Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte
Band: 71 (1994)

Artikel: Design and construction of the Sports Hall roof structure, Belgrade
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DOI: https://doi.org/10.5169/seals-54128

Design and Construction of the Sports Hall Roof Structure, Belgrade

Étude et réalisation de la structure du toit de la salle de sport, Belgrade

Entwurf und Konstruktion des Dachtragwerks der Belgrader Sporthalle

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SUMMARY

A universal Sports Hall for more than 20'000 spectators is under construction in Belgrade. The roof structure of the Hall with spans of 133/103m, is a prestressed shallow lens shaped by the two-chord orthogonal grillwork of externally prestressed reinforced concrete girders with tendons outside the cross section of the concrete. The complete roof structure is prefabricated and is very rational and economical. It covers about 1,5 hectare with the equivalent thickness of concrete in the grillwork of the main roof girders of less than 8 cm/sqm and the weight of prestressing tendons of 6,5 kg/sqm.

RÉSUMÉ

Une salle de sport de 20'000 places et d'usage polyvalent est en construction à Belgrade. La structure du toit, de 133 x 103 m de portée, à la forme d'une lentille plate précontrainte, formée par une grille de poutres en béton armé avec précontrainte extérieure. La toiture est entièrement préfabriquée, de manière rationnelle et économique. La grille principale de poutres couvrant env. 1,5 hectare a une épaisseur équivalente de moins de 8 cm/m2 et le poids du câble de précontrainte est de 6,5 kg/m2.

ZUSAMMENFASSUNG

In Belgrad ist eine Mehrzwecksporthalle für 20'000 Zuschauer im Bau. Das Dachtragwerk mit einer Spannweite von 133 m x 103 m besteht aus einer vorgespannten flachen Linse, die durch einen zweigurtigen orthogonalen Trägerrost aus Stahlbetonträgern mit aussenliegenden Vorspanngliedern gebildet wird. Die komplette Dachkonstruktion wird vorgefertigt und ist dadurch sehr rationell und wirtschaftlich. Bei Ueberdachung von etwa 1,5 Hektaren betragen die äquivalente Dicke des Hauptträgerrostes weniger als 8 cm/m2 und das Gewicht der Spannkabel 6,5 kg/m2.

1. INTRODUCTION

The construction of the Sports Hall for 20.000 spectators has been planned for the Basketball World Championship 1994, the organization of which was awarded to Belgrade before the desintegration of the former Yugoslavia.

The preliminary design of the Hall, made by the Company ENERGOPROJEKT - MDD *Urbanizam i arhitektura*, the author of which is architect Vlada Slavica, has been selected at the competition. The first four authors of this paper, professors of concrete structures the Faculty of Civil Engineering of the University of Belgrade, are the authors of the Hall structural system.

The design of the structure is realized in cooperation with the Faculty of Civil Engineering at the University of Belgrade. The next two authors of this paper are the assistants at the Faculty of Civil Engineering in Belgrade and, together with the authors of the Hall structural system, they are the designers of the Hall roof structure.

The main contractor is the consortium of two large construction companies from Belgrade: ENERGOPROJEKT - MDD *Visokogradnja* and the Construction Company GP NAPRED DD. The last two authors of this paper are the Managing and the Technical Directors of that Consortium.

The execution of prestressing was entrusted to the Institute for Testing of Materials of the Republic of Serbia IMS from Belgrade.

In spite of the fact that in the meantime, due to the United Nations sanctions against Federal Republic of Yugoslavia it has been decided for the Basketball World Championship 1994 not to take place in Belgrade, the construction of the Sports Hall has been continued but in a somewhat slower rate.

