Comparison of RCC and Post-Tensioned Flat Slabs Using ETABS

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Abstract: Flat slabs are widely used nowadays. The system's insufficient punching shear capacity is a major and serious flaw. There are numerous approaches to increasing the punching shear strength of concrete slabs to solve the problem of punching failure. Increasing the thickness of the slab adjacent to the column, as well as the thickness of the column, contradicts the architectural intent. In developing countries such as India, the benefits of prestressing, particularly post-tensioning, have yet to be recognized. In this study, the technique of post-tensioning is used to strengthen a flat slab. RCC flat slabs are compared to post-tensioned flab slabs with different tendon profiles. Tendons are available in two forms: distributed and banded. The models were built as per ACI 318-14. These slab models were created using ETABS software, and the following parameters were compared: thickness, supporting reactions, punching shear, and deflection. When compared to traditional flat slabs. The results indicate that post-tensioned flat slabs have a higher punching shear capacity even at shallower depths, resulting in more cost-effective sections. The provision of tendons also results in lower deflection.

Key words: Flat slab, Post tension, RCC, ETABS, Punching shear, support reactions, deflection.

1. Introduction

1.1. Post-Tensioning

Concrete in which internal stresses of sufficient magnitude and distribution have been introduced to counterbalance the stresses coming from given external loading to the desired degree [1,2]. Prestress is typically introduced in reinforced concrete members by tensioning steel reinforcement. Post-tensioning is a form of prestressing in which the tendons are tensioned after the concrete has been set and the tendons are instantly fixed against it [4,5]. This approach can be used with precast or cast-in-place concrete.

The main effects of prestress are axial pre-compression of the floor and an upward load within the span that balances off some of the downward dead and live loads. The load is carried straight to the supports by this transverse effect. Because of the compressive stresses caused by the axial effect, the structure will be more resistant to shear, punching, and torsion for the remaining load. Tensile cracking of the concrete is a required accompaniment to the creation of economic stress levels in the reinforcement in a reinforced concrete floor. Both the pre-compression and the upward load in the span act to lower tensile stresses in the concrete in post-tensioned floors. Under service conditions, this decreases deflection and cracking.

1.1.1. Advantages of post-tensioning. The following are the key advantages of post-tensioning over traditional reinforced concrete in-situ flooring:

• Expanded clear spans
• Thinner sections are possible
• Cracking and deflections are reduced.
• Reduced dead load; lighter buildings
• Lower storey height
• Quick construction is possible
• Improved water resistance
• Significant decrease in traditional reinforcement
• High fatigue resistance

1.2 Flat slab
It is a slab constructed directly on the columns. Hence the load is transferred to the columns directly. Inspite of having functional and architectural benefits, it is very weak in punching capacity. To have sufficient punching capacity there is need to increase the depth, which results in increase of dead weight of slab. It not only increases the cost of construction of slab, but also the member supporting them which makes in uneconomical.

1.2.1 Types of failures in flat slab. The following are the possible failures in flat slab
1. Punching failure
2. Flexural failure
3. Punching flexural failure
4. Flexural punching failure

In flat slab, punching failure is the most common and brittle mode of failure. Because of the superposition of shear and flexural stresses around the column circumference, slab column connections are critical. Punching shear can occur at load levels lower than the flexural failure strength of the slab. The punched shear strength of a slab is determined by its overall dimensions, concrete type, thickness, column geometry, flexural reinforcement, and other factors. When flexural reinforcement ratios are high, punching shear develops. In slabs where flexural failure was not the governing mode, the use of stirrups and shear studs was beneficial, resulting in increased punched shear strength and deformability.

Low flexural reinforcement ratios cause flexural failure. At low reinforcement ratios, however, the presence of transverse reinforcement has no impact on ultimate strength since the slab collapses due to flexure.

In this work post tensioning is done to flat slab to increase its punching shear capacity and develop thinner sections which can carry the same load safely.

