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Structural Safety and Reliability of Post-Tensioned Floor-Slabs

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SUMMARY

Post-tensioning with unbonded tendons offers great advantages for floor-slabs. Design and construction have to consider that a local damage accounts to the total loss of the tendon. The paper puts emphasis on the combination of prestressed and mild reinforcement and makes suggestions how to improve the reliability, ductility and redundancy of post-tensioned floor-slabs.

Keywords: Post-tensioning, floor-slabs, unbonded tendons, structural safety, reliability, ductilty, redundancy, design criteria, construction

1. INTRODUCTION

Post-tensioned floor-slabs offer great advantages for metropolitan buildings, Fig. 1. For example:

- larger spans to allow more flexibility for the use of the building
- decreased deflections in particular for long cantilevers
- feasible systems for irregular floor-slabs as the tendons can easily follow the load path
- economical building execution due to flat soffit without column drops.

Fig. 1 High rise buildings

Unbonded tendons, Fig. 2, are most common for floor-slabs. They are easy to handle but special care is required as a local failure means the total loss of the tendon.

Fig. 2 Monostrand tendons

To improve the reliability of prestressed floor-slabs emphasis has to be put on structural detailing which considers the conditions on site and allows simple execution. This includes:

- layout and profile of the tendons
- amount and placement of mild reinforcement.

There are various designs possible for each floor-slab depending on the

- combination of unbonded prestressed and mild reinforcement.

Due to the framework given by the design code of each country the design and construction of posttensioned floors vary considerably.

2. DESIGN CONSIDERATIONS OF POST-TENSIONED FLOOR-SLABS

The usable floor of high-rise buildings is generally arranged around a central core, Fig. 3. The spans of the slabs range between 9 and 12m. Due to post-tensioning the thickness of 200 to 240mm is sufficient. The comparatively thin slabs allows thinner columns and reduces the weight to be transferred to the foundations. Furthermore less weight to be considered along the height of the building is of advantage for earthquake design.

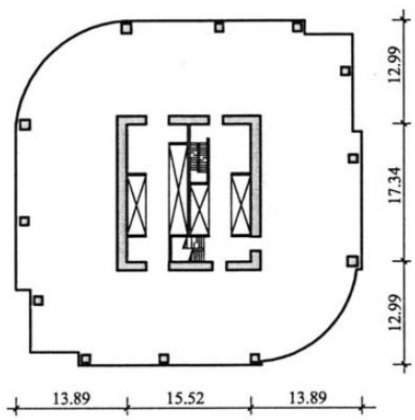

Fig. 3 Floor plan of a high rise building

Deflections are most critical for long cantilevers in particular to the effect on the external cladding. Due to the counterbalance of post-tensioning the long-term deflections are reduced.

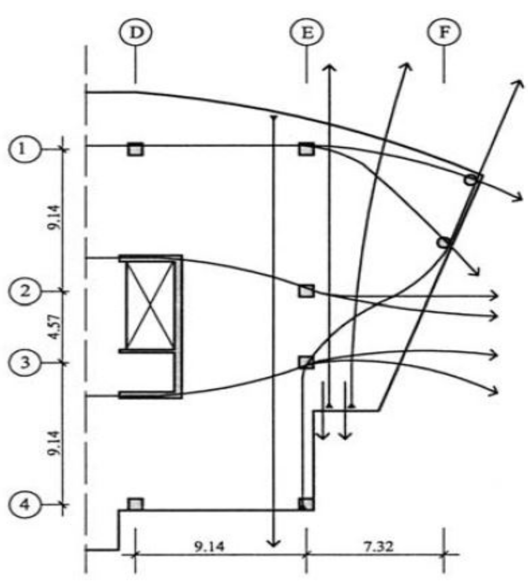

Fig. 4 Tendon layout for an irregular floor plan

For buildings with an irregular arrangement of columns a prestressed slab is superior. The decision on a reasonable load path may be given by the tendon layout as they can be placed with a horizontal sweep easily, Fig. 4. There are distributed tendons in the cantilever and banded tendons which transfer the load of the cantilever to the columns.

Once the layout of tendons has been designed the question to be answered is how much prestress should be applied. For ultimate design the tension force due to the bending moments is taken both by the prestressed and the mild reinforcement.

