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AN ARCHITECT'S RELATION TO STRUCTURE: ANALYSIS OF PINKI CULTURAL SPORTS CENTER BY IVAN ANTIĆ

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Architecture represents the synthesis of form, function and construction. In the works of the architect Ivan Antić this can be read at the first view of the building. A master in designing movement through an object, Antić constantly developed the relationship between function and form, as well as between function and construction. A detailed analysis of his work, projects and drawings, gives insight to these relations, making them clear. The observer can see the architect's logic and simplicity in designing even the most complex buildings. The relationship between the design concept and the way the structure manifests itself in his projects will be presented in this paper. The logic behind the design of Pinki Cultural Sports Center, with emphasis on structure, as well as the relationship between the architect and the engineer can be seen throughout this paper.

Key words: **sports hall, catenary, spatial structures, cable systems.**

INTRODUCTION

The construction of large scale and large span objects has always demanded the collaboration of experts from different fields. The realization of an architectural design depends largely on the relationship between the architect and the engineer and their team efforts. The interdependence of form and structure, the juxtaposition of spatial relations, and the function and construction speak about the complexity of design and the impossibility of separating these two professions. This paper shows the attitude that architect Ivan Antić had towards the structure. Understanding these two professions contributes to the successful realization of projects that over time become monuments of time, culture and people. The main purpose of this paper is to present the relationship between architecture and structure and their joint action in the design process, through chosen works of Ivan Antić. The reason behind it is that his projects clearly manifest the above mentioned relations that can be read on his buildings. His relationship with the engineers that worked with him can be seen on large span buildings, especially in an analysis of Pinki. This paper is an addition to previous analysis of Antić's projects, but it can also be the basis for further research. It confirms the importance of great engineering achievements in architecture and leaves a written trail that records notable engineers from the Balkans.

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ABOUT THE AUTHOR

The architect Ivan Antić, a full professor at the Faculty of Architecture, at the University of Belgrade, and a member of the Serbian Academy of Sciences and Arts, was one of the most significant architects of the 20th century. He worked on a variety of different projects, but those that stand out are his cultural and sports buildings. During his studies, Antić worked as a steel bridge engineer in the Ministry of Transport, where he upgraded his skill and precision in drawing (Milašinović Marić, 2005). It can also be concluded that this is why he developed an affinity towards large span structures, which can be clearly read on his buildings. Shortly after completing his studies, due to circumstances in the architectural practice of the time, at the invitation of construction engineer Milan Krstić, young architect Ivan Antić began working in the Belgrade-based studio Rad in the company of great names in engineering (Mitrović, 2012). He worked in this studio for three years, during which he improved his knowledge of structural analysis and created a network of contacts for future team work. His acquaintance with architect Ivanka Raspopović led to successful cooperation on the project for the Museum of Contemporary Art in Belgrade and the Memorial Museum Kragujevački oktobar in Kragujevac. With the engineers Milan Krstić, Petar Damjanović and many others he worked on sports buildings. Along with the experience gained in practice, he worked at the Faculty of Architecture as an assistant, teaching architectural design at the invitation of Stanko Kliska, an architect from Zagreb. The two of them had previously worked together on projects for health facilities, whose functions were extremely complex (Mitrović, 2012). These circumstances in the life of Ivan Antić, at the very beginning of his career, had an impact on his architectural style. His architecture shows the careful attention he gave to the functional and structural design of buildings, not leaving out any aspect of architecture. Ivan Antić used all his knowledge when designing an object to unite form, function and construction, thus creating a specific architectural expression.

