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Prestressed Ring Beam in the Church of St. Peter's and Paul's in Bodzanow, Design and Realization

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Abstract. The present trend in architecture is designing thin. slender and spacious architectural forms. It has become the reason for searching for new solutions and finding new ways of use of the existing construction ones. Recently, the first time in Poland, the post-tensioning has been used in realization of church building. In the Church of St. Peter's and Paul's in Bodzanow (near Cracow) was designed circumferential ring beam post-tensioned with 4 unbounded tendons to transfer peripheral tensile forces from the roof. Thanks to the use of a prestressed ring beam hidden in the wall, large cross-section of roof girders was possible to be avoided, as well as a massive reinforced concrete ring or additional steel tie-rods. The paper presents the applied solutions in details with the theoretical calculated results as well as the results of prestressing measured in site during tensioning of tendons. Based on presented results some conclusions have been drawn.

1. Introduction

The first attempts of prestressing, which is the introduction of prior compression to the concrete. had already been made by the end of the 19th century. However, in 1930s. Eugène Freyssinet tested creep and shrinkage of concrete and revealed the necessity of usage of high strength steel in the prestressed concrete structures. The first successful attempts had been carried out after the production of steel that alloys of low relaxation rates, capable of keeping a lot of stress for a longer period of time. were developed. The true evolution of prestressed concrete structures in the world has happened after World War II as a result of significant technological progress and the necessity of rebuilding destroyed cities. In Poland. prestressing has been used since 1950s when the pre-tensioned elements (large-span roof trusses. roof slabs. beams gantry and later train tracks underlay) were very commonly used. Currently in Poland. thanks to contact with the technology of the world. large investments with the use of modern prestressing systems are applied in bridge constructions. cylindrical tanks for liquids or buildings.

Post-tensioned concrete in buildings in Poland has begun to be used relatively recently. as it was only at the beginning of this millennium. The emergence of a prestressing systems with unbounded tendons in the 1990s. resulted in the development of slender slabs with large spans. The present trend in architecture is designing thin. slender and spacious architectural forms. with the limit of the points of support in order to achieve large open spaces. It has become the reason for searching for new solutions and finding new ways of use of the existing construction ones. Such an example may be the use of circumferential prestressed ring beam in a project of a church in Bodzanow near Cracow [1]. This

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solution used 4 unbounded 7ϕ5 tendons made of Y1860 steel as an internal prestressing to transfer peripheral tensile forces from the roof. Thus, delicate and slender construction form was achieved.

Figure 1. Visualization of Church of St. Peter's and Paul's

In the world. pre-tensioned precast concrete elements were used to construct churches. Sometimes. external prestressing with FRP material was used to strengthen existing facilities. Usage of post-tensioning with internal unbounded tendons in the construction of churches is unknown to the authors.

The architectural form of the presented church (figure 1) was designed by the Cracow Architectural Design Studio f-11 which implements many modern building projects [2]. In this paper, the structural details and results of theoretical calculation are presented as well as the report from realization and the results of radius displacements and concrete strains due to prestressing. Based on the obtained results some conclusion about the propriety of the design assumptions and calculation were presented.

2. General description of the designed construction

The view of the Church of St. Peter's and Paul's in Bodzanow (nearby Wieliczka) is shown in figure 1. The shape of the church was designed on a plan of a 25.5m diameter circle (figure 2a), The structure of the building is made of 12, steadily positioned on the perimeter, RC columns of the cross-section of 0.4×0.6m, On the columns, radiating roof girders made of laminated wood are sustained (figure 2b).

The preliminary analysis showed that the usage of girders, rigidly connected in the central node, without any additional perimeter tie-rods, would require cross-sections of approximately 2,2m in height. Another version assumed taking steel peripheral tie-rods, running along the chords, which would allow to decrease the height of the cross-section of the girders to 700mm. In the end, a ring beam made of prestressed concrete of a 300×500mm cross-section was chosen, hidden in the peripheral infill wall.

In the building, a ring-shaped entresol, made of reinforced concrete, was built on the level of the first floor, sustained on the external edge on 12 columns, and on the internal edge on 6 columns, made of concrete (figure 2a). Additionally, on the internal edge, between the columns, 6 suspensions to the roof girders were used.

