

Post-tensioned Concrete in Building Sector

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Introduction

Prestressed Concrete especially with post-tensioned construction has occupied a very important position, especially in the construction of bridges and storage tanks for many decades due to its decisive technical and economical advantages. The focus of this paper is on applications of post-tensioning in building sector.

The most important advantages offered by post-tensioning briefly are:

- In comparison to reinforced concrete, a considerable saving in concrete and steel since, due to the participation of the entire concrete cross-section more slender designs are possible.
- Smaller deflections compared to structural members with steel and reinforced concrete.
- Good crack behaviour and therefore better protection of the steel against corrosion.
- Almost unchanged serviceability even under considerable overload, since temporary cracks close again after the removal of overload.
- High fatigue strength, since the amplitude of the stress changes in the prestressing steel under alternating loads are quite small.

For the above reasons post-tensioned construction has also come to be used in many situations in buildings.

In addition to the already mentioned general features of post-tensioned construction, the following advantages of post-tensioned slabs over reinforced concrete slabs may be listed:

- More economical structures resulting from the use of prestressing steels with a very high tensile strength instead of normal reinforcing steels.
- Larger spans and greater slenderness. The latter results in reduced
- dead load, which also has a beneficial effect upon the columns and foundations and reduces the overall height of buildings or enables additional floors to be incorporated in buildings of a given height.
- Under permanent load, very good behavior in respect of deflections and
- cracking.
- Higher punching shear strength obtainable by appropriate layout of
- tendons
- Considerable reduction in construction time as a result of earlier striking of slab formwork.

Although some post-tensioned slab structures had been constructed in Europe quite early on, the real development took place in the USA and Australia. The first post-tensioned slabs were erected in the USA in 1955, using unbonded post-tensioning.

In the 1960s, with the development of higher strength steel, better attachment hardware, better construction techniques, and simplified design methods, the use of P-T to reinforce structures became more popular. In the succeeding years numerous post-tensioned slabs were designed and constructed in connection with the lift slab method. Post-tensioning enabled the lifting weight to be reduced and the deflection and cracking performance to be improved. Attempts were made to gain in depth knowledge by theoretical studies and experiments on post-tensioned plates. By the early 1990s the mystery of P-T subsided with further refinements to the tensioning process, the development of more corrosion-resistant anchorages, and the widespread dissemination of design software. Because of these factors, P-T has become a preferred method for reinforcing concrete today even in building sector

Post-tensioning with bonded or unbonded tendons

Bonded post-tensioning

As is well-known, in this method of post-tensioning the prestressing steel is placed in ducts, and after stressing is bonded to the surrounding concrete by grouting with cement suspension. Round corrugated ducts are normally used. For the relatively thin floor slabs of buildings, the reduction in the possible eccentricity of the prestressing steel with this arrangement is, however, too large, in particular at cross-over points, and for this reason flat ducts have become common. They normally contain tendons comprising four strands of nominal diameter 13 mm (0.5"), which have proved to be logical for constructional reasons.

Unbonded post-tensioning

In the early stages of development of post-tensioned concrete in Europe, post-tensioning without bond was also used to some extent (for example in 1936/37 in a bridge constructed in Aue/Saxony [D] according to the Dischinger patent or in 1948 for the Meuse, Bridge at Sclayn [B] designed by Magnel). After a period without any substantial applications, some important structures have again been built with unbonded post-tensioning in recent years.

In the first applications in building work in the USA, the prestressing steel was greased and wrapped in wrapping paper, to facilitate its longitudinal movement during stressing. Now the method described below for producing the sheathing has generally become common.

The strand is first given a continuous film of permanent corrosion preventing grease in a continuous operation, either at the manufacturer's works or at the prestressing firm. A plastic tube of polyethylene or polypropylene of at least 1 mm wall thickness is then extruded over this. The plastic tube forms the primary and the grease the secondary corrosion protection.

Strands sheathed in this manner are known as mono-strands. The nominal diameter of the strands used is 13 mm (0.5") and 15 mm (0.6"); the latter have come to be used more often in recent years.

Bonded or unbonded?

This question was and still is frequently the subject of serious discussions.

