SLAB

SYSTEMS

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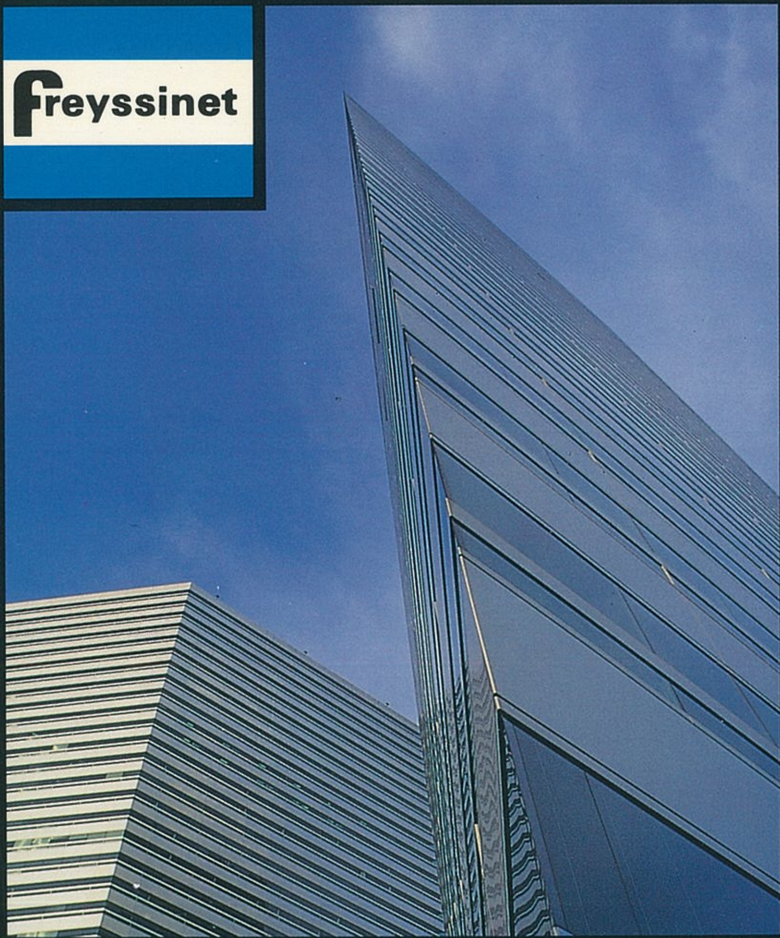

POST TENSIONING SYSTEMS

THE FREYSSINET GROUP

The Freyssinet Group of Companies is an international group based in France involved in all areas of specialist construction engineering. The organization is named after its founder, Eugene Freyssinet, widely acknowledged as the inventor of prestressing methods. Since the inception of prestressing, the Group's activities have diversified considerably, nonetheless post-tensioning, in bridges and in buildings, remains a key element in Freyssinet's involvement in construction projects and civil engineering.

As one of the largest specialist international sub-contractors, Freyssinet has been a leader in innovation and development in its fields of specialization. This brochure outlines technical aspects of the Freyssinet post-tensioned slab system, predominantly employed in buildings.

Cover photograph: "The Gateway" Singapore.

CONTENTS

1. Introduction

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Modern architecture places more and more 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.

This method of construction has, over the past 20 years, been widely used in many countries, and has proven to be more economical than many of the traditional methods.

The post tensioned structural system provides architects, consultants and investors with an economical solution to the design of floors and roofs of such projects as multi-storey office buildings, car parks, hospitals, schools, commercial and administrative centres, and apartment blocks.

The design of flat slabs has evolved since the mid fifties, when the first post-tensioned slabs were built. Experience has enabled methods and criteria to be improved with greatly simplified structural design techniques, such as the load-balancing method and the equivalent frame method, both now widely used.

Freyssinet can provide design assistance at any stage: feasibility studies, conceptual layout, structural analyses, selection of frames, complete design computations, and preparation of construction drawings and stressing data.

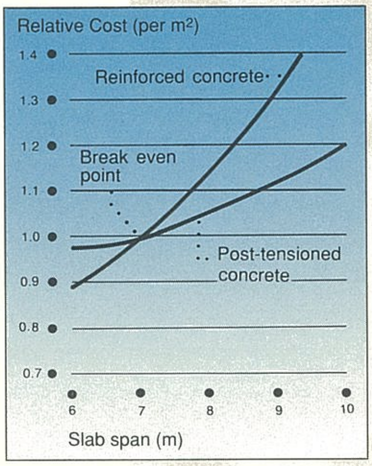

Figure 2A

Cost Comparison Reinforced vs Post-tensioned Concrete Slabs

The principal post-tensioned slab system in Asia is the well proven bonded tendon utilizing from 2 to 5 strands housed in oval ducting anchored in flat fan shaped anchorage castings. Stressing is carried out strand by strand using lightweight, portable jacking equipment. This system can be applied equally well to both suspended slabs and slabs on grade offering the following advantages:

SUSPENDED SLABS

- Large, column free floor areas.
- Superior economies for slabs with spans in excess of 7.0m.
- Reduced section depths allowing minimum building height and structure self weight, with resultant savings in the cost of both foundations and the structure itself.
- Earlier stripping of formwork and reduced backpropping requirements.
- Reduction in construction time and onsite cranage requirements.
- Elimination of undesirable deflections under service loads.
- Control of cracking and, if desired, waterproof slabs without the need for membranes.

SLABS ON GRADE

- Economic for slabs subject to heavy loadings particularly on poor ground.
- Enables pouring of large areas saving both in joints and construction time.
- Elimination of substantial foundations for slabs on poor subgrade.
- Allows reduction in slab thickness, particularly for raft slabs.
- Free of cracks and hence resistant to penetration of moisture and aggressive chemicals.

2. Economics

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The relative economics of post-tensioning versus other forms of construction vary according to the specific requirements of each case and 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 and reinforced concrete alternatives. As can be seen from Figure 2A, post-tensioning should be considered as a possible economic alternative for most structures when spans are approaching 7.0m.

For spans 8.0m and over post-tensioning will almost certainly be economic and as the spans increase so do the cost savings.

Formwork costs are similar for both reinforced and post-tensioned slabs but the savings result from the reduction in concrete and reinforcement which is possible with a post-tensioned alternative.

An example of a cost comparison on a project constructed using post-tensioning originally designed as reinforced concrete is set out in Table 2A with the following characteristics.

Structural Component	RC Design	Post-tensioned
Concrete	25%	21%
Reinforcement	35%	5%
Post-tensioning	—	25%
Formwork	40%	40%
Total	100%	91%
Cost Saving	---	9%

Table 2A

Cost Comparison-Example

Typical Span – 8.5m
Live Load – 5 kPa
Fire Rating – 2 hours
Concrete – 35 mPa

Post-tensioning is now used in most types of building structures and with most structural floor systems, typical details of which are shown in the accompanying diagrams. Of these the flat plate, flat slab and band beam systems are more often used with the band beam most commonly chosen for post-tensioned suspended slabs due to its cost effectiveness and ease of construction.

The speed of construction and hence the economics of post-tensioned concrete are highlighted in the typical multi-storey building programme shown in Figure 2B. This programme, for a floor area of approximately 1000m² requires only two sets of table formwork and allows a half level concrete pour every five days.

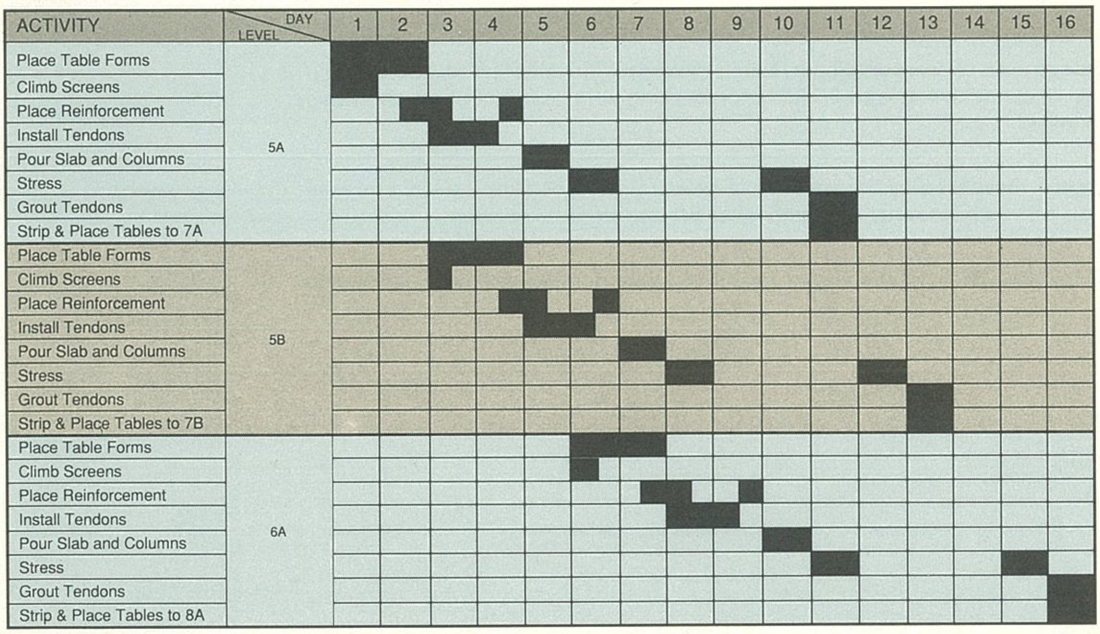

Figure 2B

Typical Construction Programme for Multi-storey Building with Post-tensioned Floor Slabs

3. Applications

3.1 FLOOR SYSTEMS

One of the most significant advantages offered by post-tensioned slabs is the ability to span longer distances for a specified slab depth. A thin flat slab can often be constructed in post-tensioned concrete when, with reinforced concrete, a deep waffle or trough floor may be necessary.