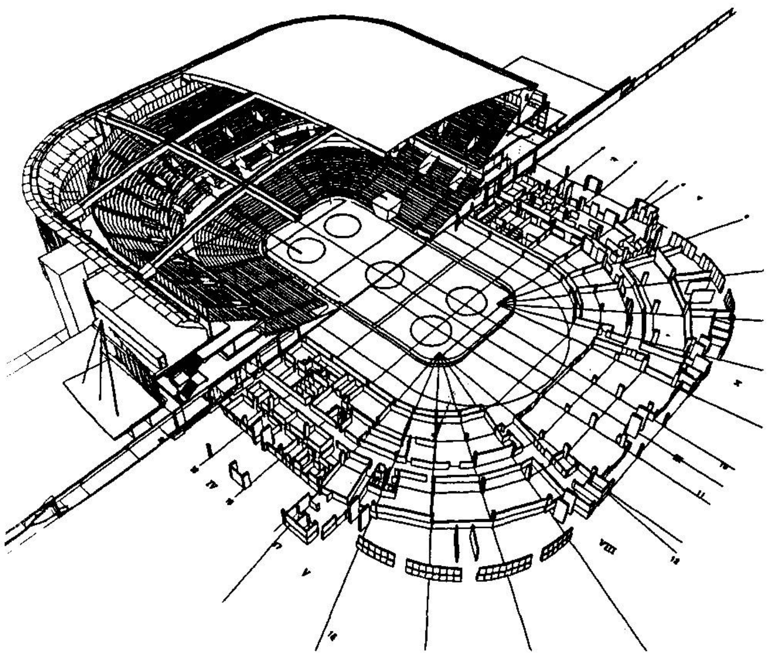

Fig. 1 Axonometric view of the Sports Hall

2. THE ROOF STRUCTURE OF THE HALL

The dimensions of the structure have been designed to provide a possibility for athletic competitions, too. The Hall is of a rectangular base with rounded corners, with spans 132.7 x 102.7 m. The building is 36 m high and the total area of the roof is more than 15.000 m^2. Figure 1 shows the computer made axonometric view of the Hall.

The roof is supported by 14 main columns in facade walls and is structurally completely independent from other parts of the building.

The main roof structure is a two-chord orthogonal grillwork made of 7 externally prestressed RC girders, 3 in the longitudinal and 4 in the lateral directions. Upper compressed concrete chords of the girders polygonally follow convex paraboloid surface with the elevation of +8.00 m with regard to the horizontal supporting plane on the tops of the main columns. Lower chords are designed as prestressing tendons, free in space, which polygonally follow the concave parabolic surface with the sag of -4.00 m with regard to the supporting plane. In 12 cross points of the grillwork the constant distance of the chords is provided by pyramid-shaped "chairs" composed of 4 RC columns of the 35/35 cm section. The RC deviator blocks are on their lower ends. Figure 2 shows the disposition of the roof stucture.

The roof structural system can be understood as a discretization of a prestressed shallow lens the compressed surface of which is composed of polygonal RC girders, its tensioned part of prestressing tendons and its constant geometry, namely the spacing between the surfaces of the system, provided by RC chairs. However, the system can be more simply understood as an orthogonal convex RC prestressed grillwork, elastically supported in its cross points by deviation forces depending on the configuration of the tendon system and on the intensity of external actions and prestressing. Excellent efficiency of such a two-chord structural system comes as a results of a very big eccentricity of the prestressing tendons, which are "taken out" from the section and have incomparably higher eccentricity of the prestressing force than classically prestressed structural elements with tendons inside the cross section of the concrete.

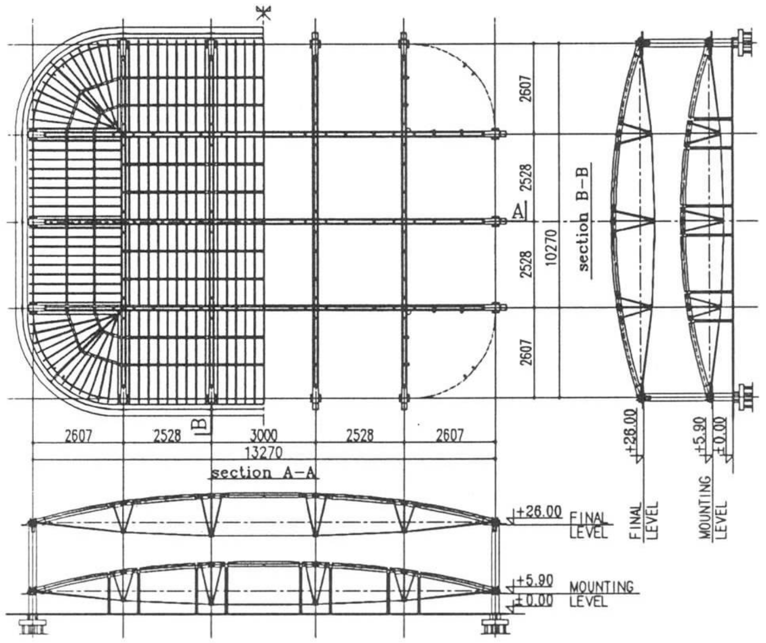

Fig. 2 The roof structure with main roof girders on mounting level on temporary scaffolds and on final level, on the tops of the main columns

