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Parametric Study of Different Unbonded Tendon Layouts in Pre-stressed Concrete Flat Plates

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Abstract

Post-tensioned unbonded tendons are widely used in flat slabs/plates when there is a demand for large span lengths, durable tendons and a reduction in the weight of structure. For post-tensioned flat slab/plates, different tendon layouts have been discussed in the literature. It is vital to compare the structural response (i.e., deflection and stresses) and the clashing of tendons of the proposed tendon layouts in the literature to select an appropriate layout. Hence, this study focuses on the analysis of three different six-panel flat plates (i.e., panel sizes: 6 m × 6 m, 9 m × 6 m and 11 m × 6 m) with five different tendon layouts, using computer programs ADAPT-Floor Pro and FEM-Design 17, based on linear finite element (FE) analysis. Short-term/long-term deflection and stress due to service load obtained from the computer programs has also been compared, to highlight the differences. Ultimate bending moment of resistance was calculated theoretically for different layouts and compared. Results from the analysis show that, when a higher portion of tendons is concentrated instead of distributed, stresses caused by other structural loads are counteracted best. The layout with all tendons concentrated also has the best results in terms of deflections.

Keywords: unbonded tendons, layout, pre-stressed concrete, flat plates

1 Introduction

Both unbonded and bonded tendons can be used to construct pre-stressed concrete flat slab/plates. The use of unbonded tendons began in the United States at the beginning of the 1950s and has been used to a great extent since when constructing parking garages and floors. In Europe, the use of this system started at the beginning of the 1970s (KB Spennteknikk 2011). Compared to bonded tendons, unbonded tendons have advantages. For example, unbonded strands need less space than multi-strand bonded systems that require a room for grouting in ducts (Fib bulletin 2005). Similarly, the absence of grouting of ducts makes the construction process easy. Moreover, as there is in-built corrosion protection, the cover to the tendon can be reduced or eliminated. As a result, the designer can choose maximum eccentricity to place the tendons. Unbonded tendons usually require lighter stressing equipment than their bonded counterparts. In addition, the pre-stressing force in unbonded tendons can be adjusted during service life. Nevertheless, the ultimate strength of a structural member with unbonded tendons is 75% that of one with bonded tendons (Gilbert et al. 2017), which is one of the disadvantages.

There are several possible arrangements of the unbonded tendons in a flat slab/plate, some of which are easier to execute, while some ensure better load balancing than others. Ideally, the tendons should be distributed between the column lines and the span, the same way that the moment is distributed. In general, the unbonded tendons in each direction may be placed in a banded, distributed or mixed layout (Aalami 2014; Sørensen 2013;

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Hodne 2017). To investigate the influence that tendon layouts have on flat slab/plates, three different slabs were defined, with three spans in one direction and two in the other. Span length, slab thickness and other parameters were chosen for each slab. Calculations for each slab were performed regarding five different tendon layouts. For each slab, the same total pre-stressing force, tendon profiles and other parameters were used, and the only varying parameters were the location and distribution of the tendons. For five different layouts by varying span lengths, long-term deflections/short-term deflections and stresses due to service load were obtained from computer programs: ADAPT-Floor Pro and FEM-Design 17.

2 Different Unbonded Tendon Layouts for Flat Slabs/Plates

According to the literature (Aalami 2014; Sørensen 2013), the possible layouts of the unbonded tendons are shown in Fig. 1a–d. In Fig. 1a, the unbonded tendons are banded and placed only along column strips. Although layout 1(a) is easy to execute, there is no contribution from the strip without tendons to balance the external load. Moreover, pre-stressed flat slabs/plates with layout (b) may be difficult to execute because of the weaving of tendons in spans (Sørensen 2013). Similarly, layout (d) minimizes the weaving of tendons (Bhatt 2011) and simplifies the execution; furthermore, it is looked upon as a one-way plate with column line tendons as supports (Gilbert et al. 2017).

In the banded direction, all the tendons of a design strip are grouped in several flat bundles and placed parallel to one another with a relatively small gap separating the constituent bundles (Aalami 2014). The tendons form a narrow band, typically up to or slightly larger than 1.20 m (4 ft) in width, following the support line. Tendons in the distributed direction are placed in bundles of one to four strands, spread over the entire width of the design strip with essentially equal spacing between the bundles.

It is vital to consider constructability when selecting a suitable layout. According to design guidelines given in the literature for unbonded tendons, the American Concrete Institute (ACI) does not recommend using layout (a) (Aalami 2014). However, no such guidelines are given in Eurocodes. Moreover, the American Concrete Institute (ACI) recommends using uniformly distributed tendons in one direction and banded tendons in the other direction (Roschke and Inoue 1990), as shown in Fig. 1d. Also, banded-distributed layouts simplify the construction sequence by reducing labor costs and construction time, compared with other layouts. Also, it can be very useful when there is an irregular column layout. One other advantage of the banded-distributed option, from a design point of view, is that both directions can be designed with the maximum permissible tendon drape (Aalami 2014).