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 depths. The depths are based upon added dead and live loads of 3 to 5 kPa with a 2 hour fire rating.

FLAT PLATE

This is the floor system most generally employed for apartment blocks, office buildings, hospitals, hotels, etc. where spans are similar in both directions. It is very economical for spans between 7 m and 8.5 m.

The principal feature of the flat plate floor system is its flush soffit which requires only simple formwork and therefore offers increased "constructability".

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

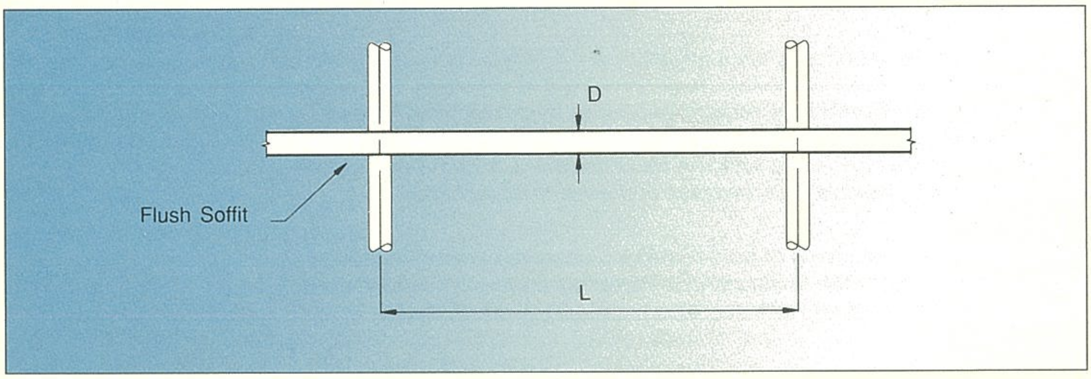

Figure 3A

Flat Plate

Span/Depth Ratios
a) Single Span, End Span
D = L/42
b) Internal Span
D = L/49

FLAT SLAB

A flat slab floor system has similar characteristics to those described for a flat plate: flat soffit, simple formwork and ease of construction with flexibility for locating services. It is used when larger spans up to 12 m are required.

The economical span range is increased by the addition of drop panels. The drop panels increase the stiffness of the floor as well as improving its punching shear strength.

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

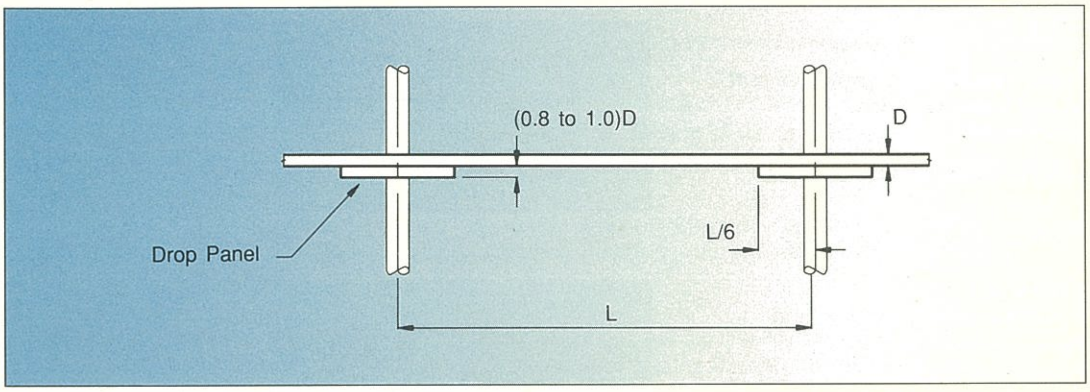

Figure 3B

Flat Slab

Span/Depth Ratios
a) Single Span, End Span
D = L/50
b) Internal Span
D = L/56

BANDED SLAB

Used in car parks, schools, shopping centres etc., where spans in one direction are predominant and live loads are relatively light. Spans up to 15m for bands and between 7 m and 12 m for the slab.

This is a common system due to minimum material costs as well as relatively simple formwork. In most circumstances the width of the band beam may be chosen to further simplify the formwork.

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

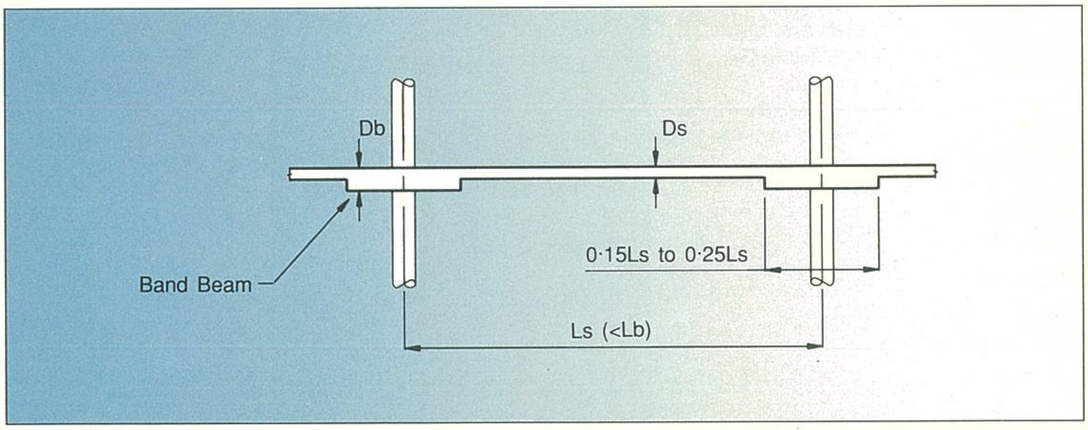

Figure 3C

Band Beam and Slab

Span/Depth Ratios
Multi-Span Band Beams
a) End Span
Lb = 24 x depth, Db
b) Internal Span
Lb = 28 x depth, Db

Multi-Span Slab
a) End Span
Ls = 50 x depth, Ds
b) Internal Span
Ls = 56 x depth, Ds

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OTHER SYSTEMS

Beam and Slab

Relatively deep beams framing into columns provide a stiff floor capable of long spans and heavy loadings.

Spans vary from 10 m to 20 m. Used for offices, public buildings etc.

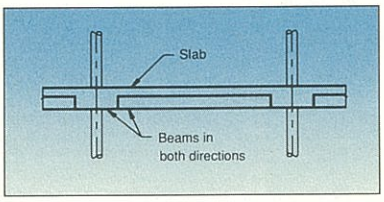

Figure 3D

Beam and Slab

Slab Band and Ribs

Recommended where spans are predominantly in one direction with heavy loading.

Band beams span in the short direction with closely spaced ribs spanning in the long direction

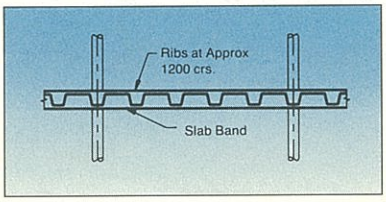

Figure 3E

Slab Band plus Ribs

Waffle Slab

Commonly used in buildings where spans are approximately equal in both directions and subject to particularly heavy loadings.

It is only economic for large spans. Typically 14 m and over.

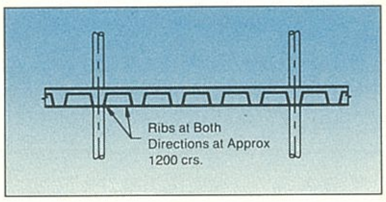

Figure 3F

Waffle Slab

The most common floor systems for offices, shopping centrees and carparks are the flat plate, flat slab and band beam and slab. Based upon a 9.0m grid system Table 3A shows approximate percentages of building materials required for the overall structural cost of a floor system.