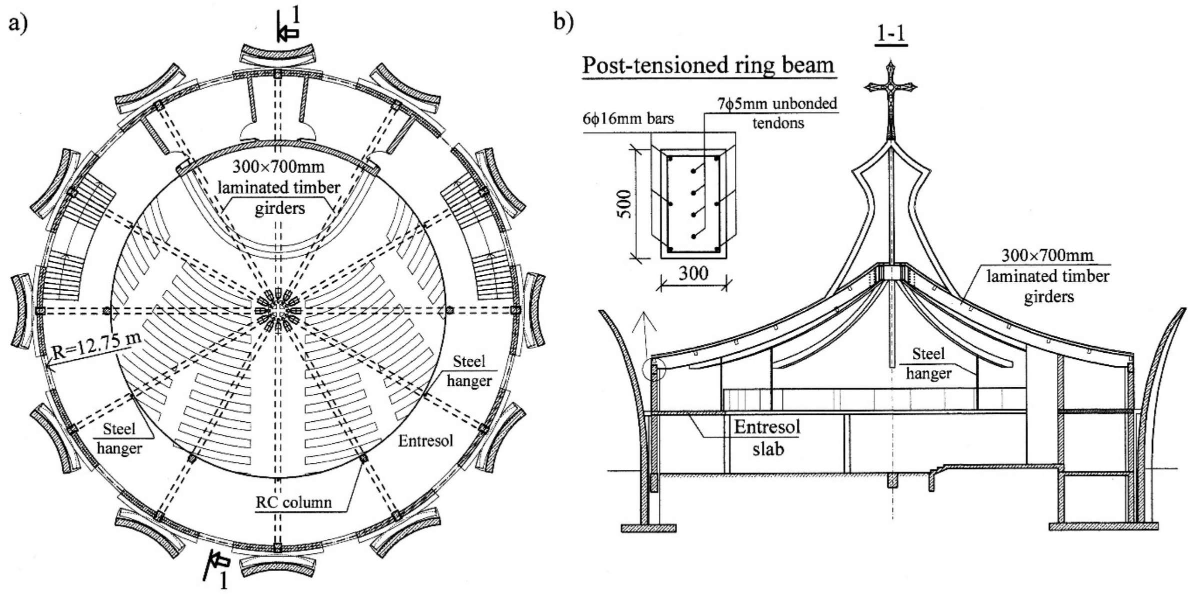

Figure 2. The church plan (a), vertical cross-section and post-tensioned ring beam (b)

3. Circumferential post-tensioned ring

The wooden roof girders form the dome with circumferential tie-beam. A good solution for this tie-beam is to make it as a prestressed element. All over the world, it is common to use a post-tensioned ring beam in liquid tanks, but this beam is often used in circular buildings with radial roof girders too, [3]. In Poland, this solution was used in the renovation the Cetennial Hall in Wrocław in 2009 [4, 5].

A reported prestressed ring beam was designed with the cross-section of 300×500mm (figure 2b and 3) and concrete class of C30/37. Prestressing with 4 unbounded tendons, positioned in the vertical axis of the cross-section, was applied. Tendons of 7ϕ5mm made of Y1860 steel were used. The ring beam is reinforced in the longitudinal direction, by 6 bars of ϕ16mm and by transverse stirrups of ϕ6mm every 200mm. It was assumed that the prestressing will be implemented once the reinforced structure will be done and before the installation of the roof girders.

All of 4 tendons are tensioned with a force equal to 200kN. Each of the tendons surrounds the entire circumferential ring beam. The tendons are anchored in anchor grooves, two tendons on two opposite sides of the ring beam alternately (figure 3).

4. Computational analysis of the construction

The analysis was carried out on the model created in the FEM system, which is shown in the figure 4. The model consisted of concrete columns, entresol slab, peripheral ring beam and roof girders. The bar and the shell elements of the geometrical and material characteristics, which matched the ones applied in the project, were used. The following two models were analyzed: prestressed model with and without the roof structure. The prestressing force was considered as the circumferential radial load applied to the ring beam and directed to the centre. The force after the total loss was assumed, which has value of 75% of the initial force (15% - immediate loss, 10% - time-dependent loss).