IVAN ANTIĆ'S ARCHITECTURE

"The only thing I have ever wanted was to have a geometric form, clean. Some rational form. Whether it be a square, a triangle, a circle or an ellipse. This can be seen in my projects." These were the words of Ivan Antić (Milašinović Marić, 2005). It is possible to perceive his wide architectural opus just by following these words. The logic behind his designs emerged from his desire for highly functional buildings, first and foremost designed for their users. At the same time, following the requirements of the project task, he developed a form that created a specific expression in space. This logic is clearly visible in his sports objects with the strict urban, functional and structural demands that the architect fulfilled with ease. His most fruitful period, when he designed sports and recreational centers in collaboration with eminent engineers, produced some of the most significant projects in Yugoslavia built between 1965 and 1980 (Milašinović Marić, 2017). By observing the buildings belonging to the Sports and Recreational Center "25. maj" on the right bank of the Danube in Belgrade it is impossible not to notice the exceptional artistic value of the composition with the existing scenery. The position of the objects on the site had its roots in the combination of different functions, while the expressiveness of the form was achieved by using complex structural systems. The restaurant, which was later privatized and turned into a gym, is situated on large cantilevers which seem to rise above the water. The floor plan of the object shows the simple geometry behind this design. It is an equilateral triangle divided into subareas based on its geometric center, which has a concrete core that gives it structural stability. When you can read the architect's logic in the design, especially when it is based on geometry, it is much easier for the engineers to find a solution for complex structures and large spans. Through communication between the architect and the engineer it is possible to build objects that become the symbol of a particular area. In order to fit the pool roof into the aesthetics of the restaurant, a concrete shell forms a hyperbolic paraboloid that perfectly complements the appearance of the entire site. Edmund Balgač, an engineer, worked with him on this project. It was a few years later that the two of them developed the idea of the cultural and sports center Pinki (Balgač, 1975) which will be analyzed in detail in this paper. Another significant building by Antić is the Olympic pool at Poljud in Split, built for the Mediterranean games, which he was invited to work on as an accomplished architect. He did not want to compromise on its strong form of a wave pointing towards the sea by adding any additional elements to this building. The structure's two main girders were made from reinforced concrete to form the wave, interconnected with beams in an orthogonal direction, which were used as the support for the stands. The structure was designed in this way because the architect wanted each element to have a specific function and for nothing to disturb the simplicity of the form. This design made it possible to have an unobstructed view of both the pools and the scenery, since it enabled the opening of large glazed surfaces, thus connecting the building with the surroundings. Antić's structural logic stemmed from his long collaborations with various engineers at the very beginning of his career. He liked to point out that there is nothing more beautiful than a large span construction, undisturbed by small elements, because in itself it has a high aesthetic value (Milašinović Marić and Marić, 2018).

CASE STUDY: STRUCTURAL ANALYSIS OF PINKI

For the design of the youth and sports center at Zemun, later renamed Pinki Cultural Sports Center (Pinki Zemun), strict demands were set before Antić by the Town Planning Institute of Belgrade, such as strict observance of the regulation lines and height. He skillfully overcame the demands and designed the object to fit perfectly into the urban tissue. Rectangular in plan, the building is 68 m wide and 54 m long. The design of the building was also conditioned by its complex function, which required the design of the object from within. All of the structural elements, as well as the design, were subordinate to the smooth functioning of the building. Since the dimensions of the object were fixed, and the program was required, the interdependence between the close functions was established first. Thus, the sports hall was close to the other sports facilities, and the pool was located below the hall, relying heavily on its foundations (The Main Project). Nowadays things have changed, and they are subletting smaller spaces for different functions.

The roof structure gives this building its character. In agreement with the engineer Edmund Blagač there were three possibilities for the form of the roof: a convex, horizontal or concave roof silhouette (Conić, 1975). Knowing that a cubic form needed some kind of an accent, to fit the demands, as well as the personal affinities of the designer, a concave roof structure was chosen to be solved as a cable suspended roof. This chosen structure, which is at the same time the roof of the sports hall, follows the slope of the stands and forms the least possible volume of space it encloses, thus contributing to the cost-effectiveness of the building in terms of its use (heating-cooling systems, ventilation).

The main facade of the building is very interesting because it clearly presents its function, as well as its structural behavior (Figure 1, Figure 2). It is possible to notice that the architect had a sincere approach to displaying the function and structure of the building, so it appears like a clear and precise mechanical system that serves sport. The flow of forces is also displayed on the facade, from the roof to the strains and from the strains to the foundation. The chosen material for the facade perfectly places the object in its site, the old core of the municipality of Zemun, and at the same time shows the beauty of the modern buildings of that time. At first glance, simple in its form, this building evinces elegance, especially because it is easy to read. Cubic form is eased with the shape of the concave roof manifested on the facade as a thin parabola above a large curtain wall, through which is possible to see what is going on inside the building. The slope of the roof follows the slope of the stands which follow the slopes of the main staircases, thus making it easy to see the movement throughout the building. Side annexes complement the building, contributing to its monumentality.

Figure 1. The main facade (Source: author)

The structure of the object was designed by engineer Edmund Balgač, who worked with engineer Miroslav Conić on the final design (Conić, 1975). The first proposal was to make a wooden roof construction with cables pulled through, but this was put aside. In the final design, wood was replaced with concrete and steel sheets. The structural elements of the object were made from reinforced concrete and poured on site, like in other buildings from that period, but there are a few specific solutions applied in this project.