Table 3A

Approximate Percentages of Floor Cost

Floor System	Flat Plate	Flat Slab	Band Beam
Concrete	26	25	25
Reinforce-ment	5	5	7
Post-tensioning	29	27	24
Formwork	40	43	44
Total	100	100	100
Relative Total Cost	1	0.97	0.96

3.2 TENDON SYSTEMS

Post-tensioned suspended slabs and slabs on grade can be constructed using bonded or unbonded tendons.

The bonded system utilizes plain strand within galvanised ducting which is subsequently injected with cementatious grout after stressing. This brochure details the bonded system used by Freyssinet.

In contrast, unbonded systems comprise individually greased strands in polythene sheathing with no grouting process. Details are available upon request. This is typically North American practice.

SLAB PENETRATIONS

Where bonded systems are used, tendons are usually spaced sufficiently far apart to allow penetrations of reasonable size to be made later, without cutting though the tendons.

With unbonded systems the tendons are spaced more closely and are less well suited to later cutting of penetrations.

Tendon layouts must always be thoroughly checked before cutting penetrations and if tendons must be cut then the effect on the slab should be assessed by a qualified Engineer beforehand.

DEMOLITION

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.

4. Construction

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4.1 INSTALLATION

The construction of post-tensioning tendons in a suspended slab or slab on grade can be separated into three distinct activities; installation, stressing and grouting.

The installation of post-tensioned slabs normally starts towards the end of the formwork activities and is coincident with reinforcement fixing.

Anchorages are fixed by bolting through a recess former, to the edge form. The galvanised duct is laid out between the anchorages to allow the pushing through of the prestressing strands, either by mechanical or manual means, depending on length.

The ducting is then profiled to the required dimensions using duct chairs and securely fixed to the formwork by the use of staples. For accurate profiling it is recommended that support centres should be kept to a maximum of 1 metre. After final taping and sealing of ducts and anchorages to prevent the ingress of concrete slurry the deck is ready for the commencement of the concrete pour.

4.2 STRESSING

The stressing procedure is specified by the design engineer to suit the particular performance of the slab but is generally carried out in two stages. Firstly, an initial stress to 25% of final load is applied at 24-48 hours after completion of the pour. The final stress is applied when the concrete strength reaches f'_{cp} = 22 MPa. This occurs between 5 and 8 days after completion of the pour depending on concrete mix design and ambient temperature. The concrete strength must be confirmed by speciments tested in accordance with the relevant building codes.

The stressing of the tendons is completed using lightweight stressing jacks driven by electrically powered hydraulic pumps. These jacks have an automatic front-pull grip which require 225 mm of strand projecting from the anchorage for stressing.

4.3 GROUTING

After certification of the stressing results by the design engineer the excess strand at the anchorages is trimmed to give a minimum cover of 25 mm. Permanent corrosion protection of the anchorages is provided by the insertion of a dry pack mortar of 2:1 sand/cement. This mortar seals the anchorage recess and allows the grouting operation, which will provide permanent bonding of the strand to the duct, to proceed.

The grout mix has a water/cement ratio in the range of 0.40 to 0.48 by weight and contains an antibleed additive. The water/cement ratio can be checked by measuring the relative density of the grout to ensure good control over sedimentation and bleeding.

The mixing and injection of the grout is completely by a portable, electrically driven mixer/pump unit with a maximum working pressure of 1000 kPa.

The grout mix is pumped through injection points at each anchorage. When grout consistent with the injected grout emerges from all intermediate vents the duct is progressively sealed off. A nominal pressure is applied at the remote vent to ensure the grout has encapsulated all strands within the duct.

This information is a guide to the general activities involved in post-tensioned construction. Freyssinet has an experienced Construction Division available to assist Developers, Engineers, Architects and Builders to co-ordinate and plan their Project.

5. System

5.1 STRAND PROPERTIES

Table 5A

Strand Properties

Standard	Grade	Size	Nominal Dia. mm	Nominal Section mm^2	Nominal Weight kg/m	Specified Breaking Load kN	Specified Breaking Load kips	Specified Load At 1% Elongation kN	Specified Load At 1% Elongation kips
Euronorm 138-6/79 standard	1770 MPa	1/2"-T13	12.5	92	0.730	164	36.9	139	31.3
	1860 MPa	1/2"-T13	12.5	93	0.730	173	38.9	147	33.1
	1670 MPa	0.6"-T15	15.2	139	1.090	232	52.2	197	44.3
	1770 MPa	0.6"-T15	15.2	139	1.090	246	55.3	209	47.0
Euronorm 138-6/79 super	1860 MPa	1/2"-T13	12.9	100	0.785	186	41.8	158	35.5
	1770 MPa	5/8"-T16	15.7	150	1.180	265	59.6	225	50.6
A.S.T.M. A416/80	250 kpsi	1/2"-T13	12.7	92.90	0.730	160.1	36.0	144.2	32.4
	270 kpsi	1/2"-T13	12.7	98.71	0.775	183.7	41.3	165.4	37.2
	250 kpsi	0.6"-T15	15.24	139.35	1.094	240.2	54.0	216.3	48.6
	270 kpsi	0.6"-T15	15.24	140.00	1.102	260.7	58.6	234.7	52.8

5.2 TENDON PROPERTIES

EURONORM SUPER GRADE

Table 5B

Tendon Forces (to EN138/6)

Nominal Diameter mm	Number of Strands	Steel Area mm^2	Minimum Breaking Load kN	Nominal Diameter mm	Number of Strands	Steel Area mm^2	Minimum Breaking Load kN
12.9	1	100	186	15.7	1	150	265
	2	200	372		2	300	530
	3	300	558		3	450	795
	4	400	744		4	600	1060
	5	500	930		5	750	1325

Table 5C

Flat Duct Dimensions

Anchor Type	No. Strands	Strand Diameter	DUCT. Size X * Y
3513	3		
4513	4	12.9	70x19
5513	5		
4515	4	15.7	70x19
5515	5	15.7	90x19

5.3 STRESSING JACKS

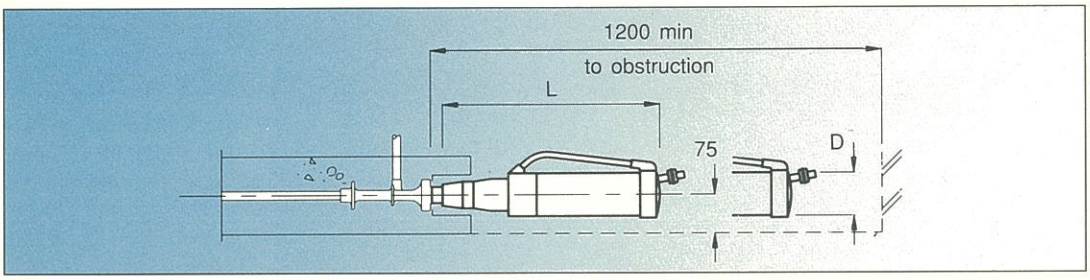

Figure 5A

Stressing at Slab Edge

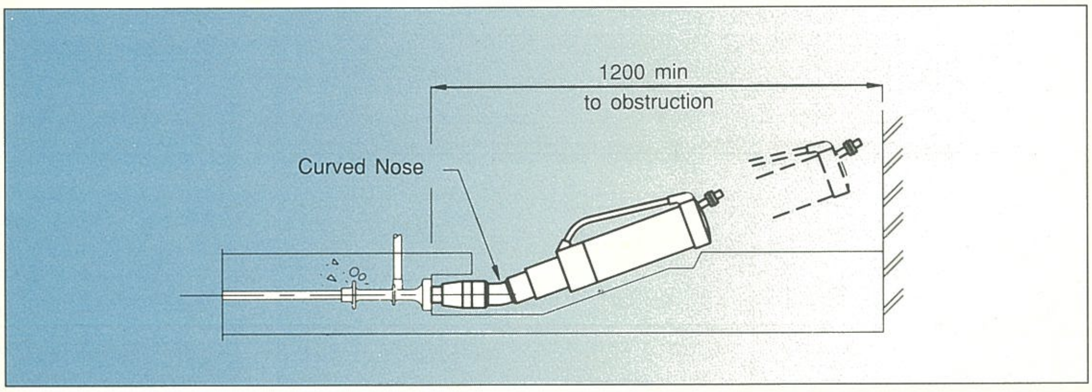

Figure 5B

Stressing in Pocket with Curved Nose

Table 5D

Stressing Jack Details

Jack Details		Jack Type	
		T20	T30
Stand Type (diam)	mm	12.7/12.9	15.2/15.7
Rated Capacity	kN	200	300
O/A Length (closed) L	mm	540	645
Body Height (daim) D	mm	120	145
Rated Pressure	kPa	54300	51600
Piston Area	mm	3700	5800
Stroke	mm	225	225
Stand Projection	mm	200	225