2. Literature Review
K. F. El-Kashif et al. (2019)[7] used a CFRP fan to examine slab-column connections. In comparison to the reference specimen, strengthening slab-column connections with CFRP string-fan shape enhanced punching capacity and ductility. When comparing the experimentally achieved punching shear load to the estimated capacities using ECP, JSCE, and ACI, it is clear that the ACI and ECP codes provide conservative punching shear capacity values; however, the differences between estimated punching shear capacity and experimental capacity are not large in the JSCE code.

Hamed S. Askar (2015) [11] evaluated the effectiveness of employing a simple and easy approach of prestressing additional bolts as shear reinforcement to repair damaged flat slabs caused by punching. The repaired specimens had a higher punching failure load than the reference slabs, demonstrating that the recommended system for mending punching shear damaged slabs is successful and practical. The ACI 318-11 [3] and CSA 23.3-04 results agreed well with the test results, but the Euocode-2 values were only moderately accurate.

Nasr Z. Hassan et al. (2017) [6] investigated the use of shear-band reinforcement to improve the punching shear strength of flat slabs. The shear band technique considerably increases the ductility of
flat slabs and eliminates brittle punching shear failure. It improves the punching shear capacity of flat slabs without compromising their flexural strength.

Bassam Qasim Abdulrahman and Omar Qarani Aziz (2020) [10] used externally bonded FRP to strengthen the reinforced concrete slab-column connection. Because there are no governing equations for strengthening, ACI, Concrete Society technical report 55, JSCE, and the equation derived by Farghaly and Ueda were compared using a numerical simulation using the ABAQUS finite element computer program. The results demonstrated that the Farghaly and Ueda equations and finite element results are very similar.

M. A. L. Silva et al. (2019) [9] investigated the effect of Carbon Reinforced Polymers on slab-column connections of flat slabs with various arrangements, using ABAQUS for finite element modelling. In the presence of end anchoring, CFRP strips significantly improved punching shear performance, and skewed CFRP placement at the shear critical area is more effective than orthogonal placement.

The regulating elements that affect the behaviour and failure mode of flat slab members at their connection to internal columns were investigated by Andrei V. Gosav et al., (2015) [8]. Even if the slabs are shear reinforced, punching failure can occur in flat slabs near inner columns. At low flexural reinforcement ratios, flexural failure may occur, whereas punching shear occurs at intermediate to high flexural reinforcement ratios, and the failure mode is determined by the layout and number of transverse bars. The presence of transverse reinforcement has little effect on ultimate strength at low reinforcement ratios. In slabs where flexural failure was not the governing mode, the use of double-headed shear studs proved helpful in improving punching shear strength and deformability.

Using SAP and MS Excel, Thayapraba M (2014) [5] analysed the economic effectiveness of post tensioned and reinforced concrete flat slab systems. The higher initial expenditure required from clients for post tensioning is undeniable. This cannot be neglected in light of the numerous advantages of Post Tensioning, as well as the high benefit-to-aspect ratio that can be obtained and has proven to be more cost effective than Reinforced Concrete Floor Systems.

SAFE was used to compare Flat Slab and Post-Tensioned Flat Slab by V. G. Mutalik Desai1 and Mohammad J. Shaikh (2016). In terms of project cost, stability, and durability, the overall study on PT flat slab shows that PT flat slab may be a better option than flat slab.

3. Objective of the work
The objectives of the current work are:
- To design and compare post-tensioned flat slabs with Reinforced flat slabs.
- In all circumstances, investigate the effect of drop on the behavior of flat slab.
- To determine the efficiency of post-tensioning in lowering flat slab depth, dead weight, and deflection.
- Make a comparison between tendons that are banded and those that are distributed.
- To create a cost-effective solution to overcome punching shear failure and to obtain thinner sections.

