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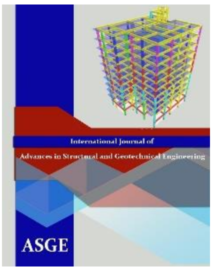

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ABSTRACT

Post-tensioned (PT) flat slabs are a commonly used construction system in multi-story buildings worldwide. This is due to time saving caused by early removal of formwork, as well as overall cost saving compared to traditional reinforced concrete flat slabs. Design of PT slabs can be accomplished using approximate methods presented by different codes of practice, which can only be applied for slabs with regular column arrangement. However, irregular structures with complex geometries need to be analyzed using different analytical approaches such as finite element method (FEM). Several commercial programs are used to analyze and design the PT flat slabs, which do not necessarily produce identical results. “SAP2000”[1], “SAFE”[2], “RAM Concept”[3] and “ADAPT Builder”[4] are examples of commercial programs used in the design of the PT flat slabs. Different layouts of the prestressing tendons in two orthogonal directions are used in construction of flat slab system; these such as[5]: Distributed/Distributed, Distributed/Banded, Banded/Distributed and Banded/Banded. Choice of distributions and layout of the tendons in the flat slab system differ according to the designer vision and experience. In this research, the design of post tensioned flat slabs is explored. The finite element programs used to design the PT slabs are evaluated and the efficiency of the different post tensioning patterns are studied. Design tables giving the recommended post tensioning rate for different spans, loadings and span-to-depth ratios are given. Finally, the economic advantage of post-tensioned over conventional reinforced concrete slabs is presented.

Keywords: Cost comparison; Flexural capacity; PT flat plates; (FEM); Structural model; Tendon patterns

Introduction

Post-tensioned concrete system are widely used as a floor system for office building, garages, shopping centers and residential building. This system is preferable due to architectural requirements to increase the spacing between columns and since most of these projects are ususlly fast track projects. The efficiency of this system is due to economic saving that result from reduced slab thickness, covering long spans, and reduced construction time due to early removal of formwork. Post-tensioned flat slab systems provide better solutions for design and construction problems encountered in structures compared to the non prestressed concrete system. In addition, advantages of prestressing are to control the crack width in concrete, reduce deflections and have higher carrying capacity compared to reinforced concrete members.The post-tensioned slabs must be designed to ensure that concrete stresses will not be excessive at service loading condition and that adequate strength in flexure and shear is provided to resist factor loads. Deflection and vibration of the slab should also remain within the acceptable limits. All these factors will control the choice of the slab thickness. Different patterns of post-tensioning tendons are used in construction of flat slab system, such as[5]; Distributed/Distributed, Distributed/Banded, Banded/Distributed and Banded/Banded. In this research, design of post - tensioned flat slabs is explored. First finite element programs used to design the PT slabs were evaluated. Next, the efficiency of the different post tensioning patterns are studied. Design tables giving the recommended prestressing steel rate for different spans, loadings and span-to-depth ratios are given. Finally the economic advantage of post-tensioned over conventional reinforced concrete slabs is presented.

EVALUATION OF AVAILABLE COMMERCIAL PROGRAMS

In this section, structural analysis of a post-tensioned flat slab is presented using the following commercial programs: “SAP2000”[1], “SAFE”[2], “RAM Concep”t[3], and “Adapt Builder”[4]. The results of these models were compared to assess the reliability of the different programs. The comparison criteria were the bending moments, the prestressing tendons losses and the amount of prestressing steel.

The post-tensioned slabs were designed according to the following assumptions:

a) Design according to (ACI318-14) [6] requirements.
b) Slab dimensions were 12x12x0.3 m with span to depth ratio (L/t) equal to 40
c) Column dimensions were assumed equal to 800x800 mm (to exclude PT Slab shear failure in order to facilitate the comparison).
d) Live load = 5 kN/m^2 and floor cover = 2.5 kN/m^2
e) Cylinder strength of concrete f`c = 35 MPa, and cylinder strength of concrete at the initial stage, f`ci = 26 MPa.

Analysis results are summarized in Figs. 1-5. Fig.1 shows the bending moment for the slab analyzed by the different program at points (a, b and c) under service loads. Fig.2 shows a comparison of the bending moment values (M) at locations (a, b and c). Fig. 3 shows the prestressing force after friction and seating losses calculated by each program at points (d, e and f). Fig.4 shows the prestressing force comparison. Fig. 5 shows a comparison of the required total tendons amounts obtained by the different programs.