Figure 5 shows the distribution of the longitudinal forces inside the ring beam and bending moments after the prestressing (dotted line), due to roof girders action (dashed line) and final values (continuous line). The axial force of 621.1kN and bending moment with changeable sign caused by the stiffness of the columns, with the value of -13.6kNm above the columns and +6.6kNm between the columns, were entered due to prestressing. As a result of the forces coming from the roof girders, the compressive axial force was reduced to the value of 391.0kN, the bending moments escalated to the value of -81.9 and +42.1kNm.

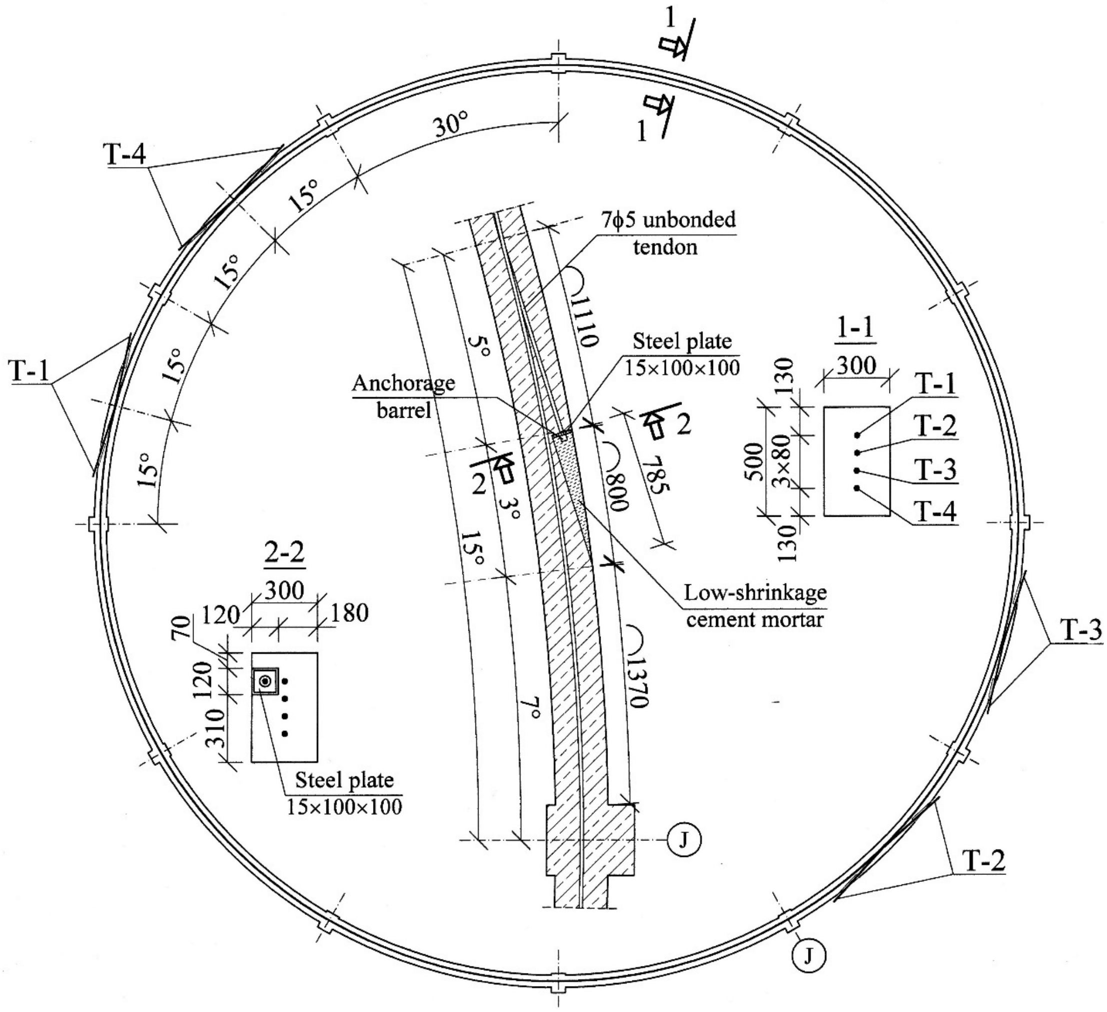

Figure 3. Circumferential post-tensioned ring – scheme of tendons anchoring

The analysis of the stress inside the ring beam (figure 6) showed the occurrence of tensioning in the cross-section above the columns, with a value of 4.0MPa (continuous line). This value does not guarantee that there are no cracks. The ratio of bending moment to