4. Structural detailing
Total six models are compared; all of these slabs have the same panel size of 7m × 7m and are supported by 400 mm × 400 mm columns. Concrete with a compressive strength of 5000 psi and steel rebar with a grade of 60 were used. In all the cases assumed additional dead load as 2 kN/m² and Live load as 4 kN/m².

In this work, unbonded tendons are used for strengthening post tensioned flat slabs. Tendons are made to balance 80-60% of the dead weight. 270 grade steel tendons are used. The jacking is done at one end (J-end) of the tendon and the other end (I-end) is dead end with anchorage in inactive state. Initial losses of 10% and final losses of 15% of the jacking force are assumed.
ACI 318-2014 was used to design all of these slabs. To balance 80-60% of the dead weight for banded slab without drop, 14 strands and 16 strands for each span in case of normal slab and slab with drop are employed, respectively. For distributed arrangement 2 strands per tendon are used in both with and without drop.

5. Methodology
ETABS 2016 is used to model and analyse all of the slabs. The information is tabulated and compared. Support reactions, punching shear, and deflections are compared, and conclusions are derived based on the comparisons.

6. Results
6.1. Comparison of depths
The depths obtained for different slabs is given in Table 1 and comparison was given in Figure 1. Depth of 305 mm is needed for the flat plate to fulfil both punching shear and deflection criteria. With such a depth, the slab will be heavy, resulting in larger sections of columns and other load-bearing components. When drop is provided, the depth can be lowered to 225mm. This reduction in depth is due to the fact that drop not only increases punching shear capacity, but also reduces moments.

When banded tendons were given, significant reduction in the depth can be observed. By using banded tendons, the depth can be reduced to 235 mm in case of slab without drop. It can be even reduced to 165 mm when drop is provided for this circumstance. When compared to a traditional flat slab, a reduction of more than 20% can be seen.

Coming to the slab with a depth of around 220 mm of banded tendons is sufficient to meet both strength and deflection requirements. With drop, this can be further lowered to 160 mm. When compared to a standard flat slab with and without drop, the depth can be lowered by up to 34% and 29%, respectively.

For higher loading cases and larger spans, sometimes it is necessary to opt flat slabs. In that situation, using a standard flat slab will result in much deeper depths (in this case, 310 mm), which is undesirable because it will result in a significant dead load and a large amount of material for construction. As a result, it is obvious that utilizing tendons can result in a higher reduction in depth. This not only decreases the depth and cost of the construction, but it also improves the structure from an architectural standpoint.

| Sl. No | Type of slab                     | Presence of drop | Depth in mm |
|--------|----------------------------------|------------------|-------------|
| 1      | Normal Flat slab                 | without drop     | 305         |
|        |                                  | with drop        | 225         |
|        |                                  | without drop     | 235         |
| 2      | Flat slab with banded tendons    | with drop        | 165         |
|        |                                  | without drop     | 220         |
| 3      | Flat slab with distributed tendons| with drop        | 160         |
To make a comparison among support reactions, 16 columns are divided into three groups: corner columns, edge columns, and centre columns. The support reactions of all columns is given in Table 2, Table 3 and Table 4. As a result, we have four corner columns, eight edge columns, and four centre columns. Because we're working with a symmetric slab with a square panel, each group's support reactions will be the same.

Conventional flat slab has very high support reactions due to its high dead weight by the provision of drop these support reactions has greatly reduced. Hence this can be an effective solution to reduce the dead load up to some extent.

Banded flat slab without drop also shows a reduction in the support reactions but they are high when compared to flat slab with drop. But this can be greatly reduced to after the provision of drop to the banded flat slab. The depth of distributed PT flat slab without drop is low when compared to banded PT flat slab this can be even reduced after the provision of drop. Among all the cases we have less self weight or support reactions in the of Distributed PT flat slab with drop making it more efficient way to reduce the support reactions in which support reactions are reduced more than 30% in all the cases compared to flat plate.

