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EXPERIMENTAL BEHAVIOR OF BONDED & UNBONDED MULTI-STRAND FULL SCALE PRE-STRESSED FLAT SLABS*

Ashraf. M. EL-shihy , Hamdy. A. K. Shehabeldin, Osman. E. A. Shaalan and Ragab. S. Mahmoud**

Structural Eng. Dept. Faculty of Engineering. Zagazig University, Egypt

ABSTRACT:

Flat slabs are economical structural systems for medium height buildings. Pre-stressed concrete flat slabs have the additional advantages that longer spans can be used with less significant deflection problems. In addition, pre-stressing reduces cracking in the slab so, it can be used for water tight floors. Moreover, greater shear strength can be obtained for the same slab depth. There are two types of post-tensioned concrete flat slabs: bonded and unbonded. In recent years, due to its several advantages, a pre-stressed concrete flat slab is used in factories having heavy live loads and large spans, which is the case study of this research. Multi-strand tendons are used in reinforcing the slab due to heavy loads and large spans. The purpose of full-scale investigation is to reduce the shortcomings of scaled models and observe the actual behavior of stress development, strains and all other results with various stages of loads. There are different ways to place the tendons in a flat slab. The most common solution is to place distributed tendons in the largest span and banded concentrated tendons in a column strip in the shortest span, and this is considered in the present study. The purpose of this research is to study the behavior of a pre-stressed concrete flat slab–column connections using both unbonded and bonded multi-strand tendons of full–scale factory floor under the design service live loads. The studied slabs have a three bays of 12 meters span by six bay of 6 meters span with 350 mm slab thickness without drop panel.

KEY WORDS: pre-stressed, bonded and unbonded multi-strand, flat slab

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COMPORTEMENT EXPERIMENTAL D'LIEES ET NON LIEES STRAND MULTI PLEINE ECHELLE PRE SOULIGNE DALLES

RÉSUMÉ:

Dalles sont un système économique pour le bâtiment de hauteur moyenne. Béton précontraint dalles présentent les avantages supplémentaires que des portées plus longues peuvent être utilisés avec les problèmes de déviation sont moins importantes. En outre pré-stress réduit la fissuration de la dalle de sorte qu'il peut être utilisé pour les planchers étanches à l'eau. Résistance au cisaillement plus grande peut être obtenue pour la même profondeur de la dalle. Il existe deux types de béton post-contraint dalles, liées et non liées. Dans les dernières années en raison des avantages de plusieurs de béton précontraint dalles, il a utilisé pour les usines qui ont de lourdes charges en direct et de grande portée comme une étude de cas de cette recherche. En raison de charges lourdes à grande portée, ce qui était considéré comme tendons multi-brins sont utilisés. Le but de l'enquête à grande échelle est de réduire la lacune de modèles réduits et d'observer le comportement réel de l'évolution du stress, les tensions et tous les autres résultats à différentes étapes de charges. Il ya différentes façons de placer les tendons dans une dalle plate. La solution la plus courante consiste à placer tendons distribué dans la plus grande portée et bagués tendons concentrés dans une bande de colonne dans une si courte période. Ceci est considéré dans la présente étude. Le but de cette recherche est d'étudier le comportement du béton précontraint plat connexions dalle-colonne en utilisant tendons multi-brin dans les deux tendons non liée et collés d'une usine à grande échelle sous les charges du service de conception. Les dalles de plancher ont étudié une baie trois des 12 mètres d'envergure de six mètres de portée Bay 6 avec 350 mm épaisseur de la dalle sans panneau déroulant.

MOTS-CLÉS: précontraint, liées et non liées Multi-Strand, de dalles plates

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** Contact author: (e-mail:ragabshaker@yahoo.com.)

1. INTRODUCTION

Pre-stressed concrete is classified according to feature of design and construction to pre-tensioned and post-tensioned. In pre-tensioned tendons are tensioned before the concrete is placed, therefore the force transmitted to concrete by friction bond action. While in post-tensioned elements, tendons are tensioned after concrete has hardened, the pre-stressing force is transmitted to the concrete by bearing action at end.

There are two types of post-tensioned concrete flat slabs, bonded and unbonded.

Unbonded post-tensioning systems are used almost exclusively in the United States, it consist of tendons that are single strands coated with a corrosion inhibitor such as P/T coating shown in Fig.(1), these strands are also protected by an extruded plastic sheathing. The sheathing allows the strand to move inside of it and prevents water from contacting the strand. The purpose of allowing the strand to move inside the sheathing is to keep the strand unbounded from the surrounding concrete.

