About the Project and Study of Post-tensioned Transfer Beams Under the Five-storey Building in the Centre of Warsaw

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***Abstract*—Construction of buildings is often associated with creation of the large, free from supports spaces in the lower floors with dense structural system on the upper floors. To transmit the load from the upper floors to the foundation, transfer slabs and beams are constructed. They are heavily loaded, bended and sheared components, which require a significant height of cross-section. The use of prestressing reduces cross-section height of reinforced concrete transfer elements. The Warsaw office and service building completed last year in the part situated above the W-Z route tunnel, contains 6 post-tensioned transfer beams with 1.80×1.60m cross-section and variable span in the supports axes from 23.80 to 28.20m. Beams represent foundation for five storey building. The paper presents basic principles of design, results of deformation of the structure during erection obtained from theoretical FEM model and measured as well as applied technology.**

Keywords-transfer beam; post-tension; composite cross-section; prestressed slab

I. INTRODUCTION

During construction of the reinforced concrete buildings, with no possibility of maintaining supports of the higher floors in the lower tier, it is often necessary to transmit loads from the upper floor to the nearest supports through the heavily loaded slab or long-span beams (transfer elements). The problem is mostly caused by a need to locate the large spaces free from supports in the lower floors. Heavily loaded, bended and sheared components of long spans require often a large height of cross-sections. The use of prestressing significantly reduces a height of element cross-section. The prestressing of transfer elements can be performed with straight-line cables at the upper and lower surface of the element respectively, in the span and over the columns. The most effective prestressing is done with curved routes adapted to the diagram of bending moments. In addition to the use of the positive effect of "hanging tendon" for bending such prestressing greatly reduces the shear forces in the vicinity of the supports. Slender elements usually require a strong prestressing with step by step introduction of forces together with the construction of the building.

Such solutions have been used successfully in the world for many years. In 1988, in Hong Kong in Pacific Place building, the use of prestressing in quantities of 22kg/m^3 at the slab transfer with thickness of 4.5m, carrying a 52-storey building made it possible to reduce the level of passive reinforcement from 500kg/m^3 in the reinforced concrete version down to 180kg /m^3 in prestressed version [3].

In 1999 in the building of Funchal Crown Plaza Hotel in Portugal six storeys have been placed on the transfer beams with a span of 18m and a height of 2.5m [3]. In later years there have been many similar construction carried out globally. The design problem of transverse slabs have been raised among others in [4]. On the other hand, reference [7] presents a slightly different design solution consisting of two slabs and walls connected into the rigid structure over a large ceremonial hall on the lower floor.

In 2014 in a building constructed on Senatorska Street in Warsaw (Fig. 1) 6 transfer beams of cross-section of 1.80×1.60m and with the span in the supports axes from 23.8 to 28.2m have been used. The tunnel of W-Z route was surrounded with 0.8m thick foundation walls. The five storey building was supported by the transfer beams on the foundation walls.

II. GEOMETRY OF THE BUILDING, LOAD CHARACTERISTIC, DESIGN ASSUMPTIONS

The above indicated building was designed on the projection of elongated rectangle measuring approx. 85×30m. The reinforced concrete tunnel of W-Z route is positioned under the end part of the building (Fig. 2 and 3). Under the whole building two floors of underground garage, which were discontinued by tunnel have been located. Along the tunnel

Figure 1. Visualization of the building with transfer beams (source: RKW Rhode Kellermann Wawrowsky Polska Sp. z o.o.).

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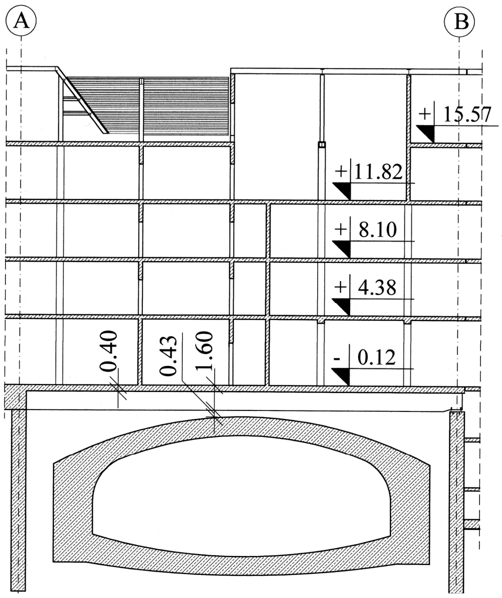

Figure 2. A part of the building above the tunnel W-Z route vertical cross-section.

walls, slurry walls 0.80m thick have been constructed.