the cracking moment is 81.9/45.0 =1.82. Such value is small and safe for the increase of deformations resulting from the cracking. The calculated width of the cracks according to [6] is 0.15mm.

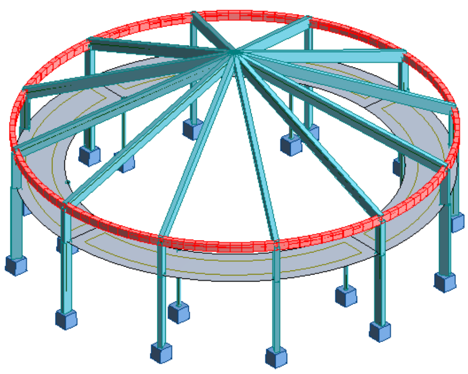

Figure 4. Church structure FEM model

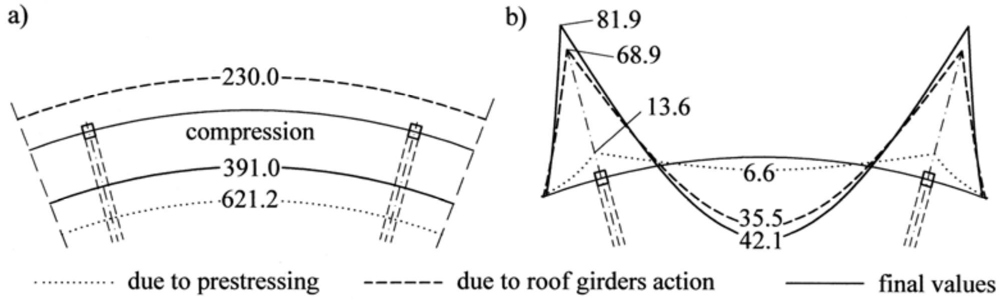

Figure 5. Diagrams of longitudinal force in kN/m (a) and bending moment in kNm/m (b) in the beam ring

Figure 7 shows the deformation of the ring beam after prestressing (dashed line) and the final deformation (continuous line) resulting from the action of the load coming from the roof girders. Prestressing leads to the regular movement of the ring beam to the centre, with a value of 2.0mm. The load coming from the roof girders leads to the deflection of the ring beam. When the axial distance of the columns (measured along the chord) is 6.8m, the value of the deflection is 3.0mm.

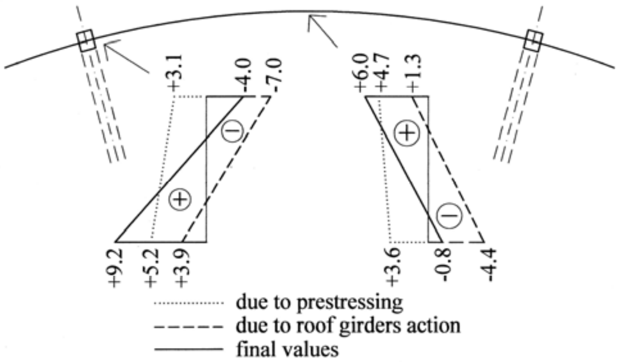

Figure 6. Concrete cross-section stress diagrams (in MPa)