As a result of the less weight from the slab, it may be possible to reduce the size of the columns and foundation, thereby lowering the overall construction cost. When we examine very tall structures with many floors, the load coming from the superstructure is reduced at every floor level, resulting in a higher reduction of the dead load coming from the superstructure.

Figures 2 to 4 represent the support reaction in each case for all the columns and the comparison was done for corner columns, edge columns and centre columns.

Table 2. Support reactions of corner columns for various slabs.

| Sl. No | Type of slab                  | Presence of drop | Support reactions of corner column in kN |
|--------|------------------------------|------------------|----------------------------------------|
| 1      | Normal Flat slab             | without drop     | 110.9114                               |
|        |                              | with drop        | 90.4424                                |
|        |                              | without drop     | 94.8602                                |
| 2      | Flat slab with banded tendons| with drop        | 79.8188                                |
|        |                              | without drop     | 91.3812                                |
| 3      | Flat slab with distributed tendons | with drop  | 78.2076                                |
Figure 2. Comparison of support reactions of corner columns.

Table 3. Support reactions of edge columns for various slabs.

| Sl. No | Type of slab                      | Presence of drop | Support reactions of edge column in kN |
|--------|----------------------------------|------------------|---------------------------------------|
| 1      | Normal Flat slab                 | without drop     | 226.8127                              |
|        |                                  | with drop        | 180.9538                              |
| 2      | Flat slab with banded tendons    | with drop        | 155.234                               |
|        |                                  | without drop     | 181.8497                              |
| 3      | Flat slab with distributed tendons| with drop        | 152.0358                              |

Figure 3. Comparison of support reactions of edge columns.
Table 4. Support reactions of centre columns for various slabs.

| Sl. No | Type of slab                      | Presence of drop | Support reactions of centre column in kN |
|-------|-----------------------------------|------------------|----------------------------------------|
| 1     | Normal Flat slab                   | without drop     | 532.4955                               |
|       |                                   | with drop        | 420.3981                               |
| 2     | Flat slab with banded tendons      | without drop     | 433.9166                               |
|       |                                   | with drop        | 344.3731                               |
| 3     | Flat slab with distributed tendons | without drop     | 412.6438                               |
|       |                                   | with drop        | 339.2323                               |

Figure 4. Comparison of support reactions of centre columns.

6.3 Punching shear comparison

While designing, preliminary depth is chosen based on deflection criterion i.e., depth estimation for the given span for which have deflection obtained will be within acceptable ranges. Design will be done for the steel after receiving the depth, and then check for punching shear capacity. If it has enough punching shear capacity the slab is safe.

Typically, a flat slab with a large span depth that satisfies deflection will fail in punching shear, necessitating the need to raise the slab's depth. If we keep increasing the depth, the depth will raise, which is undesirable. By using post-tensioning tendons, good punching shear capacity can be achieved even at the lower depths.

The punching stress ratio is the ratio of punching load to punching capacity the slab. To be safe it should be less than 1 i.e., punching capacity of slab show be more than punching force acting on it. If it is more than redesign should be done changing the dimensions or we have to adopt strengthening techniques to enhance the punching shear capacity of the slab.

All the six models were designed to be safe against punching. Punching stress ratio is kept close all these slabs (slightly less than 1) Different depths are necessary for different models since the punching stress ratios are nearly identical. When comparison is done for a flat slab with and without a drop, 305 mm depth is required for flat plate and only 225 with drop, this is because depth is increased near the column, which increases the punching shear area and, as a result, the slab's punching shear capacity. It is obvious from observation that post-tensioned flat slabs require less depth than traditional flat slabs to be safe against punching shear. Banded PT slab with and without tendons require 235mm and 165mm, whereas distributed PT flat slab requires 220 mm and 160mm respectively. As a result, It can be deduced that the addition of tendons can improve punching shear capacity. To be safe against punching, we got
slightly higher depth for banded tendons than for distributed tendons. As a result, we can conclude that banded tendons are more effective in improving punching shear capacity of flat slab. The following figures 5 to 10, shows the punching stress ratios in different slabs:

