CONCRETE FLOORS IN BUILDINGS POST-TENSIONED WITH UNBONDED TENDONS. HISTORY, DESIGN RECOMMENDATIONS, REALIZATIONS, POSSIBILITIES OF IMPROVEMENT

Rafał Szydłowski[1], Barbara Łabuzek[2] and Małgorzata Rodacka[3]

[1,2,3] Faculty of Civil Engineering, Cracow University of Technology, Cracow, Poland
TCE Structural design & Consulting, Cracow, Poland

Corresponding author email: rszydlowski@pk.edu.pl

Abstract

This paper contains recommendations concerning designing post-tensioned slabs published in technical literature, i.e., span-depth ratio and maximum span. To reflect these recommendations and show new possibilities, a few selected realizations have been described. The described examples include one of the largest solid post-tensioned slab with dimensions of 17.65 × 19.69m and thickness of 350mm designed by the authors. Additionally, the ways of improvement of post-tensioned slabs' effectiveness were proposed.

Keywords: Post-tensioned slab, span-depth ratio, unbonded post-tensioning.

1. Introduction

The development and use of post-tensioned concrete slabs in buildings have been largely determined by the development of unbonded post-tensioning. Unbonded tendons (monostrands) have been used in the United States as a form of concrete reinforcement since the late 1950s. Lack of costly and burdensome injection resulting in high labor costs and simultaneously low installation costs for unbonded post-tensioning contributed to their widespread use as concrete reinforcement. Outside the United States, the development of unbonded post-tensioning has encountered obstacles. In European countries its beginnings date back to the 1970s, and its spread to the 1980s and 1990s of the previous century.

Besides the already mentioned economic benefits, prestressed structures with unbonded tendons are characterized by a number of constructional advantages. A key benefit of post-tensioned concrete is the ability to design thinner slabs, without increased deflection, and reduce floor-to-floor height compared to structural steel or concrete reinforced solely with rebar. According to the Post-Tensioning Institute, 10 floors of structural steel have an overall height of 38 meters, versus only 33 meters for 10 floors with post-tensioned slabs. The reduction in building height, while retaining the same area of horizontal real estate, could translate into potential material savings for other vertical elements such as concrete columns, shear walls, building façades, vertical MEP piping, stairwells, elevators, and interior walls. In operational terms, there would be a reduction in the energy required for vertical transportation.

The reduction in above-grade building materials boils down to below-grade building materials. A lighter building could facilitate a reduction in foundations and retaining walls. Accordingly, a diminished excavation would lower the building's impact on erosion of the surrounding land.

Post-tensioned buildings can be constructed rapidly. It is not uncommon to have a three-to-five-day pour cycle for a high-rise PT building, even in a city with a high urban density. A quick construction schedule reduces the strain on the surrounding ecosystem and infrastructure.

Chicago is the birthplace of the modern skyscraper and has been at the forefront of skyscraper design, even as the construction volume of tall buildings has moved to Asia. Prior to 1960, 90% of its

100-meter-plus buildings were built solely with structural steel, while only 6% were with all forms of concrete. After 1960, almost 80% of its 100-meter-plus buildings were built solely with concrete. Furthermore, a growing percentage of the aforementioned concrete skyscrapers are constructed using unbonded post-tensioning as elevated concrete slab reinforcement. Between 1980 and 2006, less than 5% of Chicago's 100-meter-plus buildings had post-tensioned slabs, but roughly 50% of them either completed or under construction between 2007 and 2017, had PT slabs.

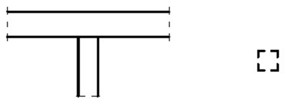
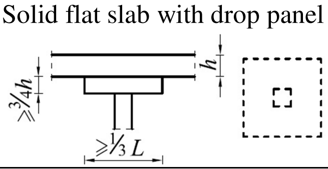
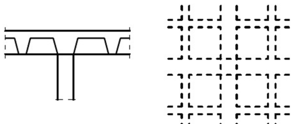
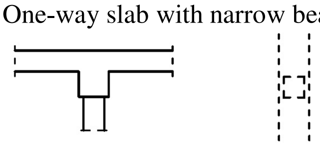
2. Design recommendations

The most important factors determining proper performance of the post-tensioned slab is the decision concerning the most suitable type of slab, taking into account the load and the span, as well as slab thickness or more precisely, the span-depth ratio. Numerous unsuccessful realization in 1970s erected in the UK and Canada constituted a trigger for an association related with post-tensioned structures to develop certain guideline concerning the design and training of construction engineers.