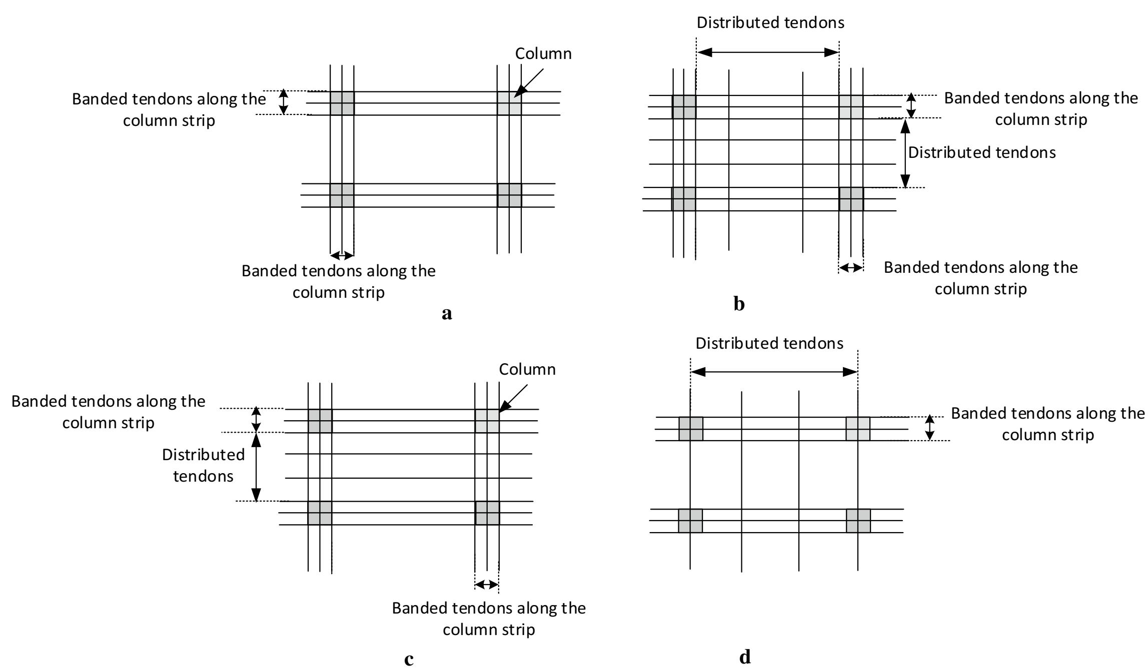

Fig. 1 Layouts for unbonded tendons (adapted from Sørensen (2013)).

Some researchers have discussed how to improve the structural response of the flat slab/plate using an appropriate tendon layout experimentally and analytically. Moreover, Burns and Hemakom (1985) carried out experimental testing and found that a banded unbonded tendon layout along the column strips greatly contributed to resisting the punching shear. Kosut et al. (1985) studied the behavior of post-tensioned four-panel flat plates with distributed and banded tendon arrangements. They observed that slabs with banded tendon layouts enhance the ultimate load-carrying capacity and the shear strength of each slab–column connection. Based on Ramos et al. (2014) experimental results of flat plates with tendons under punching shear, increasing the distance between the tendons and the column resulted in smaller load capacities.

Using SAP2000 software, Schokker et al. (2002) studied the effect of tendon layout, considering the interior panel of a flat slab of 7.1 m × 6.1 m, and found that 100% of tendons banded along the column line in each direction gave a good structural response (i.e., deflection, stress control). However, the analysis did not consider different span sizes. Nethravathi and Prasad (2018) carried out analysis using SAFE software for three unbonded tendon layouts and found that banded and distributed tendon layouts give less short-term and long-term deflection. It can be seen from the literature that tendon layout effect when the panel dimensions are unequal has not been investigated substantially.

3 Analysis of Different Tendon Layouts

3.1 Flat Plate Floor and Material Properties

A flat plate floor, consisting of three spans in the 'X' direction and two spans in the 'Y' direction, has been selected, as shown in Fig. 2. During the analysis, 'Lx' (i.e., span lengths along the '*X*' direction) of 6 m, 9 m and 11 m have been used, while keeping 'Ly' (i.e., span length along the '*Y*' direction) as 6 m. The diameters (D) of the columns have been chosen as 300 mm, 400 mm and 500 mm, respectively, for Case 1, Case 2 and Case 3. The slab thickness is set to 180 mm, 200 mm, and 270 mm for Case 1, Case 2 and Case 3, respectively, considering the span/depth ratio (Gilbert et al. 2017).

The flat plate is set to be a part of an office, and the only structural load considered besides the self-weight of the slab, and the loads due to pre-stressing, is a live load of 3 kN/m^2. Table 1 shows the properties of the material used in this analysis. Two different characteristic compressive strengths are used to obtain an adequate shear strength. Moreover, Table 2 gives all the detailed information for each layout.

Parabolic tendon profiles are chosen to have maximum eccentricity in the center line of columns and in spans, regardless of the clashing of tendons. Figures 3 and 4

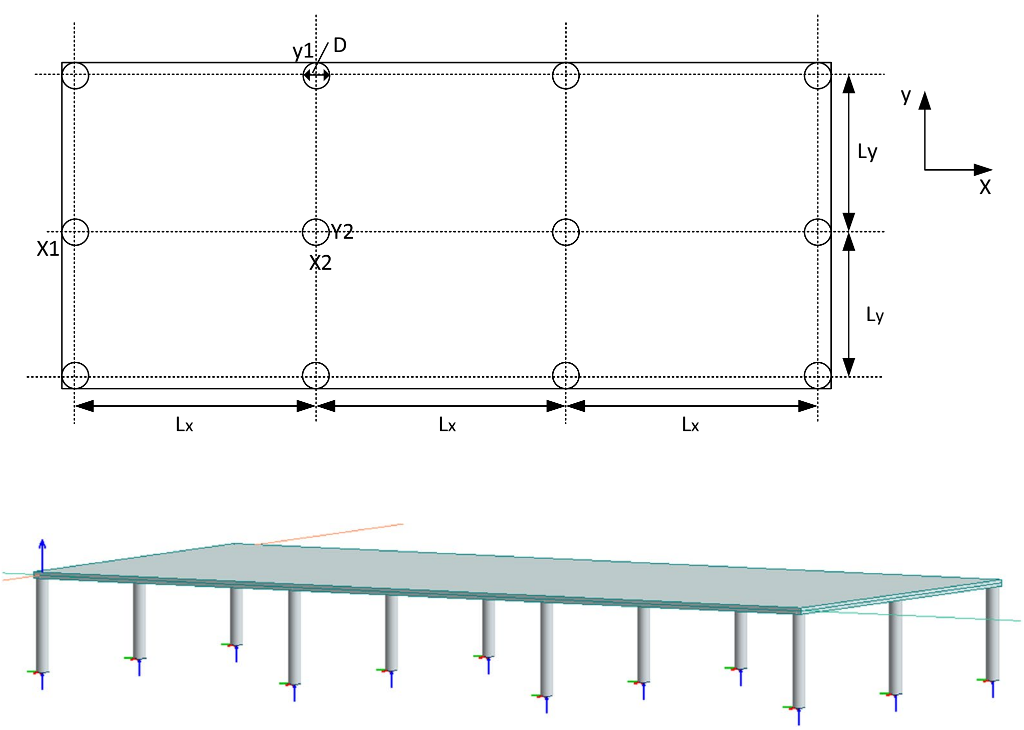

Fig. 2 Plan view of the flat plate floor and 3D model of system.

