


Control of deflections in post-tensioned slabs

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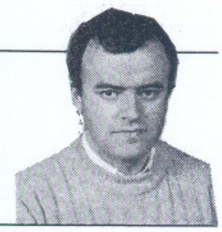


Summary
The specification of maximum span to thickness ratios allows the designer to avoid deflection calculations and is useful for preliminary design of reinforced concrete slabs. This problem is generally not addressed with the same detail in concrete codes or recommendations for post-tensioned slabs, where the multiplicity of parameters affecting deflections makes it more difficult to establish simplified rules.

The main results of a study performed on the influence of the principal parameters affecting deflections of post-tensioned slabs are presented. Recommendations are given concerning preliminary design and control of deflections without calculations in post-tensioned slabs. The presented specifications were adopted for indirect control of deflections in the 'FIP Recommendations for the design of post-tensioned slabs and foundation rafts', under preparation by FIP Commission 3. 'Practical Design. Professor Appleton is Chairman of this Commission and Dr Almeida is Secretary of the Commission.

Introduction
The use of post-tensioned solutions in building design presents, in many cases, important technical and economical advantages.

Post-tensioned slabs are usually used for long spans and/or high live loads where the control of deflections assumes a significant role. Prestress has a favourable influence, balancing a part of the imposed vertical loads, but, on the other hand, it allows for more slender slabs, which are more sensitive to deflections.

Because of the variability of parameters affecting deformations, it is important to use relatively simple procedures so that designers will not place undue reliance on computed deflection results. For reinforced concrete slabs, the specification of maximum span to thickness ratios enables the designer to avoid complex calculations and is useful in the preliminary design of the structure. This procedure of indirect control of deflections is widely adopted in concrete codes.

The problem does not present the same simplicity for post-tensioned slabs. In addition to the slenderness of the slab, there are other important parameters, namely the amount of prestress and the live load level, which significantly influence deflections.

The multiplicity of such parameters makes more difficult the establishment of simplified rules for checking deflections without calculations. In Table 1 the indications of several recommendations for post-tensioned slabs design are presented[1,2,3,4].

Most of these documents point out that the slenderness limits are only indicated to give some guidance in estimating the slab thickness. In general they recognize the influence of the live load level, at least qualitatively.

The main results of a parametric study, undertaken with the object of clarifying the influence of the principal parameters affecting deflection control in post-tensioned slabs, are presented. Indications are given concerning preliminary design and indirect control of deflections in post-tensioned flat slabs.

Deflection limits
Prestressing in post-tensioned slabs fundamentally influences the behaviour of the structure under service loads. The effects of post-tensioning tendons can be simulated by equivalent loads, inducing strain and stress resultants that counteract the applied loads.

The control of deflections allows a global evaluation of the slab behaviour, and can be the basis for the definition of the prestress design criteria in post-tensioned slabs. The prestressing force is related with a degree of prestress, k, defined as the ratio between equivalent load or maximum deflection due to effective prestress (after losses), and the corresponding values due to quasi-permanent actions. Values of k between 0.6 and 1.0 are currently obtained in practical applications, depending on technical prescriptions of codes or on economical considerations.

To conclude this section some remarks are presented about the quantification of deflection limit values. As generally recognized by concrete codes, maximum values for deflection in slabs should be related with aesthetic or functional aspects, or, on the other hand, with the sensitivity of non-structural or structural elements to excessive deformations. For the second condition, only the part

Table 1 — Span to thickness ratios proposed in technical documents for post-tensioned slabs

	l/h
ACI-ASCE Committee 423 'Tentative Recommendations for Prestressed Concrete Flat-Plates', 1974[1]	floors — 40 to 45 or 48* roofs — 45 to 48 or 52*
'FIP Recommendations for the Design of Flat-Slabs in Post-tensioned Concrete', 1980[2]	floors — 42 or 48* roofs — 48 or 52*
Concrete Society Technical Report n°25 'Post-tensioned Flat-Slab Design Handbook', 1984[3]	light loading — 40 to 48 normal loading — 34 to 42 heavy loading — 28 to 36
ACI Committee 318 'Building Code Requirements For Reinforced Concrete (ACI 318–89)', 1989[4]	floors — 42 or 48* roofs — 48 or 52*

* — If the calculated deflections and vibration performance are acceptable.

of the deflection occurring after the construction of these elements need be considered.