The first specific solution of this building is its foundations. Because of the high levels of groundwater caused by the proximity of the river Danube, in addition to the load transfer, it was necessary to secure the underground facilities from penetration by groundwater. The contractor used new machines and special hydro insulation to make this possible. A foundation slab with ribs was chosen for the construction because of the great loads it had to transfer.

The structure of the pool is indented from the rest of the object and it is connected through the neoprene bed to the

Figure 2. Detail of the main facade (Source: author)

foundations. The pool is deeper on the side under the diving board, so this difference in height was used for placing equipment necessary for the pool but which does not need full floor height. On this little segment of the building, it is possible to see the skill of an architect who thinks simultaneously about function and structure.

The solution for anchoring the tie rods is also very interesting. These foundations are at the same time the columns for the side annexes. They are shaped as troughs and are exposed to both stress and strain loads. They oppose the strain loads with their weight, and transfer stress directly to the ground with all their width. Their depth is equal to the foundation depth of the building.

Reinforced concrete frames are the main structure for the roof, the stands and the arena and they were placed every 14.4 m. Roof strains were placed every 7.2 m, which required new structural elements to accept vertical and horizontal loads from the roof and to transfer them to the frames. These elements make up a single horizontal lattice in plane with the slab, and a vertical lattice in plane with the columns. Every roof tie rod is pretensioned with different forces, which can be seen in the main project calculations. Pretensioning different forces into structural elements was solved by calculating the number of cables in each element, so it varies from two cables in the ground floor area to eleven in roof strains which carry the loads of the roof. The bottom lattice belt is also pretensioned (The Main Project).

This type of structure is special because its horizontal forces comprise a closed system. The horizontal forces from the roof are transferred through the horizontal and vertical lattices, which transfer the vertical forces to the foundation (Figure 3, Figure 4). At the bottom of the annex column, the forces change from strain to stress because they are used as the support for the slabs. In the structural analysis of the building presented with the main project, it is possible to see the relation between the reinforcement and the pretensioned cables in these columns. The pretensioned cables are used to transfer the strain, while the reinforcement was calculated for stress.

The most demanding structural component in this building, and certainly the most aesthetic, is the roof. The design and structural analysis were completed by Edmund Balgač. The structural solution does not include cables in both orthogonal directions, which makes it different from other common solutions. Cable suspended systems are usually used for large span roof structures. They are attractive and can be formed above differently shaped floor plans: circular, elliptical or rectangular. Besides being cost-effective, their advantage is that they produce only the tension forces, while the stress, bending and torsion are minimal or nonexistent. The ideal forms for these structures are catenary and parabola, while keeping in mind the forces in the cable. If the arch rise of the cable is lessened, its length is too, but the forces would be greater. The optimal shape is found when there is a balance between all of these demands to accomplish the cost-effectiveness of structure (Whal, 2007). Compared to classic structures, the advantage of suspended systems is that they can be built quickly with prefabricated elements, thus saving on material and scaffolding, as well as time. The suspended systems are made of steel rods or cables. Because they are thin, they do not have enough self-weight to oppose the external loads, which is why they have to be pretensioned. Other than by snow and seismic loads, they can also be affected by sound or other mechanical vibrations, as well as temperature. They need reinforcement in the opposite orthogonal direction for stability. Because they are usually used for roofs, their geometry is solved as a hyperbolic paraboloid to avoid water retention. These structures can be held by different types of supports: columns, wall, elliptical or circular concrete girders (Dančević, 1978).

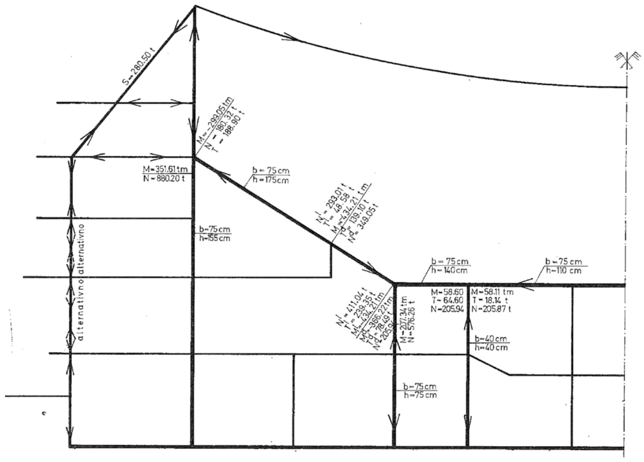


Figure 4. Closed system of forces
(Source: Balgač, 1971)