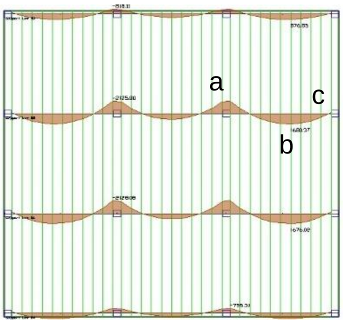


Fig. 1A “Adapt

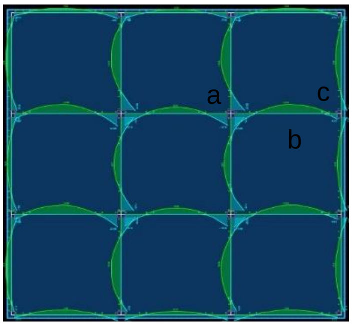


Fig. 1B “Ram program”

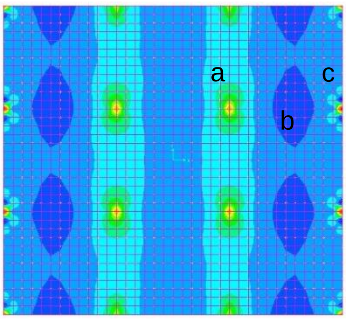


Fig. 1C “Sap2000

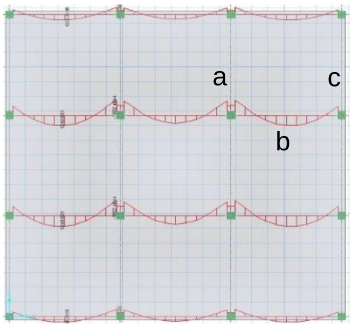


Fig. 1D “Safe program”

Fig. 1 Bending Moments Values at locations a, b and c due to service load.

(a) Point at interior column, (b) point at mid span of exterior panel, (c) point at exterior column

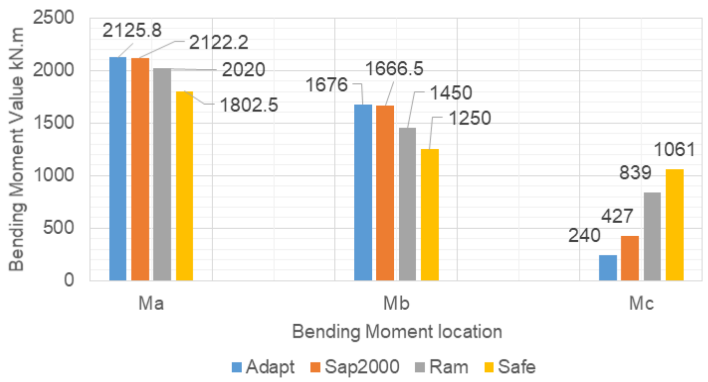


Fig. 2 Bending Moments comparison at locations a, b and c under service load.

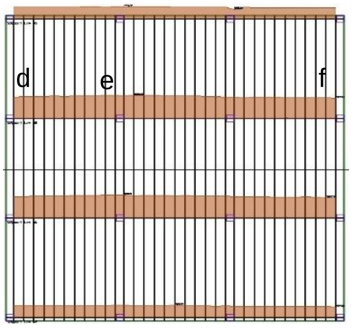


Fig. 3A "Adapt program"

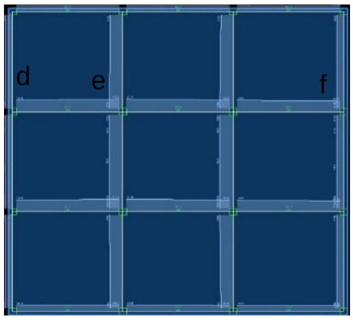


Fig. 3B "Ram program"

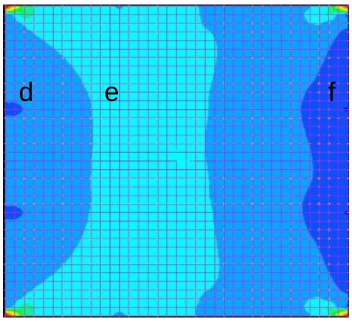


Fig. 3C "Sap2000 program"

