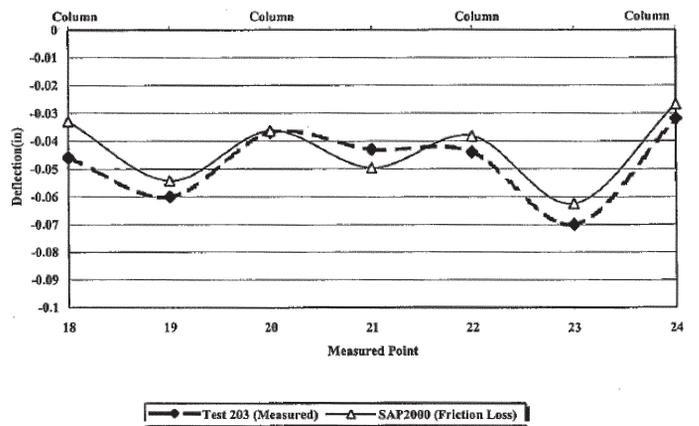


Fig. 4—Computed and experimental results for deflections in Panel DEF.

included in the calculation of equivalent loads due to prestress; however, analyses performed that ignored losses showed that losses had a relatively small effect on the results. A comparison of the deflections between the test slab and the modeled slab is shown in Fig. 3 through 5. Deflection measurements were not reported for Panels A and B. Results show generally good agreement with an average of predicted to test value of 0.94.

### PARAMETRIC STUDY OF TENDON LAYOUTS Slab details

A typical interior panel of a two-way flat plate, as shown in Fig. 6, was selected for the parametric study. The slab is based on an example from the PTI *Post-Tensioning Manual*.<sup>3</sup> Point A represents the midpanel deflection, Point B represents the deflection at midspan along the column line in the short direction, and Point C represents the deflection at midspan along

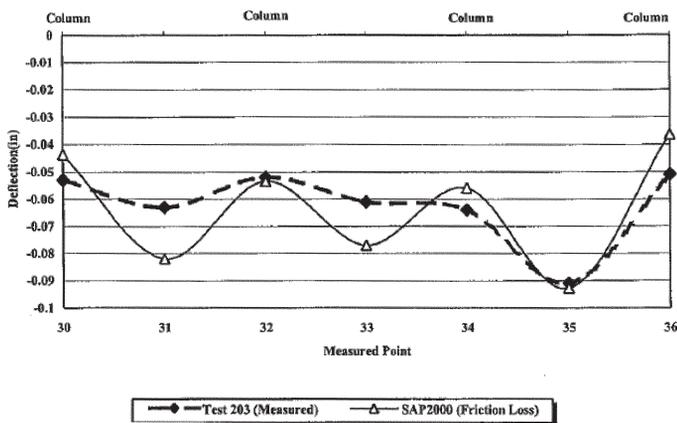


Fig. 5—Computed and experimental results for deflections in Panel GHI.

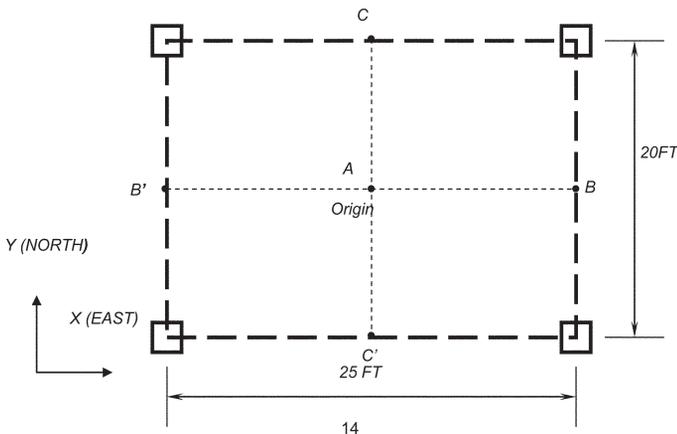


Fig. 6—Interior panel of slab for parametric study.

the column line in the long direction. Fixed supports were assumed at the face of each column and zero slope perpendicular to the slab edge at other panel boundaries. The finite element model is shown in Fig. 7.

