

POST-TENSIONING IN BUILDING STRUCTURES

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SUMMARY

This paper outlines the major advantages of the use of post-tensioning in building structures. Economics of the post-tensioning slab system are discussed including relative material contents, speed of construction, and factors affecting the cost of post-tensioning. Various post-tensioned structural systems are presented, along with their relative advantages, applicability to various situations, and span to depth ratios to enable a designer to select the correct slab and beam thickness for a variety of situations. Finally, a discussion on the flexibility of post-tensioned building structures in terms of future uses, new floor penetrations and demolition is presented.

INTRODUCTION

When Eugene Freyssinet developed and patented the technique of prestressing concrete in 1928 he little realised the applications to which his invention would be put in future years. Spectacular growth in the use of prestressed concrete took place after the Second World War with the material used to repair and reconstruct bridges in Europe. It is now an accepted Civil Engineering construction material.

The A.C.I. Committee on Prestressed Concrete gives one of the most apt descriptions of post-tensioned concrete.

'Prestressed Concrete is concrete in which there have been introduced internal forces of such magnitude and distribution that the forces resulting from given external loadings are counteracted to a desirable degree'.

In post-tensioning we obtain several distinct advantages: -

- a) Designers have the opportunity to impart forces internally to the concrete structure to counteract and balance loads sustained by the structure thereby enabling design optimisation.
- b) Designers can utilise the advantage of the compressive strength of concrete while circumventing its inherent weakness in tension.
- c) Post-tensioned concrete combines and optimises today's very high strength concretes and steel to result in a practical and efficient structural system.

The first post-tensioned buildings were erected in the USA in the 1950's using unbonded post-tensioning. Some post-tensioned structures were built in Europe quite early on but the real development took place in Australia and the USA. Joint efforts by prestressing companies, researchers and design engineers in these early stages resulted in standards and recommendations which assisted in promoting the widespread use of this form of construction in Australia, the USA and throughout the Asian region.

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Extensive research in these countries, as well as in Europe more recently, has greatly expanded the knowledge available on such structures and now forms the basis for standards and codes of practice in these countries.

Since the introduction of post-tensioning to buildings, a great deal of experience has been gained as to which type of building has floors most suited to this method of construction. Many Engineers and Builders can identify at a glance whether the advantages of post-tensioning can be utilised in any particular situation.

Current architecture in Australia continues to place emphasis on the necessity of providing large uninterrupted floor space, flexibility of internal layout, versatility of use and freedom of movement. All of these are facilitated by the use of post-tensioning in the construction of concrete floor slabs, giving large clear spans, fewer columns and supports, and reduced floor thickness.

Post-tensioning in buildings can be loosely divided into two categories. The first application is for specialised structural elements such as raft foundations, transfer plates, transfer beams, tie beams and the like. For large multi-strand tendons used in these elements, 15.2 mm diameter seven wire strands are preferred. The anchorages used are the Freyssinet C Range as shown in Figure 1 below. This system can be used internally within the concrete section or externally.



Figure 1 – Freyssinet C Range multi-strand anchorage

The second application is for building floor systems, the advantages and economics of which are discussed below. The preferred slab system for building works in Australia is the well proven bonded tendon which contains between 2 and 5, 12.7 mm diameter seven wire prestressing strands with an ultimate tensile strength of 184 kN, housed in oval ducting. The strands are anchored in flat fan shaped anchorages and stressed mono-strand (that is, one at a time) using light weight jacking equipment. Figure 2 shows the cast iron anchorage guide, stressing block, reusable recess former and wedges. Minimum slab thickness for adequate edge distance, cover to anti-burst reinforcement and the like is 130mm for 2 strands, 140mm for 3 strands and 150mm for 4 and 5 strands.



Figure 2 – Slab system anchorage components

Why use 12.7mm diameter strands?

A question that arises from time to time is why we use 12.7mm diameter strands for building works, when on face value 15.2mm diameter strands appears more cost effective. The first answer is that 12.7mm has a high strength per unit weight when compared to 15.2mm, which leads to a reduced cost. Secondly, and more importantly from an installation viewpoint, it allows greater flexibility in choosing the tendon we want to use. This is mainly due to the recommended maximum tendon spacing being limited to 8 to 10 times the slab thickness. The addition of a single 12.7mm strand in a tendon leads to a relatively small increase in overall tonnage and therefore cost, and allows for better customisation of the design.

Of course there are times when 15.2mm strand should be used. This occurs when the tendon already contains the full 5 strands in a duct and the tendon spacing is not at the maximum allowed. In our experience this occurs in less than 10% of structures. If this is the case, we should substitute 15.2mm diameter strands and increase the tendon spacing. This leads to a reduction in the number of whole tendons and a subsequent reduction in anchorage costs and labour costs since less whole tendons have to be installed. As noted earlier, 15.2mm diameter should also be used for specialised structural elements and large civil engineering applications, where the aim is to use as few whole tendons as possible.

Why a bonded system?

This is another question that arises. Why do we use bonded tendons? Well there are a number of advantages; higher flexural capacity, good flexural crack distribution, good corrosion protection, and flexibility for later cutting of penetrations and easier demolition. However there are some disadvantages such as an additional operation for grouting and a more labour intensive installation.

However, the main reason why bonded tendons are preferred relates to the overall cost of the structure and not just of the post-tensioning. With unbonded tendons it is usual to have a layer of conventional reinforcement for crack control. Using bonded tendons there is no such requirement and therefore the overall price of bonded post-tensioning and associated reinforcement is less than for unbonded tendons. For unbonded tendons the post-tensioning price may be less, but the overall cost of reinforcing materials is greater.

POST-TENSIONED BUILDINGS - ADVANTAGES

Post-tensioned concrete slabs in buildings have many advantages over reinforced concrete slabs and other structural systems for both single and multi-level structures. Some of the main advantages are described below.