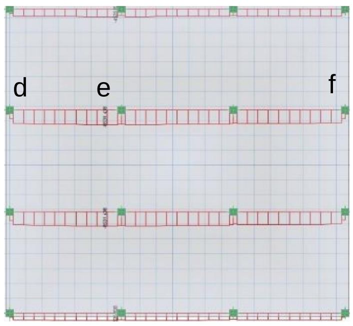


Fig. 3D "Safe program"

Fig. 3 Prestressing Force Values at locations d, e and f after friction and seating loss

(d) Point at exterior column, (e) point at interior column, (f) point at exterior column

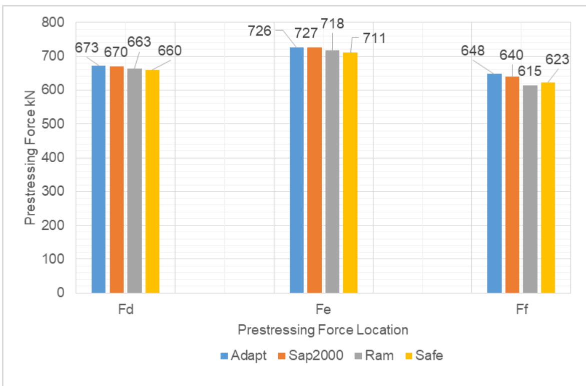


Fig. 4 Prestressing Force comparison at locations d, e and f after friction and seating loss

From the above results, the following is noted:

1. Bending moment values at points a and b are higher when calculated by “Adapt” and “Sap2000” compared to the corresponding values calculated by “Ram” by 5% and 15%, respectively and calculated by “Safe” by 15% and 34%, respectively.
2. On the other hand, “Adapt” and “Sap2000” produced the least value of the moment at point c, while “Safe” program produced the largest value with 200% increase. “Ram” program bending moment value was 96% higher than that calculated by “Adapt” and “Sap2000”. The discrepancy in the bending moments is believed to be due to the additional stiffness at the edge column assumed by the Safe program causing the edge moments to increase with a subsequent decrease in the mid span moments.
3. The calculated prestressing force losses due to friction and seating were almost the same for the four programs with only 2% difference. However, compared to manual calculations, it was noted that the curvature of the cables above columns was ignored in friction losses calculations by the four software programs.
4. The required prestressing amounts obtained from “Adapt” and “Sap2000” were the largest. Safe program produced the lowest prestressing amounts while Ram program produced the second lowest prestressing amounts.
5. Comparisons were also conducted for slabs with other aspect ratios (12x9and12x6 m). Similar conclusions as per the above were obtained for those slabs.
6. Elongation values are calculated in “Adapt” and “Ram” programs. “SAFE” and “Sap2000” programs do not provide an option to calculate the elongation. Compared to manual calculations, the calculated elongation by Adapt and Ram programs with (4% to 10%) difference compared to manual calculations.

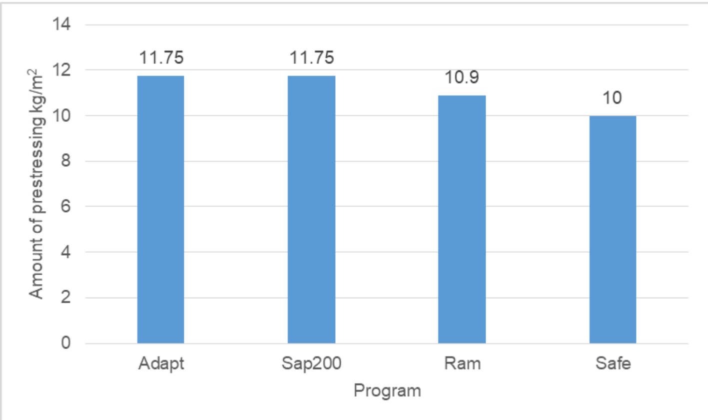
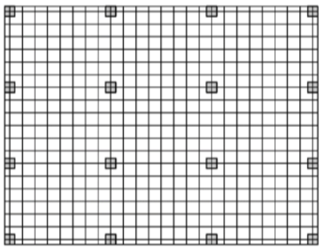