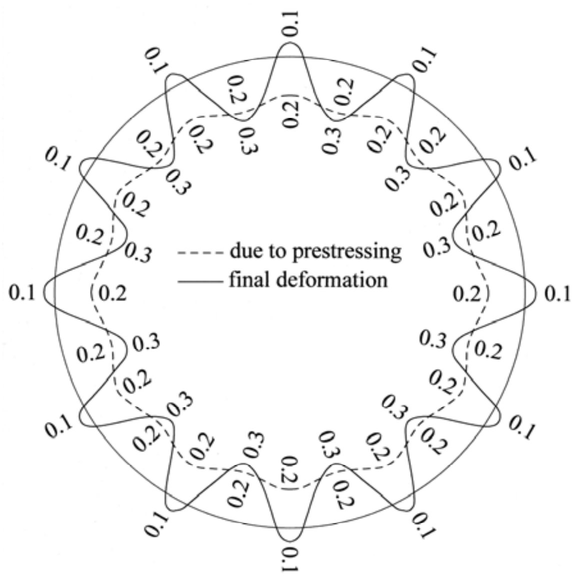

Figure 7. The ring beam deformation (in mm)

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Even the presented values come from the elastic analysis, the possibility of the cracking the cross-sections above the columns and the small ratio of the bending moment to the cracking moment, which is 1.82, suggest a small influence of the cracking to the increase of the deformation. Even, when the values of the deflection will increase several times in comparison to the presented values, the result will be safe for the structure. It should be noted that the analysis of the stresses, cracking and movement was carried out assuming a full load with snow, according to [7], which is almost a half of the total load coming from the roof. According to this, the obtained values are not permanent, but temporary.

5. Implementation of the project on site

Concreting of the circumferential ring beam which is the element closing the concrete structure of the church was carried out on February 9, 2017. Concrete with a class of C30/37 made on CEM I 42.5 cement and crushed-stone granite aggregate with the maximum aggregate size of 16 mm was used.

Figure 8 presents a view of the completed reinforced concrete and masonry structure of the church with the entresol slab and the circumferential ring beam with internal unbounded tendons installed. Photograph 8a shows the circle columns supporting the entresol on the inner edge in every second radial construction axis. On the rest of the axes, the slab will be suspended to the roof after its erection. Picture 8b shows the location of the anchor grooves on one side of the perimeter.

Figure 9a shows a method of forming a groove for anchorage. At the location of the groove, a profiled polystyrene insert was input with a hole inside, through which the tendon was passed. It was important to profile the duct and trace the tendon so that it would exit the forefront of the groove perpendicularly. In the case of non-perpendicular cable tracing in the anchorage zone, there is a risk of cutting the tendon during tensioning. Figure 9b shows the steel anchorage with a resistance steel plate installed. After the prestressing, the anchor grooves were filled with a low-shrinkage cement mortar to provide corrosion protection for anchorages and steel plates.

During prestressing of the ring beam, the measurement was carried out, whose aim was to verify the assumptions and calculation models, as well as to check the correctness of the construction execution. Radial displacement of the ring was measured as a result of prestressing and strains of the concrete in five selected cross-sections: three in the middle of the span and two near the columns.

The measurement of radial displacements was made with the use of a laser tachymeter set on a reinforced concrete slab at the center point of the church (figure 10a). Benchmarks were used in the form of aluminium sheets, with the dimensions of 30×30mm cut at an angle of 19°, so that the laser beam falls perpendicularly on sheet. Measurement of the displacement was made at all available points in the middle of the span between columns and on the columns. The accuracy of the used measuring device was ±0.05mm/m. which allows to deduct that the obtained results are measured with an accuracy of ±0.75mm. Figure 10b shows the distribution of measured radial displacements of the ring. The obtained results should be related to the calculated results (figure 7) amounting to 2mm on the whole circumference.

a) b)