Table 1 Properties of the material.

Material	Properties
Concrete	
Characteristic cylindrical compressive strength (MPa) (f_{ck})	35/45
Mean axial tensile strength (MPa)	3.2
Secant modulus of elasticity (GPa)	34
Steel reinforcement	
Characteristic yield strength of rebar: B500NC (MPa)	500
Modulus of elasticity (GPa)	200
Pre-stressing steel: (BBR VT CONA Single 0.62″)	
Diameter of a tendon (mm)	15.7
Cross-sectional area (mm^2)	150
Characteristic yield strength (MPa)	1860
Modulus of elasticity (GPa)	196

Table 2 Detailed information about different layouts.

	Case 1	Case 2	Case 3
Span lengths [m]	$Lx = 6$, $Ly = 6$ (6 × 6)	$Lx = 6$, $Ly = 9$ (9 × 6)	$Lx = 6$, $Ly = 11$ (11 × 6)
Slab thickness [mm]	180	220	270
Column diameter [mm]	300	400	500
f_{ck} [MPa]	35	45	45
Creep coefficient	2.29	1.80	1.74
Shrinkage strain [‰]	0.49	0.47	0.47
Minimum reinforcement			
Bottom mesh	ø10 c300	ø10 c200	ø12 c230
Top, over columns, *x*-direction	8 ø16	12 ø16	14 ø16
Top, over columns, *y*-direction	8 ø16	16 ø16	24 ø16

show the tendon profiles and eccentricities used when Lx = 6 m and Ly = 9 m. Table 3 shows the maximum eccentricities and number of tendons, and the amount of dead load balanced. For slabs, normally 60–80% of the dead load is balanced, while, for beams, often 80–100% of the dead load is balanced. This is recommended in American code ACI 318-02 (2002), and the maximum value is suggested, to obtain an economical design.

The number of tendons chosen is 24 and 34, respectively, in the x- and y-directions. This corresponds to an average pre-stressing of 1.79 MPa and 1.12 MPa, in addition to about 50% and 70% of the dead load that is balanced by the pre-stressing, considering the idealized parabolic model, as shown in Table 3.

3.2 FEM Tool for the Analysis

Both a linear elastic FE analysis and a non-linear FE analysis can be used to analyze pre-stressed concrete flat plates. Although concrete is a nonhomogeneous and non-linear material, linear elastic material behavior is usually considered during designing while calculating load effect. NS EN 1992-1 (2011) recommends using non-linear analysis or plastic analysis, but the non-linear analysis or plastic analysis is not often used in normal design practice, due to the high workload arising from considering all the load combinations (Rombach 2004). Therefore, linear FE analysis has been used in this study. There are two types of FEM software available: FEM-based software developed for design and analysis purposes and general-purpose software. In this study, FEM-Design and ADAPT-Floor Pro are used to include all design guidelines in accordance with NS EN 1992-1 (2011).

3.3 FEM-Design 17

In general, an analysis of a structure using FEM tools consists of idealization of the real structure, choice of the finite elements for the analysis, selection of suitable material models, discretization/mesh generation, defining boundary condition, assigning loads/actions and calculation of load effect. FEM-Design 17 is user-friendly software, developed not only for the design and analysis of concrete structures, but also to model, analyze and design steel, timber and foundation structures in accordance with Eurocode with national annexes (StruSoft 2018). In the analysis, the characteristic compressive strength of concrete is considered as 35 MPa and 45 MPa, and the properties of pre-stressing steel are

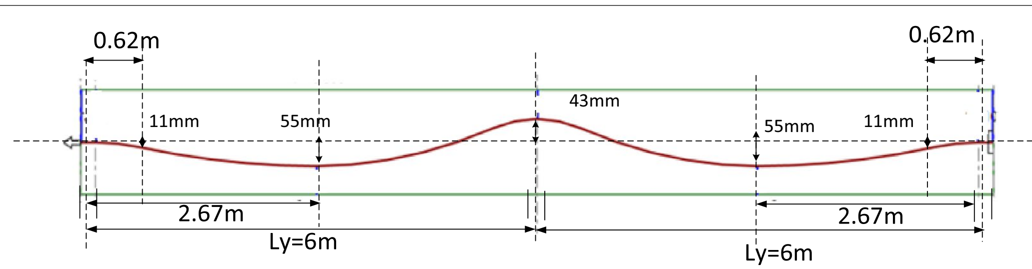

Fig. 3 Tendon profile and the eccentricities when $Ly = 6$ m.

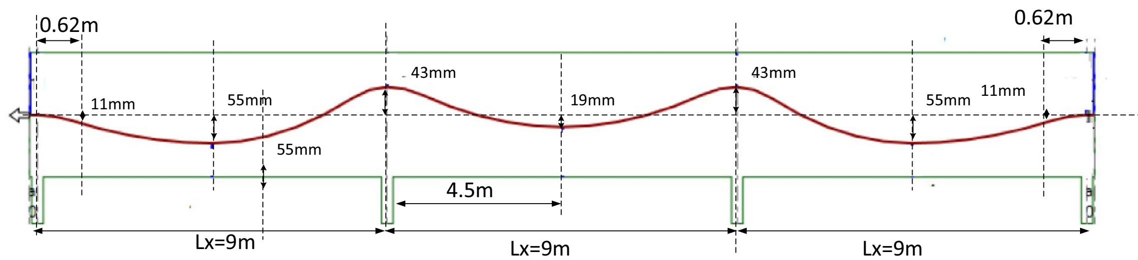

Fig. 4 Tendon profile and the eccentricities when $Lx = 9$ m.

Table 3 Summary of results from manual calculations.