Fig. 5 Prestressing steel calculated by different software programs

FEASIBILITY STUDY

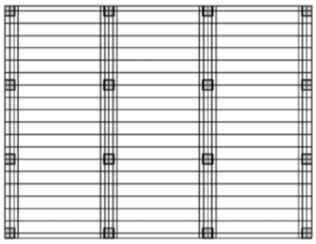
PT flat slabs with different aspect ratios and tendon patterns were modeled using “Adapt” software to study the efficiency of the different post-tensioning tendon patterns. The most common tendon patterns are shown in Fig.6, briefly mentioned as follows[5]:

1. Uniform post-tensioning tendons in both direction (Distributed-Distributed).
2. Uniform post-tensioning tendons in the long direction (X) and banded tendons in the short direction (Y) (Distributed-Banded).
3. Banded post-tensioning tendons in the long direction (X) and uniform tendons in the short direction (Y) (Banded- Distributed).



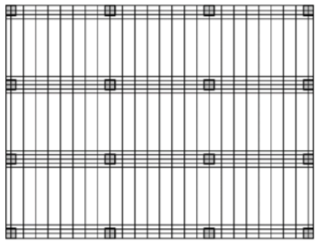
Tendon pattern number "1"

Fig. 6A (Distributed – Distributed)



Tendon pattern number "2"

Fig. 6B (Distributed – Banded)



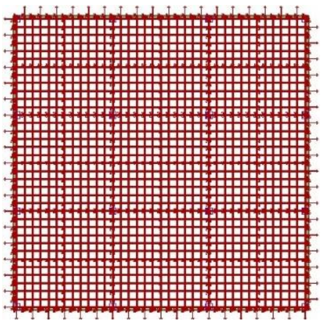
Tendon pattern number "3"

Fig. 6C (Banded - Distributed)

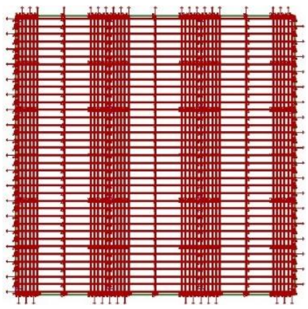
Fig. 6 Common post-tensioning tendon patterns

Analysis of PT Slabs with Aspect Ratio "1"

A 12.0x12.0 m PT flat slab was modeled using two different tendon patterns, as shown in Fig.7. The defelection behavior of the PT flat slab and the required amount of prestressing tendons were compared for the different tendon patterns.



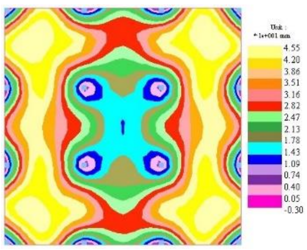
Tendon pattern number "1"



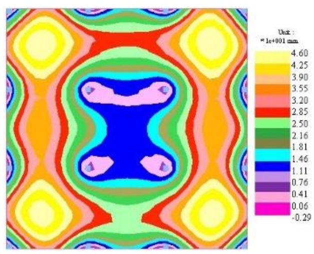
Tendon pattern number "2"

Fig. 7 Post-tensioning tendon patterns of slabs with aspect ratio "1".

To satisfy the allowable limits in tensile and compressive stresses, the required tendons amount was 11.75kg/m^2 for both patterns. Fig. 8 shows the PT-slab deflection based on this amount



Tendon pattern number "1"
Max. Deflection = 4.55cm

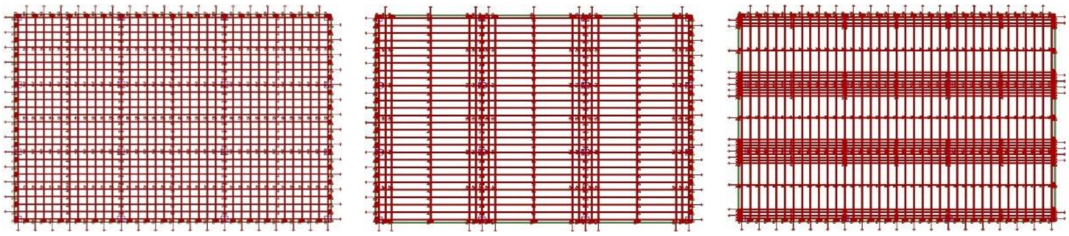


Tendon pattern number "2
Max. Deflection = 4.6cm

Fig.8 Deflection comparison for tendon patterns of slabs with aspect ratio "1".