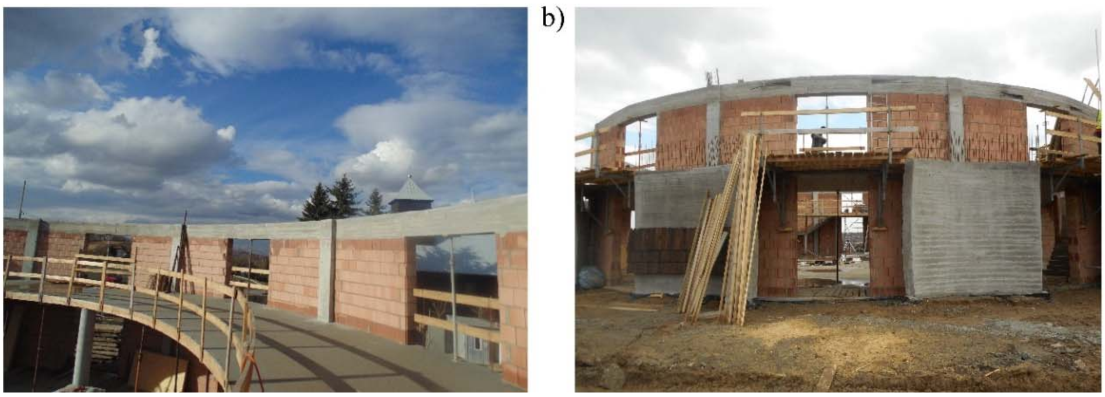

Figure 8. View of completed reinforced concrete and masonry structure

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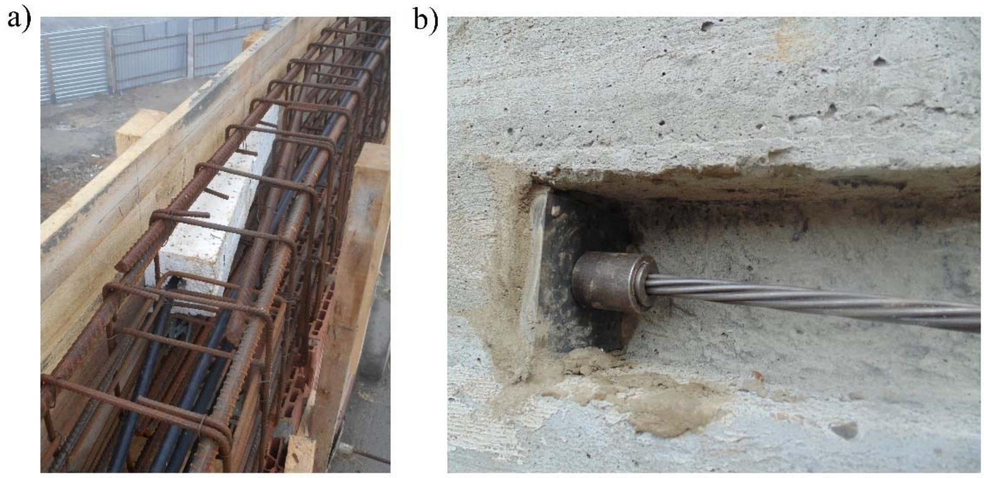

Figure 9. Ring beam reinforcement and styrofoam insert forming anchoring groove (a), steel resistant plate and tendon anchorage (b)

Although strong disturbance of regularity were observed on the perimeter (even opposite displacement with a value of 1mm in one of the spans), the average value of the measured points was 1.8mm, thus it was close to the estimated 2mm (this value is given with an accuracy to full millimetres and therefore to the nearest 0.5mm). The obtained compression effect corresponds to the expected one and the irregular deformation may be a result of impreciseness in the geometry of the ring beam arose during preparation and erection the structure, as well as the profiling of the tendons. Strong refracture of the ring line can be noticed, which could have contributed to its irregular deformation from the prestressing.

The measurements of concrete deformation were made through a DEMEC-type extensometer with a base of 200mm. The cross-sections, in which the deformation was monitored are shown in figure 11b. The measurement points were placed on the inner and outer sides of the ring. Localization of the measurement points in the column and middle-span cross-sections is shown in figure 11a and their and their view in figure 11c.