![Figure 5. Punching stress ratios for flat plate.](image1)

![Figure 6. Punching stress ratios for flat slab with drop.](image2)

![Figure 7. Punching stress ratios for Banded PT slab without drop.](image3)

![Figure 8. Punching stress ratios for Banded PT slab with drop.](image4)
6.4. Deflection comparison
In all the cases deflection is compared for load combination of 1.2DL + 1.6 LL which represents long term deflection. When it comes to post tensioning it will include Prestressing effects including secondary effect or hyperstatic effects, Hence the combination becomes (1.2DL + 1.6 LL+ PT- FINAL- HP).

When comparing a flat slab with a drop to a slab without a drop, the flat slab with a drop deflects more. This is due to the slab’s reduced depth. As a result, because the member thickness is greatly reduced, it will deflect more.

It can be observed from the above data that provision of tendons leads in less deflection as compared to a conventional flat slab, even when the depth is reduced. Tendons will provide uniform downward force above the neutral axis and uniform upward force below the neutral axis, thus balancing a portion of the external load coming on to the slab. It will also provide a vertical component of the force in the tendon, thereby reducing the net force acting on a slab section.

The sagging deflection at the centre and a very modest upward moment at the supports were practically same for standard slabs with and without drop deflection (shown in figure 11 and 12).
Figure 13. Vertical deflection pattern in Banded PT slab without drop.

Figure 14. Vertical deflection pattern in Banded PT slab with drop.

Figure 15. Deflection pattern in Distributed PT slab without drop.

Figure 16. Deflection pattern in Distributed PT slab with drop.

Coming to flat slab with banded tendons with and without drop exhibits a similar pattern of behaviour in deflection (shown in figure 13 and 14). Upward (hogging) deflection at the centre of spans can be seen in this case. The hogging moment created by the tendon placed below the neutral axis is responsible for this. As the tendons are only placed at the column strip, slight shortening of slab at the position of the columns is observed.

Similarly in case of distributed tendons upward deflection is observed due to the hogging moment created by the tendons (as in figure 15 and 16 and in Tables 5 and 6)

It quite obvious that net deflection is less in case of slabs with tendons compared to one without tendons as shown in figures 17 and 18. But upward deflection is observed in PT slabs due to the hogging moment induced by the tendon. Slab should be designed in such a way that hogging moment should not be high.

Table 5. Maximum downward deflection.

| Sl. No | Type of slab                    | Presence of drop | Max downward deflection in mm |
|-------|--------------------------------|-----------------|-------------------------------|
| 1     | Normal Flat slab               | without drop    | 7.164                         |
|       |                                | with drop       | 11.399                        |
| 2     | Flat slab with banded tendons  | with drop       | 5.395                         |
|       |                                | without drop    | 4.655                         |
| 3     | Flat slab with distributed tendons | with drop    | 5.057                         |
|       |                                | without drop    | 4.686                         |
Figure 17. Comparison of Maximum downward deflection.

Table 6. Maximum upward deflection.

| Sl. No | Type of slab                  | Presence of drop | Max upward deflection in mm |
|--------|-------------------------------|------------------|-----------------------------|
| 1      | Normal Flat slab              | without drop     | 0.367                       |
| 1      |                               | with drop        | 0.539                       |
| 1      |                               | without drop     | 1.466                       |
| 2      | Flat slab with banded tendons | with drop        | 3.569                       |
| 2      |                               | without drop     | 0.57                        |
| 3      | Flat slab with distributed tendons | with drop     | 1.734                       |

Figure 18. Comparison of Maximum upward deflection.