The slab panels were analyzed with their self-weight and equivalent prestressing load from the load-balancing method. The two load cases were run separately and then superimposed to obtain net moment and deflection values. The tendon force for each direction is kept at a consistent value to produce a uniform compression in the slab of approximately 175 psi. The average equivalent load is approximately 1.25 times the self-weight in the long direction and approximately 0.86 times the self-weight in the short direction. The average equivalent load is 1.06 times the self-weight.

## Tendon layouts

Four tendon layouts were considered in the study. Layouts fully uniform in both directions and fully banded in both

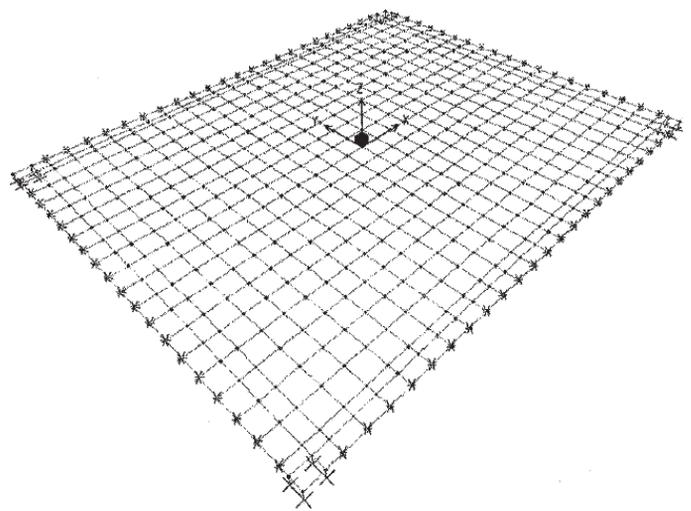


Fig. 7—Finite element model for typical interior panel.

Table 1—Tendon layouts considered

Case	Tendon layout
100C-100C	100% of tendons banded along column line in each direction
75C-75C	75% of tendons within column strip and 25% within middle strip in each direction
100C-Uni	100% of tendons banded along column line in one direction and uniformly distributed across panel in perpendicular direction
Uni-Uni	Uniform distribution of tendons in each direction

directions were considered as extremes. The other two cases consisted of a panel with one direction banded and one direction uniform, and a layout of 75% tendons within the column strip in both directions with the remaining 25% in the middle strips. The four tendon layouts are summarized in Table 1 and illustrated in Fig. 8. Analyses were performed using an idealized cable profile with kinks over the column lines and a practical profile assuming a cable point of inflection at  $0.1L$  from each column line, as shown in Fig. 9.

Case 100C-100C is essentially unreinforced over most of the slab and is included to demonstrate the effect of the extreme case producing line loads in each direction. Case Uni-Uni provides the opposite extreme. Cases 100C-Uni and 75C-75C are more traditional layouts.

## Deflection results

Deflection results for each case are summarized in Tables 2 to 5 and Fig. 10 to 13. Results from prestress forces alone, self-weight alone, and the combined effect are

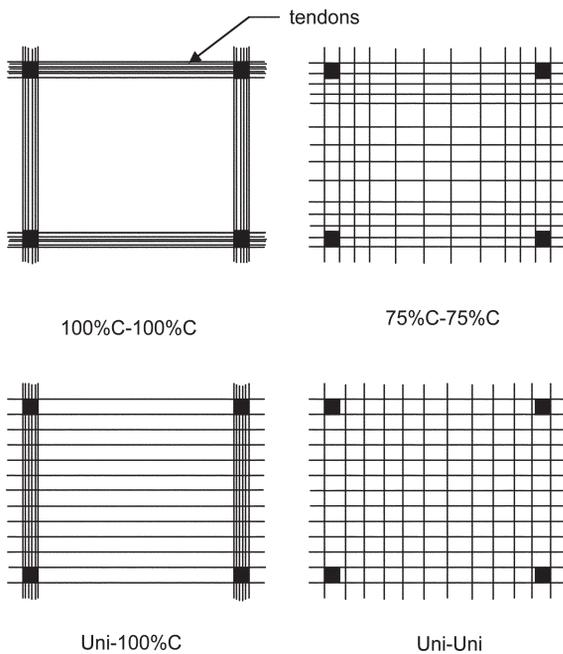


Fig. 8—Tendon layouts for parametric study.