The RC chords of the main roof girders are all of the same cross section, constant along the whole span, composed of twin girders of the rectangular cross section, 140 cm high and 40 cm wide, at a distance of 80 cm. The supporting parts of the girders, at the length up to 5.0 m from supports, are full rectangular sections 1.60 m wide, shaped as anchorage blocks for prestressing tendons of the lower chord. The design concrete grade of the main girders is C 50.

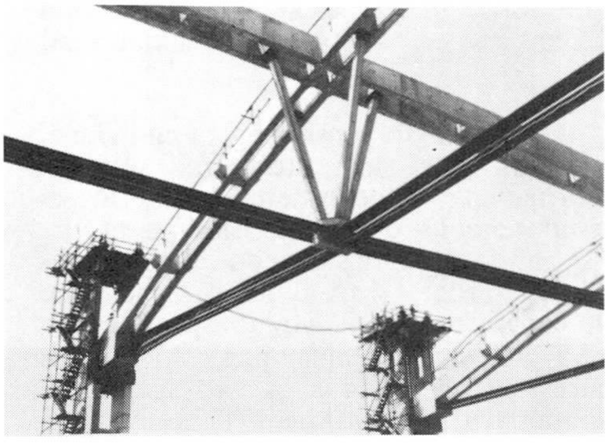

Fig. 3 RC deviator block

The lower chords of the main roof girders are composed of 8 prestressing tendons each. The tendons are made of 11 Neptun grade 1860 strands, ϕ 15.80 mm S, with nominal steel area of 150 mm^2, made of low relaxation steel, permanently corrosion protected with grease and the HPE coating. Anchors type SPB of the Strands Prestressing System, developed in the Institute for Testing of Materials of the Republic of Serbia IMS, have been used for anchorage of tendons. Deviator blocks, shown in Figure 3, are made of cast in situ RC.

Secondary roof girders are also two-chord RC systems, of the spans 23.60 and 28.40 m. The purlins are T section RC girders, with spans 7.20 to 7.60 m.

The main columns of the roof in facade walls are designed as two RC walls grade C 40 concrete, of rectangular cross section 50/220 cm at the clear spacing of 2.0 m, just necessary for the main girders supports between them.

3. DESIGN AND CONSTRUCTION OF THE ROOF STRUCTURE

3.1 Construction of the main roof girders

Only the 14 main columns were cast in situ. The complete roof structure has been prefabricated on site. The grillwork of main roof girders has been divided to a total number of 43 precast elements - 12 "crosses" that included the parts of two orthogonal girders in the cross zone above the "chairs", the total length of each being about 8.0 m in both directions and the weight about 50 t, 17 beam elements between "crosses", their length being 16-20 m and the weight about 50 to 60 t, and 14 supporting parts, between the first "crosses" and the columns, with anchorage blocks, about 22 m long and almost 100 t heavy.

The mounting level has been on +5.90 m above the floor of the Hall, Figure 2. The precast elements were temporarily supported by light steel tube scaffold towers around 12 chairs with 80 cm free joints left between them. In such a way, before the prestressing started the roof girders grillwork was supported by a total number of 220 supports: 12 x 8 x 2 = 192 temporary supports on scaffolds in the span and 14 x 2 = 28 supports on neoprene bearings in the axes of the columns at the level +5.90 m. The "chairs" RC columns have been also prefabricated. Only the deviator blocks, although designed to be prefabricated, were cast on scaffolds.

3.2 Prestressing

The prestressing of the main girders has been designed to take place in two stages. In the first stage, while the structure has been still on scaffolds, the tendons had been tensioned to the level of approximately 60% of the total force for complete prestressing. Due to prestressing the main girders have been gradually lifted from their temporary supports on the scaffolds. At the end of that prestressing stage the structure had been lifted about 16 cm in the central part of the roof, remaining supported only on 28 supports in the axes of 14 main columns, so that the scaffold were no more necessary.