Analysis of PT Slabs with Aspect Ratio "1.33"

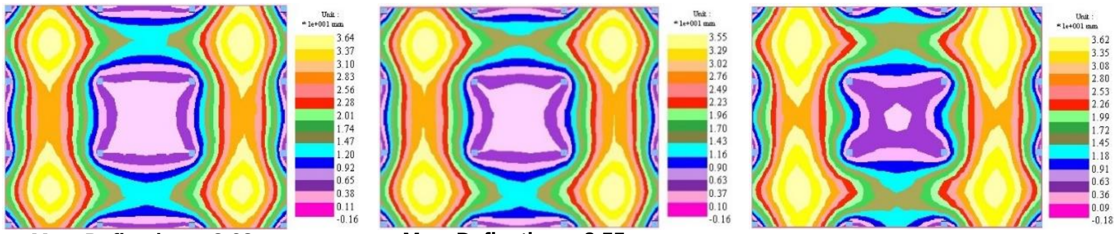
A 12.0x9.0 m PT flat slab was modeled using three different tendon patterns, as shown in Fig.9. The deflection behavior of the PT flat slab and the required amount of prestressing tendons were compared for the different tendon patterns.



Tendon Pattern number "1" **Tendon Pattern number "2"** **Tendon Pattern number "3"**

Fig. 9 Post-tensioning tendon patterns of slabs with aspect ratio "1.33".

To satisfy the allowable limits in tensile and compressive stresses, the required tendons amounts were 7.7kg/m^2,7.8kg/m^2 and 8.2kg/m^2 for tendon patterns 1, 2 and 3 respectively. Based on the calculated tendons amounts for each pattern, the slab deflections were compared as shown in Fig. 10.

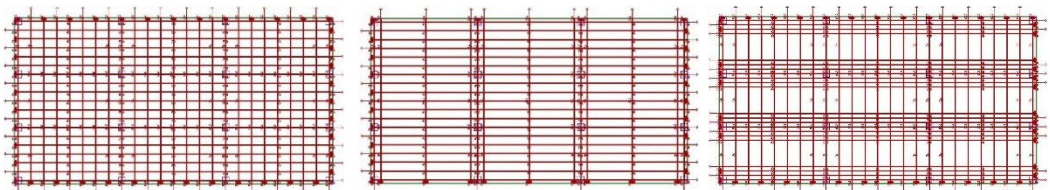


Max. Deflection = 3.62cm **Max. Deflection = 3.55cm** **Max. Deflection = 3.64cm**

Fig.10 Deflection comparison for tendon patterns of slabs with aspect ratio "1.33".

Analysis of PT Slabs with Aspect Ratio "2"

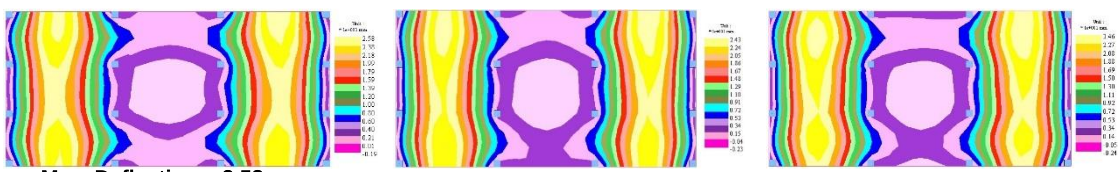
A 12.0x6.0 m PT flat slab was modeled using three different tendon pattern, as shown in Fig.11. The deflection of the PT flat slab and the required amount of prestressing tendons were compared for the different tendon patterns.



Tendon Pattern number "1" **Tendon Pattern number "2"** **Tendon Pattern number "3"**

Fig. 11 Post-tensioning tendon patterns of slabs with aspect ratio "2".

To satisfy the allowable limits in tensile and compressive stresses, the required tendons amount was 7.4kg/m^2 for all tendon patterns. Fig. 12 shows the PT-slab deflection based on the previous tendon amounts



Max. Deflection = 2.58cm **Max. Deflection = 2.43cm** **Max. Deflection = 2.46cm**

Fig.12 Deflection comparison for tendon patterns of slabs with aspect ratio "2".