This suspended roof is specific because it has no cables in the opposite orthogonal direction. The whole structure is carried by the tension cables placed on the longitudinal axes every 80 cm. The span of the roof is 51.2 m, measured in between the side girders. The engineer needed to find a solution to avoid water retention that would fit the aesthetic and structural demands of this concave roof. The solution was to change the arch rise of the parabolically shaped cables from 4.2 m to 4.85 m, thus forming a roof slope towards the longitudinal facades. In this way, the engineer made a double curvature roof structure without the use of cables in the other orthogonal direction. The structural analysis and the calculations of the cable rise are a part of the main project. The special quality of this structural design is its simplicity. Even though the roof has a double curvature, by eliminating the cables in the orthogonal direction, the engineer accomplished having no columns on the main facade, thus contributing to the overall design and aesthetics of the building. (Figure 5)

> "This system without cables in two orthogonal directions has proven its existence, easiness of construction and speed of construction" (Conić, 1975), said engineer Miroslav Conić.

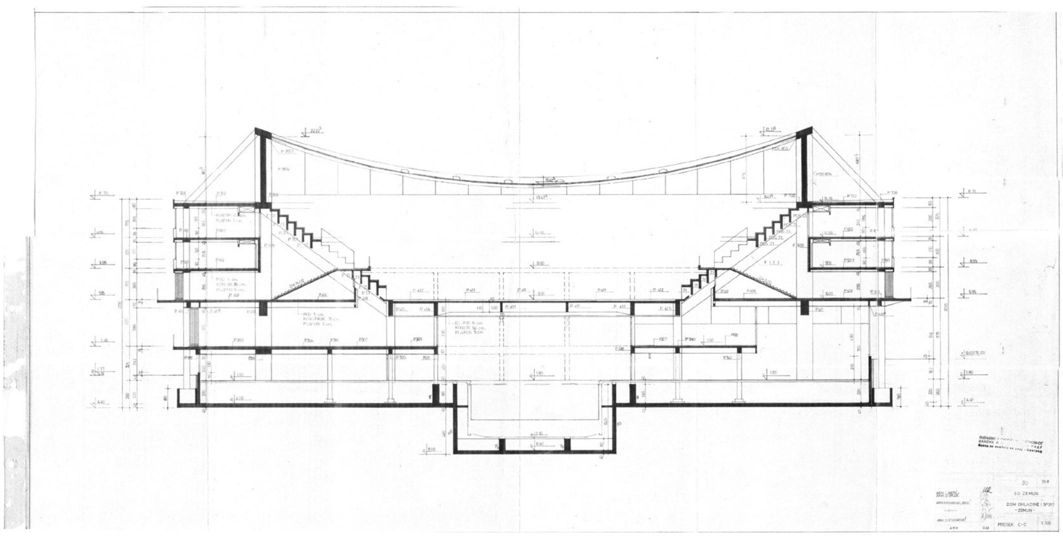


Figure 3. Section
(Source: The Main Project)

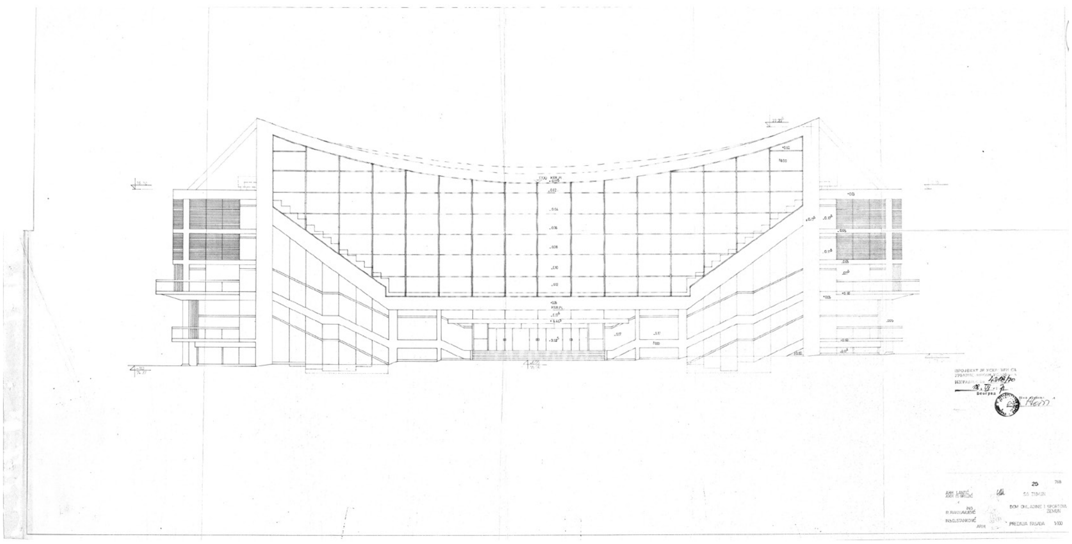


Figure 5. Elevation
(Source: The Main Project)

