POST-TENSIONING TECHNOLOGY IN SPORTS ARENAS

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SUMMARY

Two major multifunctional sports arenas, where post-tensioned reinforced concrete structural elements were applied, have recently been opened in Europe – the Zagreb Arena in Croatia and the Sports Arena Lodz in Poland.

The Zagreb Arena is a multi-functional complex with a seating capacity of 15,200 and hosted the 2009 Men’s World Handball Championship. The shell shape follows the structure logic – it partly covers the inner space with curved columns. Basic shape and structural elements are prestressed prefabricated reinforced concrete columns with heights of up to 37 m. Eighty-six columns surround the hall, support grandstands and carry the facade, as well as the suspended steel roof structure. Architectural cables carry the roof that has a main span of 110 m. The Zagreb Arena was the outright winner of the 2009 structural design category at the World Architecture Festival.

The city of Lodz office decided to build a new 12,109-seat sporting and entertainment venue. The round sports hall has a concrete structure with a steel roof and steel cover wall. The dome-shaped roof of this huge arena is supported by a massive post-tensioned concrete ring – an icon of modern engineering techniques. Inside, would be the main arena plus all the usual facilities – and a full size basketball court.
INTRODUCTION

ZAGREB ARENA

Dr. Ivo Sanader, Prime Minister of the Republic of Croatia said: “With its architectural beauty, the Zagreb Arena has become a new visual symbol and managed to change the appearance of one of the principal entrances to the city of Zagreb.”

Fig. 1 Overview (left), 2009 Men’s World Handball Championship (right)

The arena was developed in a public private partnership. The Croatian Government and the City Government of Zagreb selected a consortium composed of a property developer and a contractor. The consortium that designed and built the venue engaged a Zagreb-based architect and structural engineer studio to create and produce a unique design. Construction work started in July 2007 and only 503 days later, the arena was completed. Estimates put the cost of the venue at EUR 87 million, but the consortium stated that the price tag was nearer EUR 100 million.

The 2009 Men’s World Handball Championship effectively launched the 15,200 seat capacity multi-functional sports hall to the world. The complex is located in the southwestern part of Zagreb and is used for sporting competitions, cultural and business events including concerts, exhibitions, fairs, conventions and congresses. Currently, the Arena Complex (Arena Center) is under construction and will include the largest shopping entertainment center in the city, as well as a wide range of additional leisure facilities.

SPORTS ARENA LODZ

The City of Lodz office decided to build the new 12,109-seat sporting and entertainment venue within the complex of one of the city’s sports clubs – Lodzki Klub Sportowy. The arena is adjacent to the existing football stadium which is home to the former Polish football league champions.

Construction of the EUR 80-million-project was launched in 2006 and it opened in June 2009. The arena, with 11 VIP lounges, can host a variety of events – ranging from volleyball, basketball, boxing fights, conferences, concerts to various sport events including athletics and ice hockey. Its multi-functional approach and high standard of equipment make the arena one of the most modern buildings of its kind in Poland.
ZAGREB ARENA

ARCHITECTURE

The arena is a masterpiece of architecture and structural engineering with its unique outer appearance and its hanging roof structure. During the schematic design stage, the development of spatial and functional characteristics – to enable maximum flexibility of the venue – was vital. The telescopic system of 4,500 seats was a critical element in allowing different configurations and a quick turnaround between events. The structure is closed inwards, in the form of a shell, which reduces the span and, to a degree, provides cover for the area.

The main facade resembles a giant rib cage made of 86 large curved columns connected by a semi-translucent polycarbonate envelope that allows for various light effects. The shell shape follows the structure logic and partly covers the inner space with its 28 to 37 m tall columns. Basic shape and structural element of the facade are prestressed prefabricated reinforced concrete columns which carry the facade, support grandstands and the suspended steel roof structure.

The roof design – reminiscent of the structure of a suspension bridge – enables the slender 45 cm roof structure to cover a span of 110 m. In a way, the roof is floating over the hall. Cables and bars expand and contract with shifting temperatures, thus the position of the roof changes – together with whatever is suspended from it. In addition, over the years there will be deformation in the ribs, therefore, the roof is very flexible and getting it into the right geometric position was a challenging task.

Below the grandstands and pit is a garage with an area of approximately 30,000 m² (capacity of 817 vehicles). The garage rests on a joint-free slab which facilitated installation of waterproofing and pouring sequence. Above the garage, there is a five-floor monolithic reinforced concrete structure.
made of concrete with a minimum characteristic cylinder/cube strength of 30/37 MPa (C30/37), designed as a spatial frame with beams (of spans up to 10 m) and 24 cm thick slabs.