These walls support transfer slab carrying five storeys above ground (2 of them are hidden in the roof of the attic). Transfer slab in the pos. -0.12m forms a 6 post-tensioned beams with a cross section of 1.80×1.60m, connected to reinforced concrete slab 0.40m thick. Three beams (BS/4, BS/5 and BS/6) extend perpendicularly to the slurry walls and their range in the supports axes is 23.8m. Three beams (BS/1, BS/2 and BS/3) run from the node and the longest beam BS/1 range is 28.2m. Within the A axis beams were fully fixed in the caisson plate 1.60m thick. The B-axis contains dilatation of the building. The support of beams had to be capable of displacement of 30mm. This is provided by bridge pot bearings (Fig. 3 - the cross-section B-B). Prestressed beams are connected by a number of cross beams of the cross-section of 0.60×1.20m, 0.80×1.20 and 1.00×1.20m. Transfer slab supports 2 running diagonally reinforced concrete walls with reinforced concrete lift shafts and numerous reinforced concrete columns.

The authors of this work designed only prestressed slab based on geometry of the presented building and the load on the slab provided by the designers of the building in the form of linear loads from the walls and forces concentrated from columns. The following conditions have been imposed on the slab:

- permitted load of the tunnel is too small to carry the weight of the slab during concreting. It was necessary to find a solution for its performance without loading the tunnel with full weight of the wet concrete,
- due to the sensitivity of construction occurring above the slab to its deflection the total amplitude of deflection during construction of the building, taking into account the time-dependent (rheological) deflection of slab was limited to 30mm. It is 1/940 of span for the longest beam span of 28.2m.

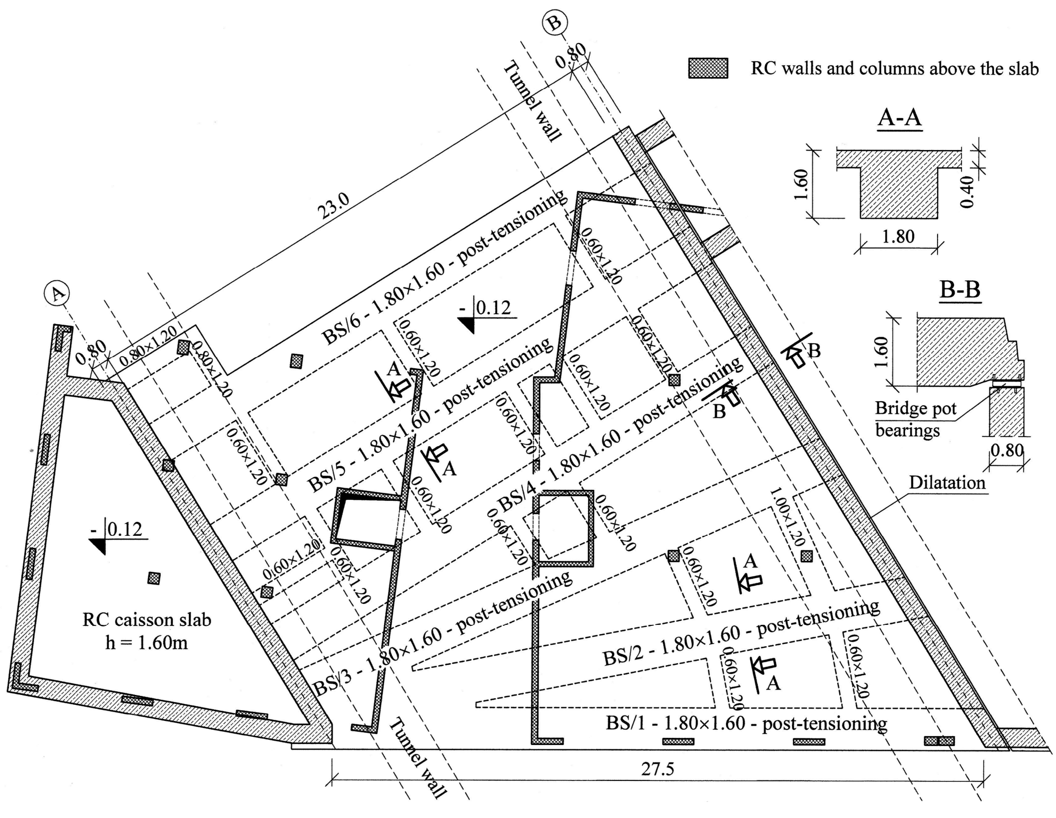

Figure 3. Structural arrangement of the slab above the tunnel with transfer beams.