The strands are anchored to the concrete by ductile iron anchors and hardened steel wedges. Post-Tensioning Institute [11] gives the benefits of unbounded post-tensioning as maximum possible tendon eccentricities which are beneficial in thin slabs, simpler and quicker installation, low losses of pre-stressing forces due to friction, and more economical installation [12]. The tendon is supported by chairs and bolsters to maintain the desired shape and height of the tendon. The disadvantage of unbonded post-tensioned flat slab is that corrosion or accidental damage to the anchorages would cause the tendon to fail and could endanger the safety of the entire structure. Bonded post-tensioning systems utilize tendons that consist of multiple strands. These strands are placed in corrugated galvanized steel, high density polyethylene (hard plastic made from petroleum similar to laundry detergent containers), or polypropylene (smooth plastic similar to plastic used in margarine tubs or straws) ducts. The strands can be installed before the concrete is placed, or sometimes the steel ducts are installed without the strands inside them. When the steel ducts are installed without the strands, the strands are pushed or pulled through the ducts after the concrete has been placed. In both situations, after the concrete has reached the required strength, the tendons are stressed and the ducts are filled with grout, the grout is used to both provide protection for the strands from corrosion and to bond the strands to the surrounding concrete. (Post-tensioning Institute [11]). The benefits of bonded post-tensioning systems are larger ultimate moment capacity and limited effects to the structure due to local failure of a tendon [12].

The parameters involved in choosing between bonded or unbonded tendons are based on the method of construction and economic considerations, where a given concrete section with bonded tendons would have a higher local ultimate strength than the same section using unbonded tendons. Approximately ultimate load, the strain, and hence the tensile stress, in a bonded tendon must increase with the strain in the adjacent concrete. An unbonded tendon can slip relative to the concrete, so that the increase in its tensile stress is much smaller.

In case of fire, the bonded tendon has the protection of the additional concrete cover, because the duct is much larger than the strand area and stressing tends to pull the tendon into the mass of concrete, away from the surface. The duct itself acts as a heat sink to a small extent.

In the case of overloading, the distribution of cracks is similar in reinforced and bonded post-tensioned floors. With unbonded tendons, the cracks are wider and further apart, unless bonded non pre-stressed reinforcement bar has been provided to distributed cracks.

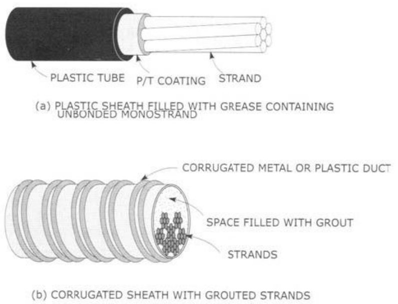


Fig. (1): Illustration of bonded and unbonded systems (11)

2. DESCRIPTION OF FULL-SCALE PRE-STRESSED FLAT SLAB

The slab thickness is 350 mm, which gives a span to depth ratio for the largest span as 34 and 18 for the shortest span, where the live load is 10 KN/ m^2.

The pre-stressed tendons give loads upwards in the span, and downward over the columns. The tendon profile is designed to balance the load in the span, the primary number of tendons is calculated to balance the self-weight as the given equation:

$$w = \frac{8 \cdot P \cdot f \cdot n}{l^2}$$

where:

w Balanced load from tendon.

f Total drape of tendon.

n Number of tendons.

l Span length.

p Pre-stressed force(after all losses).

The concrete slab was pre-stressed in both directions, in the largest span the tendons (four strands) were distributed each 550 mm from tendons to each other as shown in fig. (2), while in the shortest direction the tendons were banded as shown in fig. (3).

The columns were 600 × 1200 mm for interior columns, 500 × 900 mm for exterior columns in the largest span direction and 600 × 600 mm for both corner and exterior columns in the shortest span direction. There are non pre-stressed reinforcement 10 mm bar top and bottom in areas not showing non pre-stressed steel as shown in fig. (4), the two dead and live ends shown in fig. (5) with an additional bursting steel. The design was carried out according to ***ECP-203-2007***.