Tendon Pattern Comparison Summary

As shown above in the Analysis results, the following are noted:

1- PT slabs with aspect ratio “1”: Tendon patterns number 1 and 2 required the same prestressing steel amount and the deflection values were relatively close. However, it should be noted that tendon pattern number 2 is considered better from a constructability point of view, since banding tendons in one or two directions facilitates the tendon placement process.
2- PT slabs with aspect ratio “1.33”: Tendon patterns number 1, and 2 required almost the same prestressing steel amount, while tendon pattern number 3 required a slightly higher amount by 7%. Deflection values of tendon pattern number 2 was slightly smaller than tendon patterns number 1 and 3.
3- PT slabs with aspect ratio “2”: Tendon patterns number 1, 2 and 3 required the same prestressing steel amount. Deflection values of tendon pattern number 2 was slightly smaller than tendon patterns number 1 and 3. It should be noted that the required of minimum prestressing steel by the ACI318-14 and ECP203-2017 codes of having a minimum stress of 0.9 Mpa resulting high prestressing steel ratio in case of slabs with aspect ratio more than 1.5. Therefore, the calculated prestressing amount 7.4 kg/m^2 for the three patterns 1, 2 and 3 are the same for this case.
4- It can be concluded that the tendon pattern did not significantly alter the behavior of slabs for deflection or ultimate strength as the required prestressing steel amount remained the same for the slab with aspect ratio “1”. However, for slabs with aspect ratio more than “1”, it is preferable to arrange the tendons to be uniform tendons in long span and banded in the short. This will resulting less amount of prestressing steel as well as improved constructability. This conclusion is matched with Essawy, A.S.,[7]

DESIGN TABLES

Using the performed analyses, design tables were prepared for PT slab modules of different dimensions and different span to depth ratios. Based on a specific cylinder strength of concrete and specific service loads’ level, the required prestressing steel amount, the recommended PT pattern and the expected cost per m^2 were evaluated. The cost per m^2 is based on the average egyptian market price in year 2018, as shown in the next section. Tables 1 to 4 are examples of such design tables and are considered as a valuable tool for the designer to choose the appropriate PT pattern, slab thickness with or without drop panel and PT rate that is most suitable for the design case.

Table.1 PT Rate for Flat slab under super imposed dead load (2.5kN/m^2), live load (5kN/m^2) and $f`_c$=35 MPa.

Modules	L/d	Slab Thickness (mm)	PT Rate (kg/m^2)	Pattern	Cost (EGP per m^2)
8x4	35	220	4.05	2	611
	40	200	4.30	2	583
	45	180	5.00	2	576
8x6	35	220	4.10	2	613
	40	200	4.60	2	597
	45	180	5.60	2	603
8x8	35	220	5.50	1	676
	40	200	6.00	1	660
	45	180	8.00	1	711
10x5	35	280	5.10	2	775
	40	250	5.70	2	744
	45	230	6.10	2	723
10x7.5	35	280	5.80	2	807
	40	250	6.40	2	775
	45	230	7.10	2	768

Modules	L/d	Slab Thickness (mm)	PT Rate (kg/m^2)	Pattern	Cost (EGP per m^2)
10x10	35	280	7.70	1	892
	40	250	9.00	1	892
	45	230	10.50	1	921
12x6	35	340	6.70	2	964
	40	300	7.50	2	922
	45	280	8.00	2	906
12x9	35	340	6.80	2	969
	40	300	7.80	2	936
	45	280	8.70	2	937
12x12	35	340	11.05	1	1160
	40	300	11.75	1	1113
	45	280	12.80	1	1122

Table 2 PT Rate for Flat slab with drop under super imposed dead load (2.5kN/m2), live load (5kN/m2) and f`c=35 MPa.

Modules	L/d	Slab Thickness (mm)	Average Thickness (mm)	PT Rate (kg/m^2)	Pattern	Cost (EGP per m^2)
8x4	40	200/300	220	3.40	2	582
	45	180/300	200	3.45	2	545
	50	160/300	180	3.45	2	506
8x6	40	200/300	220	3.50	2	586
	45	180/300	200	3.60	2	552
	50	160/300	180	3.60	2	513
8x8	40	200/300	220	4.30	1	622
	45	180/300	200	4.50	1	592
	50	160/300	180	4.50	1	553
10x5	40	220/350	250	4.85	2	705
	45	200/350	230	4.85	2	666
	50	180/350	210	4.85	2	627
10x7.5	40	220/350	250	5.00	2	712
	45	200/350	230	5.00	2	673
	50	180/350	210	5.05	2	636
10x10	40	220/350	250	6.90	1	798
	45	200/350	230	7.50	1	786
	50	180/350	210	8.30	1	783
12x6	40	280/400	310	6.50	2	897
	45	250/400	280	6.50	2	838
	50	230/400	260	6.60	2	804
12x9	40	280/400	310	6.70	2	906
	45	250/400	280	6.90	2	856
	50	230/400	260	7.05	2	824
12x12	40	280/400	310	10.00	1	1054
	45	250/400	280	10.75	1	1029
	50	230/400	260	10.75	1	990