III. Technological and Material Solutions

Taking into consideration conditions set out in section II step by step concreting and prestressing of the slab have been assumed. Firstly, part of the caisson slab has been casted in order to allow the assembly of crane (the area filled with grid in Fig. 4). Because the load capacity of the tunnel was sufficient to carry the weight of wet concrete beams themselves with a height of 1.20m (Fig. 4, section B-B) the beams could be constructed in the first stage.

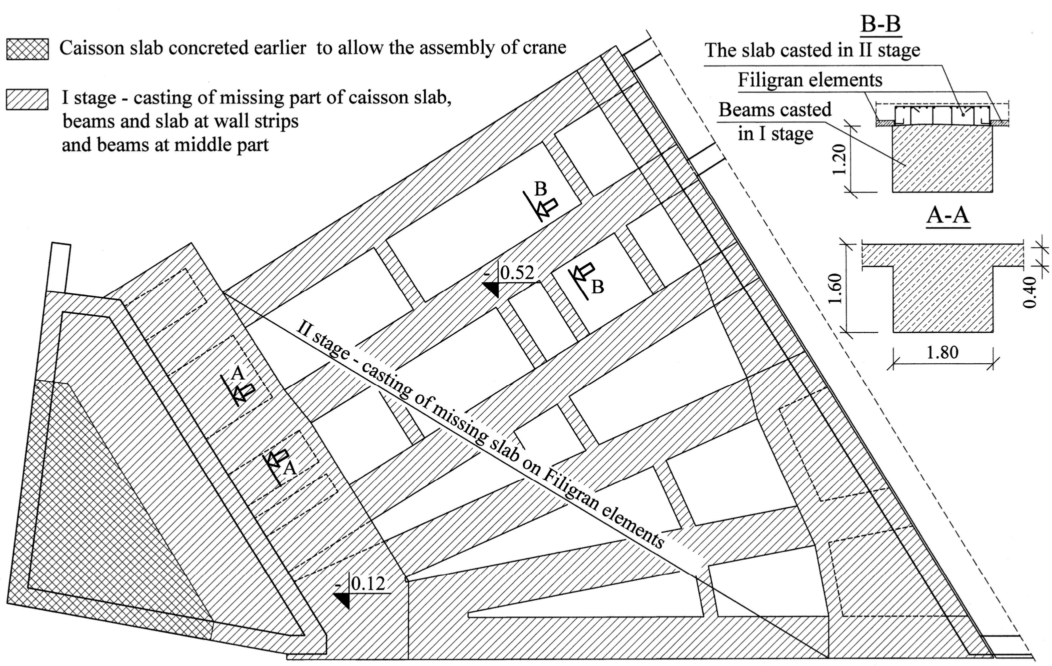

Figure 4. Technology for slab concreting.

Floor slab has been concreted only on the supporting parts along the walls together with beams, which was designed to conceal the cables floating upward at the supports. The slab in the mid part of the floor was concreted using precast Filigran elements based only on previously positioned beams. Beams have been prestressed before concreting of slab, which caused their elevation and allowed them to take over the load from the wet slab. Thus, loading the tunnel with wet slab has been avoided. In constructing the slab a fairly controversial technological solution has been applied. Second stage of prestressing has been programmed immediately after casting of slabs with the weight of wet concrete. Such a treatment aimed at eliminating a large deflection due to the weight of slab resting on slender beams with reduced height. Program of prestressing is discussed in details in section V.

Fig. 5 shows the view of the beams casted to the height of the bottom of the slab. In the photo you can see discontinued crossbars between prestressed beams. Predicted negative deflecion of beams after prestressing was in the range from 2 to 6mm and during the introduction of the first prestressing beams had to work independently (no slab). With a length of crossbars from 2.22 to 4.25m, they held the height of 0.80m therefore had a very high flexural stiffness. Elevation of one beam as a result of prestressing with an unchanged position of adjacent beams would undoubtedly result in breakage (strong cracking) of connecting crossbars. For this purpose it was decided to discontinue the crossbars using the breaks of approx. 400÷500mm. This assump-tion has enabled independent movements of beams without damaging crossbars, longitudinal reinforcement of crossbars was freely deformed in the intervals. Breaks were encased with formwork and concreted together with the slab on beams.

Figure 5. View of concreted beams to a 1.2m height with discontinued crossbars.

A. Concrete

To construct the slab, a class C35/45 concrete based on basalt aggregate and cement CEM I have been provided. Project assumed that during the implementation of the first prestressing, concrete have a min. 70% of the 28-day compressive strength and modulus of elasticity min. 30GPa. Conducted just before prestressing tests of cylindrical samples ϕ150×300mm showed an average compressive strength of concrete equal to 43.1MPa and modulus of elasticity equal to 39.0GPa.