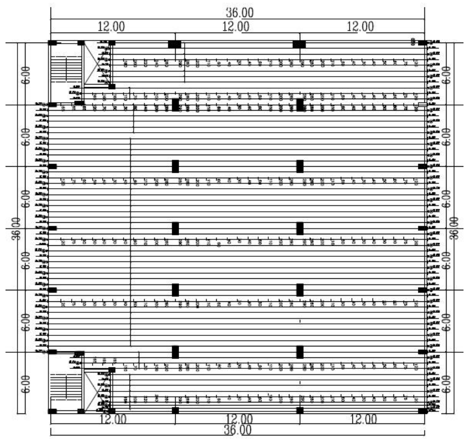


Fig.(2): Distributed tendons

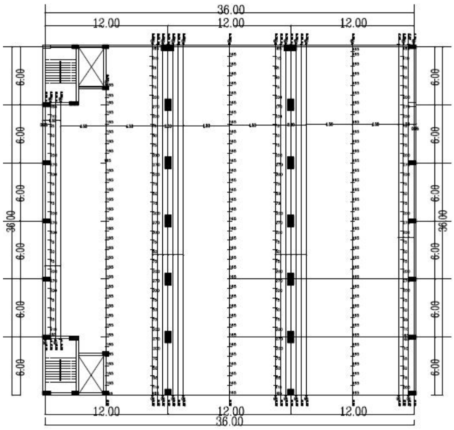


Fig.(3): Banded tendons

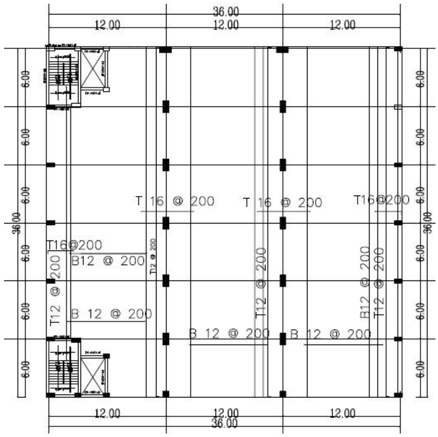


Fig. (4): Non-pre-stressed steel

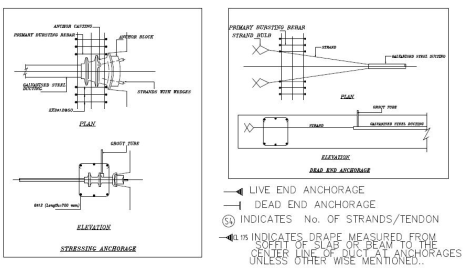


Fig.(5): Dead and live ends of tendon

3. FABRICATION OF THE PRE-STRESSED FLAT SLAB

- After finishing a framework shown in Fig (6), the bottom non pre-stressed steel was positioned as shown in Fig (7).

- The chairs of various heights were positioned to give the tendons profile for both distribution and banded directions respectively as shown in Figs.(8 and 9).

- The tendons passing through interior and exterior columns are shown in Figs. (10and11).

- Dead and live ends are shown in Figs. (12and13).

- Putting the plastic pipes at low points of ducts for purpose of grouting as shown in Fig. (14), splicing the two ducts (coupler) this is shown in Fig. (15).

- The top non pre-stressing steel was positioned as shown in Figs. (16and17).

- At dead and live ends there are bursting steel positioned for the purpose of concentrated loads from strands as shown in Fig. (18) and Fig.(19) .

Fig. (6): Flat slab form

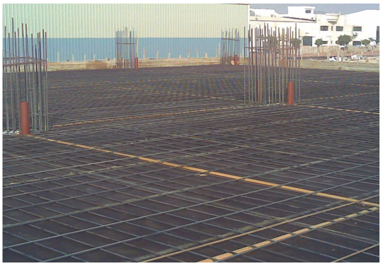


Fig.(7): Bottom Non-Pre-stressed Reinforcement

Fig. (8): Tendons positioned in two directions

Fig.(9): Tendons positioned in two directions

Fig. (10): Tendons passing through interior column

Fig. (11): Tendons passing through exterior column

Fig. (12): Dead end of stands

Fig. (13): Live end of stands

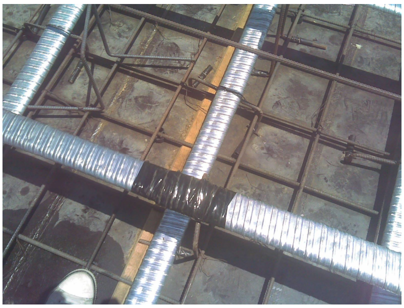
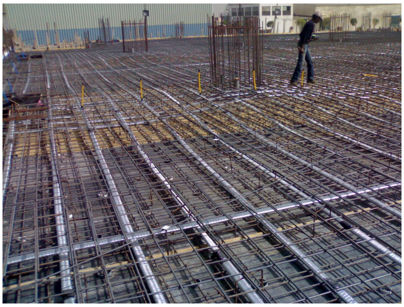