A major contribution in the regulation of designing rules was made by The Concrete Society with its guidelines issued in 1974 and then systematically expanded in 1994 and 2005. The most recent version of the recommendations from 2005 concerned the span-depth ratio for different types of slabs (Table 1). In accordance with this recommendation, the most slender slab could be erected as a solid flat slab (L/h=30÷40). Admittedly, a higher span-depth ratio can be obtained by applying a thickening (solid flat slab with drop panel) above the columns (36÷44). However, in this case defined thickness concerns merely the thickness of the slab, and not the thickening. Thus, the total height of the slab is much greater than the defined span-depth ratio. It should be noted that the authors of the recommendations reduced the range of application of this ratio to a maximum span of 13m.

Slightly different values of the span-depth ratio have been given by Khan and Williams (1994). The authors defined the following ranges: 30÷45 for one-way solid slab, 25÷35 for ribbed slab, 35÷45 for flat slabs and 20÷30 for waffle slabs. The lower value corresponds with the imposed load equal to 15kN/m^2 while the upper value is for imposed load of 2.5kN/m^2. More generally, the acceptable span-depth ratio is determined by *fib* (2005). According to these recommendation, for continuous slabs with a minimum of two spans in both directions, this value should not exceed 42 for slabs and 45 for roofs.

Table 1. Typical span/depth ratios for a variety of section types according to The Concrete Society (2005).

Section type	**Total imposed load, kN/m^2**	**Span/depth ratios $6\text{ m} \leq L \leq 13\text{ m}$**
1. Solid flat slab 	2.50	40
	5.00	36
	10.0	30
2. Solid flat slab with drop panel 	2.50	44
	5.00	40
	10.0	36
3. Coffered flat slab 	2.50	25
	5.00	23
	10.0	20
4. One-way slab with narrow beam 	2.50	42
	5.00	38
	10.0	34

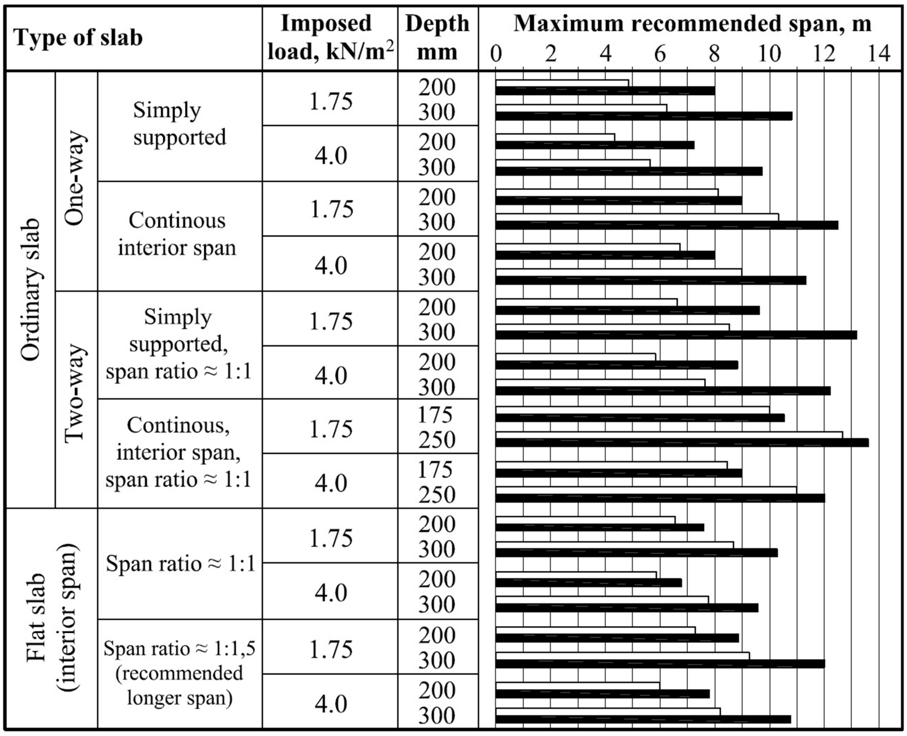


Figure 1. Examples of slab thickness and indication of maximum span for solid slabs with ordinary (▭) and prestressed (▬) reinforcement according to *fib* (2005).

In *fib* (2005) the maximum spans are shown depending on the type of slab, support type (ordinary slab – slab supported on edges, flat slab – slab without beams) and imposed load (Fig. 1). It should be noted that a load of 1.75kN/m^2 above self-weight seems to not be enough for slabs in buildings, even for roofs; it is usually the load of the floor layers. Assuming an imposed load equal to 4.0kN/m^2, for ordinary slabs, the allowed recommended span lengths for continuous slabs are equal to 12.0m for two-way slabs and to 11.4m for one-way slabs. For flat slabs these values are slightly less.