Fig. 4 Main facade with its 86 curved columns (left), suspended steel roof structure (right)

DESIGN OF POST-TENSIONED FACADE RIBS

In total, 86 concrete curved facade ribs of 28 to 37 m height were designed. A cantilever scheme with a free cantilever length of up to 15 m was chosen. A load of 2,000 kN from the roof structure is applied on top of each column. At the level of the main pedestrian area, all reinforced concrete columns are connected to the frame. When the columns were fixed, they formed a monolithic structure. This approach provides horizontal stability of columns in high seismic conditions. Concrete C50/60 was used.

All ribs were post-tensioned with latest European approved and CE-marked bonded post-tensioning technology\(^4\) consisting of 7-wire strands with a nominal diameter of 15.7 mm (0.6 inch) and a minimum characteristic tensile strength of 1,860 MPa. 42 columns are equipped with 12 tendons composed of seven 0.6-inch strands (0706), and 44 with 4 tendons 0706. In total, 214 tons of strands were installed, together with 680 anchorages.

Fig. 5 Bending moments of a typical post-tensioned column

PRODUCTION AND INSTALLATION OF COLUMNS

The prefabricated ribs were produced in an on-site plant on a fast-track timetable. Eight formworks – equipped with formwork vibrators – were set up and produced four to six elements a week. After
rebar, insertions and tendons were placed, concrete was poured and cured. Only three days later, the tendons were stressed to 30% of final prestressing force and removed from the formwork. When minimum concrete strength reached 43 MPa (cube), the tendons were fully stressed to 1,300 kN each (70% of capacity) and finally grouted.

Fig. 6 Production base (left), post-tensioning tendons (middle), lifting operation (right)

The 160-220 t lamellas were lifted by a crane and transported to their final positions with a tolerance of ±5 mm. Continuous monitoring and surveying was required during the operation. It took only 80 days to produce, transport and install all 86 ribs.

ROOF STRUCTURE

A light-weight suspended roof structure was chosen with a span up to 110 m. This structural design approach offers minimal dead loads but, on the other hand, evokes stability problems due to live loads such as wind and snow. Thus, balancing lightness and stiffness was a key challenge of structural design.

Fig. 7 Roof structure design and deformation in primary direction

DESIGN

The steel roof structure is suspended on architectural cables (locked coils) with a diameter of 66 mm and a characteristic resistance of 2,636 kN. The cables are connected to the columns on top in both primary and secondary directions. 34 mm diameter vertical and diagonal hangers carry the 2,000 t heavy structure made of double-T profiles (HEB 450).
The long-span light-weight roof needs to be stabilized by two secondary girders which are suspended from the primary structure in a transversal direction. They act not only as additional weight to prevent lifting of the roof induced by wind, but also as a balance for asymmetrical loads such as piled snow. Additionally, if a main girder cable needs to be relaxed and replaced, the loads can be transferred to its neighbor’s supporting beams. The roof structure – including 100 t of technical equipment attached to it, such as loud speakers and spotlights – deflects up to 33 cm. The structure rests on elastomeric bearings embedded in the grandstand structure.

**INSTALLATION OF CABLES AND HANGERS**

Firstly, a set of three cables was uncoiled on falsework. Next, the clamps for the hangers were installed on the rope and tightened before the bars were connected to the clamps and the whole structure was lifted by two cranes on each side. The locked coil was pulled through the openings in the rib and locked with a nut. After the hangers had been connected to the steel roof structure, the cables were stressed simultaneously and the roof structure was lifted until the roof section reached its final position. Then, the falsework was moved to the next section. Two installation teams were involved in the stressing operation.
SPORTS ARENA LODZ

ARCHITECTURE

The round sports hall has a concrete structure with a steel roof and steel cover wall. The arena is approximately six meters below the surrounding ground level. The hall is surrounded with a type of moat, over which there are bridges leading to the entrances. Inside, will be the main arena plus all the usual facilities – and a full size basketball court. The roof of this huge arena is supported by a post-tensioned concrete ring – an icon of modern engineering techniques.