Suspended roofs in Yugoslavia were rarely built before the roof structure of Pinki was made (Balgač, 1971). The first suspended roof in Yugoslavia was the German pavilion for Zagreb Fair in 1957 (Figure 6.1). The main engineer on the project was Kruno Tonković (Podhorsky, 2005). Balgač worked as an engineer on two sports halls with suspended roofs shaped as a hyperbolic paraboloid, one in Leskovac in 1961 (Figure 6.2), and the other one in Subotica in 1968 (Figure 6.3) before the construction of Pinki. These roofs were inspired by the first one of this kind, the Dorton Arena in North Carolina (Figure 6.4), designed by the architect Matthew Nowicki and the engineer Fred Severud in 1950 (NCSU Libraries). The design proposal for Pinki was put forward in 1971, and it was built in 1974 (Pinki Zemun).

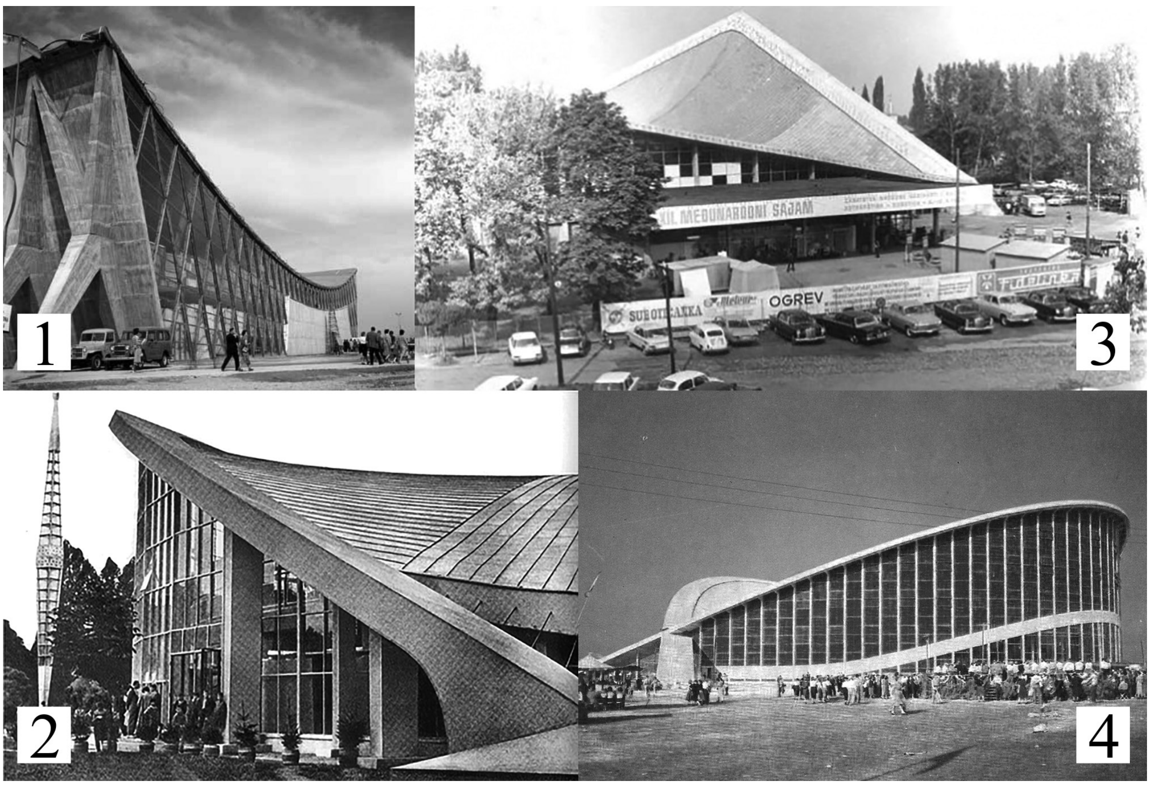


Figure 6. Examples of suspended roofs
Figure 6.1 German pavilion at Zagreb Fair
(Source: http://www.d-a-z.hr/hr/aktualna-tema/100-%25-vitic---zidne-novine-i-izlozba-uz-stogodisnjicu-rodenja,4746.html)
Figure 6.2 Sports hall at Leskovac
(Source: https://mojgradleskovac.wordpress.com/2014/12/19/)
Figure 6.3 Sports hall at Subotica
(Source: http://www.gradsubotica.co.rs/gradi-se-hala-sportova/)
Figure 6.4 Dorton arena
(Source: https://www.flickr.com/photos/north-carolina-state-archives/22112868996)