Fig. (14): Plastic pipes for grouting

Fig. (15): Duct coupler



(Fig. 16): Top non pre-stressed steel

Fig. (17): Top non pre-stressed steel

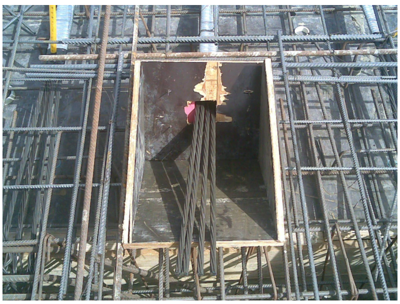


Fig. (18): Bursting steel

Fig. (19): Box for tensioned tendons

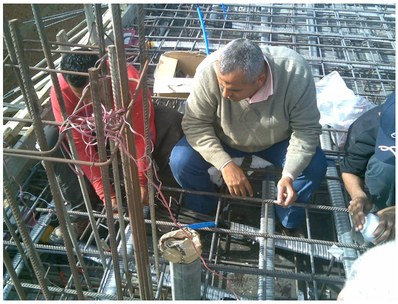


Fig. (19a): Strain gauges at exterior column

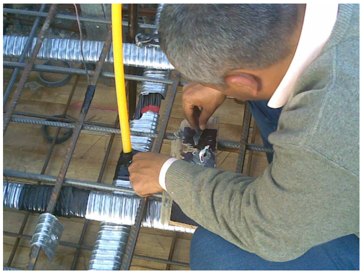


Fig.(20a): Strain gauges at interior column

Fig. (20b): Strain gauges at interior column

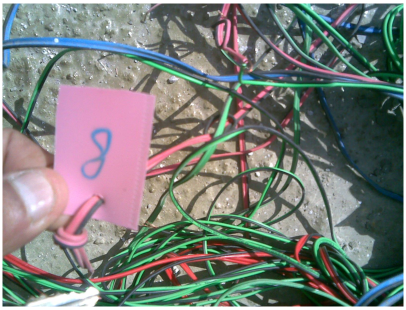


Fig.(21a): Strain gauges numbering

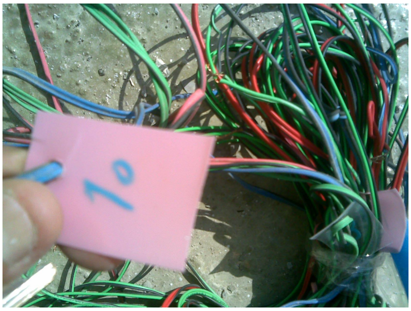


Fig. (21b): Strain gauges numbering

Fig. (22a): Concreting of slab

Fig. (22b): Concreting of slab

4. INSTRUMENTATION

Four connections were chosen for studying in this study, the strain gauges used at the strands in both directions and used at top and bottom non pre-stressed reinforcements as shown in fig. (19a and b) for exterior columns and fig. (20a, and b) for interior column.

The strain gauges of the PL-5-11 type with gauge length 5 mm, which are produced in Japan, Tokyo Sokki Kenkyujo Co., Ltd numbering in fig. (21a and21b). Concreting process of slab was shown in fig. (22a and22b). Concrete compressive strength result listed in table (1), and then the tensioned process of tendons can be done.

Table (1): Concrete compressive strength after three days

Cube NO.	Test result MPa	Average MPa	Mix result MPa
1	43.5	42.2	37.4
2	40.1	42.23	37.4
3	43.0	42.2	37.4

5. LOADING

The investigated connections were loaded by cement packages to simulate uniform distributed live loads up to service design loads. These loading processes was repeated twice, the first after stripping the shuttering for unbonded case while the second loading process after the grouting process for bonded cases.

Fig. (23): Cast instrument

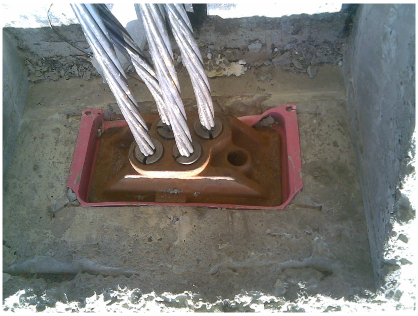


Fig. (24): Wedges in cast after tensioning of strand

Fig. (25a): Tensioning process-1

Fig. (25b): Tensioning process-2

Fig. (25c): Tensioning process-3

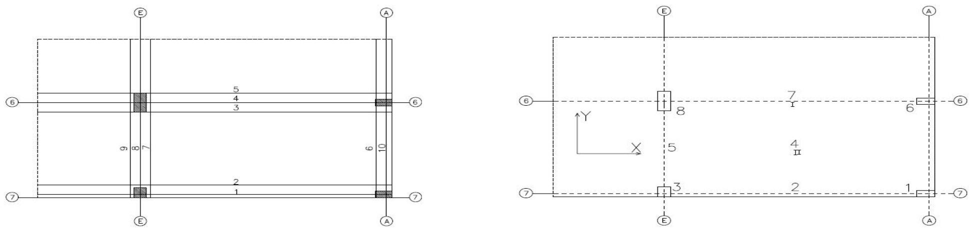
Fig.(25d): Tensioning process-4

Fig. (26): Tensioning process

Fig. (27): Registration of data

6. TEST RESULTS AND ANALYSIS

For the full-scale case study of pre-stressed concrete flat slab, three tests were carried out and the results were recorded.
The first is the studying the forces of the multi strand pre-stressed tendons with measuring the actual elongation of each strand for both distributed and banded directions.
The second is the studying the behaviors of the unbonded pre-stressed concrete flat slab at the interior, the exterior and the corner slab-column connections subjected to uniform loaded by cement packages until service design live load.
The third is the studying the behavior of the previous connections but after grouting process, which simulate bonded post-tensioned concrete flat slab using the same system of loading mentioned above.