B. Passive reinforcement

Beams used a minimum area of passive reinforcement for bending (0,0013*db*), ie. 12ϕ25mm bars. Minimum reinforcement has been located at both the lower and the upper surface (Fig. 6). Additionally, due to prestressing of beams with reduced height, at the length where beams where concreted without a slab, reinforcement under the lower surface of the slab of 8ϕ25mm bars have been used. There is also an longitudinal side surface reinforcement in the number of 6 bars ϕ20mm at each side surface.

Transverse reinforcement has been constructed in the form of ϕ12 mm six vertical branches. It was constructed from 2 closed stirrups, plus 2 vertical inserts. Construction spacing of a full set of transverse reinforcement is taken as 400mm, and the spacing due to the shear capacity varied. The smallest spacing was 100mm for BS/2 beam at axis A.

Both the design and installation of reinforcement bars in the common node BS/1, BS/2 and BS/3 have caused many problems. The sample visualization of reinforcement in the area has been shown in Fig. 7.

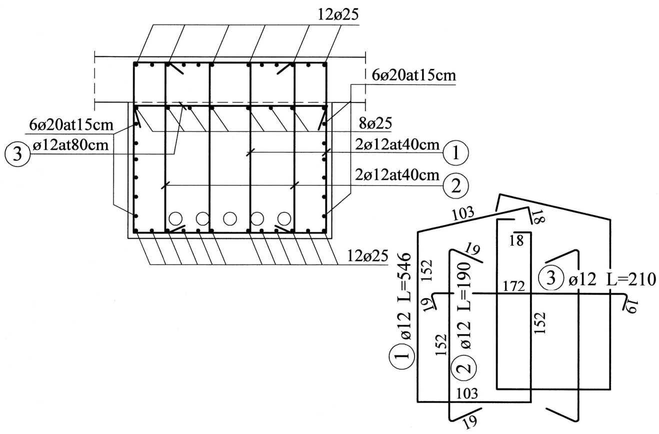

Figure 6. Passive reinforcement in view of one of the prestressed beams.

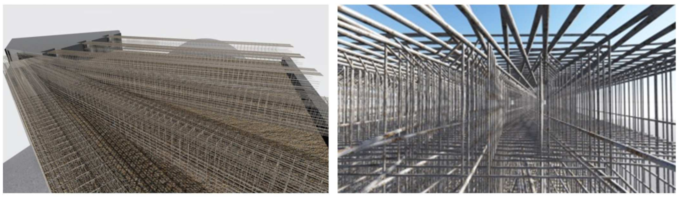

Figure 7. Visualization of reinforcement in the common node of beams BS/1, BS/2 and BS/3.

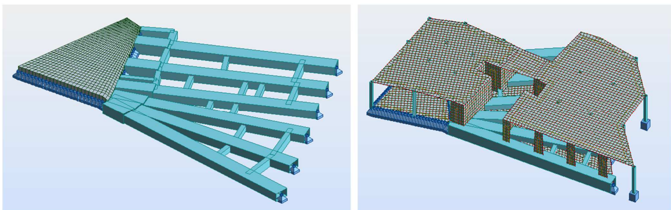

Figure 8. Models in the FEM system used in static analysis of structure.

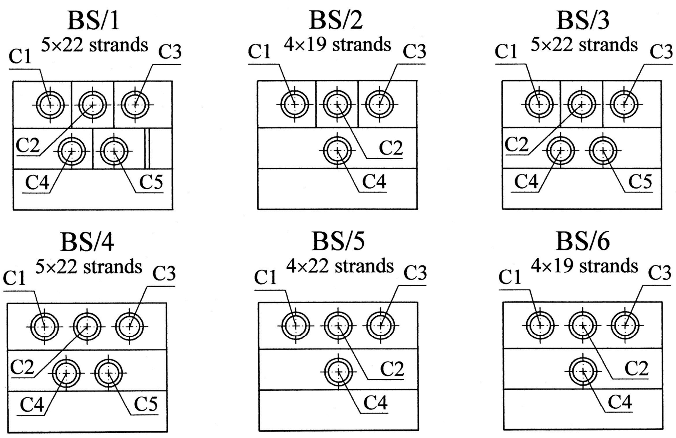

Figure 9. Prestressing cables and their distribution on beams foreheads.

IV. Model Calculations

In order to perform a static and strength analysis two models in the FEM system has been built (Fig. 8). First model was used to analyze of grate before pouring the slab, a second one was used to analysis of the completed composite slab. In order to take into account the stiffness of construction occurring above the slab, one additional storey has been built. Load of another storeys was transmited in the form of surface load to a slab of a storey above ground floor. Prestressing has been modeled with substitute load.