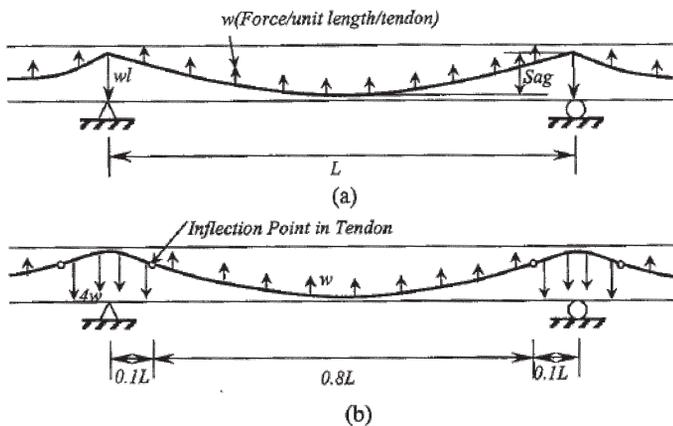


Fig. 9—Idealized and practical cable profiles.

shown. It can be seen that similar results were obtained for the idealized and practical cable profiles.

The most effective layout for producing upward camber is Case 100C-100C, whereas the least effective is Case Uni-Uni. The least variation in the deflection values is seen in the midpanel values. Larger variations are seen in the deflections at the midspan along the column lines. A slight upward camber is produced at each of the three points in Case 100C-100C and a slight downward deflection is produced in Case Uni-Uni. All four layouts are seen to be effective in producing approximately zero net deflection at the midpanel. Deflection due to a uniformly distributed live load would be proportional to the dead load (self-weight) deflection, assuming the slab remains uncracked under live load.

### Moment results

Figure 14 shows the locations where the transverse distribution of moments (kip.ft/ft) are plotted at column faces and at midspan in each direction.

Figures 15 to 18 show the effect of tendon layout on bending moment distribution for each case along the column face line in the long direction. The largest moment intensities due to prestressing are seen in Case 100C-100C near the columns. When these positive prestress moments are combined with the negative self-weight moments, positive moment results at the column. In all other cases, the combined effect produces a negative moment near the columns. For Case 100C-UNI, however, the net moments are very small. Overall, the least effective layout for balancing the self-weight with the prestress is Case Uni-Uni. As shown in Fig. 19 to 22, moments at the column face in the short direction are similar to those shown for the long direction, except in Case 100C-Uni,

Table 2—Deflection results from idealized tendon profile: east-west direction

Point (X)	Type of force	100%CW-100%CW deflection, in.	75%CS-75%CS deflection, in.	100%CW-UNI deflection, in.	UNI-UNI deflection, in.
B'	Prestressing	0.1788	0.09475	0.13979	0.06363
A		0.19922	0.19052	0.19725	0.18576
B		0.1788	0.0942	0.13979	0.06363
B'	Self-weight	-0.09111	-0.09211	-0.09111	-0.09189
A		-0.18354	-0.18679	-0.18354	-0.18685
B		-0.09111	-0.09197	-0.09111	-0.09207
B'	Combination	0.08769	0.00265	0.04868	-0.02826
A		0.01568	0.00374	0.0137	-0.0011
B		0.08769	0.00232	0.04868	-0.02826

**Table 3—Deflection results from idealized tendon profile: north-south direction**

Point (Y)	Type of force	100%CW-100%CW deflection, in.	75%CS-75%C deflection, in.	100%CW-UNI deflection, in.	UNI-UNI deflection, in.
C'	Prestressing	0.1982	0.14393	0.16571	0.11381
A		0.19922	0.19052	0.19725	0.18576
C		0.1982	0.14357	0.16571	0.11391
C'	Self-weight	-0.16243	-0.16525	-0.16243	-0.16562
A		-0.18354	-0.18679	-0.18354	-0.18685
C		-0.16243	-0.16523	-0.16243	-0.16562
C'	Combination	0.03577	-0.02133	0.00327	-0.05181
A		0.01568	0.00374	0.0137	-0.0011
C		0.03577	-0.02165	0.00327	-0.0517