(a) (b)

Fig. (28): Strain gauges for studied connections at top and bottom of slab, in both directions from points 1 to 8

6.1 Pre-stressing Force Losses for Multi-strand Flat Slabs.

Each tendon should be stressed to 75 percent of ultimate strength (*fpu*), that means for this tendon of ***140 sq.mm and 1670/1860 Mpa***, a force is :
Po = 0.75 * 140 * 1860 = 195.3 KN.
This force was readed from a jack manometer and in addition controlled from some tendons with load cells. After short time losses, the force in the tendons were calculated to be ***180.5 and 145.0 KN*** in both distributed and banded directions, where short time loses were friction, anchorage set and elastic shortening.
Long time losses from creep, shrinkage of concrete and relaxation of tendons in the period from stressing to loading, calculated according to ***ECP-203-2007***.
After the losses are calculated, it gives an average force in tendons ***156.24 and 126 KN*** for both distributed and banded directions. The concrete was at time ***42 Mpa***. The pre-stress forces after short time losses give a theoretical elongation of ***217 mm*** for the distributed tendons, which gives 6.0 mm elongation per meter of tendon length, which is close to the normally used elongation (6 – 6.5 mm). The theoretical elongation in the banded direction is calculated ***200 mm***, which gives ***5.5 mm*** per meter of tendon length, which is less than elongation in distributed directions due to six spans where three spans in the distributed direction for the same length of banded direction Measured elongations are shown in table (2) for each strand in distributed and banded directions. The measured elongation is generally considerably lower than theoretical calculated elongation.

Table (2): Measured elongation

Distributed direction		Banded direction	
Tendon	Elongation mm	Tendon	Elongation mm
Tendon 1: strand 1 strand 2 strand 3 strand 4	180 175 170 165	Tendon 6: strand 1 strand 2 strand 3 strand 4	150 165 146 110
Tendon 2: strand 1 strand 2 strand 3 strand 4	198 197 189 188	Tendon 7: strand 1 strand 2 strand 3 strand 4	170 170 150 125
Tendon 3: strand 1 strand 2 strand 3 strand 4	190 201 170 168	Tendon 8: strand 1 strand 2 strand 3 strand 4	183 179 130 120
Tendon 4: strand 1 strand 2 strand 3 strand 4	200 175 175 195	Tendon 9: strand 1 strand 2 strand 3 strand 4	160 180 163 165
Tendon 5: strand 1 strand 2 strand 3 strand 4	212 192 193 173	Tendon 10: strand 1 strand 2 strand 3 strand 4	155 160 158 155

The relation between tensioned force and both measured and theoretical elongations shown in figures (29,30,31,32 and 33) for distributed tendons where for banded tendons the same relation shown in figures (34,35,36,37 and 38).