Static analysis was performed with the incremental method by applying subsequent load from the individual stages to the respective models. It is hard to accurately determine the concrete modulus of elasticity for the massive structure taking into account load history. Rheology of concrete and its impact on stress and deformation of structure are taken into account by reducing of concrete modulus of elasticity [2] and enforced strains modeling of concrete shrinkage.

V. Prestressing and Prestressing Program

The static and strength analysis pointed to a need for prestressing in the number from 4×19 strands to 5×22 7ϕ5 strands. Diversified prestressing in beams was caused by an uneven load. Fig. 9 shows adopted prestressing and distribution of cables on beam foreheads at axis B. At the axis A cables have been anchored in the dead anchorages concreted inside a caisson slab. Fig. 10 shows a profile and a plan of prestressing cables for selected beam (BS/5). Dead anchorages were lowered in a caisson slab in order not to put excessive force on the slab eccentrics. Anchorages are positioned with alternate offset by 0.70m to avoid excessive concentration of force. Fig. 11 shows the cables in a difficult common node of BS/1, BS/2 and BS/3 beams. In order to avoid a collision, part of cable has been lowered (cross-section 1-1). On a small area there are 14 large-sized dead anchors located at different levels (Fig. 12).

Fig. 13 shows the timetable for implementation of prestressing, which was carried out in four stages tensioning selected cables with target power (tightening cables was not used). Cable 22 was tensioned with force of 4.4MN while cable 19 with force of 3.8MN. Prestressing program developed at the design stage has been adjusted and adapted to construction schedule during realization of facility (irregular construction of the building on the transfer slab). Finally, the following stages of prestressing has been completed:

- Stage I - to relieve the tunnel during concreting of slab, one cable for each beam concreted to the lower surface of the slab has been tensioned constructing a support for the slab.
- Stage II - in the course of concreting the slab in order to reduce large deflection the second cable has been tensioned in the beam. Concreting was carried out along strips parallel to beams. Cables where tensioned gradually immediately after concreting a slab near each beam.
- Stage III - third cable in each beam was tensioned after completing of walls and columns under the slab in pos. +11.82 in section I (Fig. 14) and walls and columns of ground floor on remaining area of prestressed slab.
- Stage IV - 1 or 2 missing cables in each beam has been

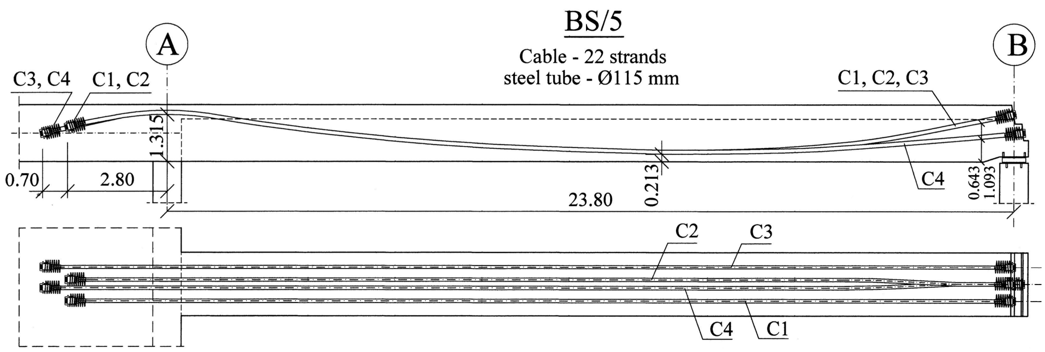

Figure 10. Prestressing for beam BS/5.

before composite (only beam with a height of 1.20m is working) compression at the bottom introduced in the first stage have been reduced by weight of wet slab and afterwards have been repeated by tension of following cables in stage II.

During the whole work cycle of cross-section small tension that did not exceed 2.0MPa have appeared. After composition of cross-section with a slab, tensions occurred only in a slab, while in lower fibers a gradual increase in compressive stresses can be observed that amounted to 19.7MPa after full prestressing of the beam BS/1. Compressive stresses at the bottom edge, taking into account all loads (also life load) and time-dependent losses of prestressing forces for

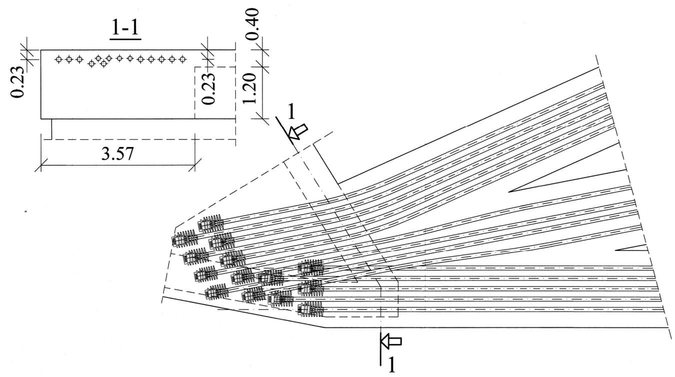

Figure 11. The arrangement of cables and location of dead anchors for beams BS/1, BS/2 and BS/3 in the node.