Table. 3 PT Rate for Flat slab under super imposed dead load (2.5kN/m^2), live load (10kN/m^2) and $f`_c$ = 35 MPa.

Modules	L/d	Slab Thickness (mm)	PT Rate (kg/m^2)	Pattern	Cost (EGP per m^2)
8x4	30	280	4.50	2	748
	33	250	5.20	2	721
	36	230	5.50	2	696
8x6	30	280	4.90	2	766
	33	250	5.50	2	735
	36	230	6.30	2	732
8x8	30	280	6.60	1	843
	33	250	7.75	1	836
	36	230	8.80	1	844
10x5	30	340	6.35	2	948
	33	300	7.00	2	900
	36	280	7.30	2	874
10x7.5	30	340	6.60	2	960
	33	300	7.60	2	927
	36	280	8.50	2	928
10x10	30	340	9.30	1	1081
	33	300	10.90	1	1075
	36	280	12.00	1	1086
12x6	30	400	8.30	2	1153
	33	350	9.00	2	1087
	36	330	9.30	2	1062
12x9	30	400	8.70	2	1171
	33	350	10.10	2	1137
	36	330	11.00	2	1138
12x12	30	400	12.60	1	1347
	33	350	14.40	1	1330
	36	330	15.40	1	1336

Table.4 PT Rate for Flat slab with drop under super imposed dead load (2.5kN/m^2), live load (10kN/m^2) and $f`_c$=35 MPa.

Modules	L/d	Slab Thickness (mm)	Average Thickness (mm)	PT Rate (kg/m^2)	Pattern	Cost (EGP per m^2)
8x4	35	220/350	250	4.20	2	676
	40	200/350	23	4.35	2	644
	45	180/300	210	4.35	2	605
8x6	35	220/350	250	4.65	2	696
	40	200/350	230	5.00	2	673
	45	180/300	210	5.00	2	634
8x8	35	220/350	250	6.10	1	762
	40	200/350	230	6.70	1	750
	45	180/300	210	6.90	1	720
10x5	35	280/400	310	6.40	2	892
	40	250/400	280	6.40	2	834
	45	230/400	260	6.40	2	795
10x7.5	35	280/400	310	6.60	2	901
	40	250/400	280	6.60	2	843
	45	230/400	260	7.00	2	822

Modules	L/d	Slab Thickness (mm)	Average Thickness (mm)	PT Rate (kg/m^2)	Pattern	Cost (EGP per m^2)
10x10	35	280/400	310	9.60	1	1036
	40	250/400	280	10.30	1	1009
	45	230/400	260	10.75	1	990
12x6	35	340/450	370	8.30	2	1095
	40	300/450	330	8.50	2	1026
	45	280/450	310	8.50	2	987
12x9	35	340/450	370.0	9.30	2	1140
	40	300/450	330.0	10.10	2	1098
	45	280/450	310.0	10.60	2	1081
12x12	35	340/450	370.0	13.30	1	1203
	40	300/450	330.0	14.30	1	1189
	45	280/450	310.0	15.00	1	1182

From the above tables, the following are noted:

1- Using slab to depth ratio between L/40 and L/45 appeared to be the economic design for PT flat slabs subjected to 5kN/m^2 live load.
2- Using slab to depth ratio equal L/50 appeared to be the economic design for PT flat slab with drop panels under live load=5kN/m^2.
3- Using slab to depth ratio between L/33 and L/36 appeared to be the economic design for PT flat slab subjected to 10kN/m^2 live load.
4- Using slab to depth ratio equal L/45 appeared to be the economic design for PT flat slab with drop panels under live load=10kN/m^2 .
5- Using drop panels produced a more economical design for slabs with different aspect ratios.