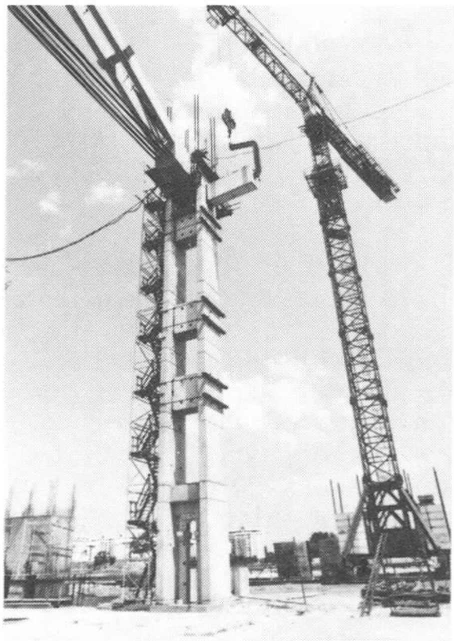

Fig. 4 Pushing of the precast supporting beam through the openings on the top of the column

After the first stage of prestressing the roof structure has been lifted to the tops of the main columns, to the design position. The construction is continued by the erection of the secondary roof girders and purlins, the roof cover and the permanent part of the equipment which is hung to the roof. Upon the application of this additional permanent load the second stage of prestressing will be carried out. The total maximum force in the tendons at the total loading is about 12.000 kN, or 54% of the breaking load of the tendons.

High sensitivity of the system to tensioning of individual tendons is characteristic for such structural systems. Because of the deformability of the system "elastic" losses (losses in prestressed tendons due to tensioning of the succeeding tendons) can many times exceed elastic losses in classical prestressed girders with tendons inside the cross section of the concrete. That is why the prestressing has been performed with 16 hydraulic jacks so that in each step of prestressing all tendons of two symmetric roof girders were simultaneously tensioned. Thereby it has been provided that forces are the same in all tendons of a girder, regardless of big elastic losses.

3.3 Lifting of the main girders to the design position

Lifting of the main roof girders from the mounting level +5.90 m to the final design level of 26.0 m has been done using 96 special hydraulic jacks by pulling the whole grillwork from the tops of the main girders. The rate of lifting was 2 m per hour plus the necessary time for dismounting and remounting the temporary bracings of the column walls, Figure 4. After the level of about 20 cm above the final position has been achieved, the precast 12 tons RC supporting beams have been pushed through the openings on the tops of the columns and the whole structure has been lowered onto the neoprene bearings, Figure 4.

Figure 5 shows the main roof girders in the design position on the tops of the main columns.