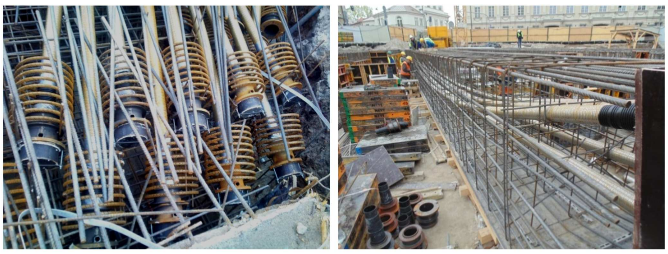

Figure 12. View of dead anchors in the node of beams BS/1, BS/2 and BS/3 (left), view of one of beams during assembly (right).

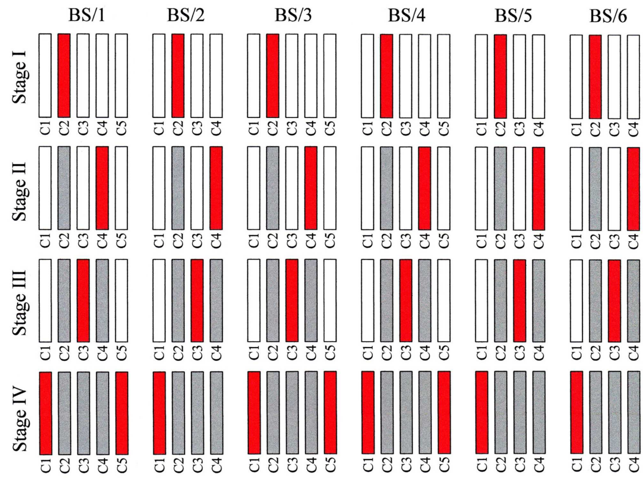

Figure 13. Schedule of prestressing (red – cables under tension, gray-tensioned cables).

tensioned at a time when almost all reinforced concrete structure was completed (only the last floor in pos. +15.57 - Fig. 2, 14 and 16 was missing) and a steel roof structure on part of the building.

VI. Theoretical Predictions and Reaction of Construction

Fig. 15 shows diagrams of theoretical stresses on the most charged span cross-section for selected BS/1, BS/2 and BS/5 beams in different stages of development (before and after each prestressing stage). It is easy to notice that in cross-section

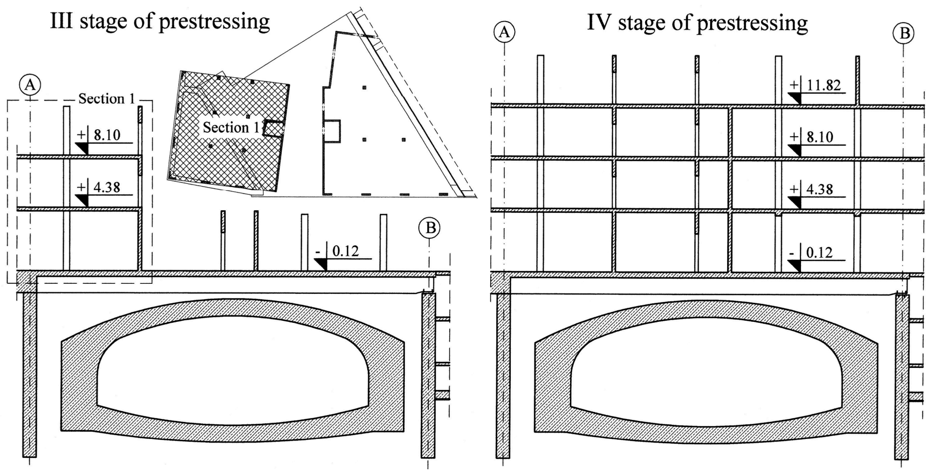

Figure 14. Progress of the building during third (left) and fourth (right) stage of prestressing.

TABLE I. VALUES OF FORECASTED DEFLECTION OF BEAMS IN PARTICULAR SITUATIONS (MM).