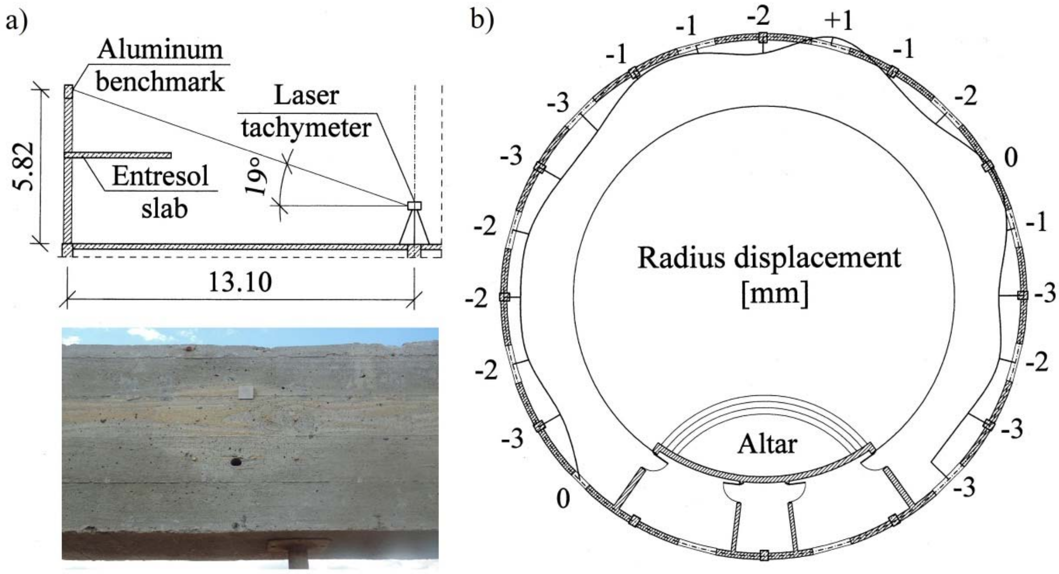

Figure 10. Method of measuring the radial displacement of the ring beam during prestressing (a), obtained results (b).

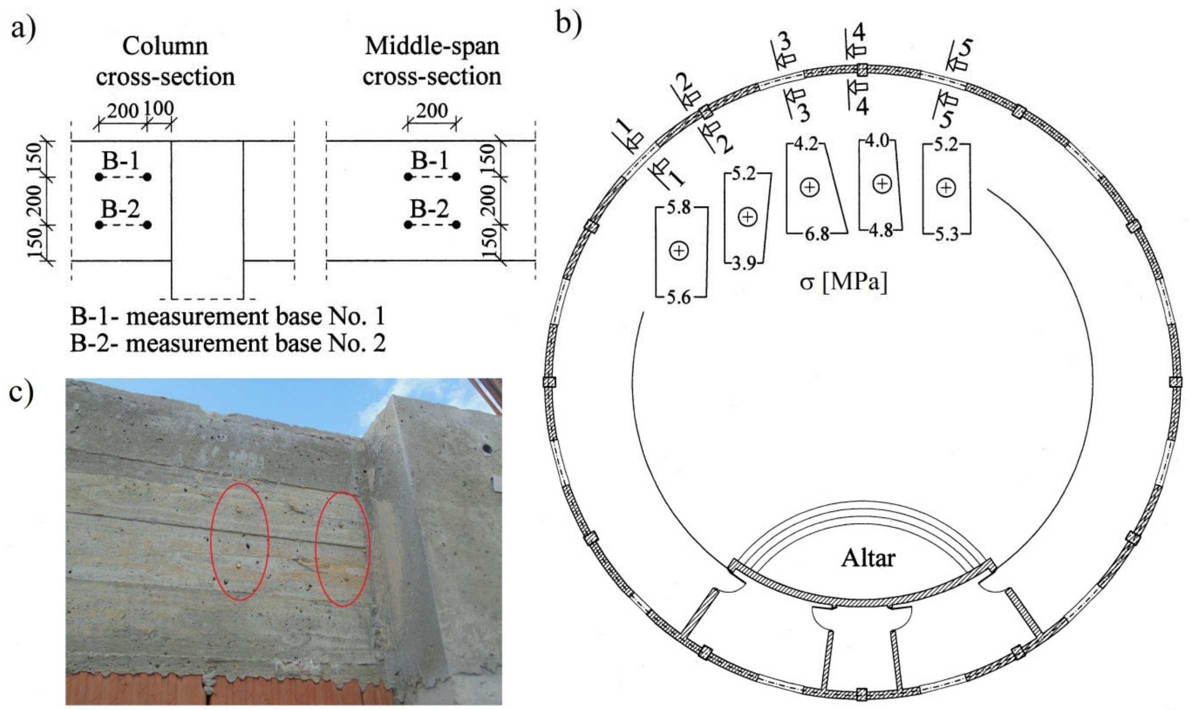

Figure 11. Localization of strain benchmarks in the column and middle-span cross-sections (a), localization of monitored cross-sections as well as the calculated stress diagrams (b), view of strain benchmarks (c)