Balgač emphasized the advantages of building suspended cable roofs. He used to say that they were rare because not many engineers were familiar with the calculations necessary for building them. He gave a thorough explanation of their structural analysis in two articles in Izgradnja magazine for roofs shaped as a hyperbolic paraboloid. By giving examples built throughout the world, he showed how cost-effective suspended roofs were because of their speed of construction on movable scaffolding. Additionally, he pointed out that this type of structure gives freedom to the architect to design different shapes (Balgač, 1969). The first structural design for Pinki was a suspended cable roof with wooden ribs. The advantage of this design, as Balgač said, was the relationship between the volume mass and the stresses allowed in the material that mostly carries only its self-weight. From these calculations he saw that wood was the most adequate material for these types of structures. The advantage of forming wooden space frames, due to their small self-weight, is presented in papers by Nenad Šekularac (Šekularac and Adžić, 2006; Šekularac *et al.*, 2011). These papers also mention that there is almost no need for the use of scaffolding, which makes these structures highly cost-effective. The suspended roof's main structural elements are cables, on their own or inside a prefabricated element, while the elements made of reinforced concrete are usually used as side girders, columns or frames. As an advantage of wooden prefabricated elements, Balgač pointed out that the construction would take up less time if all elements were prefabricated, thereby having almost no need for scaffolding. This would lessen the cost of construction in comparison to sports halls made entirely of reinforced concrete (Balgač, 1975).

Roof structure with wooden ribs

The structural design of the roof for Pinki is a cable suspended system. Its primary structural elements are pretensioned cables which are pulled through the ribs placed on every 80 cm with a span of 51.2 m. Over the ribs is the roof membrane, which carries insulation and the other necessary layers. In the first structural design, with the wooden ribs, the engineer considered using wooden beams with a cross section of 16/22 cm with 6 Ø7 cables pulled through them. The reinforcement in the opposite direction was planned to be made from wooden boards 5 cm thick attached to the wooden ribs. Since the wood would be under all the insulation it was necessary to find the right coatings to protect it. Their wish was to leave the wood as natural as possible, but the right coatings could not be found in Yugoslavia at the time. Wood seemed to the architect to be the ideal solution because it gave a certain character to the interior (Balgač, 1971). The aesthetics of wooden spatial structures are always a good choice for large spaces because of their warmth and color (Šekularac *et al.*, 2012). Wood also has good acoustics, which is another of its advantages, especially for this building, because the sports hall was planned to be beneath the roof. However, the structure's main problem was that there had not been enough research on the behavior of wood in long span structures, which is why they needed to conduct several experiments. The high cost of these experiments and the long waiting time for the results resulted in the decision to change the design to concrete ribs (Figure 7).

Roof structure with concrete ribs

The concept of the structural design remained the same, even though the material was changed for the main project. The suspended roof had ribs every 80 cm, with 6 Ø7 pretensioned cables pulled through them. Over them a roof membrane with insulation was placed. The total load for the roof construction remained almost the same. It was 4 kg/m^2 more than for the design with wood, which is around 3% of the total load. The span also remained unchanged. In this design, which is the one that was built, prefabricated elements were made of concrete with the dimensions 18x16x80cm, and were called "pearls". In their middle there is a pipe which is 1.5 cm longer than the element, through which the cables were pulled and then pretensioned. The reinforcement in the other direction was steel sheets 1.5 mm thick and 3 cm in total height, filled with concrete. Its connection with the ribs was made with concrete anchors. The spaces between the "pearls" were filled with epoxy mortar after the pretensioning to get a monolithic roof that would work as a membrane. The cables were protected by injection of suitable mortar through the pipes. (Figure 8)