**Table 4—Deflection results from practical tendon profile 0.1L: east-west direction**

Point (X)	Type of force	100%CW-100%CW deflection, in.	75%CS-75%CS deflection, in.	100%CW-UNI deflection, in.	UNI-UNI deflection, in.
B'	Prestressing	0.1692	0.08776	0.13392	0.05942
A		0.18868	0.17436	0.18508	0.17048
B		0.1692	0.08719	0.13392	0.06005
B'	Self-weight	-0.09111	-0.09211	-0.09111	-0.09189
A		-0.18354	-0.18679	-0.18354	-0.18685
B		-0.09111	-0.09197	-0.09111	-0.09207
B'	Combination	0.07809	-0.00435	0.04281	-0.03248
A		0.00513	-0.01243	0.00154	-0.01638
B		0.07809	-0.00478	0.04281	-0.03203

**Table 5—Deflection results from practical tendon profile 0.1L, north-south direction**

Point (Y)	Type of force	100%CW-100%CW deflection, in.	75%CS-75%CS deflection, in.	100%CW-UNI deflection, in.	UNI-UNI deflection, in.
C'	Prestressing	0.18831	0.13086	0.15507	0.10347
A		0.18868	0.17436	0.18508	0.17048
C		0.18831	0.13049	0.15507	0.10358
C'	Self-weight	-0.16243	-0.16525	-0.16243	-0.16562
A		-0.18354	-0.18679	-0.18354	-0.18685
C		-0.16243	-0.16523	-0.16243	-0.16561
C'	Combination	0.02587	-0.0344	-0.00736	-0.06214
A		0.00513	-0.01243	0.00154	-0.01638
C		0.02587	-0.03473	-0.00736	-0.06203

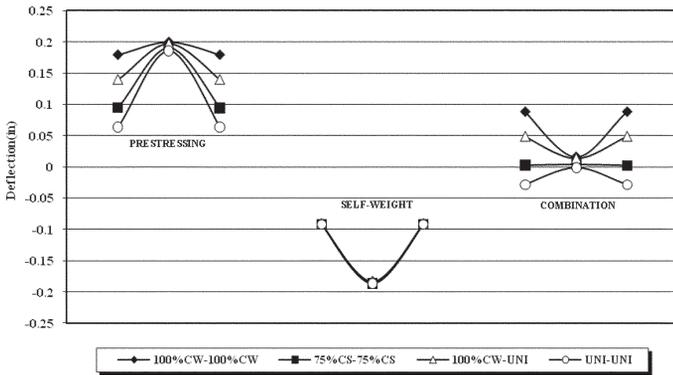


Fig. 10—Deflection results: E-W direction—idealized tendon profile.

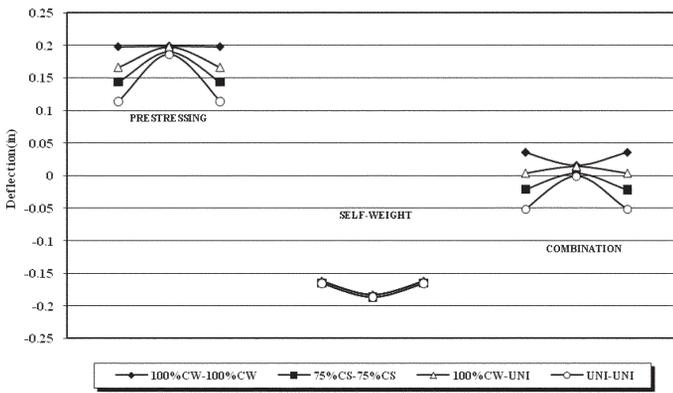


Fig. 11—Deflection results: N-S direction—idealized tendon profile.