	Case 1	Case 2	Case 3
Maximum eccentricity			
Top	23 mm	43 mm	68 mm
Bottom	35 mm	55 mm	76 mm
Maximum drape (idealized profile)	47 mm	77 mm	110 mm
Number of tendons			
X-direction	14	24	30
Y-direction	22	34	46
Dead load balanced			
X-direction	47%	47%	46%
Y-direction	49%	68%	89%

given in Table 1. Shrinkage strain of concrete has been estimated in accordance with NS EN 1992-1 (2011) (i.e., given in Table 2) and inserted into the software. The software calculates the specific normal force and bending moment causing the inserted shrinkage strain and applied to the flat plate as a load. Creep coefficient has been calculated as per NS EN 1992-1 (2011) (i.e., given in Table 2) and inserted into the software. Moreover, wobble coefficient of 0.01 per 1 m, anchorage slip of 4 mm and class 2 of relaxation of pre-stressing steel have been used in the analysis. In modeling the pre/stressed flat plate, shell elements with nine nodes (i.e., quadrilateral) and six nodes (i.e., triangular elements) were used, and the software automatically discretized the flat plate. The feature for modeling unbonded tendons was new as of January 2018 and is for analysis purposes only. The software converts the tendon profiles into equivalent loads, which are used in load combinations for the analysis. The software supports peak smoothing over singularity regions by calculating an average moment over a chosen distribution region.

3.4 ADAPT-Floor Pro

ADAPT-Floor Pro is finite element software made for the analysis and design of concrete and post-tensioned floor systems (ADAPT 2018). The software is based on the American code, but it also supports Eurocodes, but without national annexes. In this analysis, material properties given in Table 1 were used and the same wobble coefficient, anchorage slip and class 2 of relaxation of pre-stressing steel have been used. Opposite to FEM-Design 17, the modeling of tendons is not done as applied loading but as load-resisting elements. This means that the tendons are not "removed" from the concrete member. By default, the finite element types used in the program are flat quadrilateral shell elements (ADAPT 2018). The software generates an automatic adaptive mesh for flat plates, using flat quadrilateral shell elements. Shrinkage loads (represented as input strains) can be modeled as patch loads that can be assigned to all flat quadrilateral shell elements. The long-term deflection has been calculated as the instantaneous deflection due to sustained load plus the creep and shrinkage factors multiplied by that deflection.

To validate the results obtained from the FEM tools, the results from the FEM-Design and ADAPT programs are compared with each other, as well as with manual calculations for a slab, $Lx = 9$ m and $Ly = 6$ m with a height of 200 mm.

3.4.1 Modeling of Different Tendon Layouts

As shown below in Fig. 5a–e, five tendon layouts were modeled in both software packages. In layout A, banded tendons are placed in the direction of the longest span and distributed in the other direction. Moreover, in layout B, shown in Fig. 5b, banded tendon profiles are used in both directions along the column strips. Then, in layout C, banding in the direction of the shortest span and distributing in the other is used. For layout D, about 50% of tendons are banded and 50% are distributed in the direction of the longest span. Finally, for layout E, given in Fig. 5e, about 50% are banded and 50% are distributed in both directions.

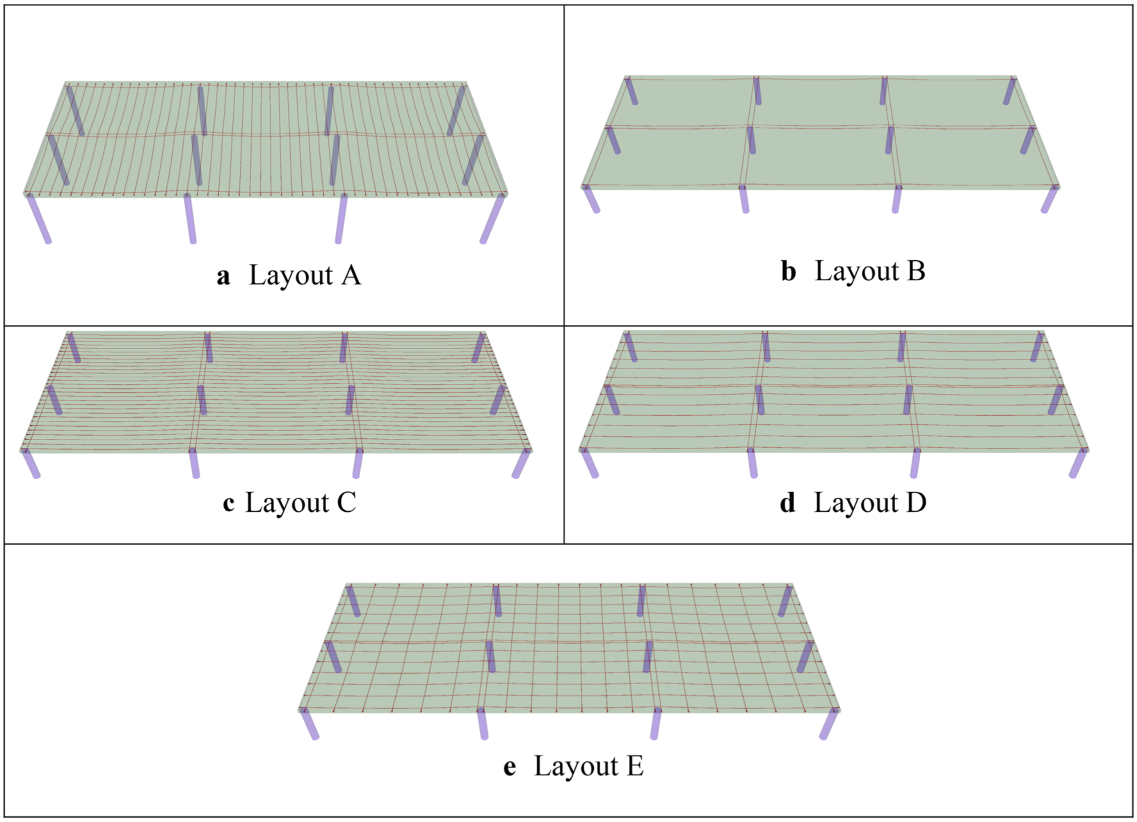

Fig. 5 Distribution of tendons in different layouts.

4 Results of the Analysis

4.1 Short-Term Deflection and Long-Term Deflection due to Service Load

The maximum deflections are estimated when the flat plate withstands a short-term load (i.e., characteristic pre-stressing load and characteristic dead load) and a long-term load in a quasi-permanent combination [i.e., permanent load + pre-stressing + 30% of variable load (i.e., 3 kN/m^2)], including the effect of creep and shrinkage. Figure 6 shows the results obtained from FEM-Design software and ADAPT software. The minus values of deflection indicate that the deflection is downward, as shown in the vertical axis of the graph. It can be seen that there is no significant difference between short-term deflections estimated from both software packages for all three cases. However, it can be seen that there is a significant difference in long-term deflection. Nevertheless, according to NS EN 1992-1 (2011) the long-term deflection is within the allowable limits (span/250).