1. *Longer Spans*

Longer spans can be used reducing the number of columns. This results in larger, column free floor areas which greatly increase the flexibility of use for the structure and can result in higher rental returns.

2. *Overall Structural Cost*

The total cost of materials, labour and formwork required to construct a floor is reduced for spans greater than 7 metres, thereby providing superior economy.

3. *Reduced Floor to Floor Height*

For the same imposed load, thinner slabs can be used. The reduced section depths allow minimum building height with resultant savings in facade costs. Alternatively, for taller buildings it can allow more floors to be constructed within the original building envelope.

4. *Deflection Free Slabs*

Undesirable deflections under service loads can be virtually eliminated.

5. *Waterproof Slabs*

Post-tensioned slabs can be designed to be crack free and therefore waterproof slabs are possible. Achievement of this objective depends upon careful design, detailing and construction. The choice of concrete mix and curing methods along with quality workmanship also play a key role.

6. *Early Formwork Stripping*

The earlier stripping of formwork and reduced backpropping requirements enable faster construction cycles and quick re-use of formwork. This increase in speed of construction is explained further in the next section on economics.

7. *Materials Handling*

The reduced material quantities in concrete and reinforcement greatly benefit on-site crane requirements. The strength of post-tensioning strand is approximately 4 times that of conventional reinforcement. Therefore the total weight of reinforcing material is greatly reduced.

8. *Column and Footing Design*

The reduced floor dead loads may be utilised in more economical design of the reinforced concrete columns and footings. In multi-storey buildings, reduced column sizes may increase the floor net lettable area.

ECONOMICS

When is Post-tensioning Cost Effective ?

The relative economics of post-tensioning versus other forms of construction vary according to the individual requirements of each case. In any basic comparison between post-tensioned and reinforced concrete one must consider the relative quantities of materials including formwork, concrete, reinforcement and post-tensioning. Other factors such as speed of construction, foundation costs, etc., must also be given consideration.

There is not always sufficient time or budget to carry out comparative feasibility studies for all structural solutions. There are however, some useful guidelines which can be employed when considering post-tensioned alternatives. As can be seen from figure 3 below, post-tensioned should be considered as a possible economic alternative for most structures when spans exceed 7.0 metres.

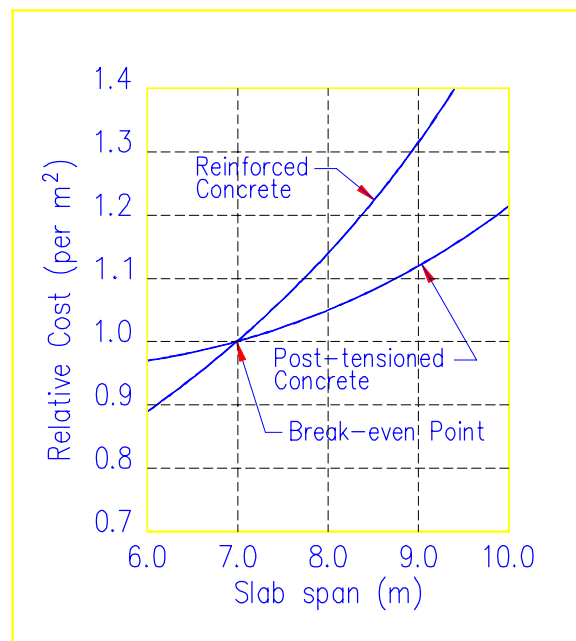


Figure 3: Cost comparison - Reinforced vs Post-tensioned flat slab.

The graph illustrates two main points. Firstly, how with increasing span the difference in cost between reinforced and post-tensioned concrete flat slabs also increases. Secondly, using an index of one for a 7.0 m span how the cost will vary for other spans. For example, a post-tensioned 10.0 m span will cost approximately 20% more than a post-tensioned 7.0 m span.

In general, for spans in excess of 8.0 metres, savings in excess of \$10 per square metre should be regularly attained in a direct cost comparison with reinforced concrete slabs.

Speed of Construction

Economics and construction speed are heavily linked in today's building construction environment. The speed of construction of a multi storey building is foremost in achieving economic building construction.

The key factor in the speed of construction of a post-tensioned framed building is expedient use and re-use of formwork. Post-tensioning allows for the early recovery of formwork by early stressing of tendons. Slab system tendons are usually stressed at the following minimum compressive strengths:-

- a) Initial stress of slab tendons 24 hours after the pour of concrete for control of early shrinkage stresses at a minimum concrete strength of 7 MPa.
- b) Final stressing of the slab system tendons may occur when the concrete has attained 22 MPa based on site cured cylinders in accordance with clause 19.6.2.8 of AS3600.

A typical floor cycle for a multi storey office development is shown below in figure 4. This building has a floor area of approximately 1000 m² and is divided into two pours per floor by a construction joint . It is normal to use two full sets of formwork in this type of construction.

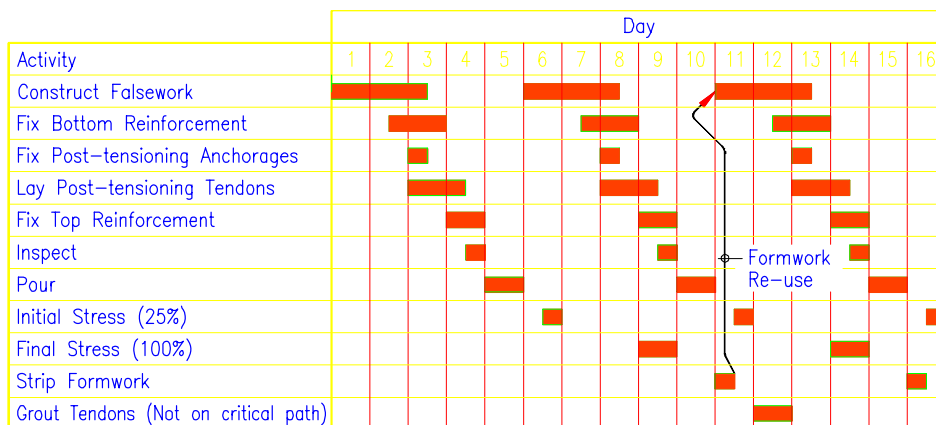


Figure 4. Typical 5 day construction cycle. Note that in tower construction it is usual to break the floor into a minimum of two pours. The above cycle is for a half floor with construction of the other half proceeding simultaneously.