Table 1 summarized the values of the concrete strains measured in the characteristic cross-sections of the ring beam (figure 11c) and the calculated stresses. The strains in each cross-section was calculated as the average value of the two measurement bases. Due to the fact that the prestressing was to be carried out not earlier than 3 weeks from concreting, mechanical properties of the concrete were not examined. The values of stresses in the cross-section were obtained by multiplying the measured deformations by the standard value of the elasticity modulus of concrete amounting to 32GPa. Because of the prestressing was completed 26 days after concreting the element, it is highly probable that the standard value was reached.

The results of the measured strains and the estimated stresses are shown in table 1 and figure 11b. While both in span cross-section and the column cross-section, no regularity of stresses was observed, it is interesting to compare the mean cross-section stresses in the middle-span and near the column. The calculated mean stresses in cross-section, right after tensioning of tendons, amount to 5.0MPa around the perimeter of the ring (do not compare with figure 6. there the stresses from prestressing are given after time-dependent prestressed losses. not after prestressing). The values of 5.7, 5.5 and 5.2MPa were obtained for the middle-span cross-sections and 4.6 and 4.4MPa for column cross-sections. The values obtained in cross-sections near the columns are therefore clearly lower than in the cross-sections in the middle of the span. This fact is certainly caused by masonry walls near the columns on which the ring beam was poured. Part of the prestressing force was transferred to that walls.

6. Conclusions

The paper shows the first in Poland examples of the usage of elements made of post-tensioned concrete in church structures. Thanks to the use of a prestressed ring beam hidden in the wall, large cross-section of roof girders was possible to be avoided, as well as a massive reinforced concrete ring or additional steel tie-rods.

Table 1. Measured concrete strains and calculated stresses

Cross-section	Surface	Read before the tension x_1	Read after the tension x_1	Strain $\varepsilon = (x_1 - x_2) \times k$ [10^{-5}] $k = 0.81$	Average strain ε [10^{-5}]	Stress $\sigma = \varepsilon \times E_{cm}$ [MPa]	Average stress in cross-section [MPa]
1-1 middle-span	Internal	851	828	18.17	17.38	5.6	**5.7**
		838	817	16.59			
	External	841	817	18.96	18.17	5.8	
		840	818	17.38			
2-2 column	Internal	846	830	12.64	12.25	3.9	**4.6**
		836	821	11.85			
	External	904	880	18.96	16.20	5.2	
		858	841	13.43			
3-3 middle-span	Internal	872	839	26.07	21.33	6.8	**5.5**
		845	824	16.59			
	External	852	833	15.01	13.04	4.2	
		824	810	11.06			
4-4 column	Internal	852	834	14.22	15.01	4.8	**4.4**
		837	817	15.8			
	External	847	826	16.59	12.64	4.0	
		935	924	8.69			
5-5 middle-span	Internal	847	820	21.33	16.59	5.3	**5.2**
		844	829	11.85			
	External	872	848	18.96	16.195	5.2	
		806	789	13.43			

The results of the measured displacements and concrete strains have largely confirmed design assumptions. While local radial displacement deviations from the predicted values were observed, the mean value amounting to 1.8mm was close to the expected value of 2mm. A significant impact of the filling walls on the stress distribution in the ring was also observed. Some of the prestressing force was taken over by the masonry walls. This explains the need of using of sliding layers between the masonry wall and concrete beam in the future. It will increase of efficiency of the beam prestressing.

In sacral architecture, a trend is beginning to dominate for creating delicate, slender construction forms with a large open space. It can therefore be concluded that the solution presented in the work will certainly not be the only project of this type, and is likely to begin a search for new applications for prestressed concrete structures in church building projects.

It should also worth to note that a quite controversial solution in the presented project is the suspension of the reinforced concrete entresol slab to a wooden structure of laminated wood. The authors of the work will monitor the deformations of individual components of the structure both during and at the time of use and report the results of the observation in technical and scientific literature.

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