According to these principles and taking into consideration the values proposed in several concrete standards, the following limits were adopted:

- Maximum deflection under quasi-permanent loads, $l/250$;
- Maximum deflection after the installation of partitions, for frequent loads, $l/500$ or 15mm, whichever is the lesser.

These limits follow closely the values proposed in other codes or technical documents[2,4,5,6], being presently adopted in the final draft of the future 'FIP Recommendations for the design of post-tensioned slabs and foundation rafts'[7].

Since a significant part of the permanent loads is balanced by the prestress, the deflections can, in general, be calculated elastically. If cracking occurs, it will be very local only over the columns, and the reduction of the global rigidity will be negligible. In this case, time dependent effects can be estimated by considering a multiplier factor, φ for additional long-time deflection.

Parametric study

Introduction

The study was addressed to flat slab systems currently adopted in building design.

A square interior panel, with spans between 7.5 and 20.0 m was considered. Solid, waffle and banded flat slab systems were analysed.

Permanent loads include the self weight of the slab and an additional dead load of 2.0 kN/m^2. Live load values between 3.0 and 20.0 kN/m^2 were considered. For the definition of the quasi-permanent and the frequent combination of actions, respectively 40% and 60% of the full live load were adopted.

Prestressing degree values between 0.6 and 1.0 were considered. This parameter was defined as the ratio between maximum deflections due to prestressing and quasi-permanent loads. A coefficient $\varphi = 2.5$, allowing for time dependent effects, was adopted.

Each one of the systems considered (structural solution and span) was analysed by the finite element method, using four node isoparametric elements.

The equations which express the slab deflection limits presented in the previous section, are non-linear functions of the depth of the slab, h, the applied loads, g and q and the degree of prestress, k. Live load and prestressing degree values were imposed and the slab depth was obtained by solving the equations using the Newton-Raphson method.