5.4 ANCHORAGES: BONDED FLAT DUCT SYSTEM-TYPE I

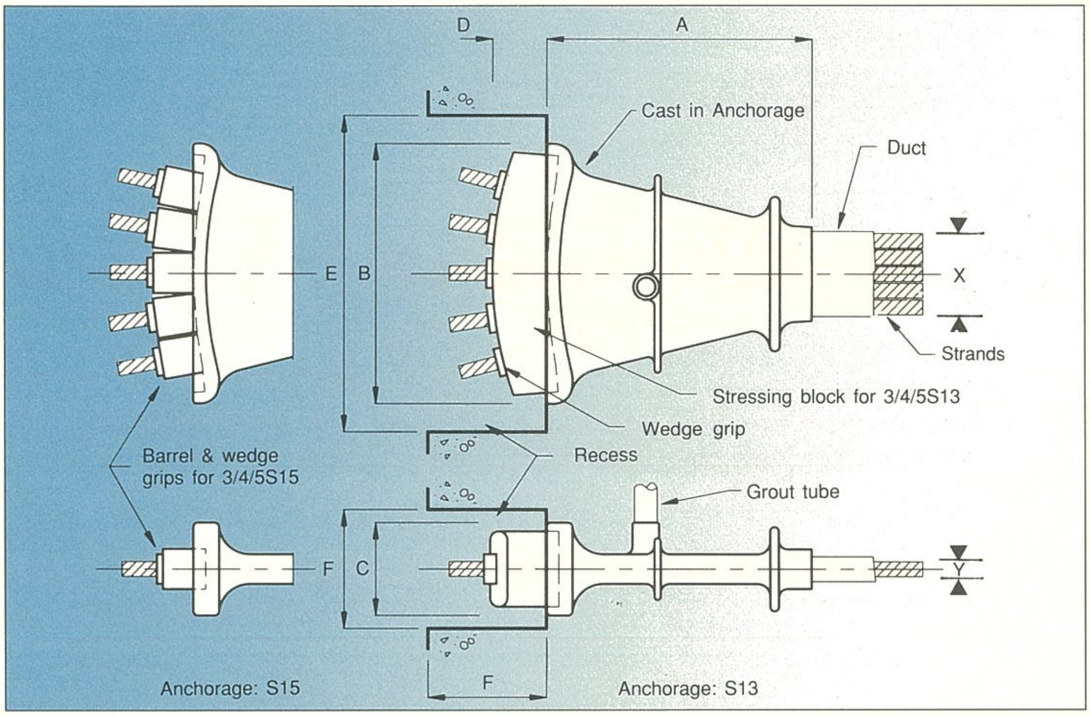

Figure 5C

Live End Anchorage

Type I

Plan

Side Elevation

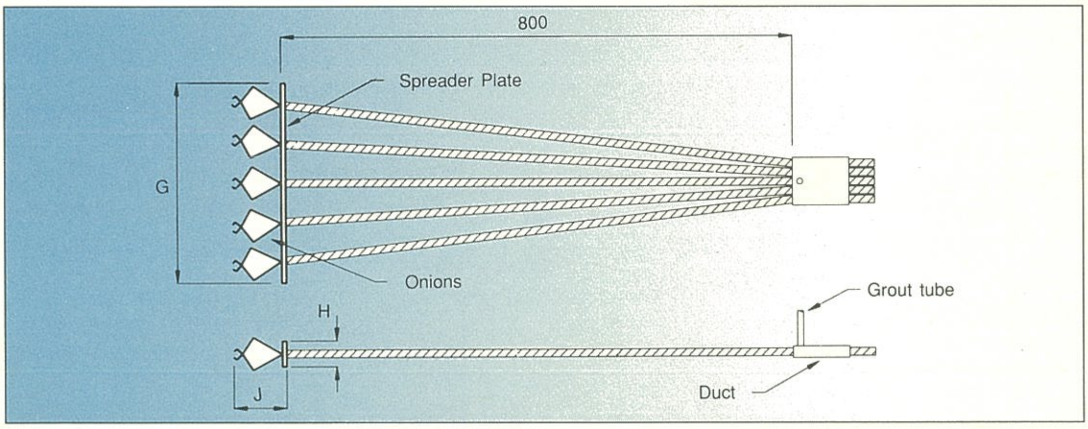

Figure 5D

Dead End Anchorage

Type I

Plan

Side Elevation

Table 5E

Slab Anchorage Dimensions Type I

Anchor Type	Number Strands	Strand Dia.	Dimensions (mm)								
			A	B	C	D	E	F	G	H	J
3S13 4S13 5S13	3 4 5	12.7	215	220	75	45	260	100	250	40	60
3S15 4S15	3 4	15.2	250	240	80	50	280	100	250	40	65
5S15	5	15.2	270	260	80	50	360	100	300	40	65

5.4 ANCHORAGES: BONDED FLAT DUCT SYSTEM-TYPE II

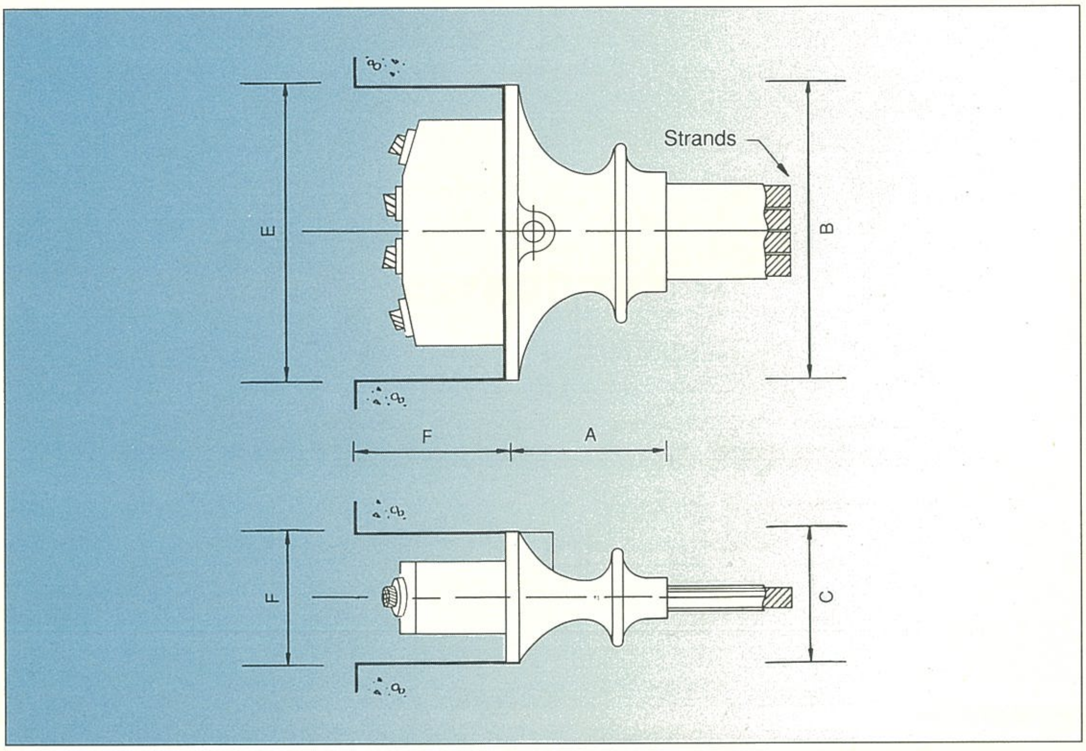

Figure 5E

Live End Anchorage Type II

Plan

Side Elevation

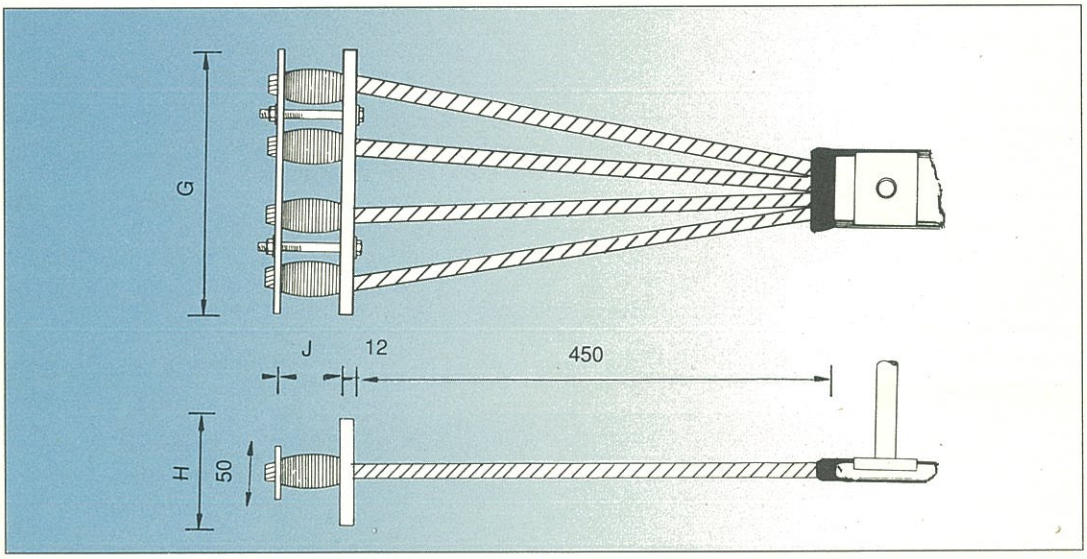

Figure 5F

Dead End Anchorage Type II

Plan

Side Elevation

Table 5F

Slab Anchorage Dimensions Type II

Anchor Type	Dimensions (mm)								
	A	B	C	E	F	F	G	H	J
4S13	95	195	85	215	90	90	250	100	30
4S15	110	230	100	230	120	110	250	100	30