The most important arguments for and against are listed below:

Arguments in favour of post-tensioning without bonding:

- Maximum possible tendon eccentricities, since tendon diameters are minimal; of special importance in thin slabs
- Prestressing steel protected against corrosion ex works.
- Simple and rapid placing of tendons.
- Very low losses of prestressing force due to friction.
- Grouting operation is eliminated.
- In general more economical.

Arguments for post-tensioning with bonding:

- Larger ultimate moment.
- Local failure of a tendon (due to fire, explosion, earthquakes etc.) has limited effects

Whereas in the USA post-tensioning without bonding is used almost exclusively, bonded post-tensioning is employed in many countries including Australia and India.

Among the arguments for bonded post-tensioning, the better performance of the slabs in the failure condition is frequently emphasized. It has, however, been demonstrated that equally good structures can be achieved in unbonded post-tensioning by suitable design and detailing.

It is always possible that local circumstances or limiting engineering conditions (such as standards) may become the decisive factor in the choice.

Typical applications

Post-tensioning can be of economic interest in the following components of a multi-storey building:

- Suspended slabs like floor slabs and terrace slabs
- Foundation slabs (rafts)
- Slabs on grade
- Cantilevered structures, such as overhanging building parts.
- Facade elements of large area; here light post-tensioning is a simple method of preventing cracks.

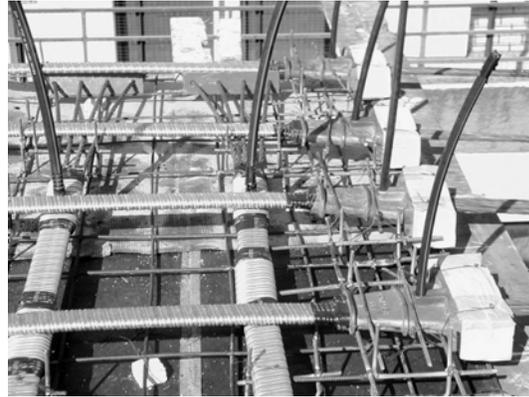
- Main beams in the form of beams, transfer girders, lattice girders or north-light roofs.

Typical applications for post-tensioned slabs may be found in the frames or skeletons for office buildings, multistorey car parks, schools, warehouses etc. where large spans are encountered.

Suspended slabs

Types of slab system

- For spans of 7 to 12 m, and live loads up to approx. 5 kN/m^2 , flat slabs or slabs with shallow main beams (band beams) running in one direction without column head drops or flares are usually selected.
- For larger spans and live loads, flat slabs with column head drops or flares, slabs with main beams in both directions or waffle slabs are used.



Issues in design

There are several issues to be kept in mind while analyzing/designing a post-tensioned flat slab system. Basically all structural elements are designed as “partially pre-stressed” members.

Method to be used

Equivalent Frame Method

This is a general and simple method. It is applicable to all floor slabs provided that it is complemented by sound engineering knowledge. With developed special purpose computer programs, it is possible to carry out “interactive” design. What is important is that a good understanding of Plate Behaviour and Post-tensioning essential to reduce iterations. The disadvantage is that when lines of support are not straight (irregular column lay-out) additional approximations are involved.

Finite Element Method

This method works on the basis of division of complicated structure into smaller and simpler pieces (elements) whose behaviour can be closely defined. Each element is formulated to capture the local behaviour of the structure, based on such factors as material properties, geometry and relationship with surrounding elements. The mathematical assemblage of these elements into the complete, complex structure allows for the automated computation of the behaviour of the entire structure in one step. The greatest advantage is that regular and irregular floor systems are handled with same ease and degree of accuracy.

Magnitude of prestressing

What needs to be remembered is that the slab is to be treated essentially as Partially Prestressed. Amount of prestress applied affects the un-tensioned reinforcement (rebar) requirements. A range of acceptable designs are possible for a given geometry and loading. The optimum solution depends on relative costs of prestressing steel and rebar, ratio of live load to dead load. Normally the level of prestress is in the range of 2 N/mm^2 . When higher prestress and/or very long spans are encountered, effect of restraint to slab shortening to be looked into.