3. Examples of implementation

The recommendations that have existed for many years concerning the design of post-tensioned slabs, cause that the majority of erected slabs does not exceed 12÷13m in span. The slabs with greater span are implemented as ribbed or waffle slabs, which can be lighter and allow to achieve more savings in the used materials (concrete and prestressing steel) compared with solid slabs but they have a lower stiffness and lower capability of accumulation of compressive stresses, which requires greater thickness of the structure. In the paper, are two of the most spectacular examples in the design of post-tensioned slabs, that have been described in foreign scientific and technical literature as well as authors' extremely large slab.

3.1. Waffle slab in the Boston Public Library

One of the biggest post-tensioned slabs (the greatest that the authors have found in technical literature) has been erected in 1972 in a new part of the public library in Boston (Pretzer 1972). The additional segment is a $23-million seven-story steel frame structure with cast-in-place concrete slabs, and backup walls for a stone facing. The first floor and the level below are supported on columns at 5.9m centers extending from the subbasement. Steel columns supporting the second floor are 17.7m in center as shown in Fig. 2, to provide large column-free areas for the main reading rooms on the first and second floors. The third through seventh floors are supported by hanging steel H-columns suspended from story-high steel roof trusses and girders which span to the main columns (Fig. 2).

The depth of the second floor's structural system was limited by architectural and mechanical features to 510mm even though the two-way slab panels spanned 18.3m in each direction. The eight post-tensioned with unbonded tendons waffle slabs were supported on 810mm-deep steel plate girders (Fig. 4). Composite design was used to reduce girder size and deflection. Cambering of the slabs and girders, and a careful sequence of construction, were necessary to permit full prestressing of the slab without bending or stressing the supporting plate girders. After stripping the slab edge forms, headed studs were welded to the top flanges of the girder through pockets and openings provided in the slab system. The slab was fully post-tensioned before these pockets were filled with concrete.

Tendons of 1 5/8in. (41mm) diameter, greased and wrapped in paper slippage sheathing, were made up of 28 high strength wires, 1/4in. (6.35mm) in diameter, with a button head positive anchorage. The tendon wire with a minimum ultimate tensile strength of 1687MPa was designed for a working force of 317kN per wire. A single tendon was used in each rib to minimize jacking costs and placement problems. The required ultimate strength moment capacity of the slab ribs was achieved by the addition of 16mm-diameter reinforcing bars. Three bars were used for the middle nine ribs in each bay, and two bars were used for the remaining outer ribs.

It should be noted that the span-depth ratio is 34.7 for this slab, therefore much more than recommended in Table 1 for waffle slabs (20÷25).