Factors Affecting the Cost of Post-tensioning

Post-tensioning costs vary from project to project depending upon a number of factors. The cost of post-tensioning is most sensitive to the following influences, some of which have been previously documented.²

1. Tendon Lengths

The major influence in the cost of post-tensioning depends primarily on the length of the tendon. Short tendons are relatively expensive in comparison with long tendons.

The relatively high cost of short tendons results from the fixed cost such as establishment, anchorages and the stressing operation being pro-rated over a lesser tonnage. Experience has also shown the labour cost for larger tendons to be appreciably less than for short tendons.

It becomes clear that designers should avoid, if possible, detailing with very short tendons.

² The University of Technology, Sydney; Post-tensioned Slab Systems - A Post Graduate Short Course, 1990

2. Tendon Arrangement

The designer should always attempt to use as few tendons as possible. This leads to tendons being placed at the maximum spacing permissible in slabs (approximately 10 times the slab thickness for one way slabs, and approximately 8.5 times the slab thickness for two way slabs).

For example, if the design calls for a tendon containing 3 strands to be placed at 1125 mm centres, it would be more economical to use 4 strand tendons at 1500 mm centres.

If 5 tendons containing 4 strands each are required in a beam, it will be much more cost effective to use 4 tendons containing 5 strands each.

3. Stressing Access

Stressing of tendons from the perimeter of the building is preferable to top pocket stressing due to the following;

- a) Clear access around perimeter permits a faster stressing cycle.
- b) A curved nose needs to be used for stressing through a top side pan, which adds to the total loss of prestress through the jack and anchorage by 3%.
- c) Access to the top side pans is restricted by the frames supporting the floor above and other construction debris, increasing the time required to stress the tendons.

4. Structural System

The tendon installation, and therefore fixing times for a banded slab is faster than for flat plate and flat slab structures.

In banded slabs the order of laying is:

- a) Bands first
- b) Slabs second
- c) Slab distribution tendons last

With flat plates and flat slabs the tendons are interwoven which demands greater installation time than a comparable banded slab, and therefore increased labour costs.

5. Main Contractor

The ability of the main contractor to manage the sub contractors efficiently on site is paramount as this has a direct bearing on productivity and therefore labour costs. The main contractor also has a role to play ensuring all sub-contractors have continuity of work thereby minimising down time. The prevailing industrial climate also plays a role.

6. Site Access

Restricted site access to the construction site is likely to affect all aspects of the project as materials handling will be slower.

7. Treatment of Construction Joints

Wherever possible construction joints should be stitched using conventional reinforcement in lieu of post-tensioning couplers. The couplers are made up of expensive components and require significant labour and importantly, supervision, to install. Even if couplers are used, significant amounts of conventional reinforcement are required to keep the joint closed until the prestress is applied. Further guidance is offered in the next section.

Of the above, the average tendon length has the most significant impact on the cost of post-tensioning and historically there is a reasonable correlation between the two, with the other influences creating a scatter of results which provide an upper and lower bound on the cost of post-tensioning. Figure 5 shows a general range of current costs in Australia based on using 4 strand tendons in a banded slab arrangement and stressing externally.

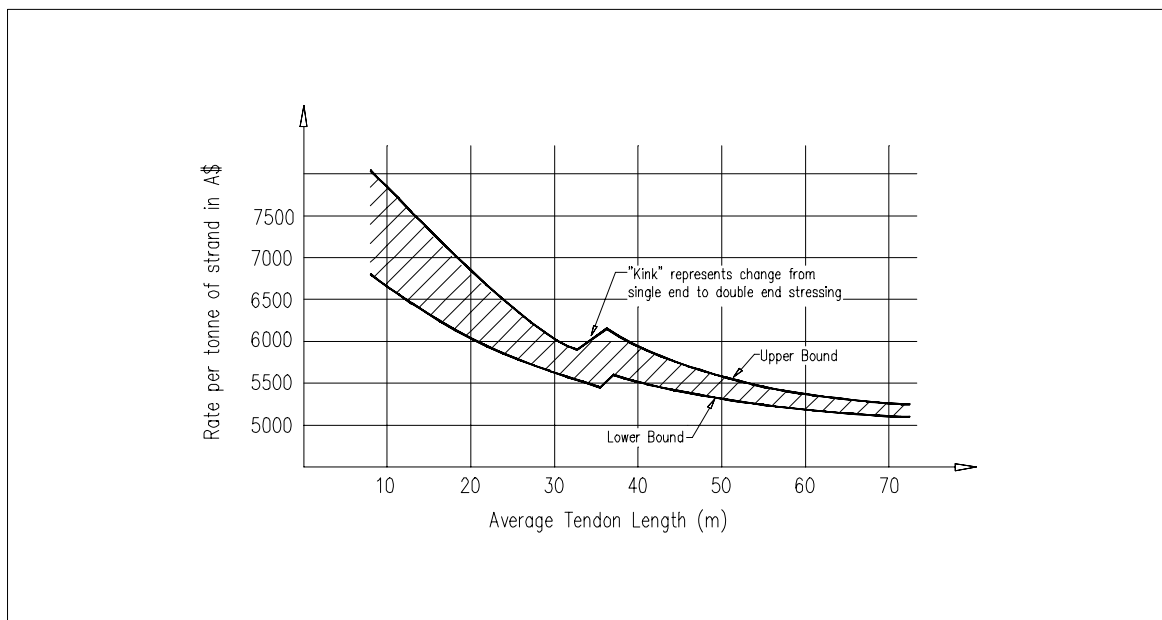


Figure 5. Graph showing cost of post-tensioning per tonne of strand versus average tendon length. Note that the cost per tonne of strand is inclusive of labour to install, stressing, grouting, and post-tensioning materials such as anchorages, ducts, etc.