The results also show that the tendon layouts with the least number of distributed tendons (layouts B and D) have the smallest deflections, based on the results from both FEM-Design and ADAPT software. This observation is valid for all three cases: Case 1, Case 2 and Case 3. Moreover, considering an idealized tendon profile, one would expect that the equivalent load due to tendon curvature in the layouts with many distributed tendons would better counteract the dead load. The case is that realistic tendon profiles will result in downward equivalent forces in some areas. When a tendon is concentrated, these downward forces will be at the top of the columns and not lead to any deflections. When a tendon is distributed, the downward force will be in spans and hence increase the downward load in this area, resulting in increased deflections.

4.2 Maximum Compressive and Tensile Stresses at Service

The stresses at service were obtained at the quasi-permanent load combination [i.e., permanent load + pre-stressing + 30% of variable load (i.e., 3 kN/m^2)]. The maximum stresses were at the sections in span *X1–X2*, in span *Y1–Y2*, at the column center line along the *X*-direction (i.e., at column *X2*) and at the column center line along the *Y*-direction (i.e. at column *Y2*) (see Fig. 2 flat plate floor). The results are presented in Tables (i.e. Table 4 and Table 5) and are shown to one decimal place, to more easily detect differences.

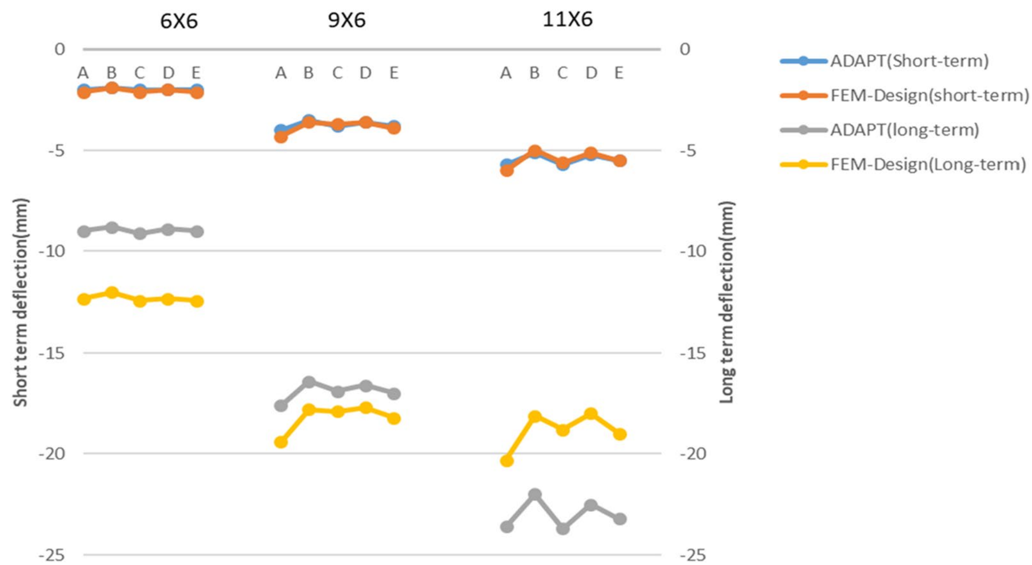

Fig. 6 Tendon layout analysis—deflections in millimeters.

Table 4 Tendon layout analysis—stresses in *X*-direction [in MPa] (tension is positive).

	ADAPT-Floor Pro				FEM-Design 17			
	In span X1–X2		At column X2		In span X1–X2		At column X2	
	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom
6 × 6								
A	− 3.0	0.5	0.9	− 3.2	− 3.6	0.3	6.7	− 9.0
B	− 3.1	0.3	1.0	− 3.1	− 3.2	0.4	4.7	− 7.1
C	− 3.1	0.5	1.2	− 3.2	− 3.4	0.9	6.5	− 8.7
D	− 3.1	0.5	1.1	− 3.2	− 3.2	0.4	5.8	− 8.1
E	− 3.0	0.6	1.1	− 3.2	− 3.4	0.8	6.6	− 9.0
9 × 6								
A	− 4.5	1.5	2.0	− 5.1	− 5.0	1.6	8.5	− 11.7
B	− 4.8	1.1	2.2	− 4.8	− 4.9	0.7	5.5	− 8.3
C	− 5.0	1.0	2.2	− 4.8	− 5.0	1.0	6.6	− 9.6
D	− 4.9	1.1	2.1	− 4.8	− 4.9	0.7	5.8	− 8.8
E	− 4.7	1.3	2.1	− 4.9	− 4.9	1.1	6.9	− 9.9
11 × 6								
A	− 5.1	1.9	2.4	− 5.6	− 4.6	1.3	6.3	− 9.5
B	− 5.4	1.4	2.8	− 5.3	− 4.6	0.4	2.8	− 5.5
C	− 5.4	1.4	2.9	− 5.4	− 4.8	0.4	3.8	− 6.6
D	− 5.4	1.5	2.8	− 5.3	− 4.6	0.4	3.2	− 5.9
E	− 5.2	1.6	2.7	− 5.5	− 4.6	0.7	4.6	− 7.6

From the analysis, it is found that FEM-Design has estimated significantly higher stresses over columns in the floor in all four cases, compared with the estimated values from ADAPT software. The reason for this is that ADAPT software calculations are based on a full width of the strip (i.e., Lx or Ly), where the bending moments from permanent and variable loads are averaged over the cross section. The stresses calculated will then be the same throughout the whole width of the strip. FEM-Design calculates the stresses for each node in the mesh and interpolates the result between them. Then, the stresses obtained from FEM-Design have been manually averaged across the width of column strips (i.e., Ly/2 or Lx/2). Therefore, a comparison of stress values between the two software programs has not been carried out. According to the estimated stresses using ADAPT software, it can be seen that there are small differences in the results among the tendon layouts. This is because ADAPT software uses average values across the design strips. Using the full width approach, the design stresses will have small variations. For a better comparison of the stress contribution the tendon layout makes, the results from FEM-Design have been looked into more closely. Results show that the tensile stresses in the top fiber of a section at the column center line will be the least when using banded tendons. This implies that tendon layout B has the best effect on stresses.