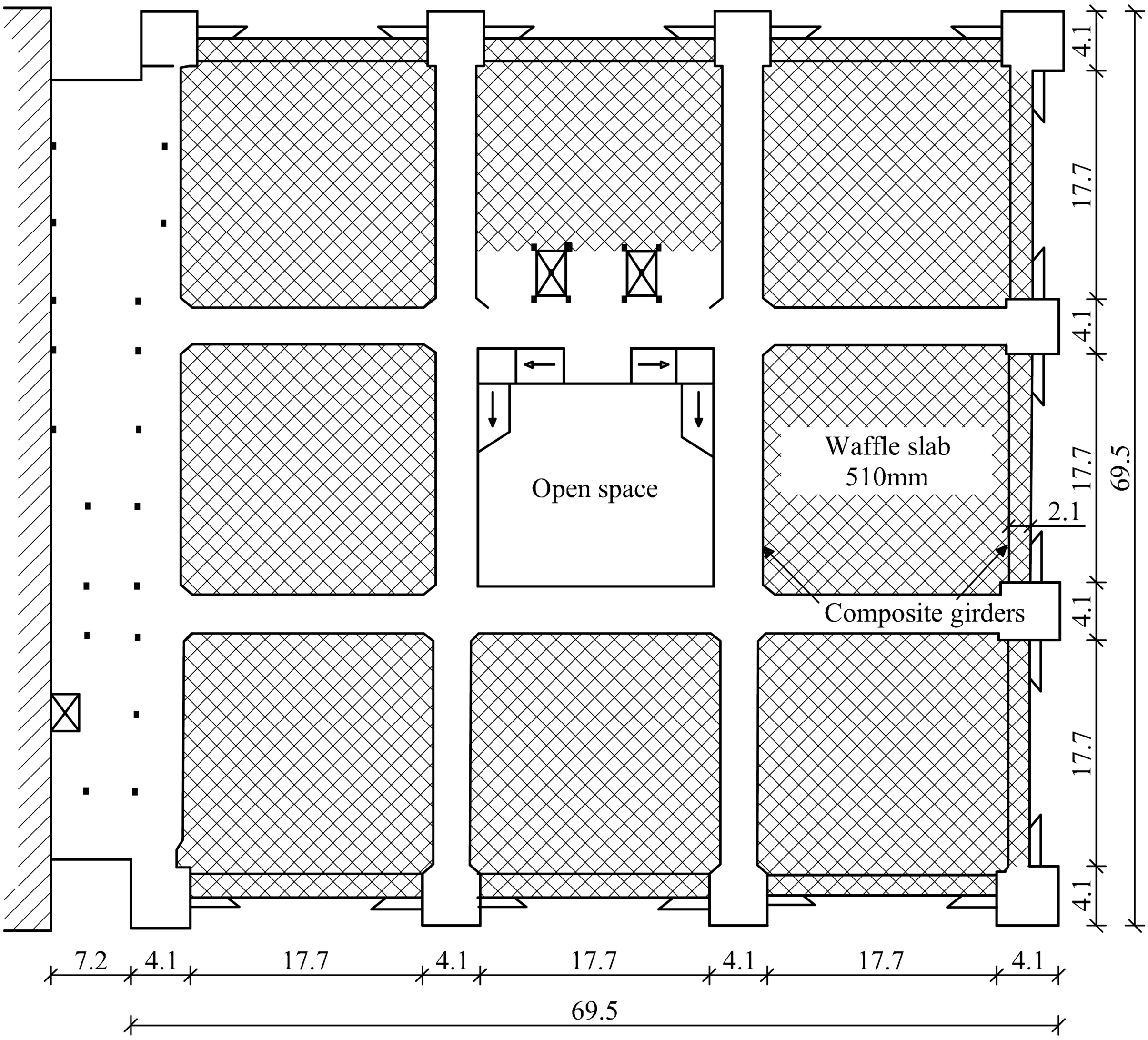


Figure 2. Second floor plane (Pretzer 1972).

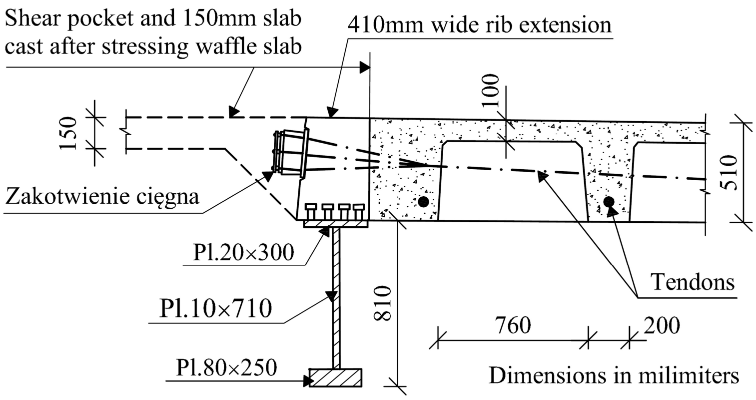


Figure 3. Section through plate girder at stressing end (Pretzer 1972).

3.2. Flat slab in Vidamar Resort Madeira Hotel in Funchal

An extremely large span of the slab was built in a hotel building in Portugal (*fib* 2005). The Vidamar Resort Madeira Hotel in Funchal is a two-structure building with 6 floors over the main entrance level and 3 below. The guestrooms, all facing the seashore on a regular basis, are about 3.5m wide which permitted a basic 7m-span structural layout with a 250mm-thick reinforced concrete slab. For functional and architectural reasons, in certain areas of the hotel spans from 10 to 12m were required. A larger span was achieved over delivery area. By applying 16 monostrands in each direction, a flat slab panel with dimensions 13.14 × 13.29m (Fig. 4) and thickness equal to 250mm was obtained.