Situation	*BS/1*	*BS/2*	*BS/3*	*BS/4*	*BS/5*	*BS/6*
Stage I – after prestressing of reduced beams	-6	-4	-2	-2	-2	-2
After pouring a slab	18	15	12	12	11	10
After II tension stage (with wet concrete)	6	4	3	3	3	3
After IV tension stage	10	9	10	10	12	9
Final bending values	26	22	19	18	16	12

Figure 16. Status of the building during introduction of last prestressing (left), view of protected anchorages on a beam forehead (right).

three presented beams range from 3.2 to 6.0MPa. This is a fairly high level of compressive stresses which confirms a strong prestressing, but main factor determining level of prestressing in this case were strict conditions for deflection.

Table 1 shows the forecasted values of deflection in the most important stages of implementation while on Fig. 17 results of geodetic surveying of slab displacement have been presented. It can be seen that negative deflection of beams after first prestressing has been underestimated in calculations. The actual deflection after pouring a slab and second stage of cables tensioning was therefore smaller than calculated deflection. Table 2 also shows large deflection of beams with reduced height under the weight of wet slab (10 to 18mm). Unfortunately, geodetic measuring of deflection at this stage was not possible, but measurement taken after the second stage of prestressing shows a substantial reduction (deflection after completing the slab ranged from 0 to 2mm). This reduction was achieved through introduction of prestressing force in the beam immediately after concreting a slab (with "wet" concrete). Analyzing displacement of control points after fourth stage of prestressing, deflection of each beam will amount to 12.5mm, 12.5mm, 15.5mm, 13.5mm, 11mm and 7.5mm for the beam from BS/1 to BS/6. This shows underestimation of calculations of deflection at this stage (see Table 1). It should be emphasized that these are deflection under the total, self-structure weight of the building (transfer slab has not responded with additional deflection on slab in pos. +15.57m missing during the fourth stage of prestressing). Comparing actual and calculated deflection values it can be concluded that values of the final deflection provided in Table 1 may also be somewhat underestimated. However, given the level of load during last measurement and age of slab (4 months), it can be concluded that imposed condition of 30mm will be maintained with a certain reserve. It should be imposed on deflection measured from the moment of slab concreting and