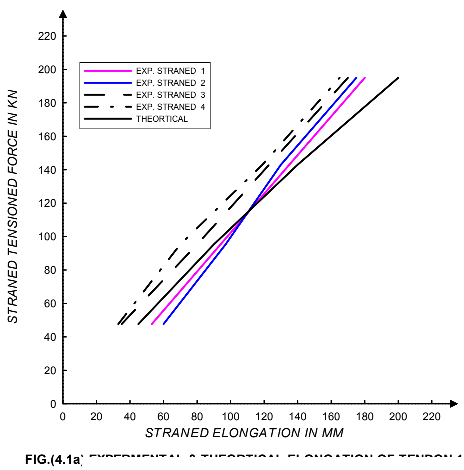


Fig. (29): Experimental & theoretical elongation of tendon 1

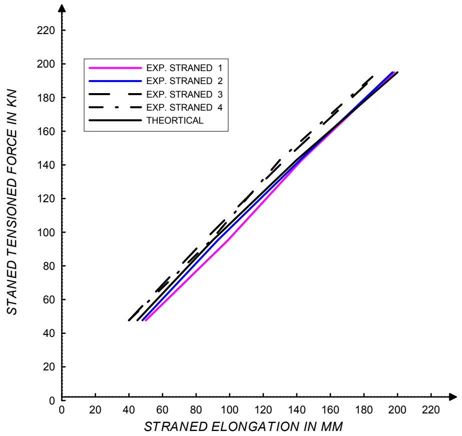


FIG.(4.1b) EXPERMENTAL & THEORTICAL ELONGATION OF TENDON 2

Fig. (30): Experimental & theoretical elongation of tendon 2

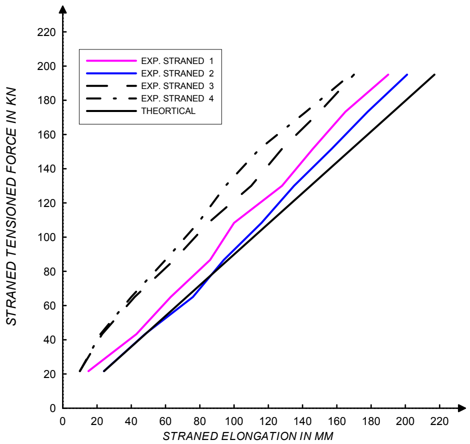


FIG.(4.1c) EXPERMENTAL & THEORTICAL ELONGATION OF TENDON 3

Fig. (31): Experimental & theoretical elongation of tendon 3

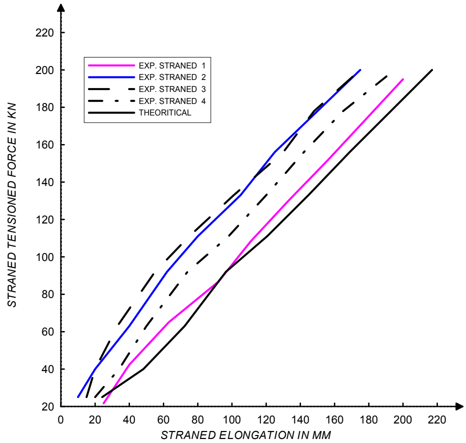


FIG.(4.1d) EXPERMENTAL & THEORTICAL ELONGATION OF TENDON 4

Fig. (32): Experimental & theoretical elongation of tendon 4

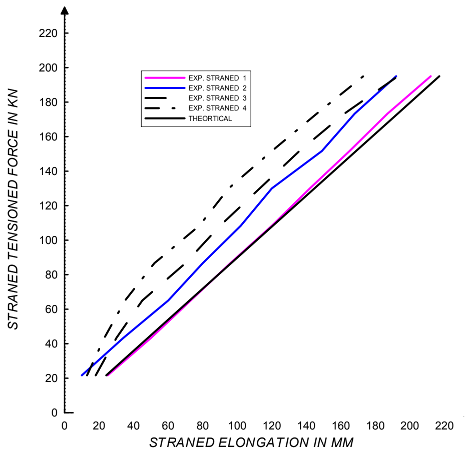


FIG.(4.1e) EXPERMENTAL & THEORITICAL ELONGATION OF TENDON 5

Fig. (33): Experimental & theoretical elongation of tendon 5

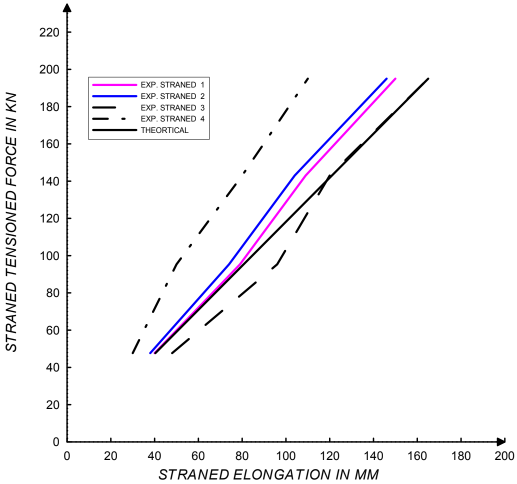


FIG.(4.2a) EXPERMENTAL & THEORTICAL ELONGATION OF TENDON 6

Fig. (34): Experimental & theoretical elongation of tendon 6

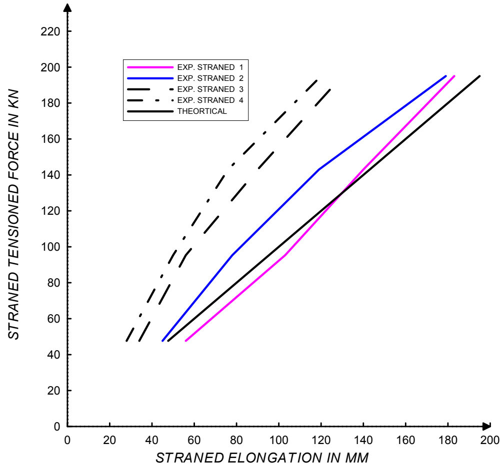


FIG.(4.2c) EXPERMENTAL & THEORTICAL ELONGATION OF TENDON 8

Fig. (36): Experimental & theoretical elongation 8

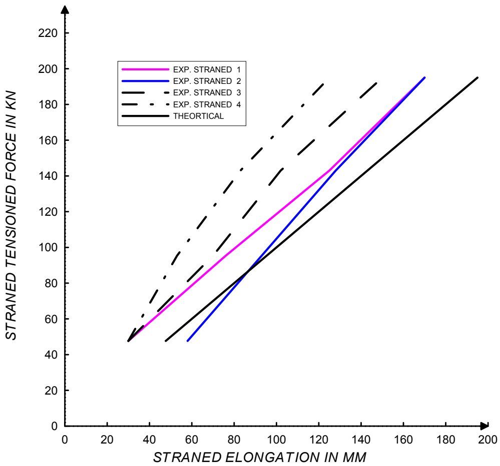


FIG.(4.2b) EXPERMENTAL & THEORTICAL ELONGATION OF TENDON 7

Fig. (35): Experimental & theoretical elongation of tendon 7

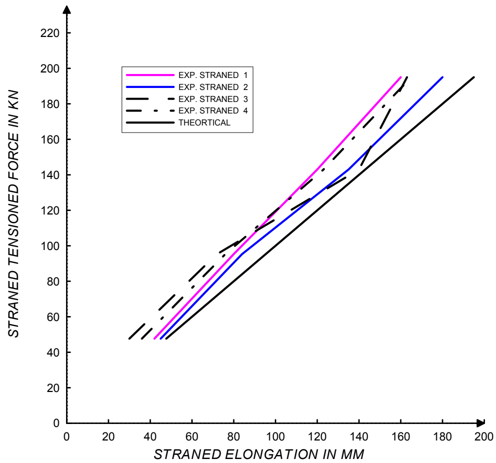


FIG.(4.2d) EXPERMENTAL & THEORTICAL ELONGATION OF TENDON 9

Fig. (37): Experimental & theoretical elongation of tendon 9

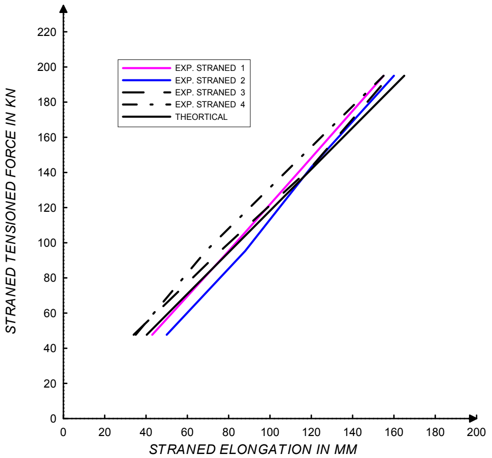


Fig. (38): Experimental & theoretical elongation 10

From the measured elongation, the average force can be calculated as:

$$P = E * A * \frac{\Delta L}{L}$$