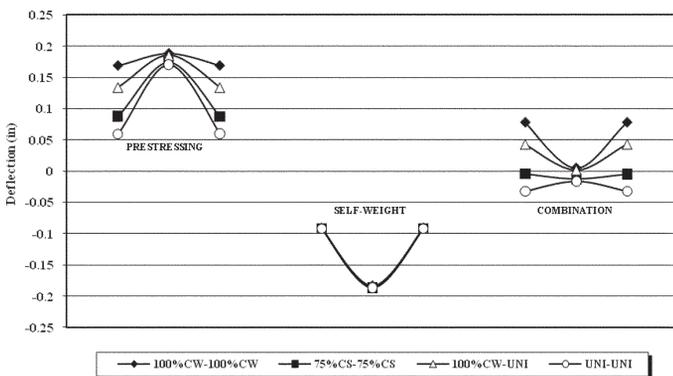


Fig. 12—Deflection results: E-W direction—practical tendon profile.

which shows net positive moment in the vicinity of the columns. Similar plots for moment distributions at the midspan locations indicated very small net moments for all cases,<sup>4</sup> indicating that all tendon layouts were effective

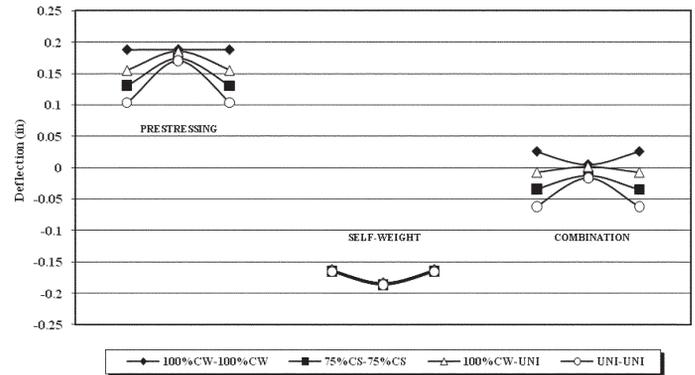


Fig. 13—Deflection results: N-S direction—practical cable profile.

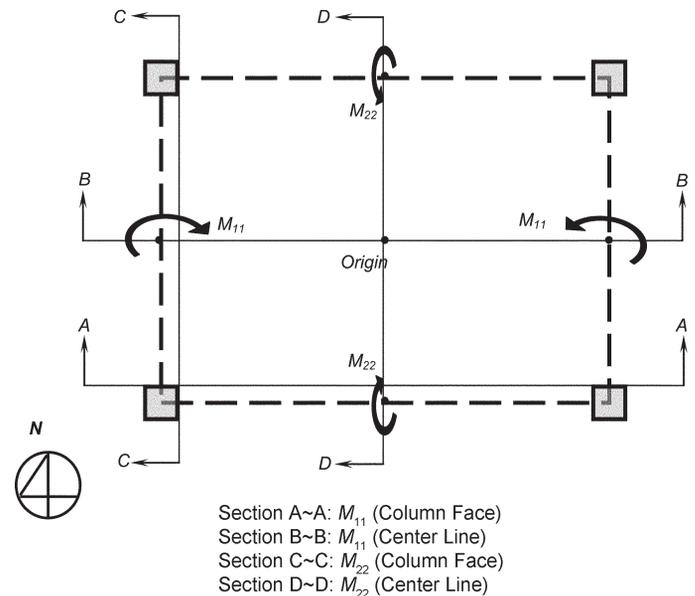


Fig. 14—Sections for moment plots.

in balancing moments due to prestress and self-weight at the midspan locations. Moments due to live load are proportional to the self-weight moments, assuming the slab remains uncracked.