Deflection

Deflection is an important serviceability limit state that needs closer attention especially in flat slabs. Deflection is influenced by temperature, creep, shrinkage and pre-camber if any. It cannot be avoided but should be controlled. Excessive deflection may have effect on internal partitions, claddings and finishes. Code General Guidelines differ from country to country. ACI : 318 – 2000 specified a $\text{Span/depth} \leq 42$ for floors and ≤ 48 for roofs when Prestressed flat slabs are designed.

Punching Shear

This being a sudden failure that occurs without notice, it needs closer attention. Many a times flat slab junctions at edge and corner columns may govern thickness since there may be a larger moment-shear-torsion transfer there. Shear reinforcements will help to some extent and prestressing enhances the shear capacity marginally. No specific guidelines either in Indian or British codes for estimating the shear enhancement due to prestressing. Concrete Society (UK) Report No. 43 gives some guidelines. Generally the beneficial effects of PT are ignored by designers.

Seismic Suitability

It is well known that flat slab systems are inferior to beam-slab systems under lateral loads, be it due to wind or earthquake. It is essential to provide lateral load handling members like shear walls and/or core walls. The slab then behaves like a diaphragm transferring the lateral loads to these members. Ensuring proper

diaphragm action is essential. PT slabs are thinner/lighter and hence have less seismic mass. Also, the storey height is reduced and hence there is less demand on seismic resistance. Pre-compression enhances precracked capacity of the diaphragms.

Closure Strips

These are also referred to as a pour strip. They are generally necessitated due to site specific requirements like inability for deployment of large areas of shuttering, very long cable length necessitating both ends stressing etc. This is a temporary separation of about 1m between two regions of slab which will be constructed and post-tensioned separately. The gap between the two slab regions is closed by placing and consolidating non-shrink concrete. The width of the strip is decided by net distance required to position the jacks. The preferred location is typically quarter span where moments are small. Proper corrosion protection is to be given to anchors during the time the anchors are kept exposed to atmosphere. The time to keep the gap open is dependent on the time taken for most of the shortening process to be over. If the pour strip concrete is poured earlier, cracks may develop since edges on either side of proposed would be moving away from each other during the process of shortening. The reinforcement across the closure strip has to take care of the stresses in that non-prestressed region since it would be a part of the continuum.

Construction Procedures

General

The construction of a post-tensioned slab is broadly similar to that for an ordinarily reinforced slab. Differences arise in the placing of the reinforcement, the stressing of the tendons and in respect of the rate of construction.

The placing work consists of three phases:

Firstly, the bottom ordinary reinforcement of the slab and the edge reinforcement are placed. The ducts or tendons must then be positioned, fitted with supports and fixed in place. This is followed by the placing of the top ordinary reinforcement. The stressing of the tendons and, in the case of bonded tendons the grouting also, represent additional construction operations as compared with a normally reinforced slab. Since, however, these operations are usually carried out by the prestressing firm, the main contractor can continue his work without interruption.

A feature of great importance is the short stripping times that can be achieved with post-tensioned slabs. The minimum period between concreting and stripping of formwork is about 72 hours, depending upon concrete quality and ambient temperature. When the required concrete strength is reached, the full prestressing force can usually be applied and the formwork stripped immediately afterwards.

Depending upon the total size, the construction of the slabs is carried out in a number of sections. The divisions are a question of the geometry of the structure, the dimensions, the planning, the construction procedure, the utilization of formwork material etc. The construction joints that do occur, are subsequently subjected to permanent compression by the prestressing, so that the behaviour of the entire slab finally is the same throughout.

The weight of a newly concreted slab must be transmitted through the formwork to slabs beneath it. Since this weight is usually less than that of a corresponding reinforced concrete slab, the cost of the supporting structure is also less.

Fabrication of the tendons

Bonded post-tensioning

There are two possible methods of fabricating cables:

- Fabrication at the works of the prestressing firm
- Fabrication by the prestressing firm on the site

The method chosen will depend upon the local conditions. At works, the strands are cut to the desired length, placed in the duct and, if appropriate, equipped with dead-end anchorages. The finished cables are then coiled up and transported to the site. anchorages.

In fabrication on the site, the cables can either be fabricated in exactly the same manner as at works, or they can be assembled by pushing through.