Moreover, to compare the effect of pre-stressing in different layouts, stress contours from FEM-Design software are observed for Case 3:11X6 flat plate, as shown in Fig. 7a–e.

4.3 Clashing of Tendons

In the analysis, the issue of intersecting tendons in opposite directions has not been accounted for when choosing the tendon profiles. ADAPT software has a function that detects the clashing of tendons. The results for tendon layouts A–E for the Case 3 slab are presented in Fig. 8a–e. Places where tendons intersect each other are represented by a small pink cross. Tendon layout E has many intersecting tendons in spans, and it will cause weaving of tendons, which will be expensive, due to the extra amount of time it will take to change tendon profiles individually. The other layouts intersect at columns and at edges. Over columns, the issue can easily be solved by adjusting the tendon profile in one of the directions. For

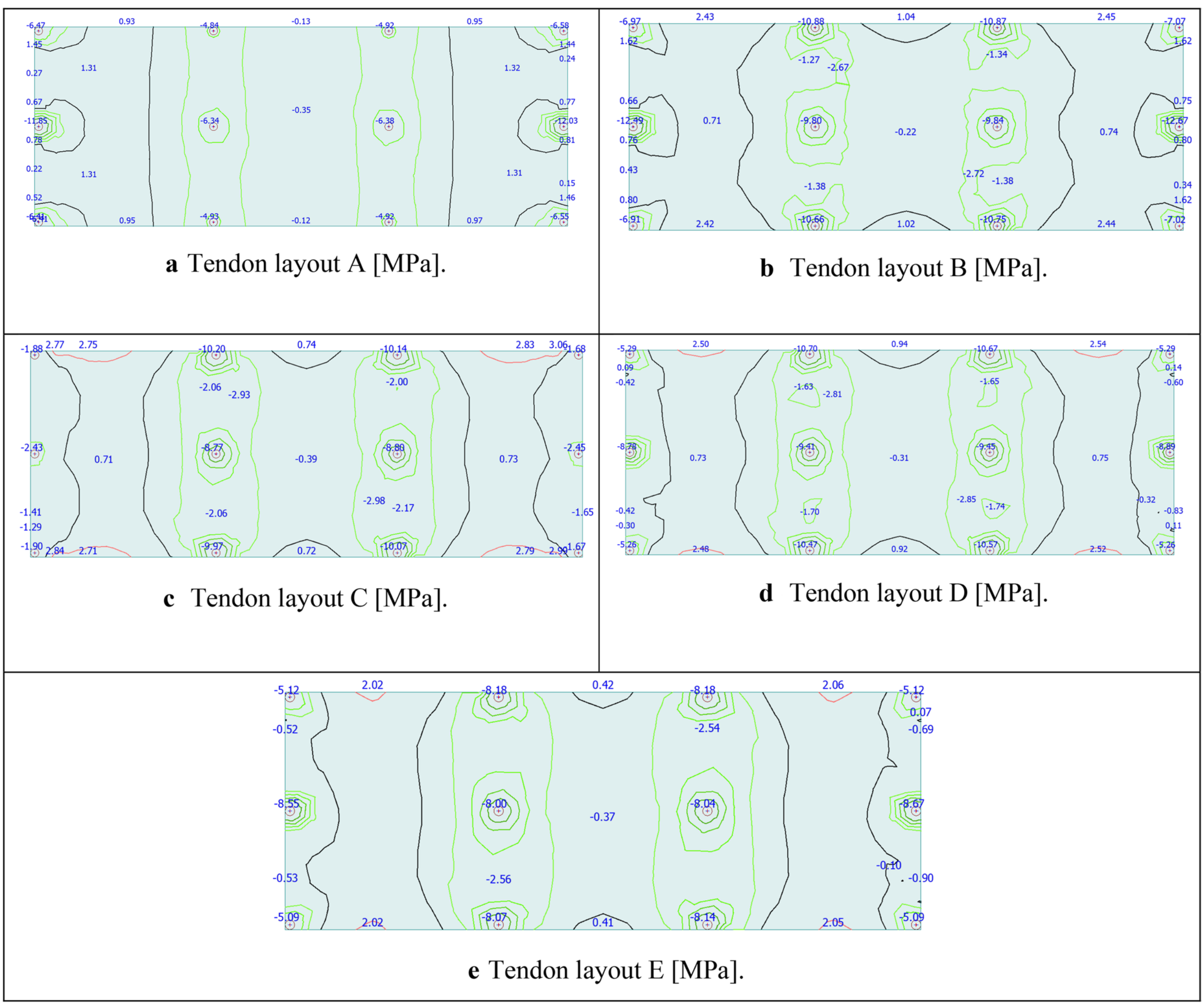

Fig. 7 Stresses in top fiber in x-direction due to pre-stressing actions.