## CONCLUSIONS

This analytical study of tendon layouts demonstrated the following in uncracked slabs:

- A finite element model with prestressing forces applied as equivalent loads using the load-balancing technique can accurately predict behavior at service load levels.
- Midpanel deflection values are relatively insensitive to tendon layout for the cases considered.
- Moment distributions across the slab panels at the

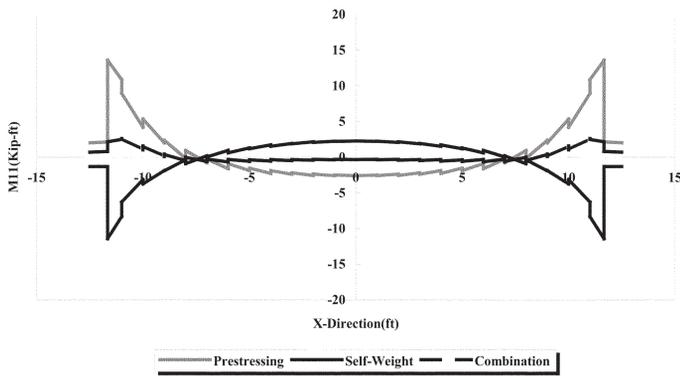


Fig. 15—Moment diagram ( $M_{11}$ ) at the column face: Case 100C-100C.

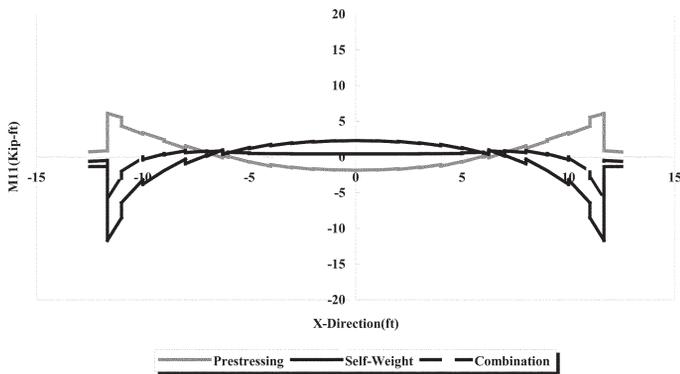


Fig. 16—Moment diagram ( $M_{11}$ ) at the column face: Case 75C-75C.

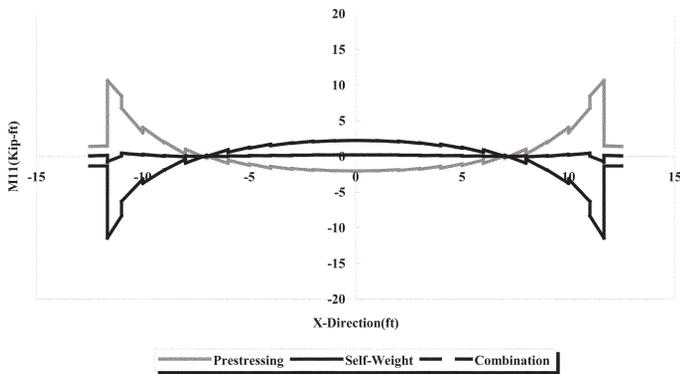


Fig. 17—Moment diagram ( $M_{11}$ ) at the column face: Case 100C-UNI.

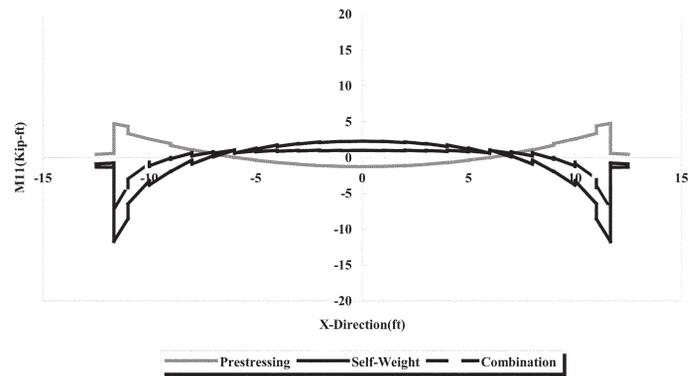


Fig. 18—Moment diagram ( $M_{11}$ ) at the column face: Case UNI-UNI.