Economical Design

Of course, the economics of post-tensioned buildings is heavily dictated by the design of the structure. The designer has a role to play in the minimisation of material quantities, the selection of the most economical structural system, and the simplification of the detailing allowing for ease and speed of installation. A few design considerations are briefly mentioned below.

1. Partial Prestressing

The advent of what is commonly termed partial prestressing has had a significant effect on the quantity of post-tensioning installed into building structures. Tensile cracking is allowed to occur, with crack control being provided by the bonded tendons and/or supplementary reinforcement. A cracked section analysis needs to be carried out to determine the cracked moment of inertia for use in deflection calculations as well as the steel stresses to confirm adequate crack control. The availability of computer software to carry out these calculations has meant that more often than not the amount of post-tensioning is selected to satisfy deflection criteria.

2. Selection of Column Grid

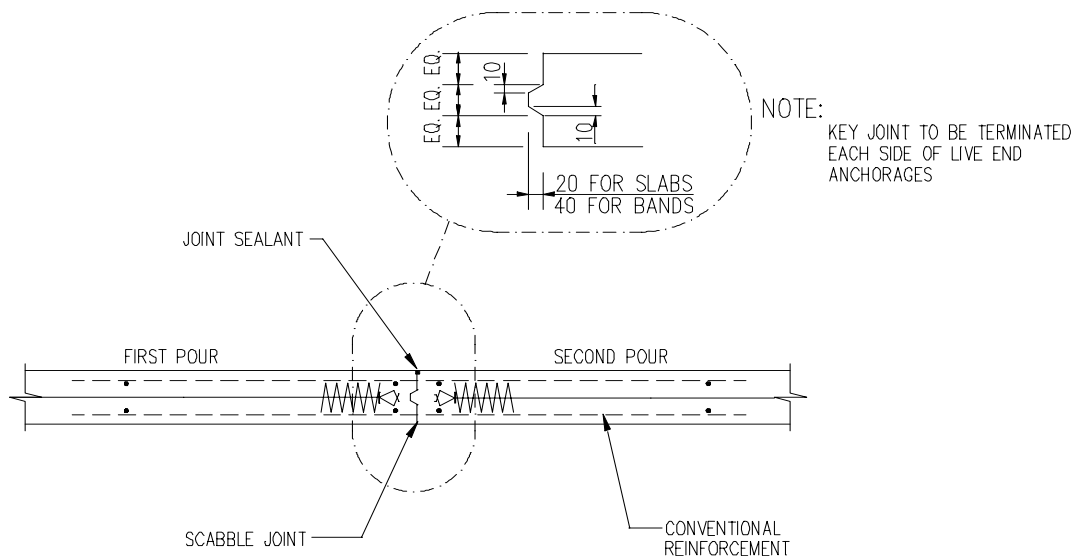
A column grid spacing of between 8 and 10 metres for car parks, shopping centres and offices usually results in the most economical structure while maintaining architectural requirements.

3. Formwork Layout

Formwork layout should be selected to enable quick fabrication with a minimum of form ply cutting. Widths of beams should be standardised in consultation with the main contractor and importantly, the width of the slab between bands should be selected as a multiple of 1200 mm to suit the standard formwork sheet widths.

4. Construction Joint Treatment

As mentioned previously the detail at the construction joint will play a significant role in the economics of the floor system. Post-tensioning couplers should be avoided due to their cost and slow installation. Construction joints should be stitched with conventional reinforcement as shown in figure 6 below.



TYPICAL CONSTRUCTION JOINT DETAIL

Figure 6 – 'Stitched' construction joint detail

Note that the amount of reinforcement required to keep a construction joint closed (say a crack width of 0.2 mm as for reinforced concrete) depends highly on the restraint of the overall frame. If the frame is very flexible, or alternatively if the construction joint is adjacent to very stiff elements such as core walls, then the amount of reinforcement required is quite low. On the other hand, if the frame is very stiff, large quantities of reinforcement will be required at which point an expansion joint should be positioned rather than a construction joint.

5. Simplicity In Detailing

As with all methods of construction the speed of installation is highly dependent upon the quality of the structural detailing. The designer needs to understand the installation process and be conscious of how their decisions on detailing affects all parties concerned on site. Detailing should be standardised and as simple as possible to understand. Congested areas should be carefully assessed and, as appropriate, large scale drawings and details produced.

6. Anchorage Reinforcement

Standardisation of anchorage reinforcement is important. For the slab system, helical reinforcement is preferred by the main contractor due to the speed and ease of installation. It must be noted that by providing a single helix around an anchorage is not adequate since tensile forces are also generated between anchorages. It is usual to detail u-bars plus longitudinal reinforcement along the perimeter to control these forces and to reinforce the un-tensioned area between anchorages.

