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# The largest pre-stressed concrete Dome in the world – the case study of "Hall 1 of the Belgrade Fair"

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**Abstract**

The aim of the paper is to present the largest pre-stressed concrete free-standing structure in the world – the Dome of the "Hall 1 of the Belgrade Fair", designed by Academician Branko Žeželj, prominent Serbian scientist, inventor and structural engineer, one of the founders of the Institute for testing of materials IMS in Belgrade, conveniently positioned just across the street. Built in capital of Serbia in period 1955- 1957, the Dome of "Hall 1 of the Belgrade Fair" reaches 106 meters, and was the largest dome in world for eight years, until 1965. The building is still the largest dome in Europe and remains the world's largest pre-stressed concrete dome. In this paper this large and unique construction is analyzed from point of view of structural integrity.


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*Keywords:* Pre-stressed concrete Dome; Free standing structure; Branko Žeželj

## 1. Introduction

"Hall 1 of the Belgrade Fair" (Fig. 1a, b) is the main exhibition hall at Belgrade Fair out of three exhibition halls within Belgrade Fair complex. The Hall 1 is 27.8 m high, has circular cross section with diameter of 106 m and occupies area of 8970 m$^2$. The upper galleries around the perimeter, which are 4.7 m and 8.7 m above the ground, forms the outer contour of the Hall 1 enclosed by glass walls, and goes on a diameter of 117 m. The construction of the Hall 1 consists of three structurally separate constructions: construction of the Dome and its supports, which covers the biggest part of the roof with diameter of 97.5 m; construction of galleries and their supports; and the basement rooms and ground floor (Žeželj, 1957; Žeželj, 1960). It has been designed by the architect Milorad Pantović and the structural engineers: Branko Žeželj, Boško Petrović and Dimitrije Ćertić (Žeželj, 1957; Stambolić, 2017).

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The Hall 1 is the most prominent example of the application of concrete pre-stressing patented system IMS-Žeželj which was fully designed and developed by Branko Žeželj (1910-1995) within Institute for material testing of materials IMS in Belgrade. The pre-stressing patented system IMS-Žeželj has been worldwide patented and accepted as one out of three pioneering concrete pre-stressing technologies and Branko Žeželj is remembered to be one of the greatest and most active constructors in the world (Muravljov, 2010; Jelić, 2017a,b). The Hall got the status of the monument of culture in 2009 by the decree of the Government of the Republic of Serbia.

At the time when the Hall 1 has been designed a calculation of the Dome construction system could be made only for the symmetrical load. Therefore for the estimation of the deflections of the Dome under unsymmetrical load, the Dome test model on a reduced scale 1:10 has been made out of the same material (Fig. 2).

In this paper the structural integrity of the Dome system, using Finite element software SAP2000, is compared with the deflections measured on the Dome test model on a reduced scale 1:10. The paper contributes to understanding of the ribbed type Dome pre-stressed free-standing structures. In that respect, in part 2. of the paper the Dome system structural elements, static data with the deflections measured on the Dome test model on a reduced scale 1:10, and geometric parameters are presented, while in part 3 deflections of the Dome based on finite element analysis are presented and compared with the deflections measured on the Dome test model on a reduced scale 1:10.

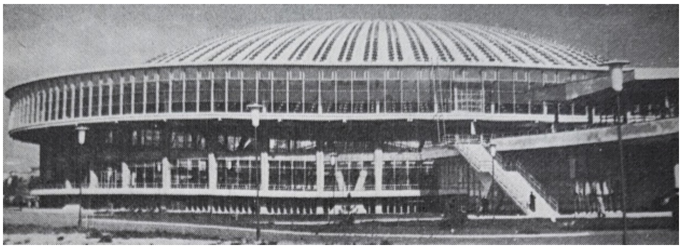
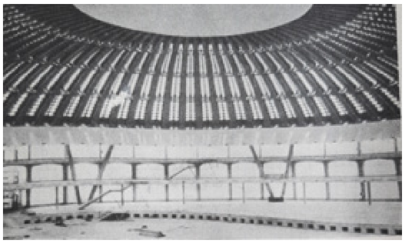
a)  b) 

Fig. 1. (a) Hall 1 of the Belgrade Fair, (b) Inside the Hall 1 (Žeželj, 1960)

Fig.2. Branko Žeželj in front of the model of the Dome of Hall 1 of the Belgrade Fair (1:10) (Muravljov, 2010)