In North America the decision on the prestress force generally is made on permissible tensile stresses for unfactored loading. Both the American [1]and the Canadian Code [2] allow tensile stresses of the concrete of $f_c = 0.5 \sqrt{f'_c}$ which corresponds to $f_c \approx 3$ MPa for a concrete strength of 35 MPa. This degree of prestress generally is the basis for the ultimate design which gives the amount of additional mild reinforcing required.
The German Code [3] generally allocates partial prestressing and does not mention any permissible tensile stresses. However several design steps are required to establish proof of serviceability.

3. ULTIMATE DESIGN

For ultimate loading the stress increase for unbonded tendons is much less than for bonded tendons because unbonded tendons must average out their increase over the total length between the anchorages. This means that the flexural tension force taken by the tendons increases only by about 10% whereas the common load factor for dead and live load amounts to 33 to 50% depending on the code applied.

The amount of mild reinforcement As required by the Canadian Code will be calculated for a oneway slab as given by Fig. 5 and on the assumptions:

$\Upsilon_{D+L} = 1.33$	common load factor
$\Phi = 0.9 / 0.85$	resistance factor for tendons / reinforcing bars respectively
$f_y = 400$ N/mm²	yield strength of reinforcing bars
$f_{pr} / f_{pe} = 1.05$	increase of stress in tendons for ultimate design secondary moments neglected.

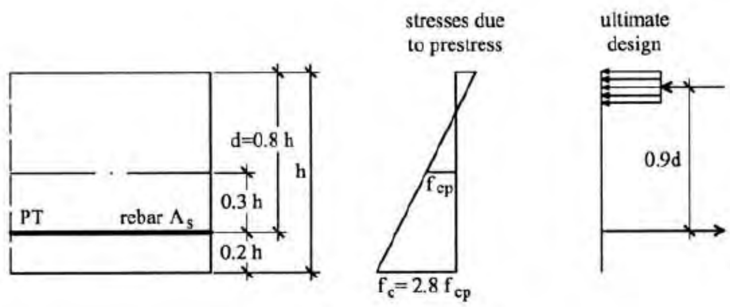

Fig. 5 Stresses due to prestress, ultimate design

$$M_{ult} = \frac{1.33}{6}\left(2.8 f_{cp} + 3.0\right) b \cdot h^2 = M_{p,ult} + M_{s,ult} \quad (1)$$

$$M_{p,ult} = N_{p,ult} \cdot 0.9 \cdot 0.9 d = 0.680 f_{cp} \cdot b \cdot h^2 \quad (2)$$

$$M_{s,ult} = A_s \cdot f_y \cdot 0.85 \cdot 0.9 d = 245 A_s \cdot h \quad (3)$$

$$\frac{A_s}{b \cdot h} = \left(0.272 - 0.024 f_{cp}\right) 10^{-2} \quad (4)$$

The contribution of the mild reinforcement to take flexural tension at ultimate design can be calculated from:

$$\frac{M_{s,ult}}{M_{ult}} = \frac{0.665 - 0.060\,f_{cp}}{0.665 + 0.621\,f_{cp}} \tag{5}$$

Fig. 6 shows that the mild reinforcement required does not depend much on the average compressive stress f_{cp}. However the

• resistance provided by mild reinforcement decreases with increasing f_{cp}.

4. DUCTILITY

A minimum flexural resistance is required to avoid brittle failure mode. According to the American and Canadian Code both the prestressed and the mild reinforcement are considered to calculate the cracking moment and the resistance to take it. This means that the degree of prestress affects the amount of mild reinforcement required that is less for highly prestressed slabs say f_{cp} = 2.0 to 2.5 MPa. Fig. 6 shows that the amount required is less than for ultimate design. Therefore it can be assumed that the

• failure is not brittle.

The German Code requires that the mild reinforcement has to be calculated for the cracking moment M_{cr} that is calculated on the tensile strength of the concrete. This is more conservative as the flexural tension has to be met by the mild reinforcement only. Besides the bottom reinforcement has to be continuous from end support to end support.