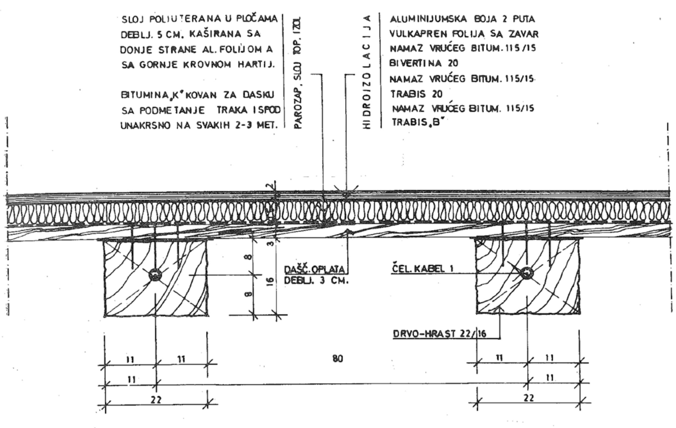


Figure 7. Detail of wooden ribs (Source: Balgač, 1971)

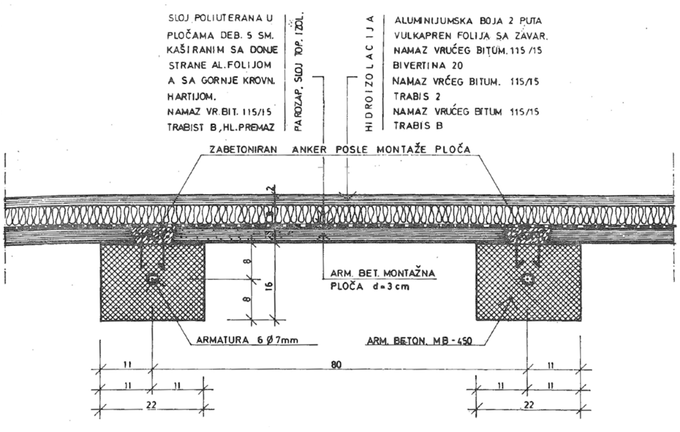


Figure 8. Detail of concrete ribs (Source: Balgač, 1971)

Structural forces in the suspended roof

Independent of the material used for the construction of the suspended roof of Pinki, its structural system remains the same. It must be mentioned that engineer Balgač tried to keep the load in the same frame, whether the roof was made of wood or concrete. The cable is shaped as a catenary under the influence of self-weight (Engel, 2001). Starting from this fact, the forces in the cable can be calculated as an evenly distributed load in the vertical axis of the cable, following the load flow. When the ends of the cable are fixed at the same height, the force inside the cable depends on the total load *q*, its span *l* and rise *f* which it forms (Figure 9). The greatest forces appear inside the cable with the smallest rise (4.2 m), so it had to be calculated first (The Main Project).

Pretensioning the cables inside the concrete ribs was carried out while they were still placed on the movable scaffolding. The cables passed through both side girders and the center of the concrete "pearls", after which a tension force was applied. Forces which appear inside structural elements are called rebound forces and they pulled the "pearls" up, at the same time pressing them against each other, and against the last ones onto the side girders (Balgač, 1971). This is the pretensioning process that was applied to this structural system. The rebound forces were used to unload the ribs and to transfer the forces to the side girders. They had to be greater that the total load for the rib to be constantly in a state of stress.

The value for the snow loads is another one in the line of specific solutions in this project. Contemporary regulations say that the snow loads for Belgrade are 75 kg/m^2, but for this project a value of 180 kg/m^2 was used. The engineer explained that this was done as insurance in case of a lot of water retention. If it rained heavily, or snow melted, the relatively low roof slope would not allow the water to flow immediately, and for this reason he used greater loads for his calculations (Balgač, 1971).

Special characteristics of the Pinki structural system

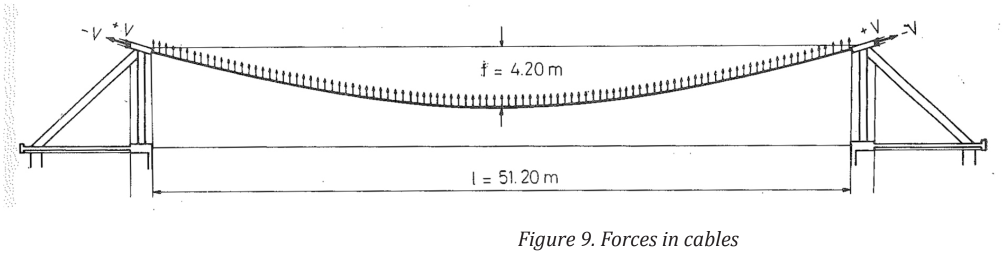
In comparison with the examples of buildings with suspended roof systems built before Pinki, the first difference is their position in the urban tissue. Unlike the Dorton arena or German pavilion which seem like a sculpture in a park or on a plateau, this building in Zemun is larger in size and situated inside an urban area. Because of the project demands and the position of the site, Ivan Antić, together with the engineers, did not have the necessary space to design special forms for structural elements. The main difference between these objects is the flow of forces inside the closed or open system. At Pinki, they strived to make a simple and economic design, so they formed a closed system of forces in which the whole weight of the building was a reaction to the roof forces. If they had made an open system, the roof strains would have had to be anchored straight into the foundations, which required extra space around the building.