## 2. The Dome system

### *2.1 Structural elements*

The Dome system consists of following structures: (i) central circular cap of reinforced concrete, which has diameter of 27 m; (ii) the 80 I cross section precast reinforced concrete semi-arched ribs, each 35 m long and 34 tons weight, which supports (i); (iii) the pre-stressed concrete great support hollow ring with diameter of 94 m and trapezoid cross section, which supports (ii) (Fig. 3). Between the structure (i) and the structure (iii) three intermediate rings stiffen the ribs of the Dome laterally. The structure (iii) is supported by eight pairs of inclined columns in "V" form. The structure (i) of the Dome comprises two slabs of reinforced concrete 8 cm thick and 80 cm apart, which are stiffened by three circular and eight radial ribs between the slabs. The spaces between the ribs are filled with curved lightweight concrete slabs which contain circular roof lights (Fig. 3) (Žeželj, 1960). The support columns of the structure (iii) of the Dome lies on a circle of diameter of 106 meters (Fig. 3). The foundation of the Hall 1 was made on 35 „Frankie" pre-stressed concrete piles, above which is the supporting pyramid of the V shape column (Fig.3) (Žeželj, 1957; Petrović, 1968).

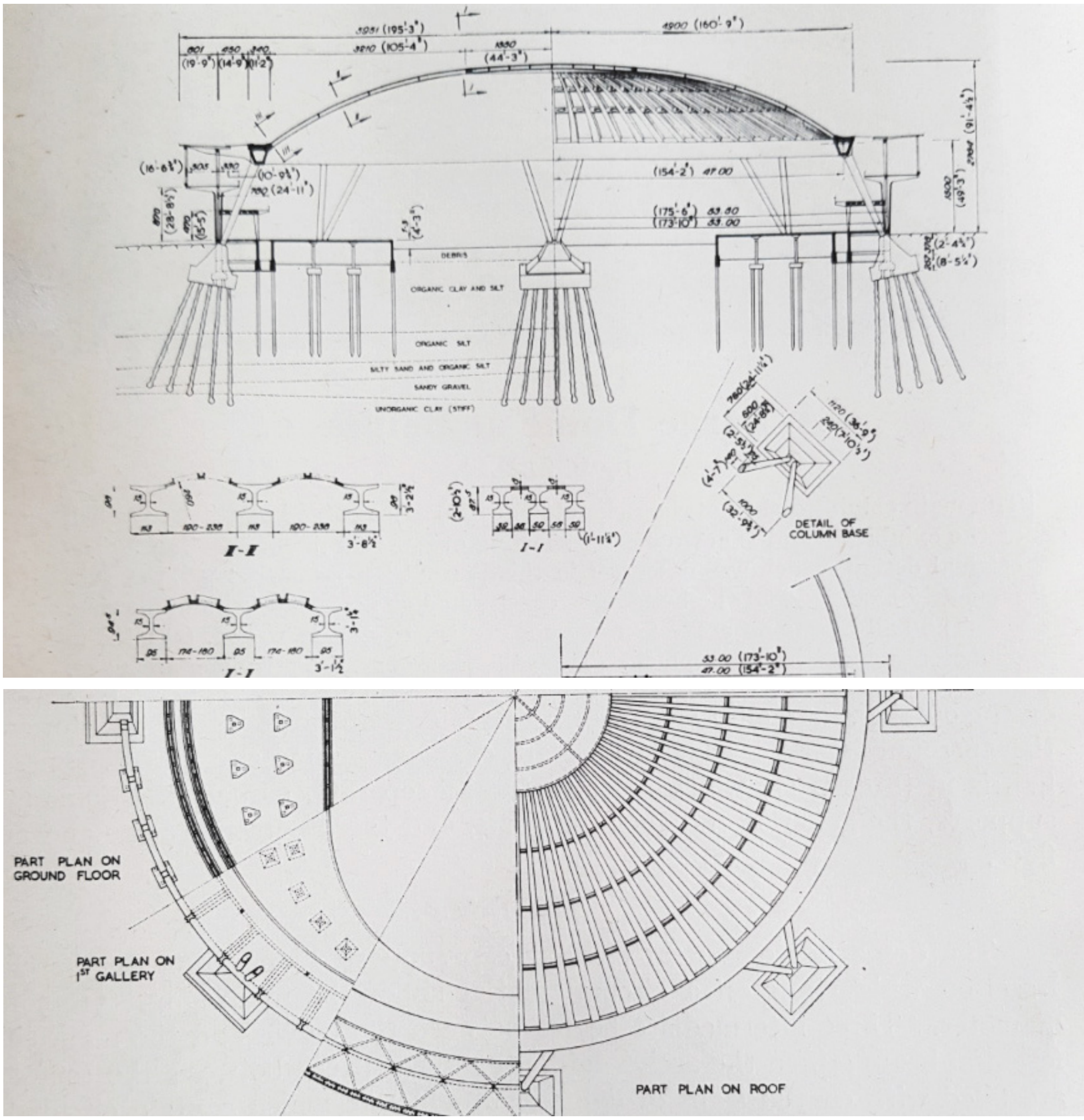



Fig. 3. Cross sections of the Hall 1 of the Belgrade Fair (Žeželj, 1960)

*2.2 Static data and deflections measured on the Dome test model on a reduced scale 1:10*

Having in mind that the most of the load is permanent and symmetrical about the center of the Dome, and that the system of the ribbed Dome represents four times statically indeterminate system, in the design several assumptions were made:

- the structure (iii) of the Dome was considered as circumferential beam, and that it would not defect vertically;
- the ribs were fixed at the lower ends in structure (iii), and hinged at the upper ends in the structure (i);
- the intermediate horizontal ties between arches were hinged (Žeželj,1960).