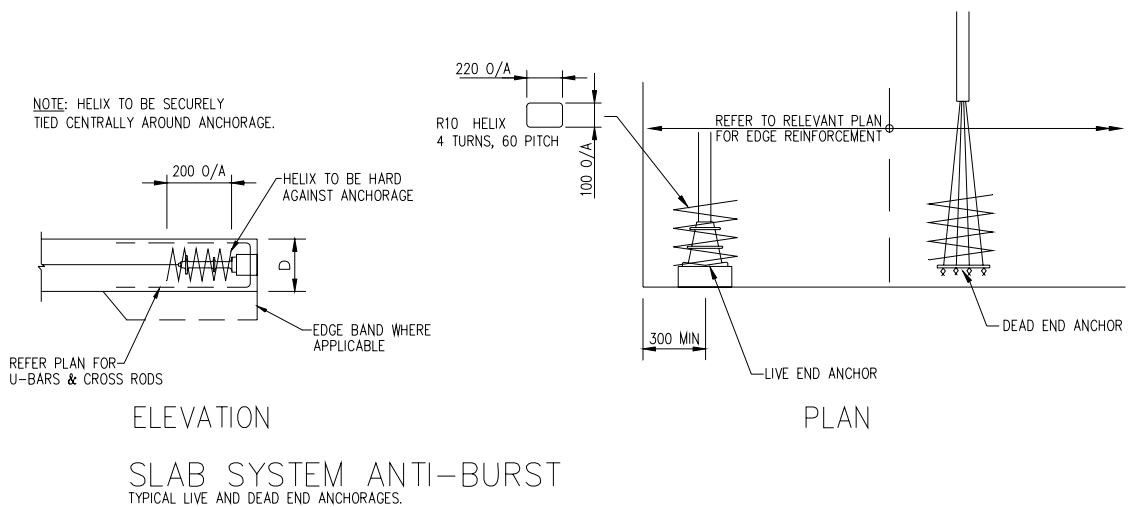


Figure 7 – Slab system anti-burst reinforcement.

7. L/D Ratios

Choosing the right L/D ratio for the structural system and applied loading is important. Choosing a high L/D ratio may minimise the amount of concrete, but will increase the amount of post-tensioning and/or reinforcement required, and perhaps cause increased vibration. Choosing a low L/D ratio in order to minimise post-tensioning may not secure the expected result due to minimum reinforcement rules and adequate residual compression levels to ensure shrinkage cracking is controlled.

8. Load Balancing

The selection of the load to be balanced by the post-tensioning tendons is an important factor in the economics of post-tensioned systems. One of the major advantages of post-tensioning is to reduce the long-term deflection of the structure, however selection of too high a load to balance may incur prestressing costs reducing the economy of the prestressed solution. A combination of a lower level of 'balanced load' and the addition of normal reinforcement at peak moment regions will prove to be a more economical solution in most applications. Table 1 is a guide to the amount of load to balance under a range of building uses.

Occupancy of building	Partitions and Other Superimposed Dead Load kPa	Live Load kPa	Load to Balance kPa
Car Parks	Nil	2.5	(0.7-0.85)SW
Shopping Centres	0.0 - 2.0	5.0	(0.85-1.0)SW
Residential (check transfer carefully)	2.0 - 4.0	1.5	SW + 30% of partition load
Office Buildings	0.5 - 1.0	3.0	(0.8-0.95)SW
Storage	Nil	2.4 kPa / m height	SW + 20% LL

Note: SW denotes self weight, LL denotes live load.

Table 1. General level of load to be balanced by post-tensioning tendons to give an economic structure.

9. Terminate Tendons Wherever Possible

Often the amount of post-tensioning required within a member varies across its length. For example, end bays usually require a greater level of prestress to control deflections than internal bays. Terminating the post-tensioning once it is not required can be achieved by either terminating whole tendons or terminating individual strands using a 'short dead end'.

10. The Use of Finite Element Analysis for Selected Projects

With the advent of sophisticated finite element analysis programs that are relatively easy to use, significant economy can be gained for selected projects. The types of structures benefiting from FEA methods are residential flat plate construction with an irregular supporting column grid and transfer structures such as transfer plates and raft foundations.

We find that the use of FEA methods for these types of structures allow for a better determination of structural load paths and enables the designer to detail and drape the post-tensioning tendons to better reflect the slab bending moments. This is what leads to economy.

STRUCTURAL SYSTEMS

The three most common floor systems used for building structures such as offices, shopping centres and car parks are the flat plate, flat slab and banded slab. For high rise construction a fourth system is widely used which consists of band beams at relatively close spacing spanning from the building perimeter to the service core.

Although economy of each of these depend primarily on the span and applied load, it is generally true to say that a band beam scheme is cheaper than a flat slab which in turn is cheaper than a flat plate.

To illustrate this an analysis was carried out on a structural scheme for each of the three systems to show the percentage cost of each structural component. The schemes were based on a column grid of 8.5 m and imposed load of 5 kPa. A total relative cost figure, also shown, is obtained by multiplying each structural element by its cost rate. This rate varies from country to country, but the trend will remain unchanged. Refer to table 2 below.

FLOOR SYSTEM	Flat Plate	Flat Slab	Banded Slab
Concrete	25	24	24
Reinforcement	6	6	8
Post-tensioning	26	23	20
Formwork	43	47	48
TOTAL	100%	100%	100%
Relative total cost	1	0.97	0.96

Table 2. Percentage floor costs.

Post-tensioning is not limited to simple flat slabs and the range of structural types which can be economically stressed is almost limitless. Some of the most common floor systems are presented below along with recommended concrete sizes and span to depth ratios.

Note that the span to depth ratios given depend on the element being an internal bay, end bay or simple span. Figure 8 explains the differences.