By comparing Pinkis suspended roof to previous suspended roofs, it can be seen that Balgač had come up with a more simple and economic solution than the previous complex ones. The most significant difference was the absence of cables in an orthogonal direction that are usually used as reinforcement for the whole system. Instead of the cables, the roof membrane was made out of steel sheets filled with concrete that acted as necessary reinforcement. This solution contributed to the simple construction of the roof, and because of saving time, construction costs were reduced. Looking at the structural system, it can be seen that by eliminating the cables in the opposite direction, the columns on the main facade were not needed (Table 1). This also affected the appearance of the building, leaving the main facade open, which the architect then designed to be a tall glass curtain wall to observe the events inside the sports hall. It has to be emphasized that this is the only example of a sports hall with a suspended roof in which the main hall is situated on the first floor of the building, thus resulting in the need for a higher roof as well. This was one of the challenges in the structural design because it required a special solution for the foundations (Table 1), as shown previously in this paper.

CONCLUSION

The sports hall Pinki, designed by architect Ivan Antić, is one of the most important examples of architecture in the 20th century, and from its detailed analysis it is possible to conclude that for this type of building the relationship between the architect and the engineer is very important. The architect, together with the engineer, came up with a simple and cost-effective solution that responded to all the demands placed in front of them, thus creating a new recognizable symbol of Zemun. The cubic form of the object was refined with the parabolic shape of its roof, creating a game of geometry and transfer of loads visible on the building's facades.

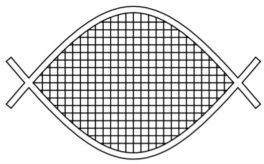
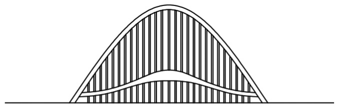
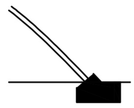
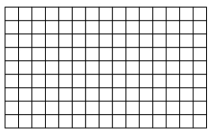
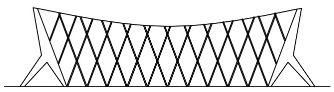
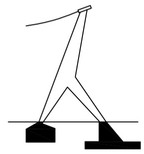
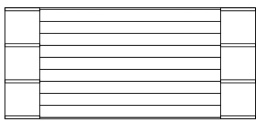
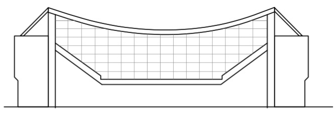
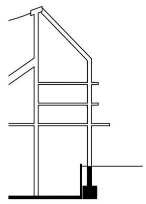
All Antić's sports objects give a sense of easiness accomplished through geometry and slim, simple large span structures. In comparison to the freedom he had while designing Sports Recreational Center 25. maj or the pool at Poljud, where he had a large enough area to design free forms in the space, what makes the project for Pinki special



$$S = q\frac{l^2\sqrt{l+\frac{4f}{l^2}}}{8f}$$

Figure 9. Forces in cables
(Source: Balgač, 1971)

Table 1. Comparative analysis of suspended roofs

	POSITION OF CABLES IN THE SUSPENDED ROOF	MAIN FACADE	FOUNDATIONS
DORTON ARENA, 1950.	cables in orthogonal directions 	strong girders, columns on the facade 	girders are founded directly into foundations (open system of forces) 
GERMAN PAVILION, ZAGREB FAIR, 1957.	cables in orthogonal directions 	visible columns 	combined foundations (ones accept strain, others accept stress) 
PINKI, 1974.	cables in longitudinal direction 	no structural elements on the facade of the sports main hall 	the whole weight of the building accepts the forces from the roof 

(Source: authors)

is the simplicity of the solution in which he had to put all the complex functions under one roof and still create a unique building. This is the exact spot where Andric's skills as an architect are best presented. Through the synthesis of form, function and construction he gave, at first glance very simple solutions, using the logic acquired during his work in practice and with the support of many significant engineers from that period.

> In the words of Ivan Antić: "The duty of us architects is to design a building that won't jut out in the scenery, which will be beautiful, which will, with all of that, have the right measure, the subconscious dose of the inborn norms and the love for the city you were born and raised in" (Milašinović Marić, 2005).

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