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5.5 COUPLERS

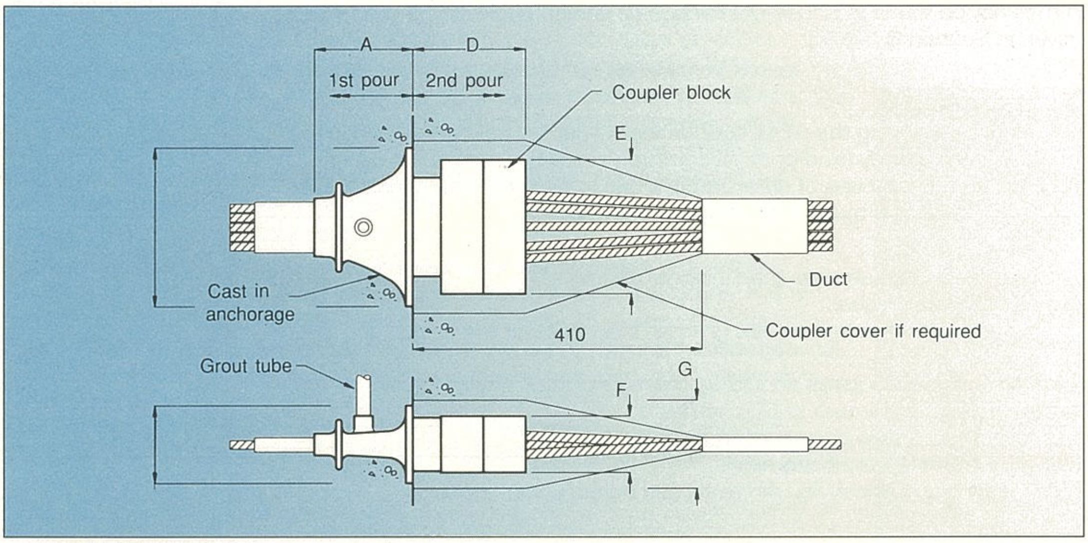

Figure 5G

Slab Coupler Anchorage

Plan

Side Elevation

Table 5G

Slab Coupler Anchorage Dimensions

Coupler Type	Number Strands	Strand Dia.	Dimensions (mm)						
			A	B	C	D	E	F	G
3SC13	3	12.7	140	225	110	120	170	60	100
4SC13 5SC13	4 5	12.7	140	225	110	160	190	80	100

4SC15 and 5SC15 details for specific applications provided on request.

5.6 INTERNAL STRESSING POCKETS

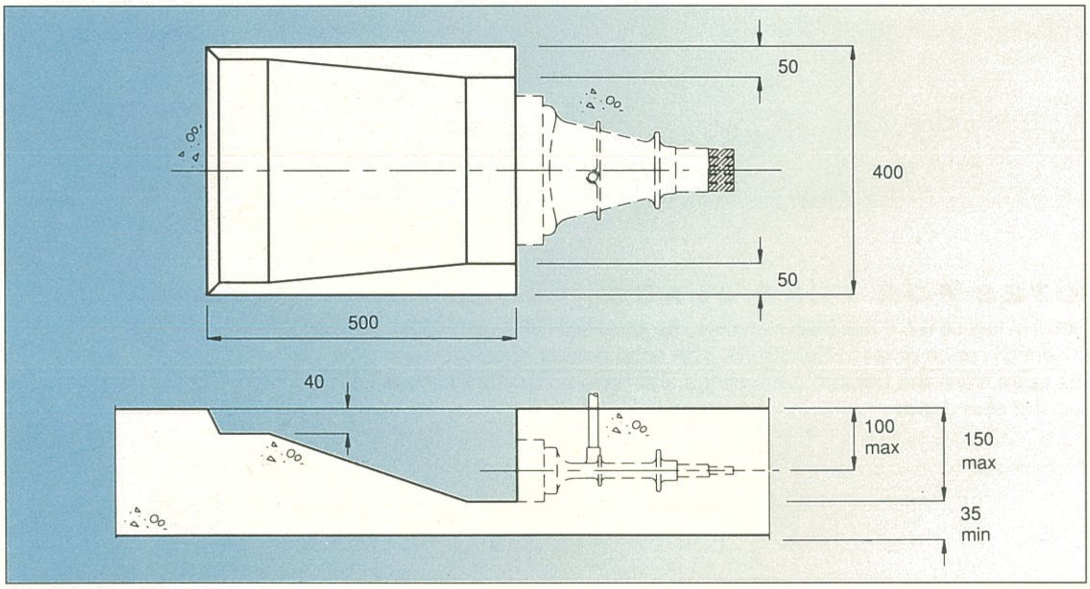

Figure 5H

Stressing Pocket Dimensions for Single Anchorage

Plan

Side Elevation

Double and triple anchorage stressing pockets are also available. Details provided on request.

6. Design

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6.1 SCOPE

This section of the manual is intended to provide information that could be useful in the design of post-tensioned slabs which may not be found in Codes of Practice or design publications currently available. References are given in Section 8.

6.2 OPTIMUM LAYOUT

Recommendations are often saught regarding the most economical layout for post-tensioned slabs. While support positions and spans are usually fixed prior to commencement of structural design, adjustment of these relationships and awareness of other factors can influence costs considerably. The following points are a guide to producing more cost effective designs.

- End spans should be approximately 20% shorter than internal spans.
- Internal spans should be approximately equal.
- Cantilevers should be used where possible and be not greater than 30% of the length of the a adjacent span.
- When required, expansion or contraction joints should be placed at about quarter span.
- Tendon length should be limited to a maximum of 60 metres.
- Tendons of 30 metres or less should have dead end anchors at one end.
- The use of tendons shorter than 8m is not economical.
- Couplers should be avoided where possible in lieu of reinforced construction joints.

6.3 DESIGN APPROACH

For an economical solution, suspended slabs may be designed using the load balancing method. This will determine the number of tendons required and their profile. The result must then be checked for serviceability and ultimate capacity.

The selection of the load to be balanced in an important factor in the economics of post-tensioned slabs and beams and should be carefully chosen to provide a balance between keeping prestressing costs to a minimum and providing a slab with satisfactory service load behaviour. Under the imposition of very high superimposed or live loads a proportion of the long term load should be balanced along with the self weight of the concrete. Table 6A can be used as a preliminary guide to the selection of the load to be balanced.

Table 6A

Preliminary Loads to Balance

Occupancy and Use	Superimposed Dead Load SDL (kPa)	Design Live Load LL (kPa)	Load to Balance (kPa)
Car Parks	–	3.0	(0.7-0.85) SW
Shopping Centres	0.0 to 2.0	5.0	(0.85-1.0) SW
Home Units	2.0 to 4.0	2.0	SW+30% SDL
Offices	0.5 to 1.0	3.0	(0.8-1.0) SW
Storage	–	2.4/m height	SW + 20% LL

Note: SW denotes self weight.

6.4 DESIGN NOTES FOR FLAT SLABS

The most economical structural layout for a flat slab requires the provision of a slab with a depth determined from the span/depth ratios given in Section 3. The drop panels should extend a minimum of 0.17 times the span from the column centrelines and have an additional depth of between 0.8 and 1.0 times the slab depth.

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The most economic tendon layout involves draping the tendons that occur over the extent of the drop panel to the edges of that drop panel. The remaining tendons are draped to the column centrelines.