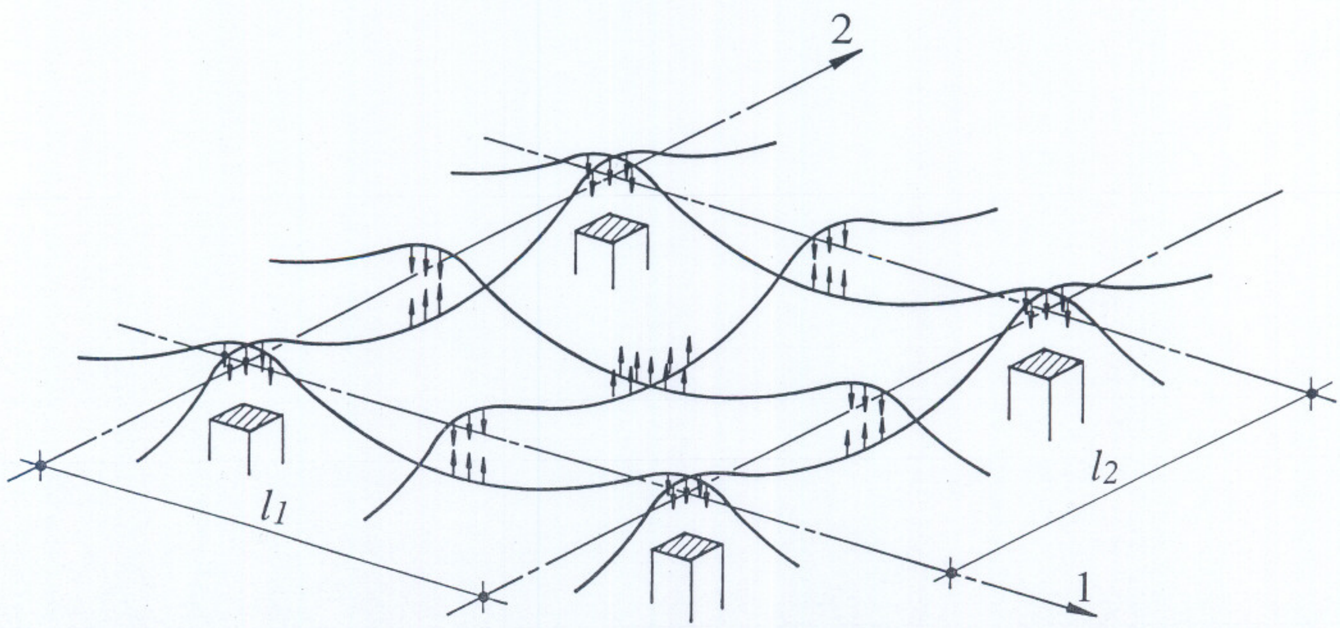


Fig 1. Equivalent loads due to prestress in an interior panel

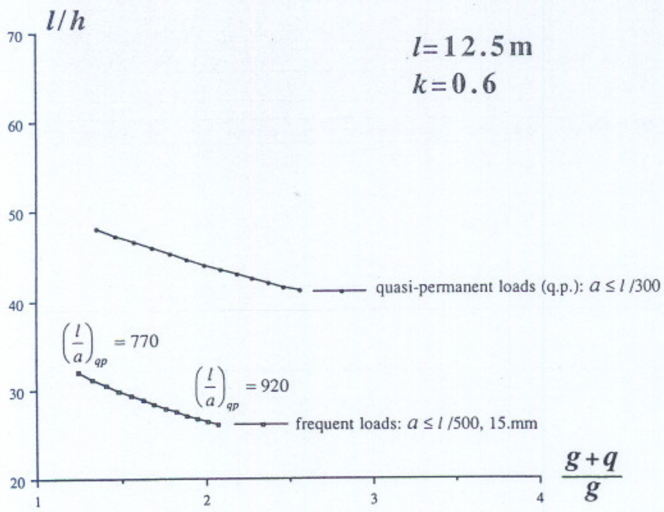


Fig 3. Solid slab, l = 12.5 m, k = 0.6. Deflection limits

Results

Fig 3 shows the curves *l/h* obtained for a solid slab with $l = 12.5$ m and $k = 0.6$, to each one of the maximum deflection conditions presented before.

The maximum deflection limit related to damage on non-structural elements is obviously critical when this problem is relevant. The difference between the curves would be greater for higher prestressing degrees. It can be observed that deflection values of about *l*/800 under quasi-permanent loads are obtained when using (*l/h*) values corresponding to the second condition.

The prestressing degree has a relevant influence on the maximum (*l/h*) values.

It should be pointed out that the curves indicate the maximum (*l/h*) values for the assumed deflection limits. For high values of prestressing degree, in particular for $k = 1.0$, deflection criteria can lead to slenderness values too high from a practical point of view. In this case, the slab depth should be conditioned by other criteria, e.g. safety against ultimate limit states, control of vibrations or economical considerations. In order to control these situations, a check was performed on the average concrete stresses due to effective prestress. Practical applications, as well as some technical documents[2,3,4] recommend the adoption of an average prestress of about 1.0 to 3.0 MPa for solid slabs. Values outside such limits lead, in general, to uneconomical solutions and, for the upper limit, the problems related to the restrained shortening of the slab can be important.