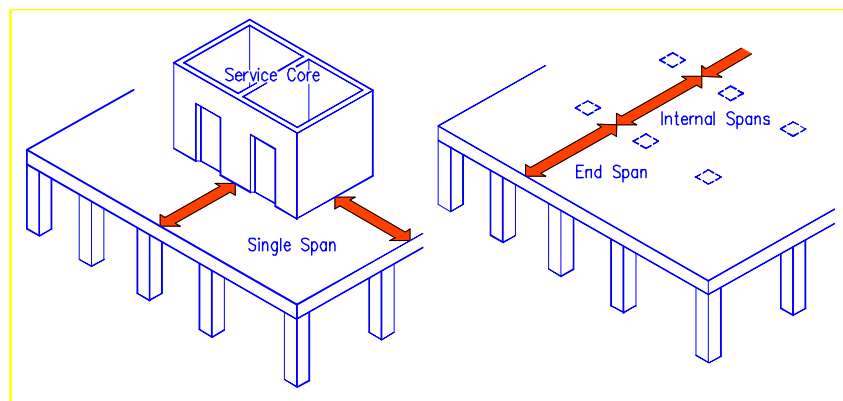


Figure 8: Examples of single spans, end spans, and internal spans.

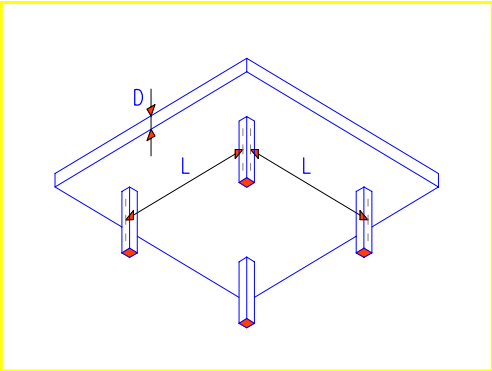
It should be noted that although often only of secondary consideration, the choice of the system can depend upon factors other than column spacing, imposed loads and economics. Headroom clearance for services, or a flat soffit for aesthetics are two other possible governing criteria.

1. Flat Plate (figure 9)

This system is commonly used in Sydney for high rise residential construction where the span is usually 7 to 8 metres. The most attractive feature of this floor system is its flush soffit which requires simple formwork and greatly simplifies construction.

The depth of a flat plate is often dictated by shear requirements. Thinner slabs or longer spans can be constructed if column capitals or shear heads are employed.

Used	Where spans are similar both directions
Economic Span Range	7.0 to 9.0 m
Imposed Loads	Up to 7.5 kPa



	Imposed Load (kPa)	Span/Depth Ratio
Single Span	3	33
	5	31
	10	28
End Span	3	39
	5	36
	10	32
Internal Span	3	45
	5	42
	10	38

Figure 9: Flat plate

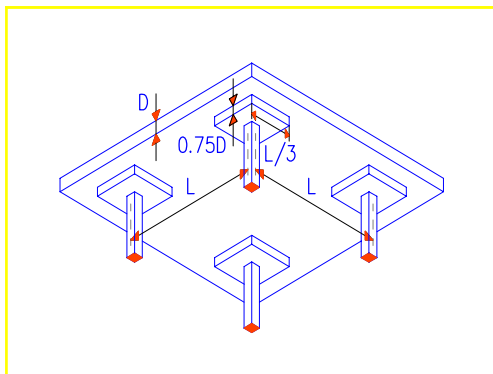
2. Flat Slab (figure 10)

A widely used system today for many reasons - flat soffit, simple formwork and ease of construction, as well as flexibility for locating services.

The economical span range over a flat plate is increase by the addition of drop panels. The drop panels increase the flexural stiffness of the floor as well as improving its punching shear strength.

This system provides the thinnest floors and can lead to height reductions and substantial savings in facade costs.

Used	Where spans are similar both directions
Economic Span Range	Up to 13.0 m
Imposed Loads	Up to 10.0 kPa



	Imposed Load (kPa)	Span/Depth Ratio
Single Span	3	38
	5	35
	10	32
End Span	3	46
	5	43
	10	40
Internal Span	3	52
	5	49
	10	45

Figure 10. Flat slab

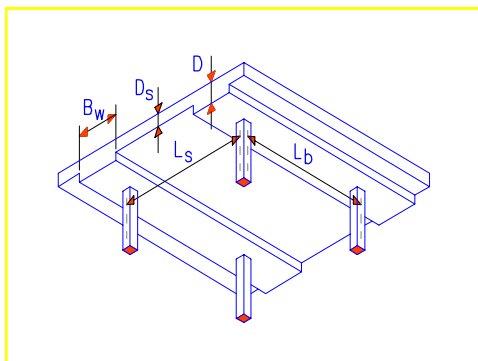
3. Banded Slab (figure 11)

This system is used for structures where spans in one direction are predominant. It is also a very common system due to minimum material costs as well as relatively simple formwork. In most circumstances the width of the band beam is chosen to suit the standard sizes of the formwork. The sides of the band can be either square, or tapered for a more attractive result.

The band beam has a relatively wide, shallow cross section which reduces the overall depth of the floor while permitting longer spans. This concrete section simplifies the formwork and permits services to easily pass under the beams. The post-tensioned tendons are not interwoven leading to fast installation and decreased cycle time.

The band beam system has another advantage which is not widely appreciated. In most circumstances depending on the actual geometry of the cross section the beam can be considered as a two way slab for fire rating and shear design. This enables considerable economies to be achieved in both post-tensioning and reinforcement quantities.

Used	Span predominant in one direction
Economic Span Range	Band Beam: 8.0 to 15.0 m Slab: 6.0 to 10.0 m
Imposed Loads	Up to 15.0 kPa



		Imposed Load (kPa)	Span/Depth Ratio
Slabs (Ls)	Single Span	3	38
		5	35
		10	32
	End Span	3	46
		5	43
		10	40
Band Beams (Lb)	Single Span	3	20
		5	18
		10	16
	End Span	3	24
		5	22
		10	19
Internal Span	3	27	
	5	25	
	10	22	

Figure 11. Banded slab. Note that the band width, B_w is generally in the range $0.15L_s$ to $0.25L_s$. The band sides can be square or tapered.