In the latter method, the ducts are initially placed empty and the strands are pushed through them subsequently. If the cables have stressing anchorages at both ends, this operation can even be carried out after concreting (except for the cables with flat ducts).

Unbonded post-tensioning

The fabrication of monostrand tendons is usually carried out at the works of the prestressing firm but can, if required, also be carried out on site. The monostrands are cut to length and, if necessary, fitted with the dead-end anchorages. They are then coiled up and transported to site. The stressing anchorages are fixed to the formwork. During placing, the monostrands are then threaded through the anchorages.

Construction procedure for bonded post-tensioning

In slabs with bonded post-tensioning, the operations are normally carried out as follows:

1. Erection of slab supporting formwork
2. Fitting of end formwork; placing of stressing anchorages

3. Placing of bottom and edge reinforcement
4. Placing of tendons or, if applicable, empty ducts* according to placing drawing
5. Supporting of tendons or empty ducts* with supporting chairs according to support drawing
6. Placing of top reinforcement
7. Concreting of the section of the slab
8. Removal of end formwork and forms for the stressing block-outs
9. Stressing of cables according to stressing programme
10. Stripping of slab supporting formwork
11. Grouting of cables and concreting of block-outs

* In this case, the stressing steel is pushed through either before item 5 or before item 9.

Construction procedure for unbonded post-tensioning

If unbonded tendons are used, the construction procedure set out earlier is modified only by the omission of grouting (item 11).

All activities that follow one another directly can partly overlap; at the commencement of activity (i+1), however, phase (i-1) must be completed. Experience has shown that those activities that are specific to prestressing (items 4, 5 and 9) are with advantage carried out by the prestressing firm, bearing in mind the following aspects:

Placing and supporting of tendons

The placing sequence and the supporting of the tendons is carried out in accordance with the placing and support drawings. In contrast to a normally reinforced slab, therefore, for a post-tensioned slab two drawings for the prestressing must be prepared in addition to the reinforcement drawings. The drawings for both, ordinary reinforcement and posttensioning are, however, comparatively simple and the number of items for tendons and reinforcing bars is small. The sequence in which the tendons are to be placed must be carefully considered, so that the operation can take place smoothly. Normally a sequence allowing the tendons to be placed without «threading» or «weaving» can be found without any difficulty.

To assure the stated tolerances, good coordination is required between all the installation contractors (electrical, heating, plumbing etc.) and the organization responsible for the tendon layout. Corresponding care is also necessary in concreting.

Stressing of tendons

For stressing the tendons, a properly secured scaffolding 0.75 m wide and of 2 kN/m² load-bearing capacity is required at the edge of the slab. For the jacks

used there is a space requirement behind the anchorage of 1 m along the axis and 120 mm radius about it. All stressing operations are recorded for each tendon. The primary objective is to stress to the required load; the extension is measured for checking purposes and is compared with the calculated value.

Slabs on ground

Post-tensioned slabs have equal application on the ground, where they can minimise the use of joints and overcome problems with raft slabs in areas of high hydrostatic load. The long spans provide a better surface for materials handling equipment to operate on in warehouses, and greater strength in applications where heavy equipment uses the slab regularly (a 230mm thick post-tensioned slab at Penang Airport in Malaysia has been designed for three jumbo jets). More worse the ground condition or the higher the load, more attractive would be the use of post-tensioned slabs. By having a joint at one or two locations only it becomes economic to install a superior (albeit costly) joint that overcomes traditional problems.



In short the advantages of post-tensioned slabs on ground are

- No cracks or slab curl
- No saw-cuts or Construction Joints
- Recovers shape after overload
- Short construction period
- Higher load capacity
- Thinner slab
- Moisture resistant
- Zero maintenance cost

The design basically is dependent on

- Slab Geometry
- Subgrade properties

- Concrete properties
- Loading
- Prestress level

The process is iterative, but guidelines and softwares are available for design. The construction is simple but care is to be exercised regarding stressing pockets and use of special stressing jacks.

Conclusion

Prestressing, especially post-tensioning is playing a big role in the building construction sector today. The design and construction methodologies have been fairly well tuned over the years. An effort is made in this paper to “de-mystify” post-tensioning in the buildings so that more and more people make use of this time tested technology.