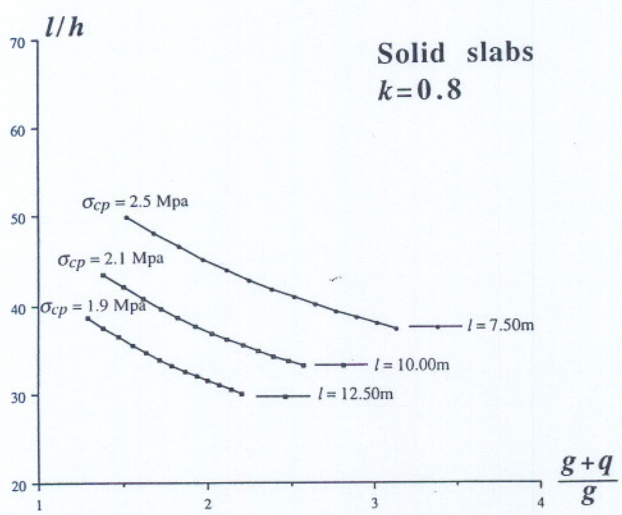


Fig 6. Solid slabs. (l/h) limits for k = 0.8

Figs. 6 and 7 summarize the results obtained for solid slabs. The curves obtained by limiting the average prestress to 3.0 MPa are represented if relevant.

Concerning the more wide objective of establishing simplified rules for deflection control without calculation it seems appropriate to consider a degree of prestress of about $k = 0.7$. In fact, in this case the average prestress obtained varies between 1.2 to 2.0 MPa. In addition, it was observed that the ordinary reinforcing ratio, ρ, in the positive region of the column strips was limited to about 0.5%.

The main results obtained for waffle slabs are illustrated in Fig 9. Taking into account the systems more generally used for waffle slabs, an average value of 2 was considered for the ratio between the self-weight of the solid and ribbed zones. In using the curves for waffle slabs, permanent loads should refer to the ribbed zone of the slab.

For the span range common to solid and waffle solutions, differences are reduced when comparing the curves (*l/h*) particularly for banded waffle slabs with a rigid solid band, $b_\omega \geq l/4$, connecting the columns. Fig 11 shows both curves for $l = 10.0$ m and $k = 0.7$.

On the other hand, for greater spans the influence of low rigid solid bands between columns is relatively unimportant. The curves obtained for a span of 15.0 m are shown in Fig 12, comparing a solution with a solid zone to another with a solid zone and solid bands with $b_\omega = l/8$.