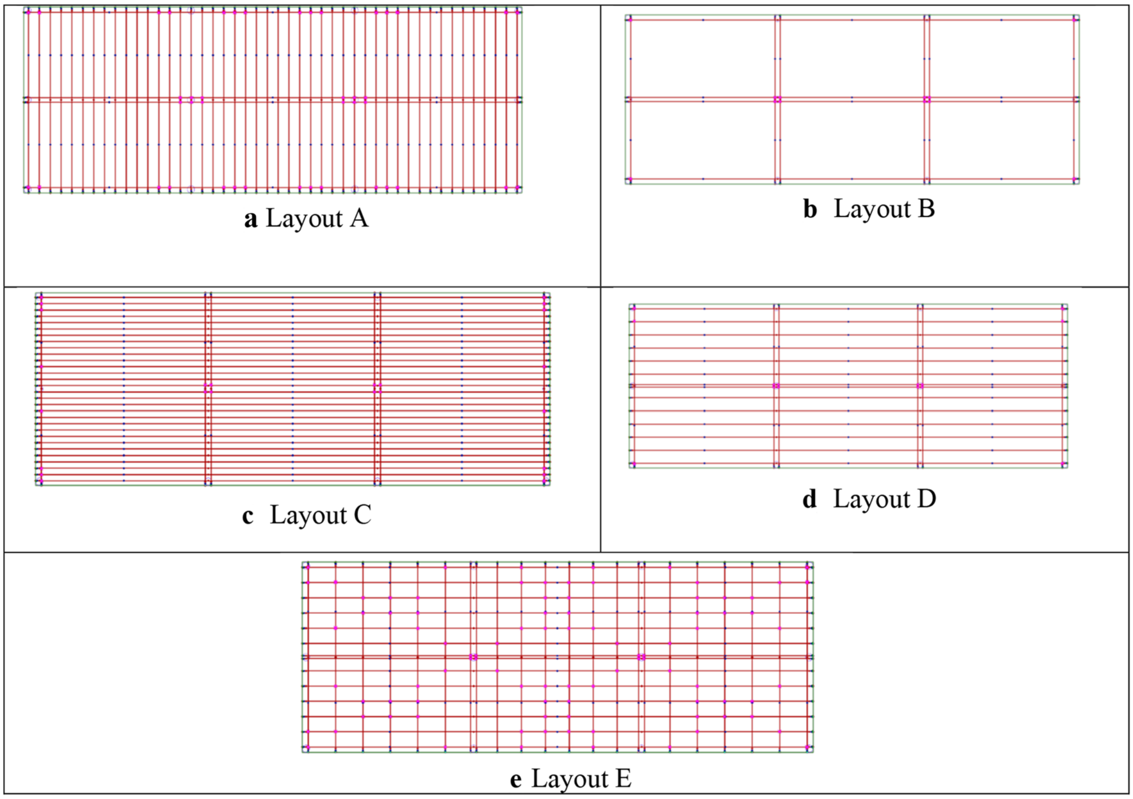

Fig. 8 Clashing of tendons in different layouts.

layout B, the tendons intersect in the corners. This can also easily be adjusted. For layouts A, C and D, adjusting some of the tendon profiles individually may be necessary at the edges. Since banded tendons will be placed close to each other, it is expected that layout B will be the most economical layout, due to placement costs.

4.4 Ultimate Limit State (ULS)

Maximum design bending moments have been calculated manually, taking into account all the load combinations specified by NS EN 1992-1 at the ULS. At the ULS, variable load of 3 kN/m^2, self-weight of the slab and the pre-stressing loads were considered. A partial factor of safety for permanent load of 1.2, variable load of 1.5 and pre-stressing force of 1 have been used to calculate the maximum design bending moments. This analysis has been carried out based on the beam theory and an idealized tendon profile. Moreover, the total negative bending moment (i.e., hogging bending moment) has been distributed between the column strip (i.e., 70% of the total negative moment) and the middle strip (i.e., 30% of the total negative moment), in accordance with NS EN 1992-1. Similarly, the total positive bending moment has been distributed between the column strip (i.e., 60% of the total positive bending moment) and the middle strip (i.e., 40% of the total positive bending moment). Figure 9 shows the sizes of the column strips and middle strips, and Table 6 shows the maximum design bending moments to design the slab sections “in span” and “at the center line of the column” for the middle strips and column strips. According to Table 6, it can be seen that, among the different layouts, there are no significant differences in the maximum design bending moment.

Manual calculation has been carried out to find the moment of resistance/moment capacity (M_{Rd}) at the same slab cross sections given in Table 6 among the different layouts. In this calculation, it is assumed that the plane section remains plane and concrete does not carry any tensile forces, and the M_{Rd} of column strips and middle strips is calculated using Eq. (1):

$$M_{\mathrm{Rd}} = 0,8 * \alpha * (1 - 0,4\alpha) * b * d_{\mathrm{eff}}^2 * f_{\mathrm{cd}}, \tag{1}$$

$$\alpha = \frac{s_p + s_d}{0,8 * f_{\mathrm{cd}} * b * d_{\mathrm{eff}}}, \tag{2}$$

Table 5 Tendon layout analysis—stresses in *Y*-direction [in MPa] (tension is positive).

	ADAPT-Floor Pro				FEM-Design 17			
	In span Y1–Y2		At column Y2		In span Y1–Y2		At column Y2	
	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom
6 × 6								
A	− 2.8	0.3	1.3	− 3.6	− 2.8	0.3	6.6	− 9.0
B	− 2.8	0.1	1.0	− 3.4	− 2.8	− 0.7	4.8	− 7.4
C	− 2.8	0.2	0.9	− 3.4	− 3.2	− 0.3	6.8	− 9.5
D	− 2.8	0.2	1.0	− 3.4	− 3.2	− 0.3	5.9	− 8.6
E	− 2.8	0.3	1.1	− 3.5	− 3.2	0.2	6.7	− 9.3
9 × 6								
A	− 2.0	− 0.1	0.2	− 2.3	− 2.3	0.3	7.1	− 9.3
B	− 2.0	− 0.2	0.1	− 2.2	− 2.1	− 2.0	3.6	− 6.4
C	− 2.0	− 0.1	0.2	− 2.2	− 2.4	− 1.2	5.8	− 8.5
D	− 2.0	− 0.2	0.1	− 2.2	− 2.4	− 1.7	4.4	− 7.2
E	− 2.0	− 0.2	0.1	− 2.2	− 2.5	− 1.0	5.6	− 8.2
11 × 6								
A	− 1.6	− 0.2	− 0.1	− 1.7	− 1.5	− 0.5	4.5	− 6.4
B	− 1.6	− 0.4	− 0.2	− 1.6	− 1.3	− 3.0	0.0	− 2.9
C	− 1.6	− 0.3	− 0.2	− 1.6	− 2.0	0.2	2.1	− 4.9
D	− 1.6	− 0.4	− 0.2	− 1.6	− 1.6	− 2.7	0.8	− 3.7
E	− 1.6	− 0.3	− 0.2	− 1.7	− 1.6	− 1.6	2.7	− 5.1