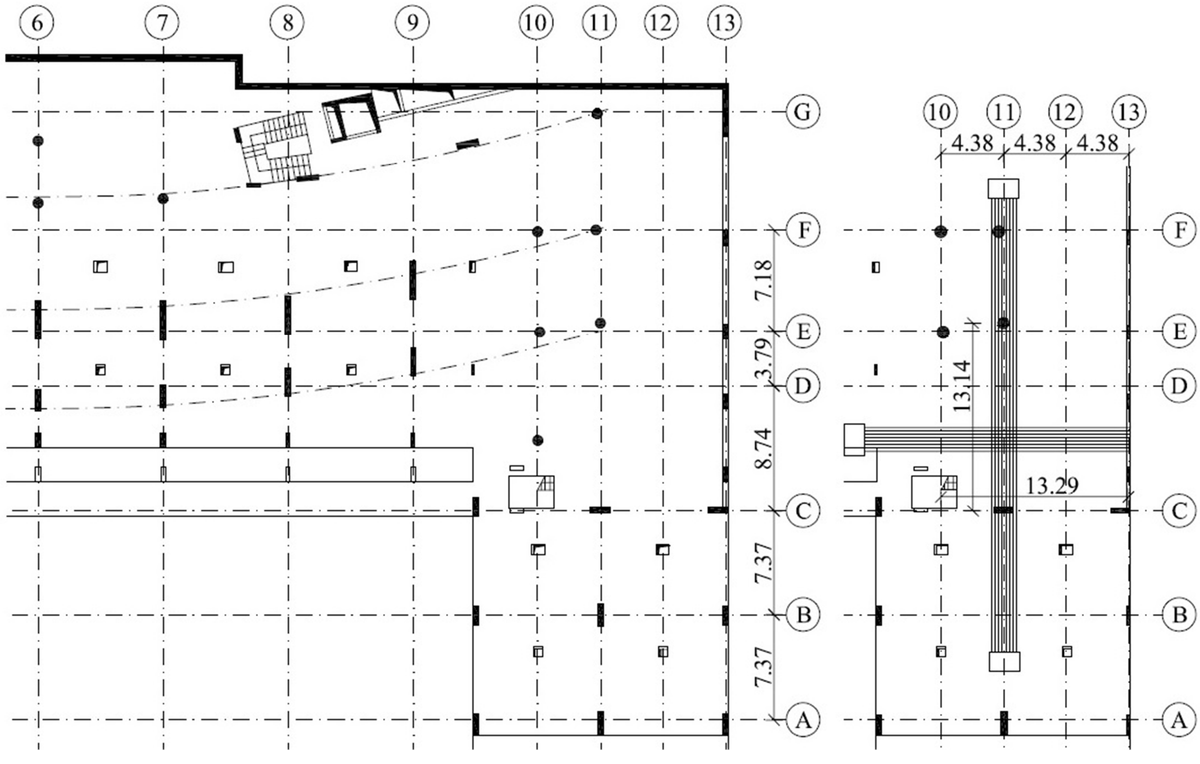


Figure 4. Prestress layout over the deliveries area in order to obtain bigger spans (*fib* 2005).

3.3. The largest span post-tensioned slab in the building of the Artistic And Cultural Center in Kozienice

One of the biggest, and probably the largest post-tensioned slab span with a solid cross-section was constructed in Poland in 2014, in the building of the Artistic and Cultural Center in Kozienice. Due to functional and architecture requirements, it was essential to design as thin as possible concrete slabs. Finally, three slender post-tensioned slabs was designed, including roof slab Sl-3 above the cinema hall with dimensions of 17.65 × 1.69m and a thickness of 350mm (Fig. 5). This slab is supported by three reinforced 250mm-thick walls and a reinforced beam. The slab was prestressed in two ways by using unbonded 0.6in. tendons in a spacing of 220mm (Fig. 6). The span-depth ratio for this slab is 50.4 (cf. section 2). Due to the record high span, measurements of the deflection were carried out. Deflection after 4 years of erection was 54.5mm, which is 1/323 of the span. The most important fact is that the growth of deflection in previous years has slowed down, which allows to conclude that the acceptable value equal to L/250 will not be achieved.

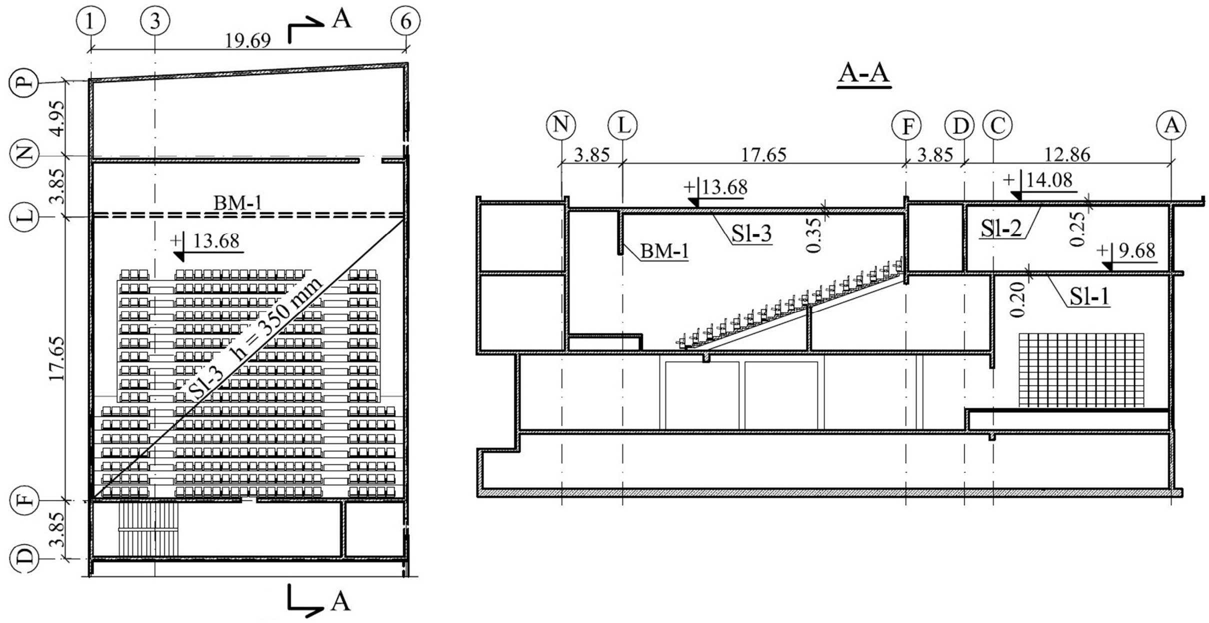


Figure 5. Segment plan and vertical section of the building with unique span post-tensioned slab Sl-3.