This gives an average force ***162 and 120 KN*** for both distributed and banded tendons respectively. The measured pre-stressing forces in the multi strands in a duct, four strands for this study are lower than the calculated force by 5%, 8%, 12%, ***and*** 13% for strand 1, 2, 3 and strand 4 respectively, which gives an average 9.5% for distributed tendons. For banded tendons the measured pre-stressing force are lower than the calculated force by 11%, 15%, 17.5%, and 25% for strand 1, 2, 3 and strand 4 respectively, which gives an average 17%.

There are many reasons for decreasing the measured force as larger anchorage set for
the first strand whereas the second strand friction losses and the components of the first strand force is then in the opposite direction of pre-stressing.

6.2 Tendon Forces Development for Bonded & Unbonded at Loading Process

After removing the form, then the slab under dead load and the pre-stressing force after all losses, which is the balanced case as shown in the previous figures of strain of non pre-stressed steel.

To studying the tendons force at case of unbonded pre-stressed concrete flat slab by sequence of loading process using cement packages until service design live load.

After grouting process and the grout gain the required stress, using the same previous system of loading to study the tendons force at case of bonded pre-stressed concrete flat slab.

The results obtained from two cases of loading recorded and plotted in figures (39, 40, 41, and 42) for the tendons in the distributed direction and tendons in the Banded direction shown in figures (43, 44, 45, and 46).

The tests results indicated that the higher tendon force at the bonded than the unbonded post-tensioned concrete flat slab in the two directions distributed and banded tendons, which is due to the full bond between pre-stressing tendons and concrete section across the duct.