It should be noted that for bonded tendon systems the behavior of a post-tensioned structure at the ultimate condition is not dissimilar to that of a reinforced concrete structure. The most efficient use of materials will be made by concentrating tensile force carrying elements in the region of the columns. The column strip middle strip design method documented in the literature is well suited to this approach.

For serviceability, the "hypothetical" flexural tensile stresses prescribed in BS8110 should be treated with caution. As outlined in section 6.1.4 of the British Concrete Society's Technical report No. 23, stress change in prestressed or conventional reinforcement is a more accurate parameter to reflect the condition of cracking. Where available, detailed cracked section analysis limiting the change in steel stress to 150 MPa between decompression load and full service load will produce the most accurate results. The "hypothetical" or "fictitious" stresses are best suited for preliminary design.

For slab design in a typically highly indeterminate building structure, where parasitic restraint effects may be quite significant, it may be more prudent to reply on appropriate detailing with well distributed bonded reinforcement, rather than hypothetical stress levels. Higher levels of prestress will often lead to higher stress gradients between zones of post-tensioning, and zones conventionally reinforced, with the possibility of cracking problems.

Example

For a slab with a span between columns of 9m, drop panels extending 3m overall and 80% of the panel load balanced in the column strip.

L_c = 6 m - column strip span
L_m = 9 m - middle strip span
y = 0.8 - fraction of load balanced in column strip

$$L_{eq} = \sqrt{y \cdot L_c^2 + (1-y) \cdot L_m^2}$$
$$= \sqrt{0.8 \times 6^2 + 0.2 \times 9^2}$$
$$= 6.71 \text{ m}$$
$$x = \frac{0.8 \times 6^2}{0.8 \times 6^2 + 0.2 \times 9^2}$$
$$= 0.64$$

i.e., place 64% of tendons in column strip as an initial estimate.

In highly prestressed slabs, with higher creep and elastic shortening, there is also the increased likelihood of restraint cracking. For these reasons, and those of economy, a partial prestress approach (BS8110 class 3), with moderate levels of prestress, is generally preferred to working stress methods for post-tensioned slab design.

To avoid separate load balancing calculations for both column and middle strips a relationship can be found between the two strips which simplifies the procedure and yields an economic solution. This relationship is termed the 'Equivalent Drape Length'. It takes into account the span between column centrelines, the span between drop panel edges and the distribution of tendons between the column and middle strips.

Once the equivalent drape length is found an initial estimate of the total number of tendons required for a panel, can be determined in one calculation using the normal load balancing methods. These tendons will all have the same drape, i.e.

$$P = \frac{w \cdot L_{eq}^2}{8 \cdot h}$$

where P = effective prestress force for the panel.
L_{eq} = equivalent drape length (m)
w = load to balance for the panel.
h = drape.

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Generally, by placing 65% of the strands required for the panel in the column strip and draping them to the edges of the drop panels approximately 80% of the panel load will be balanced in the column strip. This will satisfy code distribution requirements and result in a slab with a satisfactory service load behaviour and ultimate load capacity.

The formula for the equivalent drape length is:

$L_{eq} = \sqrt{y \bullet L_c^2 + (1-y) \bullet L_m^2}$

where L_c = span betweendrop panel edges.

L_m = span between column centrelines.

y = fraction of load to balance in column strip for span under review

The distribution of tendons between column and middle strips can be determined from the following

$$x = \frac{y \bullet L_c^2}{y \bullet L_c^2 + (1-y) \bullet L_m^2}$$

where x = fraction of tendons in column strip.

6.5 LEVEL OF PRESTRESS

The average residual prestress level in a slab can be used as a guide to check the economics of the design and that the slab will perform as expected by the designer.

Table 6B

Recommended Levels of Prestress

Criteria	Residual Prestress Level
Considered inadequate to resist cracking without additional reinforcement. Generally not economical.	Below 1.4 MPa
Minimum required for a waterproof slab.	2.0 MPa
Typical design range for control of cracking. Creep and shortening usually acceptable. Most economical range.	1.4-2.4 MPa
Recommended maximum value. Above this level creep and shortening can become excessive.	3.5 MPa

As prestress levels increase it becomes necessary to pay particular attention to the effects of possible restraints on the slab. Movement joints should be incorporated or temporary separation joints provided where the slab is connected to stiff vertical elements such as lift cores. The size of pours should also be kept to a minimum, and expansion joints provided at closer spacings when high prestress levels are being used.

In the secondary direction for one way slabs a residual prestress level of 0.7 to 1.0 MPa should be provided for a minor to moderate degree of crack control.

6.6 WATERPROOF SLABS

Slabs which are required to be waterproof often act as roof slabs and are subject to high temperature differentials as a result of daily exposure to direct sunlight on their upper surface.

For a slab to be waterproof the formation of shrinkage and temperature cracks must be prevented. This can be done by providing the slab with a minimum residual prestress level, after all losses, of 2.0 MPa in each direction. The tendons should also be distributed uniformly across the width of the slab.

Additional untensioned reinforcement should be placed at the upper face of the slab to help cope with the additional stresses generated by differential creep and shrinkage between the slab and its restraints and temperature differentials. It will also help to control early shrinkage cracking prior to the application of the prestress. Common practice is to provide mesh reinforcement in all slabs with exposed surfaces.

6.7 SLABS ON GRADE

Post-tensioned slabs on grade can be divided into two categories.

1. INDUSTRIAL SLABS

These are designed to ensure slab tensile stresses are within acceptable limits because of the transitory nature of the loading. The slab must be checked for stresses due to concentrated live loads such as wheels, columns, the effects of sub grade reaction, temperature, shrinkage, creep and subgrade friction.

For slabs subject to nominal loadings only, an effective residual prestress level of a minimum of 1.0 MPa is recommended. A 25 to 50 mm layer of sand on suitably compacted sub grade, overlain with polythene sheeting will keep the frictional restraints on the slab to within acceptable limits (coefficient of friction 0.3 to 0.6).

2. RAFT FOUNDATIONS

These offer savings of approximately 30% in thickness over a comparable reinforced concrete foundation. Rafts on soft soil conditions are generally designed as for a suspended slab after estimating a pressure distribution pattern over the slab subgrade. Consideration in design must be given to the effects of subgrade friction as mentioned previously.

6.8 DUCT FRICTION

When estimating duct friction losses in design it is recommended that the following coefficients are used when standard galvanised ducts are specified.

Friction Curvature Coefficient	μ	=	0.2
Wobble Factor	β	=	0.024

Consideration should also be given to site conditions which may affect these values.

Duct Friction can be increased by:

- poorly aligned ducts
- grout leakage into ducts during concrete placement
- excessive surface rust on the strand

Duct friction can be reduced by:

- specially coated ducts
- the use of soluble oil in the ducts

Account must also be taken of ducts that are deviated in plan as this can significantly increase friction losses.

Duct friction losses may be estimated using the following formula. This is similar to the expression in international building codes.

$$P_x = P_j e^{-\mu(a_x + \beta L_x)}$$

where P_x = the force in the tendon at a distance $_x$ from the jack.
P_j = the jacking force.
a_x = sum of the absolute values in radians of successive angular deviations of the tendons over a distance Lx.
L_x = the length of a tendon in metres from the jacking point to a distance x from the jack.

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6.9 JACK AND ANCHORAGE FRICTION
No allowance need be made for jack friction losses as they are compensated for during equipment calibration. A recommended allowance of 2% is made for friction losses through the anchorage and an additional 3% when internal or top stressing pockets are used.

6.10 DRAW-IN
The normal draw-in for the slab system anchorage is 6mm.

6.11 TENDON EXTENSIONS
The extension of a tendon during jacking is used to check that the load is correctly applied and all design assumptions are correct. This check is done by comparing the measured value against the calculated extension which is derived from the prestress force, the load-elongation curves and the assumed friction values for the tendon.

Any discrepancy between the two figures greater than 10 percent of the calculated extension, should be investigated.

Measured extensions however can vary considerably from those calculated for several reasons other than friction. These are as follows:

Extensions are sensitive to variations in tendon area and modulus of elasticity (Es) but are insensitive to large variations in the co-efficient of friction.

The modulus of elasticity varies with each coil of strand and is valid only for the linear portion of the manufacturers load extension curve. The strand area quoted by the manufacturer and used in their calculation of Es is the nominal area only.

6.12 DUCT PROFILING
The distance between ducts should be not less than the minimum clearances specified in the relevant structural codes or greater than approximately eight times the slab depth.

Severe duct curvatures should be avoided where possible and have a minimum radius of curvature of 5000 mm unless friction and local bearing stresses have been fully investigated.

6.13 STRESSING PROCEDURE
Stressing of the slab system is normally carried out in two stages, for two reasons:

1. Early application of an initial prestress limits the formation of shrinkage cracks that would otherwise occur in a slab with little untensioned reinforcement.