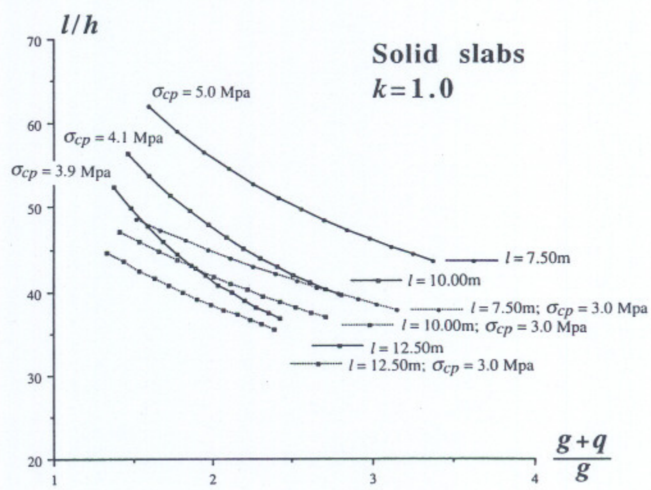


Fig 7. Solid slabs. (l/h) limits for k = 1.0

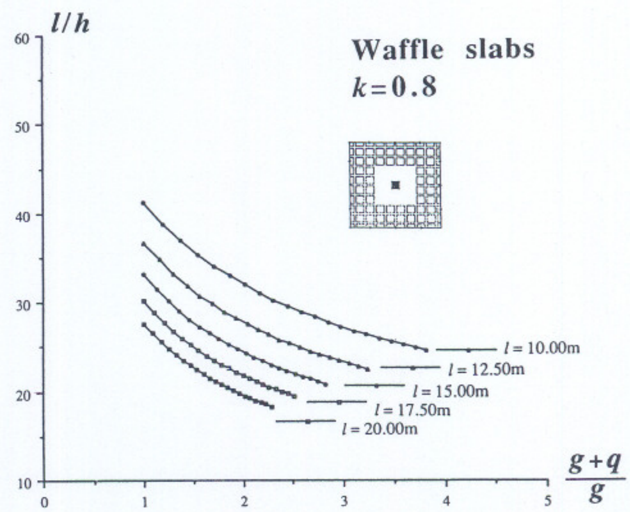


Fig 9. Waffle slabs. (l/h) limits for k = 0.8

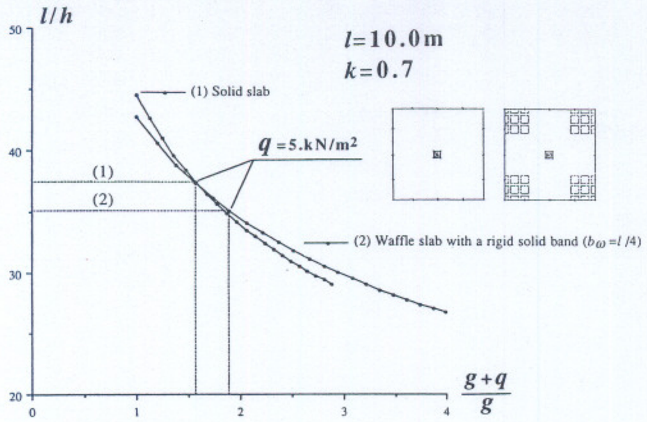


Fig 11. l = 10.0 m, k = 0.7. (l/h) values for solid slabs and waffle slabs with $b_\omega = l/4$

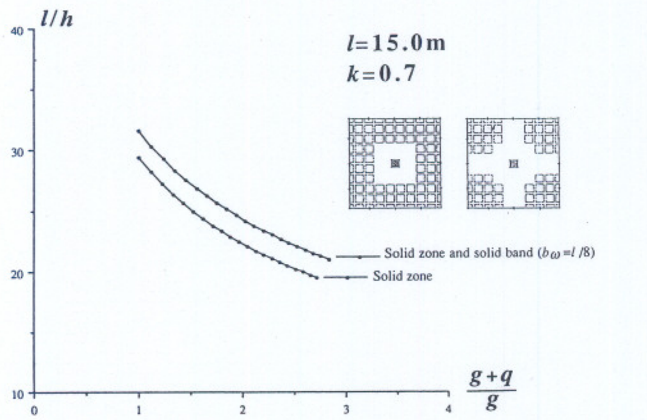
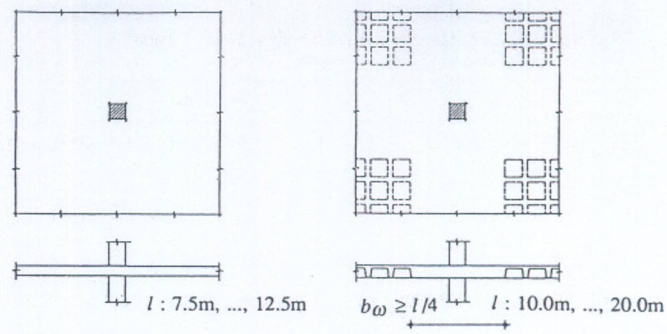
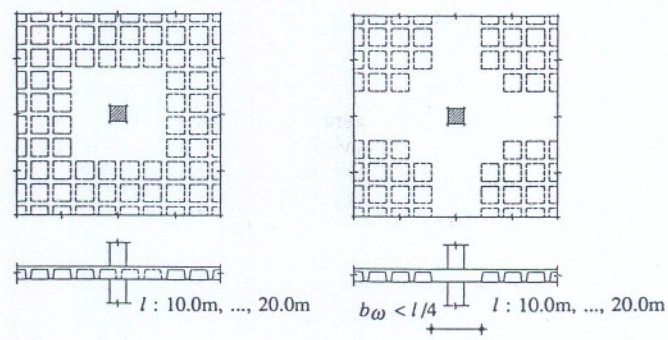