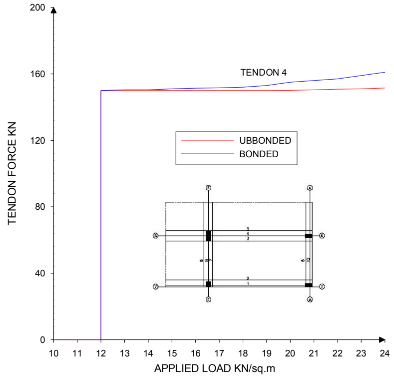


Fig. (39): Force in tendon 4

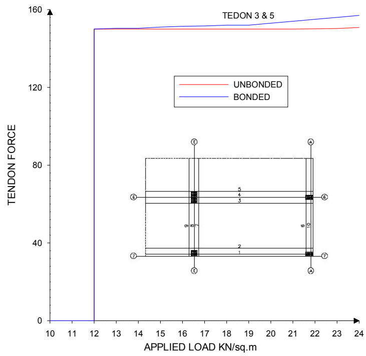


Fig. (40): Force in tendon 3&5

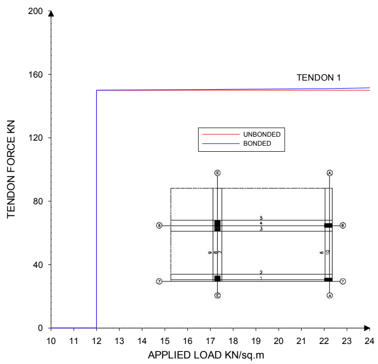


Fig. (41): Force in tendon 1

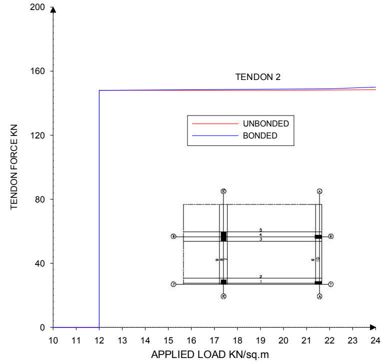


Fig. (42): Force in tendon 2

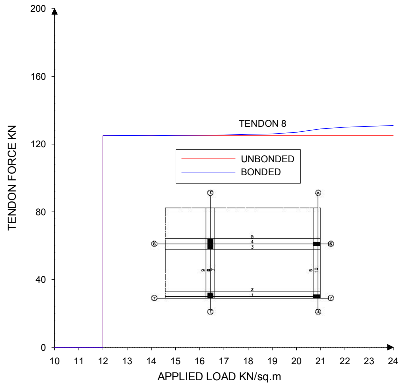


Fig. (43): Force in tendon 8

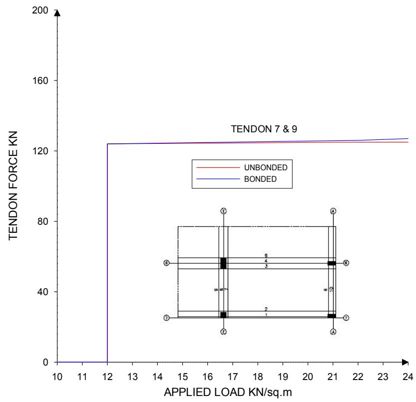


Fig. (44): Force in tendon 7&9

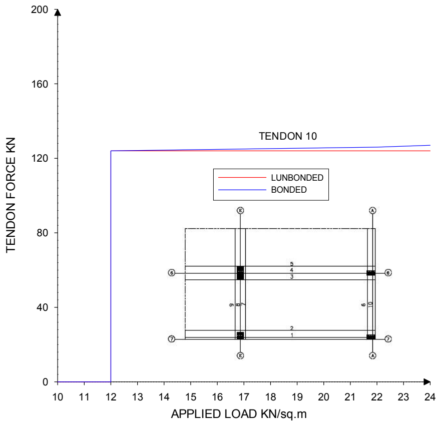


Fig. (45): Force in tendon 10

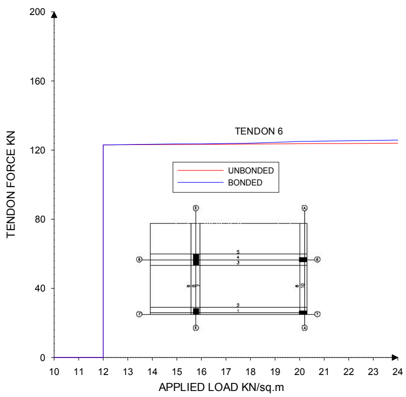


Fig. (46): Force in tendon 6

From the relations the first tensioned strand force is less than the theoretically calculated by about 10 percent, whereas the second strand force less than the first one and so on for third and fourth but with various ratios, this due to many reasons as the friction between the first strand with surrounding duct, where the second friction with the adjacent strand and the force component of the tensioned strand in the opposite direction of tensioned with the larger anchorage set of the first tensioned strand.

There are two cases of loading are carried out in the present study to simulate the difference between unbonded and bonded post-tensioned concrete flat slabs.

7. CONCLUSIONS

For two-way post-tensioned concrete flat slabs with banded tendons in one direction and uniform distribution in the other direction simplify the process of placing which pass at a high point over support and low point at mid span. From the present experimental study the main conclusions are:

1 - The measured pre-stressing forces in the multi strands in a duct, four strands for the present study are lower than the calculated force by 5%, 8%, 12%, ***and*** 13% for strand 1, 2, 3 and strand 4 respectively, which gives an average 9.5% for distributed tendons.

2 - For banded tendons the measured pre-stressing force are lower than the calculated force by 11%, 15%, 17.5%, ***and*** 25% for strand 1, 2, 3 and strand 4 respectively, which gives an average 17%

3 - The tests results indicated that the higher tendon force for bonded than the unbonded post-tensioned concrete flat slab in the two directions distributed and banded tendons by about ***10 percent*** at service design live load , here it was expected ***35 percent*** at failure.

4 - The tests results indicated that the tendon force for the unbonded post-

tensioned concrete flat slab for inclined pre-stressed tendons passing through the column increased by about ***15 percent*** at service design live load , where expected ***25 percent*** at failure.

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