2. When the concrete has reached its required compressive strength the full prestress load is applied enabling early formwork removal and backpropping if required.

For band beams it is advisable to complete the stressing of slab tendons prior to the stressing of beam tendons in each stage to ensure the slab transfers its load to the band beams.

Recommended procedure is set out below for typical applications.

Table 6C

Typical Stressing Sequence

Stage	Strands/Tendon	Load In Strands	Earliest Start	Min. f'_{cp} MPa
1	All	25%	24-48 hours	7
2	All	100%	5-8 days	22

6.14 DRAWING NOTATION

The following are recommendations to designers for notes to be included in post-tensioning drawings.

GENERAL NOTES:

1. All stressing workmanship and materials shall comply with the Relevant Structures Code and the Specification.

2. All test certificates, calculations and shop drawings to be submitted to the Engineer, as required by the Specification, prior to construction.

3. Formwork shall be designed to support reactions during stressing.

DESIGN ASSUMPTIONS:

The design assumptions used in the calculation of prestress losses were:

Friction curvature coefficient	m	=	0.2
Wobble Factor	b	=	0.024
Draw-in at anchorage		=	6 mm
Relaxation of prestressing steel (after 1000 hours at $0.70f_p$)		=	2.5%

POST-TENSIONING NOTES:

1. Strand shall be 12.9 mm nominal diameter, 7-wire stress relieved, super grade, low relaxation in accordance with EURONORM 138-6/79 unless noted otherwise.

2. Jacking force shall be 140 kN per strand (75% min breaking load) (or 156 kN per strand (85% minimum breaking load)) unless noted otherwise.

3. Dimensions are to the underside of the duct from the soffit of the slab except at the anchorages where dimensions are to the centreline of the anchor.

4. Anchorage Designation

   ▶———————————— denotes live end anchorage

   |———————————— denotes dead end anchorage

   ——————▶▶—————— denotes couplers

5. Ducting shall be galvanised metal 70 x 19 for up to 5S13 and 4S15 and 90 x 19 for 5S15.

FREYSSINET NOTATION

The following is a guide to the tendon notation used generally on post-tensioning drawings.

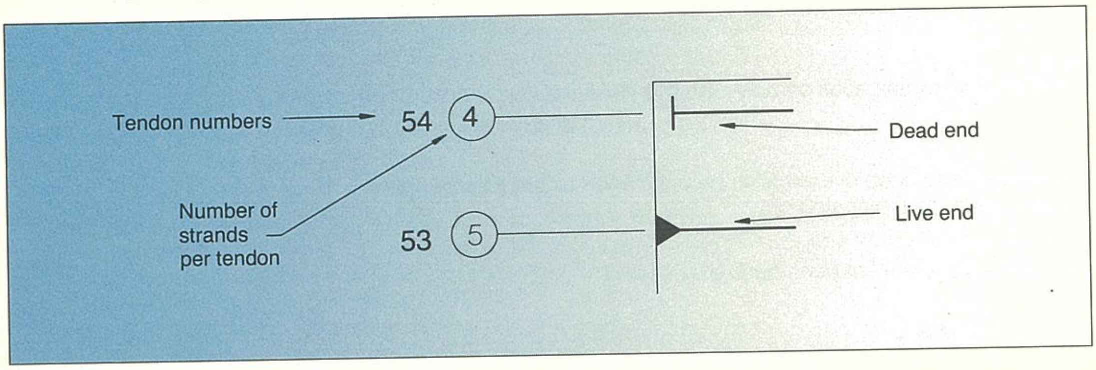

Figure 6A

Drawing Notation

6.15 RAPT – "Reinforced And Post-Tensioned"

The specialist prestressing computer package "RAPT" is employed by the Freyssinet Group. It is comprehensive limit-state package in line with recent developments in building codes. Freyssinet Far East provide sales and technical support for this package to those consultants and construction groups specialising in prestressing.

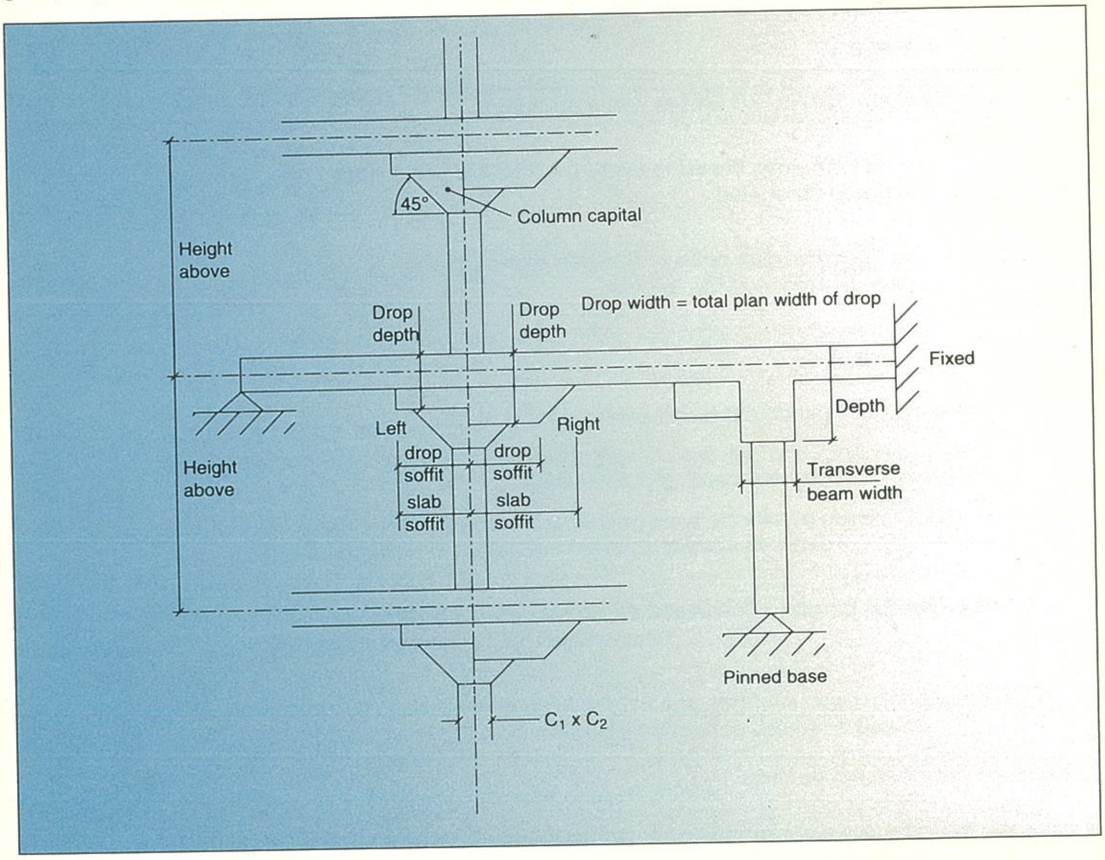

Figure 6B

Column and Drop Panel Data Input

7. Detailing

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7.1 COMMON JOINT DETAILS

Where post-tensioned slabs are used consideration needs to be given to the practical requirements and behaviour of slabs of this type. Particular attention to detailing of connections is the key to ensuring that maximum benefits will be achieved and most problems will be avoided during construction. Some characteristics of post-tensioned slabs which often require attention are:

- Post-tensioned slabs tend to be poured in larger areas than reinforced slabs and the presence of continuous tendons will influence the suitability and location of construction joints.
- Post-tensioned slabs undergo elastic shortening during stressing and are subject to slightly higher levels of creep than reinforced slabs.
- Temporary access to live end anchorages is required for completion of stressing operations.
- Joints providing for movement over the life of the structure are preferred particularly for connections near the edges of large slabs. Where fixed joints must be used the introduction of the permanent connection should be postponed as long as possible to allow maximum shortening to occur.

There are many ways of providing for these factors. A few of the more typical details used are shown in the following figures.