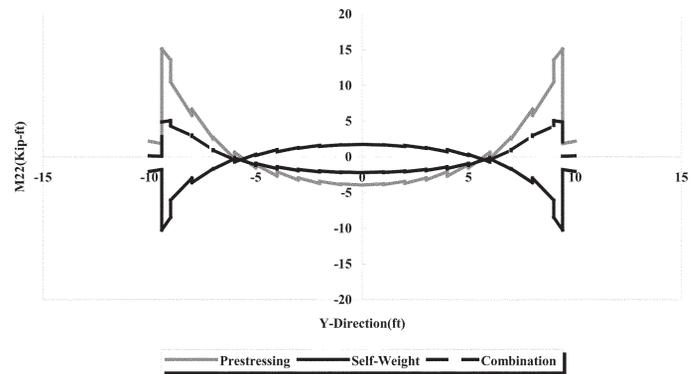


Fig. 19—Moment diagram ( $M_{22}$ ) at the column face: Case 100C-100C.

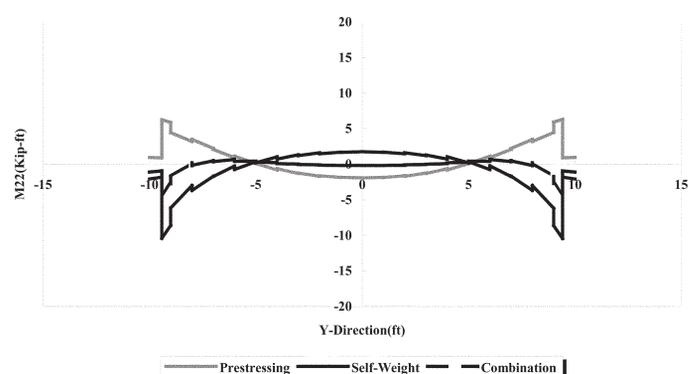


Fig. 20—Moment diagram ( $M_{22}$ ) at the column face: Case 75C-75C.

balanced load condition may vary significantly among different tendon layouts, sometimes resulting in different signs at critical sections adjacent to columns.

- Moment intensities under live load in the vicinity of columns can be relatively high as determined

from the distribution of moments under self-weight, confirming that the practice of providing mild steel in the vicinity of the column at the top of the slab is helpful for crack control.

- Net midspan moments are relatively small at the balanced moment level for all tendon layouts considered.

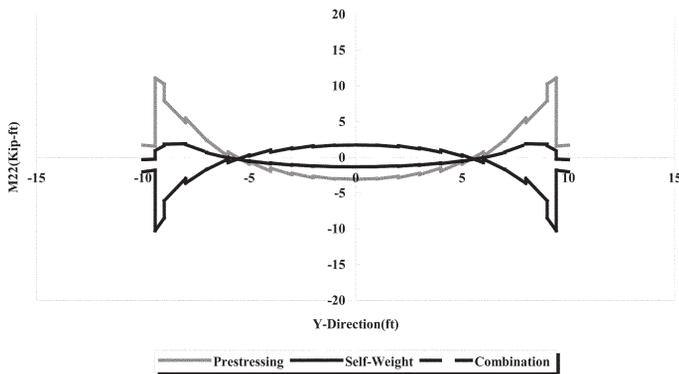


Fig. 21—Moment diagram ( $M_{22}$ ) at the column face: Case 100C-UNI.

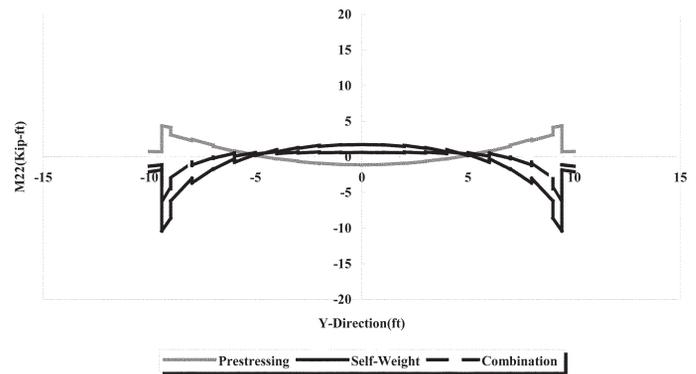


Fig. 22—Moment diagram ( $M_{22}$ ) at the column face: Case UNI-UNI.

- The results show that the system consisting of uniformly distributed tendons in one direction and banded tendons along column lines effectively accounts for two-way action at service load levels.

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