7. Conclusions and summary
Flat slabs have a wide range of uses, but the fundamental disadvantage is the lack of punching shear capacity. Most flat slabs fail in shear, even if they have sufficient flexural capacity. In order to achieve
good punching shear, the depth must be increased. Large depths should be supplied for larger spans to be safe. This is not only unattractive from an architectural standpoint, but it also adds dead weight to the structure, increasing building expenses. Hence, flat slabs are strengthened using post tensioning to achieve acceptable punching shear capability at lower depths.

In this work we made comparison between reinforced flat slab and post tensioned flat slab with and without drop. Tendons are arranged in two ways i.e., distributed and banded. Total six models were designed and comparison is made between the depth, support reactions, punching shear and deflection and the following conclusions are made:

1. Depth can be safely reduced by the provision of drops. So, drops can be an effective solution to reduce the depth of the flat slab for shorter spans. This will reduce the weight of the slab. For short spans drops are the effective way than post tensioning because minimum depth should be provided and drops are sufficient to have safe punching capacity.
2. For very larger spans strengthening the flat slab by post-tensioning by the provision of drops can be very beneficial to obtain very lesser depths.
3. Distributed tendons are more effective in obtaining lesser depths compared to the banded tendons.
4. Support reactions are less in post-tensioned flat slab due to the reduction of dead weight, which results in less material requirement for construction. Hence cost of construction is reduced.
5. Since the support reaction for PT slabs is lower, the components that take load from the slabs, such as columns and foundations, can be built for lower loads, resulting in smaller sections and reinforcement, lowering the overall construction cost.
6. Punching shear strength of a flat slab can be increased by using post-tensioning technique and achieving more punching shear strength even at lesser depth. There by, overcoming one of the major problems in the design of flat slab.
7. Downward deflections can be greatly reduced by the provision of post-tensioning tendons resulting in good serviceability.
8. Provision of distributed tendons along with drop is the most effective way considering the overall performance of the flat slab.

References

[1] Lin, Tung Yen, and Ned Hamilton Burns. "Design of prestressed concrete structures." (1981).
[2] Punmia, B.C., Jain, A.K. and Jain, A.K., 1992. Reinforced Concrete Structures Vol. II. Firewall Media.
[3] ACI Committee, 2008. Building code requirements for structural concrete (ACI 318-08) and commentary. American Concrete Institute.
[4] Concrete Society, Slough (United Kingdom);, 1994. Post-tensioned concrete floors design handbook.
[5] Thayapraba, M., 2014. Cost Effectiveness of Post-Tensioned and Reinforced Concrete Flat Slab Systems. International Journal of Innovative Technology and Exploring Engineering (IJIITEE) ISSN, pp.2278-3075.
[6] Hassan, Nasr Z., Mostafa A. Osman, Awad M. El-Hashimy, and Heba K. Tantawy. "Enhancement of punching shear strength of flat slabs using shear-band reinforcement." HBRC Journal 14, no. 3 (2018): 393-399.
[7] El-Kashif, K.F., Ahmed, E.A. and Salem, H.M., 2019. Experimental investigation of strengthening slab-column connections with CFRP fan. Ain Shams Engineering Journal, 10(3), pp.639-650.
[8] Gosav, A.V., Kiss, Z.I., Oneţ, T. and Bompa, D.V., 2016. Failure assessment of flat slab-to-column members. Magazine of Concrete Research, 68(17), pp.887-901.
[9] Silva, M.A.L., Gamage, J.C.P.H. and Fawzia, S., 2019. Performance of slab-column connections of flat slabs strengthened with carbon fiber reinforced polymers. *Case Studies in Construction Materials, 11*, p.e00275.

[10] Abdulrahman, B.Q. and Aziz, O.Q., 2020. Strengthening RC flat slab-column connections with FRP composites: A review and Comparative study. *Journal of King Saud University-Engineering Sciences*.

[11] Askar, H.S., 2015. Usage of prestressed vertical bolts for retrofitting flat slabs damaged due to punching shear. *Alexandria Engineering Journal, 54*(3), pp.509-518.