Furthermore, the calculations of the magnitudes of the stresses were based on the assumption that the symmetrical load would be the weight of the Dome (75% of total symmetrical load) and uniformly distributed snow on the Dome. Besides aforementioned, under the greatest symmetrical load assumed in the design, the stress in the concrete in the upper and lower edge of the structure (i) is 81 kg/cm$^2$ and 3 kg/cm$^2$ respectively. In ribs the compression due to symmetrical load varies from 22-30 kg/cm$^2$. In addition, the estimation of effects of unsymmetrical load and wind were based on the tests of the model of the Dome in 1:10 scale. Keeping in mind that the weight of the model represented only 7% of the total stress and that the weight of the real Dome produces 70% of the stress, the additional load of 200 kg/m$^2$ was applied on the model of the Dome in order to simulate the real conditions (Žeželj, 1960).

The deflections of the Dome for 10 positions along the radius of Dome are presented in Fig. 4 under symmetrical and unsymmetrical load. Namely, diagram (a) on Fig. 4 presents deflections of the Dome due to weight of the Dome and diagram (b) presents deflections of the Dome when only half of the Dome is loaded.

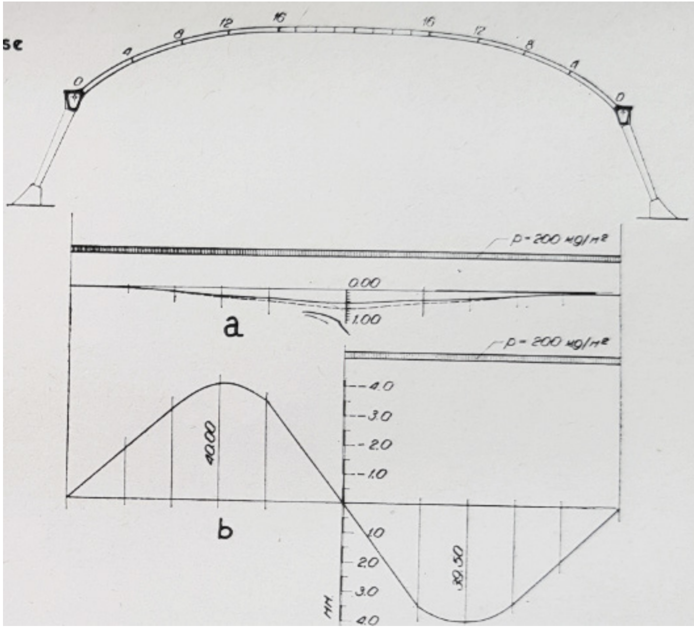



Fig. 4. Deflections of the model of the Dome in 1:10 scale (Žeželj, 1960)

Based on the results of the test on the model of the Dome it following was concluded:

- the critical factor would be the compressive stresses provided that the loads were symmetrical;
- under unsymmetrical load bending moments and tensile stresses were produced;
- even when the greatest unsymmetrical load was applied, namely 2.66 times the load due to snow, the tensile stresses were not large, and the factor of safety was not exceeded in the structure (Žeželj, 1960).

The structure (iii) of the Dome is the most heavily loaded part, and at the edges of this structure stresses up to 105kg/cm$^2$ occur, so the pre-stressing is necessary in some parts in order to reduce the tensile stresses. In order to resist to horizontal and vertical forces the structure (iii) is hollow with trapezoidal cross section. Furthermore, the structure (iii) is exposed to positive bending moments in sections between the supports/inclined columns and to negative bending moments in the section over the supports/inclined columns (Žeželj, 1960). The bending moments act in vertical plane (+Mv=1314 tm and –Mv=1105 tm) and in horizontal plane (+Mh=533 tm and –Mh=536 tm). Furthermore, the structure (iii) is exposed to significant torsion moment (Mt=156 tm) and to shear load (Žeželj, 1957; Žeželj, 1960). In order to resist loads the structure (iii) was pre-stressed as follows (scheme of cables is shown on Fig. 5):

- on the outside of the structure 142 group of cables, each comprising 6 cables/steel wires of 5mm diameter, were placed by steel spacers projecting from the concrete and each cable was tensioned simultaneously at 6 points of the circumference with a total permanent circular pre-stressing force of 1420 tons in order to resist the horizontal forces;
- on the top of the structure, in the section over the supports/inclined columns, group of 64 cables, each comprising 6 cables/steel wires of 5mm diameter, were placed around the curve by steel spacers embedded in the concrete with a force of 640 tons in order to resist the negative bending moments;

- in the bottom of the structure, in the section between the supports/inclined columns, group of 60 cables, each comprising 6 cables/steel wires of 5mm diameter, were placed through ducts formed by inflatable rubber tubes and exert a force of 600 tons in order to resist the positive bending moments;
- in the inner wall of the structure, series of cables were applied in order to resist oblique tensile forces near the supports (Žeželj, 1960).