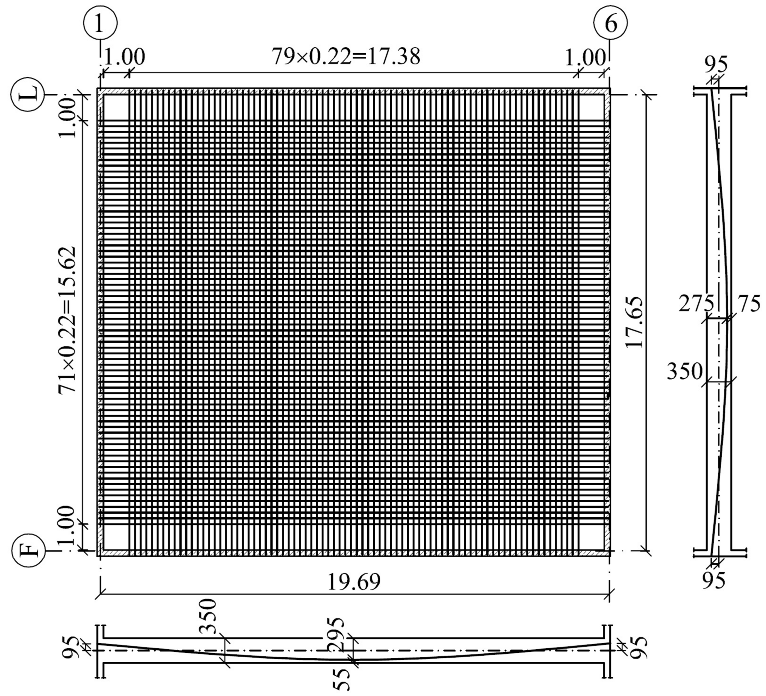


Figure 6. Prestress layout at the slab Sl-3 over the cinema hall.

4. Possibility of improvement

The guidelines which have been drawn up in numerous studies, concerning the design of post-tensioned slabs (cf. section 2), caused that post-tensioned solid slabs, larger than 12÷13m are practically not designed. The recommended span-depth ratio was repeatedly exceeded (cf. section 3.1

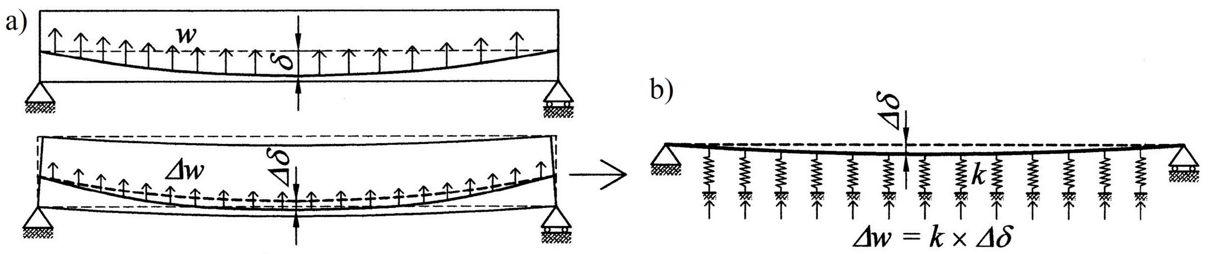


Figure 7. Tendon deformation due to slab deflection (a), operation of tendons as an elastic base (b).

– L/h = 34.7 for the waffle slab and -section 3.2 – L/h = 52.6 for solid slab). An exception (taking into account slab span) is the authors' project described in section 3.3, where the span of 17.65 × 19.69m with a thickness of 350mm was achieved. The studies were conducted for 4 years, and show that is possible to design slabs with larger spans than those designed so far.

A few years ago, the Cracow University of Technology initiated researches aiming to increase the effectiveness of prestressing slabs made of both post-tensioned (Szydłowski & Łabuzek 2017; Szydłowski & Mieszczak 2017; Mieszczak & Domagała 2018) and pre-tensioned elements (Derkowski & Surma 2014; Derkowski & Skalski 2017). According to the authors, what might help in the improvement of slabs effectiveness is the inclusion of the effect of slab deformation on prestressing force and equivalent load increase (Fig. 7). Deflection of slab causes an increase in the tendon sag, and therefore increases its impact on the slab. This impact should be taken into account at the iteration design stage. A proper but more complicated solution is modeling prestressing as elastic support (Fig. 7b). These issues are currently the main topic of the authors' studies.