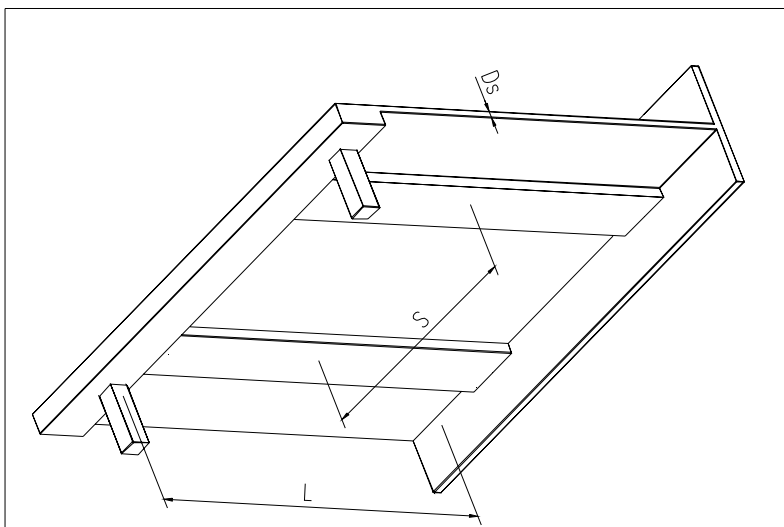
4. High Rise Banded Slab (figure 12)

This system has gained favour over the past 10 to 15 years for high rise construction and consists of band beams at relatively close centres spanning between a perimeter beam and the service core. The system suits system formwork due to the amount of re-use in high rise construction.

Services may either pass under the shallow bands or, alternatively, pass under service 'notches' in the band soffit.

For clear slab spans in excess of 4.5m the use of post-tensioning is economical perpendicular to the bands and assist in reducing the weight of slab carried by the bands.

Used	Long span high rise construction
Economic Span Range	Band Beam: 9.0 to 15.0 m
Imposed Loads	Up to 7.5 kPa



	Slab Span	Band Width	Span / Depth Ratio
Band Beam (L)	S= 4800, D _s = 120 RC	b _w = 1000	22
	S= 6000, D _s = 120 P-T, 150 RC	b _w = 1500	20
	S= 8400, D _s = 160 P-T	b _w = 1800	18

Figure 12. High Rise Banded Slab.

FUTURE FLEXIBILITY, PENETRATIONS & DEMOLITION OF POST-TENSIONED STRUCTURES

Post-tensioned floor slabs in Australia are now universally regarded as the most cost effective form of construction for shopping centres, office buildings, and carparks where spans exceed 7.5 metres. The preferred post-tensioning system used is the well proven 'bonded' tendon utilising from 3 to 5 individual prestressing strands housed in oval ducting and anchored in flat fan shaped anchorage castings.

A question often asked of post-tensioned slab systems is what happens if we wish to make a penetration in the slab after construction.

From time to time it has been brought to our attention that certain members of the building profession see this question as a major obstacle and are reluctant to accept the use of prestressing in some types of buildings. This is often due to a perceived lack of flexibility in the structure when it comes to the formation of openings through the slabs some time after construction.

This section will outline the options available to enable the designer to produce a building which is both economic to construct and easy to modify in the future.

Planning For Openings

1. Possible Future Requirements

There is no doubt that during the lifetime of a structure the requirements of a tenant may alter with time or the tenant may change several times. Each new tenant will have his own requirements for mechanical, hydraulic and electrical services, as well as loading arrangements and general layout.

Therefore, for a building to remain readily lettable in the future it must have the flexibility to accommodate openings for stairs, services or lifts, and the possibility for changes in loading patterns.

2. Choice of Building System

No building system can be infinitely flexible in terms of future tenant requirements.

Whether a slab is constructed from post-tensioned concrete, pre-cast concrete, structural steel or insitu reinforced concrete there will be certain areas such as main beam strips where holes cannot be accepted without significant difficulty.

3. Overall Structural adequacy

Whatever the building system and material, it is important to locate the new opening with due regard to the structural stability of the remaining portion of slab. The Structural Engineer must check the penetration location and advise any remedial work required, such as trimming beams, regardless of the structural system.

A post-tensioned slab will have similar strengths and weaknesses in terms of its flexibility as insitu reinforced concrete. For example, if a new stair well were to be located in the centre of a panel such that short cantilever slabs were retained on all sides to counterbalance the adjacent bays, it is quite possible that no additional supporting members would be required.

A precast system or steel framed structure may require the removal of the whole panel, construction of trimmer beams around the new void, and replacement of the slab to the surrounding edges.

Designing Post-Tensioned Slabs For Future Openings

1. Locating post-tensioning tendons

For post-tensioned slabs and beams where tendon positions may not be readily identifiable, soffit marking can be employed. Prior to casting the slab, stainless steel staples are used to secure the ducts to the formwork. When the formwork is struck, the position of the tendons is obvious, especially if the staple lines have been linked by painted lines.

Alternatively, chalk lines can be marked on the slab top surface to aid in the locating of post-tensioning tendons. This procedure will assist in locating openings away from tendons.

2. Structural systems in post-tensioned concrete

a) Band Beam and Slab

For rectangular grids the band beam and slab solution may be appropriate. This is the system typically used for shopping centres and car parks due to the economic benefit and relative insensitivity to floor height restrictions.

Normally band beams span in the long direction and impose the same constraints on hole placement as would a steel or reinforced concrete beam. However, small hydraulic type penetrations (approximately 150 mm diameter) can usually be accommodated without the need for remedial action.