Table 1 Facts & figures

<table>
<thead>
<tr>
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<th>Weight of roof structure:</th>
<th>1,500 t</th>
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<td>Arena area:</td>
<td>14,500 m²</td>
<td></td>
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<tr>
<td>Building volume:</td>
<td>385,000 m³</td>
<td>Roof ring height:</td>
<td>3.70 m (inner 2.50 m)</td>
</tr>
<tr>
<td>Outer diameter:</td>
<td>140 m</td>
<td>Ring width:</td>
<td>4.70 m (inner 3.20 m)</td>
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<tr>
<td>Height:</td>
<td>36 m</td>
<td>Ring length:</td>
<td>440 m</td>
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Fig. 10 Roof structure and outer post-tensioned concrete ring

THE RING

The roof support ring rests on 16 concrete columns (spaced every 26 m) at around 15 m above arena level. It is a massive concrete structure that, in cross-section, is a concrete box – shaped like a leaning rectangle with 0.5 m thick walls. On the outer side of the roof ring, there is a ‘gutter’ made of prefabricated concrete elements, permanently fixed to the ring structure. The box is strengthened with cross-walls every eight meters, where steel roof girders are supported on the ring.
The ring structure (made of C30/37 concrete) was poured in stages – first the bottom slab, then side walls, next cross-walls and lastly, the top slab. Strands were pushed into ducts after the concreting operation was finished.

TENDONS

The box-shaped concrete structure of the ring is post-tensioned with 28 1906 internal tendons (72 t of strands) and 88 706 external tendons (12 t of strands). The internal tendons – spaced equally on the cross-section of the ring, with seven tendons in one section – take horizontal forces from main loads (dead loads).
Fig. 12 Internal post-tensioning layout

External tendons – placed in appropriate numbers wherever needed, as dictated by the bending moment diagram – take bending moments from excess loads. Because the ring is so large in diameter, it is divided into four quarters – resulting in an internal tendon length of around 120 m. The internal tendons are anchored in four specially designed anchor blocks inside the ring. The external tendons are anchored in cross-walls – the longest tendon was some 25 m long.
POST-TENSIONING SEQUENCE

The post-tensioning sequence assumed that all internal tendons were tensioned to a stressing force of 3,976 kN (75% of characteristic ultimate tendon resistance) in a first sequence in order to carry the dead loads from the roof. The stressing of all external tendons followed. The round shape of the structure meant that it was important to apply stressing force equally around the perimeter, as well as on the cross-section of the ring. Therefore, two multi-strand stressing jacks were used and operated on opposite sides of the ring. Due to high values of loss of stressing force – because of friction on curves – it was necessary to stress all internal tendons from both ends. This all resulted in time and effort being spent on moving and preparing the stressing sets and operations. The stressing sequence for the external tendons using two mono-strand sets was also developed so that equal stressing force was applied to the structure. All the work inside the ring box was carried out by hand – it was not possible to use a crane as there were no openings in the top of the ring structure and cross-walls precluded the use of a small crane to operate inside the ring box. In total, 103 km of strand and 32 t of grout were used.
BEARING SYSTEM

The bearing system involved the installation of 64 elastomeric bearings and 16 specially designed steel directional slide bearings. The system has a set of five bearings on each column – four elastomeric slide bearings and one steel-guided slide bearing. The elastomeric bearings transfer vertical load from the ring to the column, allowing movement in all directions. Meanwhile, the steel-guided bearings take horizontal forces and allow radial movement – blocking forces from any other direction to prevent unequal deformation of the ring.

CONCLUSIONS

The simple, elegant and efficient structural concept of the Zagreb Arena was recognized at the World Architecture Festival in Barcelona (4-6 Nov 2009), where it was declared the outright winner in the 2009 structural design category. The external inward leaning ribs, braced by a ring beam, supported the suspended roof – and the prestressed prefabricated columns were a huge undertaking in their own right.

The massive post-tensioned roof ring – needed to support the dome-shaped roof of the new Sports Arena in Lodz – is a key element of the new arena and a masterpiece of structural engineering.

Together, these two iconic structures admirably demonstrate the architectural creativity and durability which is achievable with leading-edge post-tensioned concrete design. They both represent state-of-the-art construction engineering and the highest technical standards in design and execution.
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Zagreb Arena

OWNER: City of Zagreb
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Sports Arena Lodz

OWNER: City of Lodz Office
MAIN CONTRACTOR: Skanska S.A.
DESIGNER: ATJ Architekci /KiP Sp.z o.o
BBR NETWORK MEMBER: BBR Polska Sp.z o.o (Poland)

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4 BBR VT CONA CMI Internal Post-tensioning System
5 Designer: Ph.D. Ing. P. Pachowski, Post-tensioning Specialist: BBR Polska
6 Courtesy of ATJ Architekci
7 BBR CONA Internal Post-tensioning System
8 BBR CONA External Post-tensioning System