Another way of improvement of slabs' effectiveness is the application of internal relief inserts. The authors' analysis shows that in spans exceeding 16m, self-weight can be more than 70% of total slab load. To achieve more slender and larger span slab, it is necessary to reduce self-weight with the least decrease of bending stiffness. A good way to do this might be internal relief inserts, made of synthetic void formers. In technical reports, it is considered that the thinnest slab could be obtained only with a solid cross-section, which forms great a container for compressive stresses. The authors'

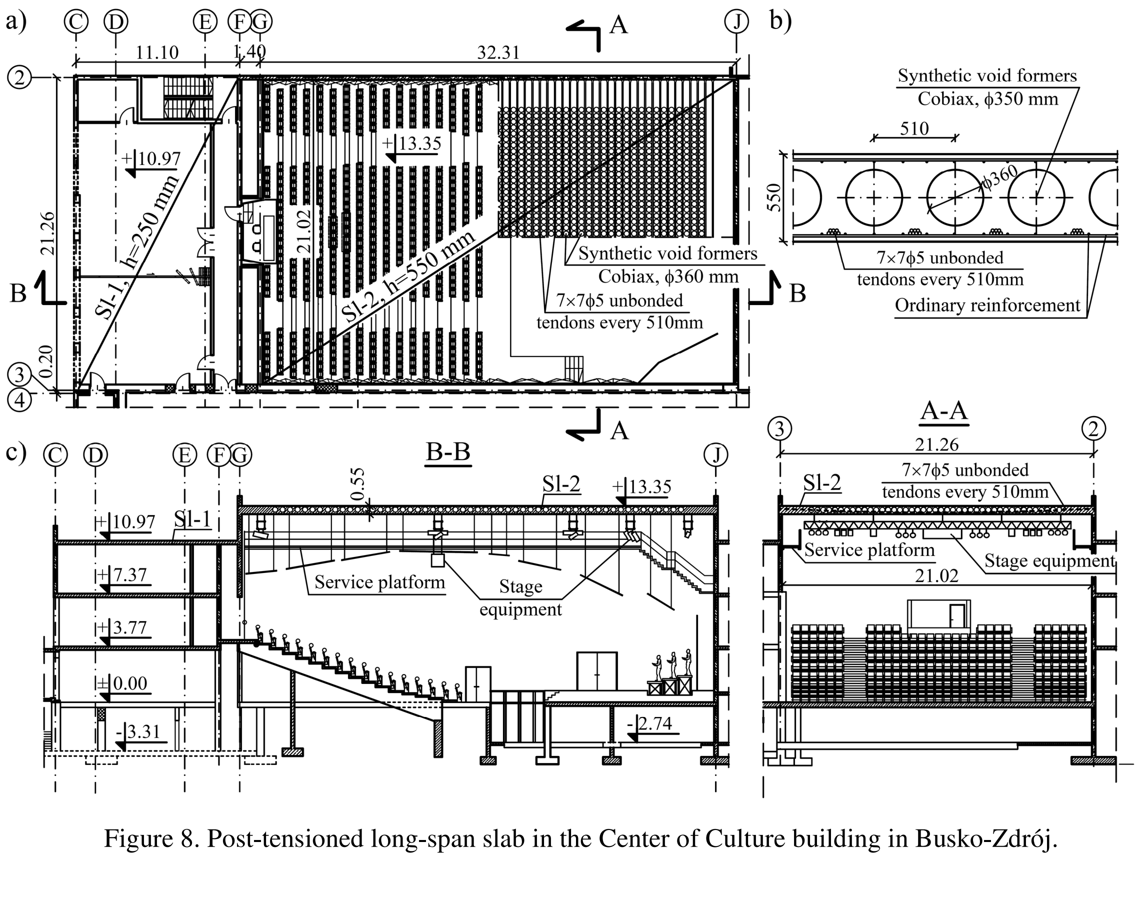


Figure 8. Post-tensioned long-span slab in the Center of Culture building in Busko-Zdrój.

analysis shows that light internal relief fillers give better results than solid slabs. This is caused by a significant decrease of self-weight (up to 30%) with a simultaneous slight decrease of stiffness (8-12%).