COST COMPARISON BETWEEN PT AND RC SLABS

To evaluate the efficiency of the PT slab, its cost was compared to the conventional reinforced concrete flat slab using prices for the concrete floor constituents. A cost comparison was performed for the following modules: 8x8, 10x10 and 12x12m.

The following data was assumed in the analysis:

1- Designed as per ACI Code
2- Cylinder strength of concrete used is 35 MPa.
3- Assumed column dimensions were 800x800 mm.
4- Live load = 5 kN/m^2 and floor cover = 2.5 kN/m^2
5- Ultimate tensile stress of Prestressing Steel = 1860 MPa
6- Yield stress of reinforcement steel = 400 MPa

A summary of the required material quantities in the PT flat slab system and the conventional reinforced concrete flat slab system for the selected modules are shown in table 5.

Table. 5 Concrete and steel quantities for PT and RC flat slabs

Modules	Floor System	Average Concrete (m^3/m^2)	Non-Prestressed Steel Quantities (kg/m^3)	Prestressing Steel Quantities (kg/m^2)
12X12	RC Flat Slab	0.40	180	----
	PT Flat Slab	0.30	50	11.75
10X10	RC Flat Slab	0.32	165	----
	PT Flat Slab	0.25	50	9
8X8	RC Flat Slab	0.25	145	----
	PT Flat Slab	0.20	50	6

The cost of one square meter of the floor area of the buildings was estimated for the two alternatives taking into consideration the average egyptian market price in year 2018 for concrete and steel. The following material cost was used for the price estimation:

- Concrete cost = 1200 EGP/m^3
- Conventional reinforcement cost = 15000 EGP/ton
- Prestressing System cost (Inclusive) = 52000 EGP/ton

The final price comparison between the PT and conventional slabs is shown in table 6. The expected saving from using the PT option is presented in each case.

Table. 6 Cost comparison between PT and RC flat slabs

Modules	Floor system	Cost (EGP per m^2)	Saving (%)
12X12	RC Flat Slab	1560	-----
	PT Flat Slab	1196	23%
10X10	RC Flat Slab	1176	-----
	PT Flat Slab	955	19%
8X8	RC Flat Slab	844	-----
	PT Flat Slab	702	17%

From the comparison, it can be concluded that using PT flat slabs shall provide at least 17% savings in the cost of the concrete floors. This is in addition to the reduction in the weight of the building, which is translated to reduction in the size of footings. Moreover, reduction in the construction time and an increase in the clear height of each floor are also expected when using PT slabs compared to conventional RC flat floors.

CONCLUSIONS

The following conclusions were drawn from this study:

1- Comparison of the computer software used for PT slab design showed that “Adapt” and “Sap2000” software programs produced larger bending moment values at mid spans and smaller values at the edge columns. This contrasted with “SAFE” program which produced higher moment values at the edges and smaller values at mid span. “Ram" program produced moment values that were in between the two extremes. This discrepancy can be attributed to the higher stiffness of edge columns assumed by “SAFE”, which in turn will require additional non-prestressed steel at the edges.

2- Calculated prestressing force losses due to friction and seating were almost the same for the four programs with only 2% difference. However, compared to manual calculations, it was noted that the curvature of the cables above columns was ignored in friction losses calculations by the four software programs.

3- Elongation values are calculated in “Adapt” and “Ram” programs. “SAFE” and “Sap2000” programs do not provide an option to calculate the elongation. Compared to manual calculations, the calculated elongation by Adapt and Ram programs with (4% to 10%) difference compared to manual calculations.

4- It can be concluded that the tendon pattern did not significantly alter the behavior of slabs for deflection or ultimate strength as the required prestressing steel amount remained the same for the slab with aspect ratio “1”. However, for slabs with aspect ratio more than “1”, it is preferable to arrange the tendons to be uniform tendons in long span and banded in the short. This will resulting less amount of prestressing steel as well as improved constructability.

5- Design tables were constructed for specific dimensions, concrete strengths, and service loadings to provide the most economical span to depth ratio and the expected prestressing steel rate.

6- From the tables it was concluded that using drop panels produced a more economical design.

7- The economic advantage of the PT flat slabs over the conventional RC slabs was shown to be more than 17% for slabs of 8 x 8 m square panels and higher.

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