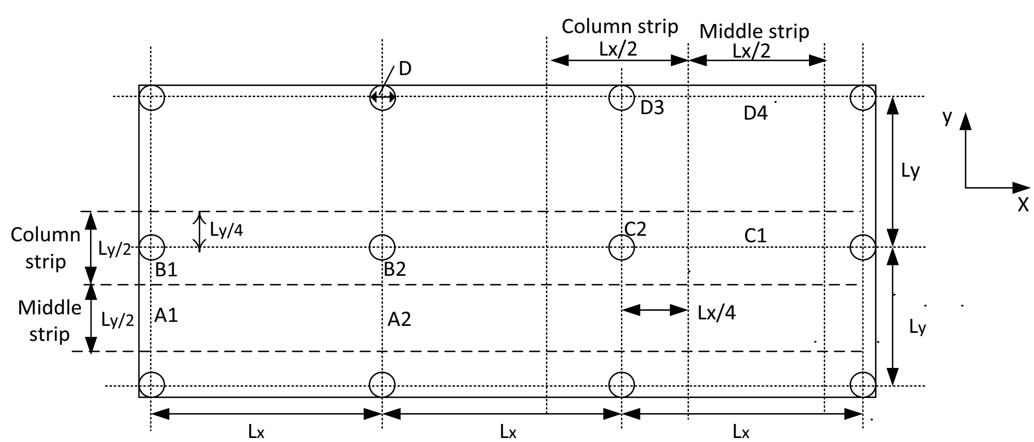

Fig. 9 Column strip and middle strips in pre-stressed concrete flat plate.

$$S_p = N\left(P_{\mathrm{mt}} + \Delta\sigma_{p,\mathrm{ULS}} * A_p\right), \tag{3}$$

where S_p is the total tensile forces in the tendons at the ULS; P_{mt} is the effective pre-stressing force in a tendon; N, the number of tendons; A_p, the cross-sectional area of a tendon; $\Delta\sigma_{p,\mathrm{ULS}}$, 100 MPa as recommended in NS EN 1992-1; S_d, total tensile forces in the reinforcement at the ULS; b, the width of the section; d_{eff}, the effective depth; and f_{cd} is the design cylindrical compression strength of the concrete

Table 7 shows the $\left|\frac{M_{\mathrm{Ed}}}{M_{\mathrm{Rd}}}\right|$ ratio among the layouts, which is an indicator to check whether the critical section has enough capacity to withstand the design bending moment or requires steel reinforcement to attain the required capacity of the section. In layouts C, D and E, sections at "Column strip-over column B2" need additional steel reinforcements to reach the required

Table 6 Maximum design bending moments (M_{Ed}) at ULS when Ly = 9 m and Lx = 6 m.

Layout	*X*-direction (kNm/m)				*Y*-direction (kNm/m)			
	Column strip		Middle strip		Column strip		Middle strip	
	At column B2	In span A1–A2	At column line B2–A2	In span B1–B2	At column C2	In span D3–C2	At column line C2–C1	In span D4–C1
A	−121	100	−58	64	−65	41	−19	29
B	−121	100	−58	64	−54	44	−30	26
C	−128	98	−51	66	−54	44	−30	26
D	−126	98	−53	65	−54	44	−30	26
E	−126	98	−53	65	−59	42	−25	28

Table 7 $\left|\frac{M_{Ed}}{M_{Rd}}\right|$ when Ly = 9 m and Lx = 6 m.

Layout	*X*-direction $\left(\left|\frac{M_{Ed}}{M_{Rd}}\right|\right)$				*Y*-direction $\left(\left|\frac{M_{Ed}}{M_{Rd}}\right|\right)$			
	Column strip		Middle strip		Column strip		Middle strip	
	At column B2	In span A1–A2	At column line B2–A2	In span B1–B2	At column C2	In span D3–C2	At column line C2–C1	In span D4–C1
A	0.85	0.70	2.68	2.00	1.22	0.87	0.26	0.32
B	0.85	0.70	2.68	2.00	0.57	0.47	1.30	0.64
C	1.34	1.08	0.67	0.73	0.57	0.47	1.30	0.64
D	1.13	0.91	0.91	0.91	0.57	0.47	1.30	0.64
E	1.13	0.91	0.91	0.91	0.79	0.60	0.51	0.41

capacities, as the $\left|\frac{M_{Ed}}{M_{Rd}}\right|$ exceeds 1. In layouts A and B, the critical slab sections at "Middle strip" demand additional steel reinforcement. Moreover, in layouts B, C and D, "Middle strip-at column line C2–C1" needs additional reinforcement to attain the required moment capacity. According to the analysis, layouts E and D demand less additional reinforcement. Finally, it can be concluded that all the layouts need additional steel reinforcements for different slab sections, in order to attain the required moment capacity.

5 Conclusions

Based on the analysis, the following conclusions are drawn:

- Considering short-term and long-term deflections and stresses at the top and bottom of the sections, tendon layout E gives the highest deflection and stresses. However, the long-term deflection and stresses are within the allowable limits, according to NS EN 1992-1. Compared with other layouts, the structural response is the least. Because of tendons in spans in both directions, a great extent of weaving is necessary for such a design. This would increase the time of the construction process, and, hence, it would normally not be economical.
- Layout D is a continuation of layout C; some of the distributed tendons from C are concentrated over supports. This layout would distribute the tendons better in terms of the bending moments, and it would also give lower stresses and a reduction in deflections.
- Tendon layout B has the best results in terms of stresses and deflections. Many tendons are banded, and the construction time would hence decrease compared to the other layouts. When looking at the middle strips between columns, the bending moment capacity is low. In flat plates with distributed tendons, these tendons will transfer the loads to the concentrated tendons, which will transfer them to supports. Layout B has no distributed tendons and would hence require extra reinforcement in spans to be a suitable design.
- The layout where the tendons are distributed and concentrated in both directions does fit the bending moment distribution the best, but the amount of weaving of tendons in spans will increase the construction time and hence make it uneconomical.

A commonly used layout is one with concentrated tendons in one direction and distributed tendons in the other direction. Analysis shows that the use of banded tendons along the column center lines reduces the tensile stresses in the top fiber in a section over the column center line. A design engineer can take into account this finding while placing tendons in a flat plate design. Moreover, when considering the clashing of tendons, it can be seen that banded tendons will be placed close to each other, resulting in the most economical layout, due to placement costs. When tendons are distributed in both directions, it results in many clashing points, which leads to an increased unnecessary cost for weaving. Moreover, future research will focus on the analysis of layouts, using non-linear finite element analysis to study the optimization of the design.

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Authors' contributions
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