Figure 8 shows plan (a) and vertical section (c) of the center of culture building in Busko-Zdrój, where it was desirable to design a flat slab with the smallest thickness possible due to numerous facilities under the roof slab and required space necessary to operate them. The authors' idea was to design a one-way simply supported slab with a span of 21.26m and thickness of 550mm. Light internal relief fillers in the form of a sphere with a diameter of 360mm were used in the project. The spheres were arranged in rows every 510mm with ribs formed between them. Every rib has 7 unbonded tendons running in two rows (Fig. 8b). Figure 9 shows the results of elastic defection in the version with internal relief fillers (a) and without (b). The following loads were assumed: self-weight of slab 12.1kN/m^2 with internal relief fillers and 15.4kN/m^2 without them, roof slab layers 1.5kN/m^2, facilities above and below slab 3.0kN/m^2, snow 1.0kN/m^2 and effective prestressing force 0.8×220=176kN for one tendon. A concrete class of C30/37 with basalt was assumed (E_{cm}=1.2×34=40.8GPa). Elastic deflection (Fig. 9) was computed for all permanent loads, prestressing and a half load of snow. Deflection equal 27mm was obtained for a slab with internal relief fillers and 37mm for a solid slab. According to the Concrete Society (2005), long-time deflection might be estimated as three times the elastic deflection for this load combination. In this way the total deflection for the slab with internal relief fillers was 81mm and 111mm without. The limit for deflection is L/250, and it is 85mm for the described slab. The obtained results show the positive aspect of the application of internal relief fillers, which allows to reduce deflection with the same thickness and amount of prestressing compared to the solid slab. It was achieved by reducing slab weight by 22% and stiffness in bending by only 12%.

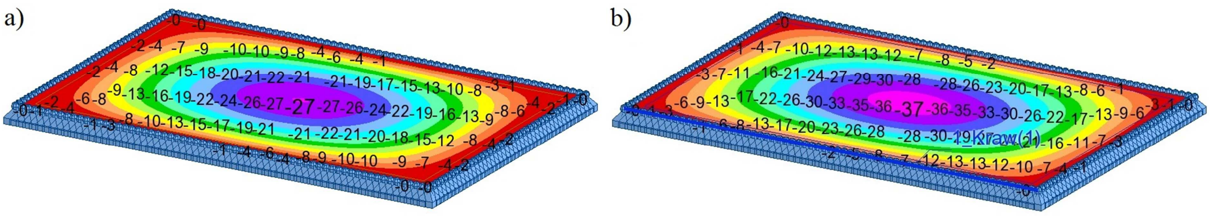


Figure 9. Elastic deflection of slab with lightweight inserts (a) and with solid cross-section (b).

5. Conclusions

This paper demonstrates some of the chosen recommendations and examples of post-tensioned slabs. The examples, especially of the authors' projects, show the possibility of designing slabs much more larger and more slender than recommended. Ways of further improvement of slab effectiveness might involve a different approach to computational analysis by taking into consideration the influence of slab deformation on prestressing action or the application of internal relief inserts.

References

Khosa, N. (2018), Why Unbonded Post-Tensioned Concrete? CTBUH Journal, Issue 1, pp. 58–58.

The Concrete Society (1974), The design of post-tensioned concrete flat slabs in buildings. Technical Report 8, Camberley, UK.

The Concrete Society (1994), Post-tensioned concrete floors – Design Handbook. Technical Report 43, Camberley, UK.

The Concrete Society (2005), Post-tensioned concrete floors – Design Handbook. Technical Report No. 43, Cromwell Press, Wiltshire, UK.

Khan S. & Williams M. (1994), Post-tensioned Concrete Floors, Butterworth-Heinemann, Bodmin, UK.

FIB (2005), Post-tensioning in building. Bulletin No. 31, Lausanne, Switzerland.

Pretzer A. (1972), Unusual Application of Prestressed Waffle Slabs and Composite Beams, ACI Journal, December, pp. 765–769.

Derkowski W. & Surma M. (2014), Influence of concrete topping on the work of prestressed hollow core slabs on flexible supports, 4th International fib Congress 2014: Improving Performance of

Concrete Structures, Proceedings, pp. 339–341, Mumbai; India; 10-14 February 2014.
Derkowski W. & Skalski P. (2017), New Concept of Slimfloor with Prestressed Composite Beams, Procedia Engineering, Vol. 193, pp. 176-183.
Szydłowski R., Łabuzek B. (2017), Post-Tensioned Concrete Long-Span Slabs in Projects of Modern Building Construction, IOP Conference Series: Materials Science and Engineering, 245 (2017) 022065.
Szydłowski R., Mieszczak M. (2017), Study of application of lightweight aggregate concrete to construct post-tensioned long-span slabs, Procedia Engineering, Vol. 172, pp. 1077-1085.
Mieszczak M., Domagała L. (2018), Lightweight aggregate concrete as an alternative for dense concrete in post-tensioned concrete slab, Materials Science Forum, Vol. 926 MSF, pp. 140-145.