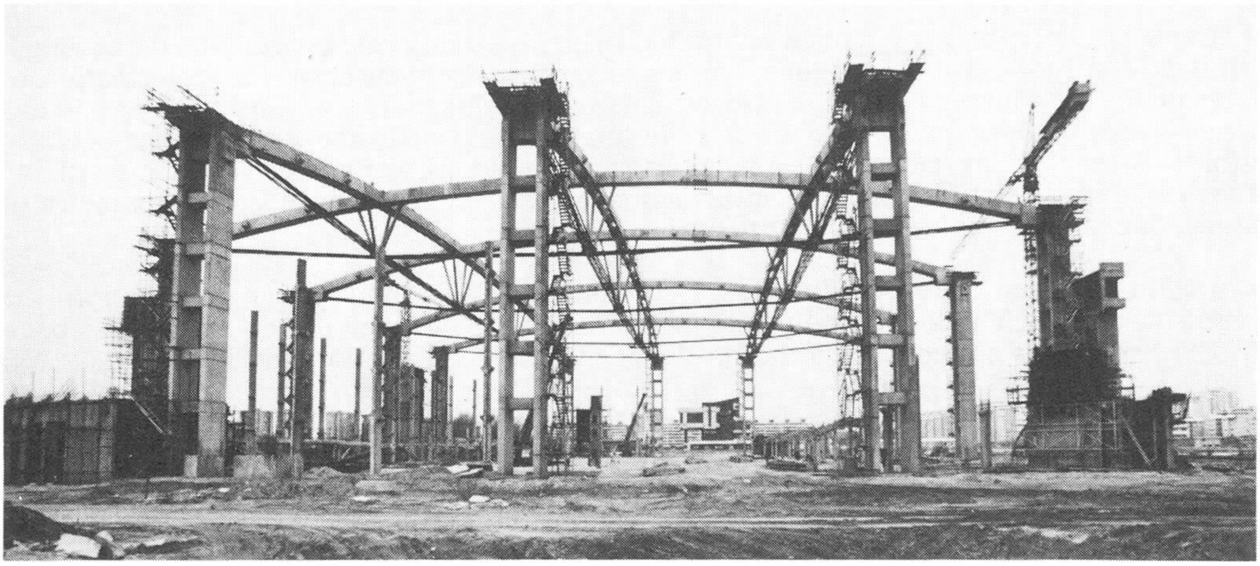

Fig. 5 Main roof girders in the final design position on the tops of the main columns

3.4 Design models

Because of the significant influence of the building technology, the design models had to strictly follow the construction stages.

The first design model covered only the self-weight of the precast elements supported by the temporary scaffolds, before they have been made monolith and without the influence of tendons. The next model has already been a monolith structure of the grillwork with tendons, but still supported on 192 temporary supports on the scaffolds, beside 28 supports in the axes of the columns. In each stage of prestressing that design model was continually transforming into a new structural system because of gradual lifting from scaffold supports, transferring the structure, towards the end of the first stage of prestressing, to the final system of the grillwork supported on 14 main columns only.

The detailed design models of the structural system in all stages of its gradual constituting have enabled the establishment of the optimum shape of the structure together with the most rational sequence and intensities of prestressing. By the optimum analysis it has been achieved for all girders to have equal cross sections, constant along the whole span and the same number of tendons. Besides the obvious technological advantages, such solution has provided the total utilization of the material to be very near to the optimum one.

The previous analyses and experiences with similar linear two-chord big span systems [1] to [3], have shown that the effects of the Second Order Theory slightly deviate from those calculated without taking into account the deformations of the system. This is clear keeping in sight that vertical displacement of the roof lens as a whole is of little importance as the external loading is mainly dead load, the depth of the lens remains practically constant and axial forces "travel" with the system, remaining axial in the deformed system, too.

A similar conclusion refers to the effects of creep. As the structure is suitably "load-balanced", so that there is no significant elastic deflections for the main part of the permanent load, there will be no important deflections due to time dependent deformations of concrete as well.

3.5 Control measurements of stresses and deformations

The complexity of the roof structural system, its sensitivity to relatively small changes of prestressing forces, and especially permanent chainging of the system during the first stage of prestressing required the detailed control of the behaviour of the structure during construction.

The forces in the tendons have been controlled by pressure in jacks, by the pulled-out length of strands and by direct assessment of forces in tendons by measuring the deformation of strands under the transverzal load. However, data on the elongations of tendons could, in this case, give reliable information on the forces in tendons only while the structure has been on scaffolds. After that the measured elongations of the tendons were a result not only of the change of stress in the tendons but, much more, a result of the change in the geometry of tendons, due to deformation of the structure.

The friction has been measured directly on the tendons of two main roof girders, before the prestressing started. The loss of the prestressing force along the span due to friction has been only 5 to 8%, which has confirmed the results of the preceeding laboratory research.

The deformations of the structure have been geodesically observed on 354 points on the main roof girders and on the main columns and the deflections during the prestressing were also continually monitored by deflectometers on all 12 crossing points of the main girders.

The obtained results have very precisely confirmed the design analyses and have enabled the planned building procedure to be conducted with full reliability.

4. CONCLUSION

The prestressed concrete roof structure of the Sports Hall in Belgrade is a very rational and economical structural system. By external prestressing with high eccentricity of tendons both the dead and live loads have been resisted by relatively small forces in the tendons. With such systems the deformations from dead load may be very easily governed with suitable geometry and the choice of intensity of prestressing forces while the live load deformations remain significantly below the permitted limits. The total snow and wind deflection in the middle of the roof of the Hall is lower than 18 cm, namely about L/600 with regard to a smaller span.

The complete RC roof structure is prefabricated on site. It has been relatively quickly mounted and is very lightweight. It covers the area of about 1.5 hectare, with the equivalent thickness of concrete in the main roof girders of less than 8 cm/m^2, the weight of prestressing tendons of about 6.5 kg/m^2 and the weight of reinforcement lower than 12 kg/m^2.

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