Inclined position of the supports/columns toward the center of the Dome provided lateral stability. Each column is an inverted truncated ellipsoidal cone and the greatest stress in the concrete is 90kg/cm$^2$.

The concrete of the structural elements had a crushing strength at 28 days of at least 450 kg/cm$^3$ and contained at least 350 kg of cement per m$^3$ of concrete. The pre-stressing wire has a breaking strength of 150 kg/mm$^2$ and the yield strength of 125 kg/mm$^2$.

The pre-stressing wire has tensile strength of 150 kg/mm$^2$ and a yield strength of 125 kg/mm$^2$. The initial stress was 105 kg/mm$^2$, which resulted in residual stress of 85 kg/mm$^2$.

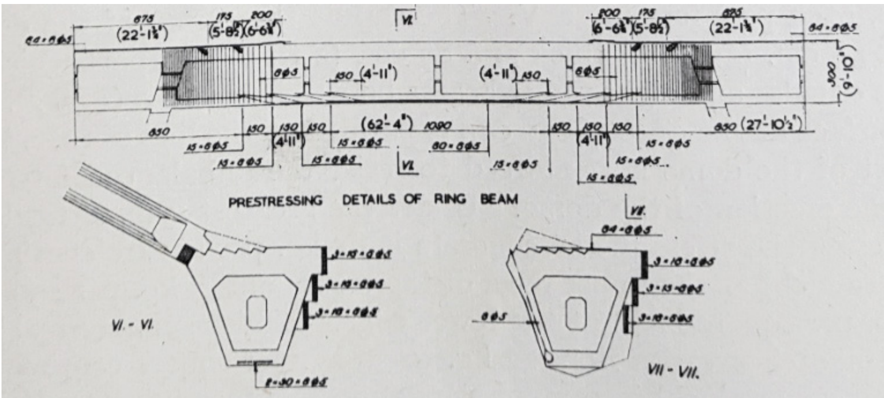



Fig. 5. Pre-stressing details of the structure (iii) of the Dome (Žeželj, 1960)

## 2.3 Geometric parameters

The geometric parameters of the Dome are presented in Fig. 6. Height to span ratio of the Dome i.e H/D is 0.14 as the height of the Dome is 12.87 m and the Dome span is 94 m. The height of the trapezoidal cross section of the structure (iii) (the Great ring on Fig.6) is 300 cm, the width of upper side is 360cm, and the width of the bottom side is 140 cm (Petrović, 1968). The thickness of the upper, bottom and the rest of two sides of the trapezoid cross-section of the Great ring is 70 cm, 40 cm and 24 cm, respectively. The thickness of I profile of the ribs is 15 cm while the height and width differ. On the lower ends of the ribs the height of I profile is 98 cm and the width is 113 cm, and at the upper end of the ribs the height of I profile is 87.5 cm and the width is 59 cm.

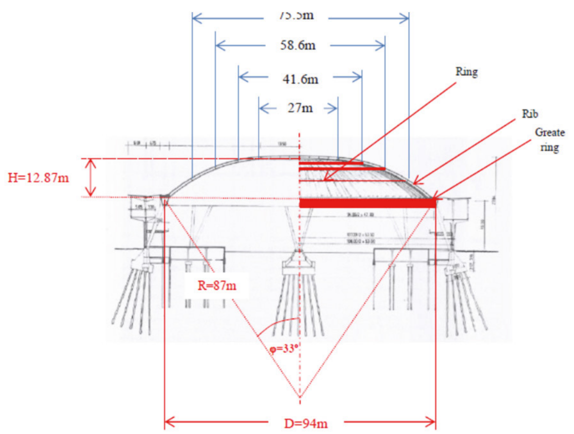



Fig. 6. Geometric parameters of the Dome

## 3. Conclusion

Based on the given data, deflections of the Dome was analysed under symmetrical and unsymmetrical load and compared with the deflections measured on the Dome test model on a reduced scale 1:10. Next step in this analysis will be to use the Finite Element Method, which was not available at the time this spectacular construction was designed and erected. This will be the basis for the complete structural analysis, including its resistance to cracking.

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