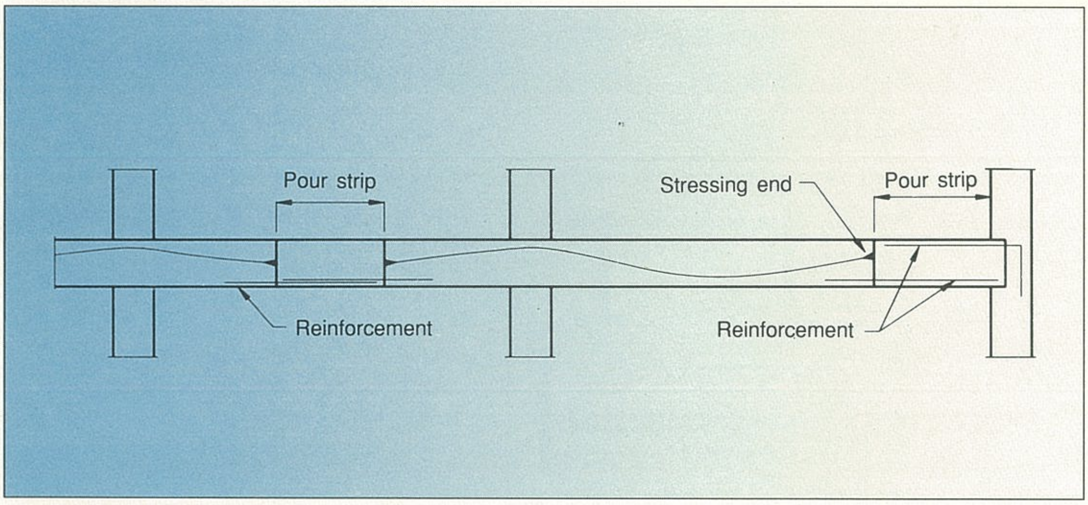

Figure 7A

Fixed Joints

– Fully Restrained

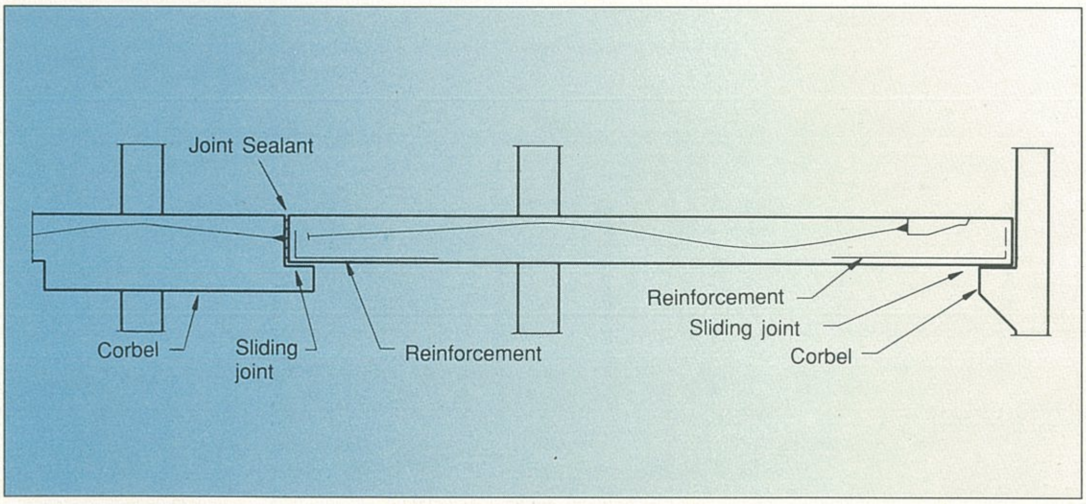

Figure 7B

Movement Joints

– Free Sliding

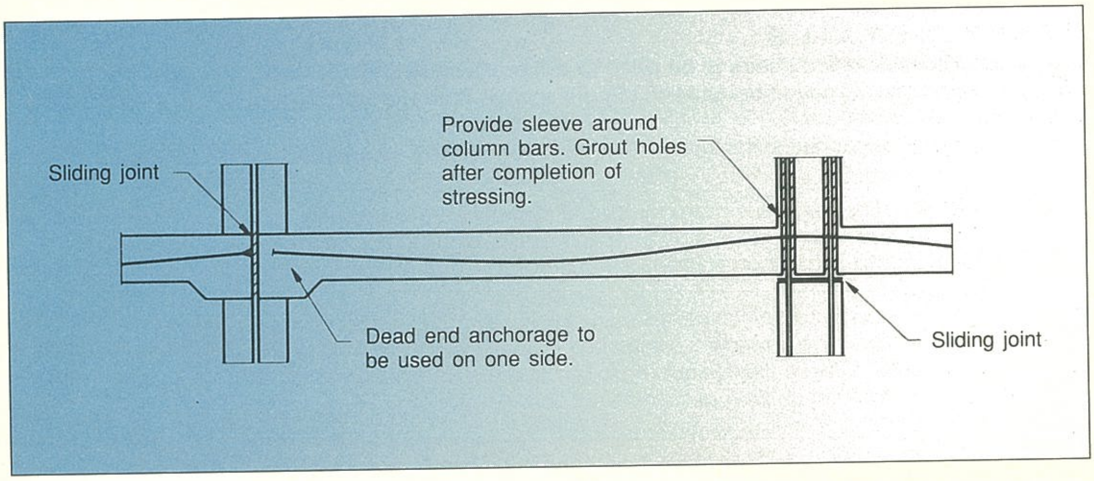

Figure 7C

Column Joints

7.2 ANCHORAGE REINFORCEMENT

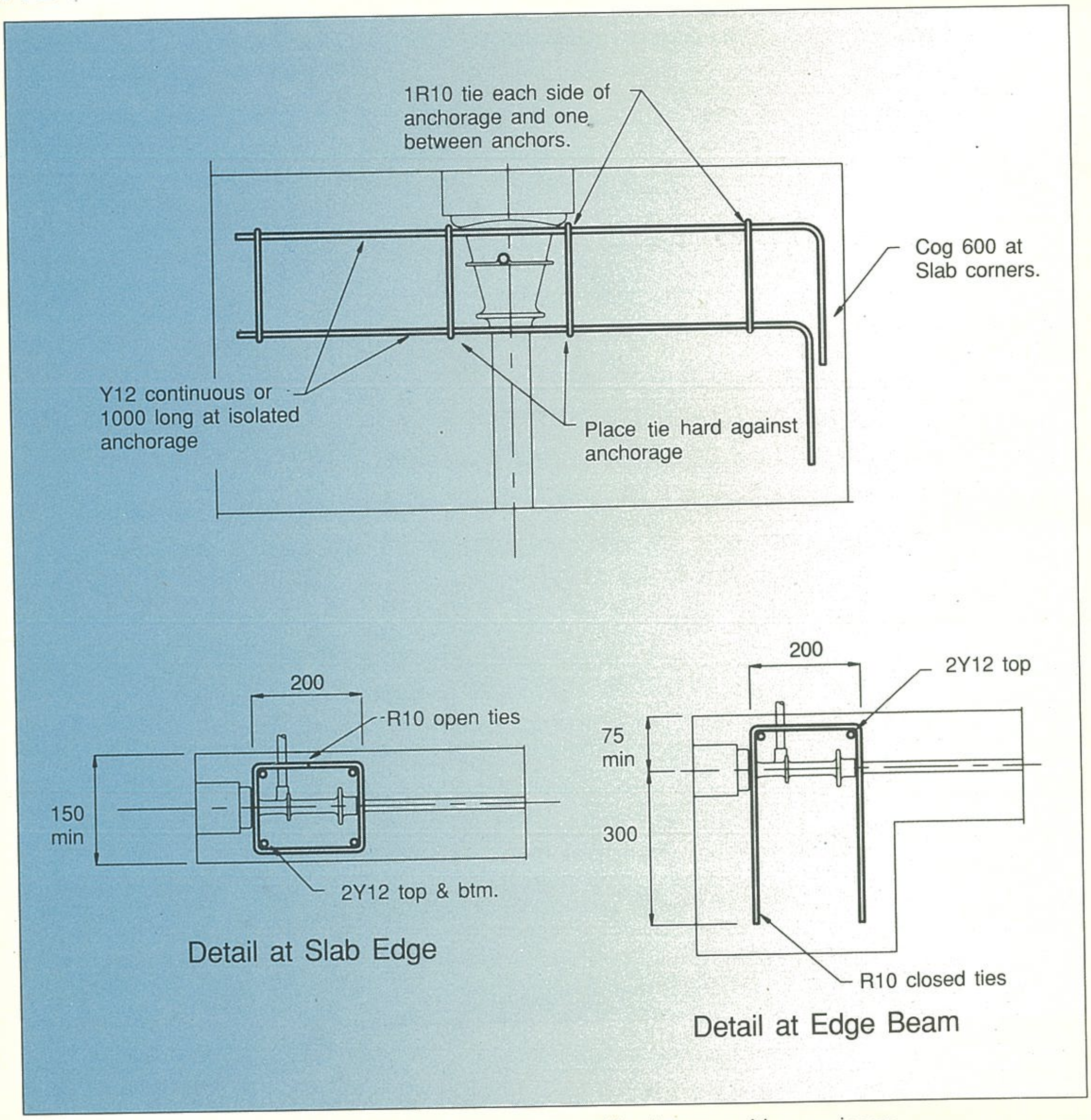

Figure 7D

Typical Anchorage Reinforcement for Slabs

Note: Reinforcement is indicative only. To be confirmed by the consulting engineer.

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