The slabs however, are usually quite lightly prestressed with tendons in one direction only at approximately 1500 mm centres. Reasonable size openings or large slots are therefore easy to accommodate without the need to cut post-tensioning tendons.

b) Flat Slabs and Flat Plates

For structures requiring minimum floor to floor height and regular grids the two-way post-tensioned flat slab is usually the most cost effective solution.

The normal installation procedure would concentrate the tendons into 'column strips' along the column grids at approximately 600 mm centres with tendons away from the column strip at approximately 1400 mm centres.

Consequently small holes for services could be located without the need to cut tendons.

Using this structural system it is possible to leave the central panel as traditionally reinforced and designed as a 'soft zone' to easily accommodate large openings. The cost penalty for the extra reinforcement required would need to be offset against the perceived benefits.

c) Ribbed and Waffle Slab

Larger grids or heavier loads may dictate the introduction of ribs spanning either one-way or two-way (waffle) depending upon the aspect ratio of the grid.

Rib spacings for post-tensioned slabs are generally larger than for reinforced concrete, being typically 1.2 to 1.5 metres. Consequently small to moderate holes can easily be cut through the topping slab without disturbing the ribs. Indeed with tendons confined to the ribs their location is readily identifiable, assisting in the siting of the openings.

Cutting Of Tendons

1. Bonded Tendons

Bonded tendons are located within oval shaped galvanised ducts which are injected with cement grout following the post-tensioning procedure. Consequently when such a tendon is severed, the free end will become de-tensioned but after a short transmission length the full tendon force will be effective. This distance is in the order of 800 to 1000 mm.

Present quality assurance methods and supervision ensure that the tendons have been adequately grouted after the application of prestress.

If a penetration is required that will need the termination of a bonded tendon, then the procedure follows that for a fully reinforced structure.

Cutting a bonded post-tensioned tendon is, structurally, the same as cutting through conventional reinforcement. The tendon, however, needs to be 'terminated' in order to give full corrosion protection (as does conventional reinforcement).

Tendons are easy to cut using a disc cutter. In fact, cutting tendons requires less effort than for a fully reinforced slab due to the relative amount of reinforcing material to be cut.

2. Unbonded Tendons

These tendons come individually greased and plastic coated and are therefore permanently de-bonded from the slab.

When unbonded tendons are severed, the prestressing force will be lost for the full length of the tendon.

Note that this form of post-tensioning is not allowed in suspended slabs in Australia and therefore problems associated with cutting unbonded tendons are not applicable.

When contemplating the cutting of an unbonded tendon it is therefore necessary to consider the aspects as noted below.

a) Cutting the tendons.

The strand is packed with grease which prevents an explosive release of energy when the tendon is severed. Even so a gradual release of force is recommended. This can be achieved by using two open throat jacks back to back. After cutting the strand the force can be gently released by closing the jacks.

b) Propping the slab.

Adjacent spans may require temporary propping depending upon the number of tendons severed at one time. It is rare for a slab to carry its full design load. A design check based on actual loading at the time of the modification may show props to be unnecessary.

c) Forming the hole.

When the edge of the slab is re-concreted new anchors are cast in to enable the remaining lengths of tendon to be restressed, thus restoring full structural integrity. The above operations are not difficult but will require the expertise of a post-tensioning sub-contractor.

Demolition Of Post-Tensioned Structures

In the case of post-tensioned structures using bonded tendons, demolition can be carried out using techniques similar to those used to demolish reinforced concrete structures. Due to its induced compression the concrete is significantly harder and whilst tendons are made from high tensile strand there is considerably less steel to cut and generally concrete sections will be thinner than comparable reinforced concrete structures.

Only in the case of transfer slabs or beams, which have been progressively stressed, must extra precautions be taken to avoid upward bursting of concrete as the self weight of the structure above is progressively removed.

The cutting of unbonded tendons may result in dramatic collapse of a structure, but properly considered, can be used to advantage, enabling rapid demolition of large areas as the force in the supporting tendons is released.

In Summary

It is not uncommon for post-tensioning to be rejected in certain types of building project due to a perceived lack of flexibility. This, in the majority of cases, is based more on a fear of the unknown than on sound technical knowledge.

With a little forethought it can be seen that post-tensioning need not mean a dense mat of tendons in all directions. Tendons are usually spaced sufficiently far apart to allow penetrations of reasonable size to be made later, without cutting through the tendons.

Where there is a reasonable possibility that a penetration may be required in the future, slabs can be built with 'soft zones' to allow later perforation by voids without cutting tendons.

Should it be necessary to cut tendons this can easily be achieved using well established methods and in short, whilst the modification of a post-tensioned slab may require more planning than other forms of construction, its use will present the client with a building which is both economical to construct and flexible for its life.

CONCLUSION

In conclusion it is worthy to reinforce a few key points.

There is a definite trend towards large spans in buildings due to the fact that there is now more emphasis on providing large uninterrupted floor space which can result in higher rental returns.

Post-tensioning is an economical way of achieving these larger spans. For spans 7.5 metres and over, post-tensioning will certainly be economic and, as the spans increase, so do the savings.

The most significant factor affecting the cost of slab system post-tensioning is the tendon length. Other factors create a scatter of results leading to an upper and lower bound. Notwithstanding this, it is always advisable to obtain budget prices from a post-tensioning supplier.

The main structural schemes available are the flat plate, flat slab and banded slab, with the latter generally leading to the most cost-efficient structure. However, other factors such as floor to floor heights, services, etc., must be taken into account in the selection of the floor structure.

For high rise construction and highly repetitive floor plates, the use of more specialised structural schemes is appropriate with emphasis on systems formwork.

It is not uncommon for post-tensioning to be rejected in certain types of building project due to a perceived lack of flexibility. However, tendons are usually spaced sufficiently far apart to allow penetrations of reasonable size to be made later, without cutting through the tendons. Should it be necessary to cut tendons this can easily be achieved using well established methods.