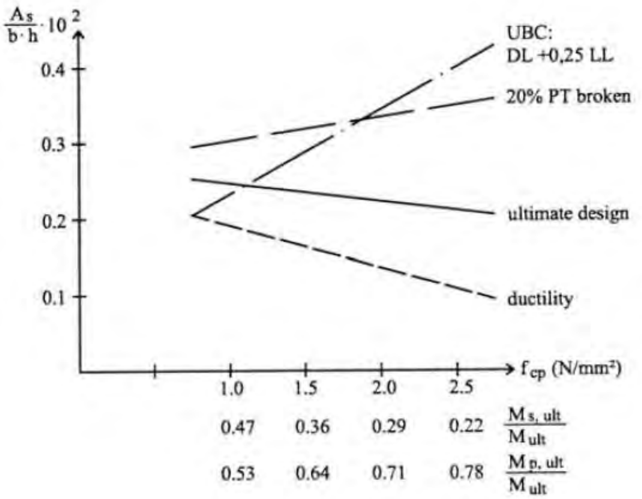

Fig. 6 Canadian design: Mild reinforcement required for one-way slab where extreme tensile stress f_c = 3 MPa

5. COMBINATION OF PRESTRESSED AND MILD REINFORCEMENT

Fig. 6 shows that the proportion of the ultimate moment taken by the mild reinforcement decreases from 47% to 23% for f_{cp} = 1.0 or 2.5 MPa respectively or on the other hand the proportion of the tendons increases from 53% to 77% respectively.

However ultimate design is only one design step. Post-tensioned floor-slabs are sensitive to the effective prestress.
• A single damage accounts to the total loss of the tendon.

For that reason the Uniform Building Code [4] suggests that one-way unbonded post-tensioned slabs shall be designed to carry the dead load of the slab plus 25% of the live load by mild reinforcement – with a load factor and capacity reduction factor of one. Fig. 6 shows the mild reinforcement required to meet this provision on the assumption that the live load is 50% of the dead load. Moderately prestressed slabs say $1.0 \le f_{cp} \le 1.5$ MPa do not need much additional reinforcement. However the additional mild reinforcement required is substantial for slabs designed for high average compressive stresses.

The consequences of loss of prestress may be demonstrated in another way assuming that 20% of the tendons are broken. If no moment redistribution is taken into account this can be covered by additional mild reinforcement as shown in Fig. 6. Again highly prestressed slabs are more affected than those with a low value of f_{cp} which need little extra reinforcement. Generally no extra reinforcement is provided to cover this case. Therefore the load factors (margin 33-50%) and the resistance factors (margin 11% for tendons and 18 % for mild reinforcement) will be affected.
Consequently
• moderately prestressed slabs provide higher redundancy.

So far as deflections are not decisive it is up to the structural engineer to decide how much of the ultimate moment should be taken by prestress or mild reinforcement respectively.

For the proportion of the ultimate moment covered by prestress $\alpha = M_{p,ult} / M_{ult}$ the average compressive stress f_{cp} and the mild reinforcement required A_s amount to

$$f_{cp} = 1.47\,\alpha\,\frac{M_{ult}}{b \cdot h^2} \qquad (6)$$

$$\frac{A_s}{b \cdot h} = 0.408\,(1-\alpha)\,\frac{M_{ult}}{b \cdot h^2}\,10^{-2} \qquad (7)$$

These formula are based on the Canadian design of one-way slabs and the assumptions as given above. Fig. 7 shows the correlation of f_{cp} and α depending on the ultimate moment. On the other hand Fig. 7 demonstrates the increase of mild reinforcement as the degree of prestress is reduced.

Because the amount of mild steel provides the redundancy it is recommended
• take only $0.50 \le \alpha \le 0.60$ of the ultimate moment to be covered by prestress.