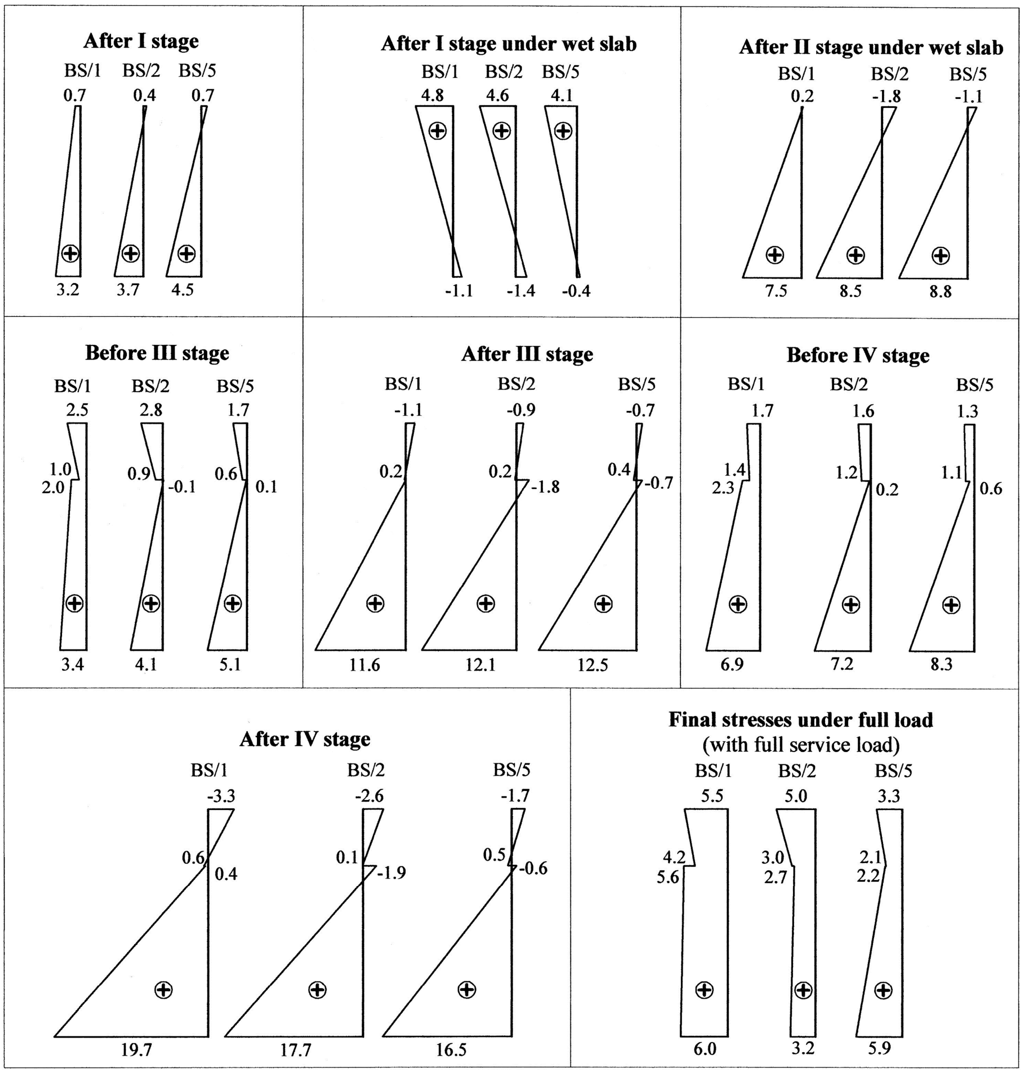

Figure 15. Forecasted stresses in span cross-section of beams BS/1, BS/2 and BS/5 in various stages of implementation and construction works.

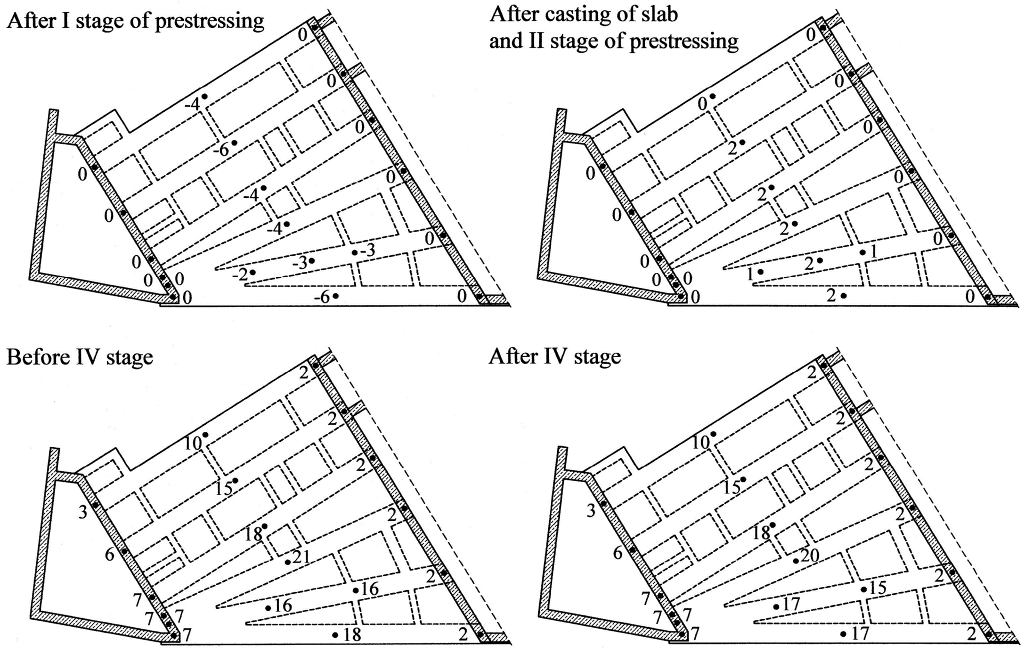

Figure 17. Vertical displacements of control points of the slab (mm).

introduction of second prestressing (only they affect the structure above), and these deflection are respectively 10.5mm, 10.5mm, 13.5mm, 11.5mm, 9 mm and 7.5mm for beam from BS/1 to BS/6. The ratio of given deflections to the theoretical span is as follows: 1/2690, 1/2430, 1/1780, 1/2070, 1/2640, 1/3170 while the ratio of beam spread to beam height ranges from 17.6 for beam BS/1 to 14.9 beams BS/4, BS/5 and BS/6. So small deflection can be primarily attributable to high compressive stresses in lower fibers. It is interesting that the last prestressing was able to raise the whole building by 1mm (compare the displacement of beams BS/1 and BS/6 before and after the fourth stage of the prestressing in Fig. 17).

VII. CONCLUSIONS

The paper presents results of implement prestressed transfer slab in the building. Slab made over an underground tunnel supports 5 storeys. Presented project is a first venture of this type in project workshop of authors. Results of measurements of deflection during construction of the building indicate slight deviations from predicted values. Values were calculated, however in simple models using a substitute load method, it is difficult to expect precise compliance. The values of deflection in final monitored stage of implementation, however, shows that imposed conditions are met with a certain reserve. It can be noted, that maximum span/depth ratio for post-tensioned beams carrying 5 storeys is 17.6. This is higher in comparison with reported similar realizations. It was achieved by four step prestressing and high level of bottom compressive stresses.

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