Fig 12. Waffle slab, l = 15.0 m, k = 0.7. Influence of low rigid solid bands, $b_\omega = l/8$



$\frac{g+q}{g}$ \ l (m)	7.5	10.0	15.0	20.0
1.0	45	42	33	27
2.0	41	34	26	20
3.0	35	29	22	16



$\frac{g+q}{g}$ \ l (m)	10.0	15.0	20.0
1.0	37	29	24
2.0	30	22	17
3.0	25	18	14

i) The tables presented have been obtained considering that prestress is designed to balance approximately 70% of the quasi-permanent actions. More slender slabs may be possible using higher prestressing degrees;

ii) For branded waffle slabs, permanent loads values to be used should refer to the ribbed zone.

Fig 13. Span to thickness ratios for post-tensioned slabs[7]

Note

The results shown in the various Figures are typical. Other Figures for different values of k and l are available and can be obtained from the Librarian at the Institution of Structural Engineers.

The Figures available are:

Fig 4. Solid slabs, 1 = 12.5m. Influence of degree of prestress
Fig 5. Solid slabs (l/h) limits for $k = 0.6$
Fig 8. Waffle slabs (l/h) limits for $k = 0.6$
Fig 10. Waffle slabs (l/h) limits for $k = 1.0$.

Conclusions

In post-tensioned flat slabs an important part of the permanent loads is in general balanced by the prestress ($k \geq 0.6$), which increases the sensitivity to deflections. Aesthetic or functional requirements, in general related to the total deflection for permanent loads, are never critical when compared to criteria established to avoid damage in non structural elements.

For high values of the prestressing degree (k values about 1.0), the slenderness of the slab is not conditioned by the control of deflections. It will be by other criteria, e.g. safety and serviceability, economical considerations or, in particular cases, by the control of vibrations.

The slenderness of the slab, the ratio between live and dead loads and the degree of prestress significantly influence the deflections in post-tensioned slabs. A prestressing degree of about 0.7 seems appropriate to establish recommendations for control of deflection without calculations.

The results obtained can be summarized in the tables presented in Fig 13. These tables allow very easy application, having been adopted as specifications for indirect control of deflections in the future 'FIP Recommendations for the design of post-tensioned slabs and foundation rafts'[7].

References

1. ACI-ASCE Committee 423, 'Tentative Recommendations for Prestressed Concrete Flat Plates', *Journal of the American Concrete Institute*, v. **71**, No. 2, February 1974.
2. 'FIP Recommendations for the Design of Flat Slabs in Post-tensioned Concrete (using unbonded and bonded tendons)', *Cement and Concrete Association*, Wexham Springs, 1980, 21 pp.
3. Concrete Society Technical Report No 25, 'Post-tensioned Flat-Slab Design Handbook', *Concrete Society*, London, 1984, 43 pp.
4. ACI Committee 318, 'Building Code Requirements for Reinforced Concrete (ACI 318-89)', *American Concrete Institute*, Detroit, 1989, 353 pp.
5. ENV 1992-1-1, Eurocode 2, 'Design of Concrete Structures — Part 1 — General Rules and Rules for Buildings', *CEN, European Committee for Standardization*, Brussels, 1991, 253 pp.
6. CEB-FIP Model Code 1990, 'Design Code', *Thomas Telford Ltd.*, London, 1993, 437 pp.
7. FIP Commissión 3, Design, 'Post-tensioned Slabs and Foundation Rafts, final draft', *FIP Commission 3*, February 1994, (to be published).