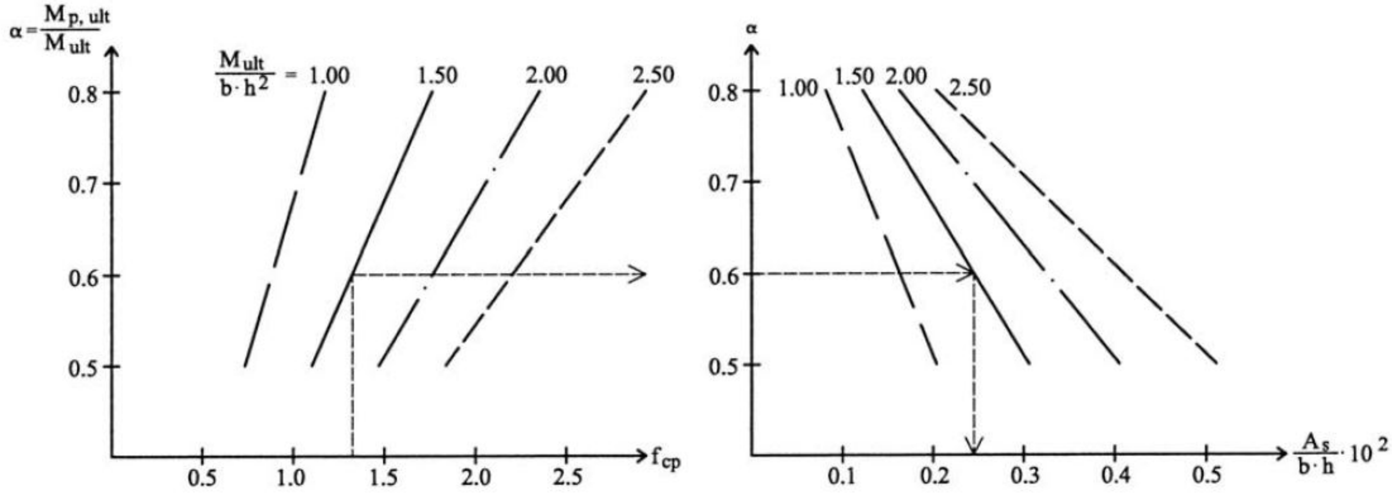

Fig. 7 Canadian design: Average compressive stress and mild reinforcement depending on proportion of ultimate moment covered by prestress

6. STRUCTURAL DETAILING

In North America the predominant method of placing tendons in two-way slabs is the banded distribution in one direction and the uniform distribution in the other direction with a minimum of 2 over the column. This method simplifies the process of placing tendons and allows most eccentricities in both directions.

A reversed parabola is the most common gradient as it provides uniform distributed counterbalance. However the tendon profile is not that much of importance for floor-slabs as for bridges. Tests have shown that there is no much difference for tendons that are supported only by two chairs over the support and are placed horizontally for most of the span [5]. The "free tendon profile" depends on the stiffness of the tendons. This method spares chairs and reduces field labour costs and is less prone to field errors.

There are substantial differences between the North American and the German practice with regard to the amount and the placement of mild reinforcement. In North America floor-slabs are without any bottom reinforcement where the extreme fibre stress in tension is below $f_c = 0.2\sqrt{f'_c}$. The German Code does not permit any section without bottom reinforcement as

• bottom reinforcement continuous between end supports improves the safety substantially.

The concerns about post-tensioned floor-slabs result from problems with some buildings and in particular with parkades, which were built before the mid 1980th. The causes predominantly are related to tendons susceptible to water ingress and poor workmanship. New systems use extruded sheathing where the thickness of the sheathing has been increased to 1.5mm. The protection against corrosion has been improved in particular at the anchors Fig. 2. The Canadian experience on the durability of post-tensioned tendons has been reported by [6]. The advice given in [7] will resolve field problems.

7. CONCLUSIONS

Post-tensioning of floor-slabs is different from post-tensioning of bridges. The design and construction have to be simpler but the care on site allows no cuts to the tendon sheathing.

A straight forward design is of advantage to decide on the layout of tendons in particular for irregular floor-slabs as the load path and the distribution of tendons are linked together.

For two-way slabs banded tendons in one direction and uniform distribution in the other direction simplify the process of placing. Take only two chairs over the support and allow a tendon profile that is horizontally for most of the span: ”free tendon profile”.

Post-tensioned floor-slabs are sensitive to the effective prestress. Damage at any one location will result in the total loss of the tendon. The redundancy of post-tensioned slabs can be improved by reducing the prestress and increasing the amount of mild reinforcement. It is suggested to cover 50 – 60% of the ultimate flexural tension by tendons and to take the remaining 40 – 50% by mild reinforcement.

Apply bottom mild reinforcement throughout the slab. For two-way slabs the top reinforcement should be concentrated over the columns.

Structural detailing and careful workmanship are most important to achieve durability. In case of problems on site the lines of communication should go full circle.

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