doi.org/10.62683/SINARG2025.019

Review paper

CONSTRUCTION SOLUTIONS OF THE OLD ŽEŽELJ BRIDGE IN THE SPHERE OF INNOVATIVE ACHIEVEMENTS IN DOMESTIC BRIDGE ENGINEERING

Dušan Kocić [1], Milan Gligorijević [2], Marjan Petrović[3], Nemanja Petrović[4]

Abstract

In this paper, a retrospective of the construction solutions of the old Žeželj Bridge on the Danube in Novi Sad will be presented. It was built between 1957 and 1961 and was designed by academician Branko Žeželj, a civil engineer after whom the bridge was colloquially named. The bridge consists of two arches with spans of 211 and 165.5 meters, with the roadway suspended from them. An innovative radial cable prestressing of the arch cross-section was applied, a method patented by engineer Branko Žeželj. Upon completion, and for many years afterward, it was the bridge with the largest arch span—both the largest arch in Europe and the longest-spanning arch in the world for railway traffic. The construction system of this bridge was unique in the world and was first applied in Yugoslavia, serving as a model for many bridges worldwide. For this reason, Branko Žeželj was awarded at the World Congress for Prestressing (FIP) held in Rome in 1960 for his significant innovations in prestressed concrete construction technology. As proof of the bridge's high-quality construction, it was only destroyed after six strikes during the NATO aggression in 1999. Nineteen years later, a new steel bridge, visually reminiscent of the original, was opened.

Key words: *bridge structures, radial prestressing, construction technology.*

[1] Civil engineer, assistant, Academy of Technical-Educational Vocational Studies - Civil Engineering, Serbia, dusan.kocic@akademijanis.edu.rs, ORCID 0009-0006-4886-0482
[2] PhD, Faculty of Civil Engineering and Architecture - Department of Constructions, Serbia, milan.gligorijevic@gaf.ni.ac.rs, ORCID 0009-0005-3538-3851
[3] PhD, lecturer, Academy of Technical-Educational Vocational Studies - Civil Engineering, Serbia, marjan.petrovic@akademijanis.edu.rs, ORCID N/A
[4] PhD, lecturer, Academy of Technical-Educational Vocational Studies - Civil Engineering, Serbia, nemanja.petrovic@akademijanis.edu.rs, ORCID 0000-0003-4010-2311

1. INTRODUCTION

The development of construction in Yugoslavia after World War II progressed rapidly. Due to swift industrial growth and the need for rapid reconstruction of a war-ravaged country, the golden era of the construction industry began. The need for mass construction of buildings forced engineers to seek new and faster construction solutions. Academician Branko Žeželj designed and patented more than 20 innovations, becoming a pioneer in the application of prestressed concrete technology in the former Yugoslavia and globally.

One of his structural solutions was the bridge over the Danube in Novi Sad. According to its structural system, this bridge belonged to the category of concrete arch bridges. It was built using prestressed concrete technology. For large-span arch bridges, the most crucial aspect of design and construction is the assembly plan [1].

The bridge consisted of two concrete arches from which the roadway deck was suspended via concrete hangers. To ensure the necessary navigable profile of the river, Branko Žeželj devised a unique method for constructing the arches, which involved building the arch in three segments. For bridges over large rivers such as the Danube and Sava, assembly from sections on the banks or using floating equipment is often employed to avoid temporary supports in the riverbed [1].

The Žeželj Bridge was constructed between 1957 and 1961. It was the world's first arch bridge built using prestressed concrete technology and a unique construction system. The main arch spanned 211 meters, making it the largest concrete arch bridge in Europe at the time, and the largest in the world to carry railway traffic. Destroyed during the NATO bombing in 1999, it was a key transportation link over the Danube in Novi Sad, connecting the city with industrial zones and the Pan-European Corridor X [2].

The Žeželj Bridge was not only a vital traffic connection linking the banks of the Danube and enabling the flow of people and goods along an important European corridor, but it also stood as a powerful symbol of Novi Sad's identity. Its recognizable silhouette was etched into the collective memory of the citizens as an architectural landmark of the city and a testament to the engineering progress of its time (Figure 1). As such, the bridge transcended its functional role and became part of the cultural and visual identity of the urban landscape. The demolition of the bridge in 1999 caused significant disruptions to both rail and road traffic, breaking the continuity of one of the most important transport links across the Danube [3].

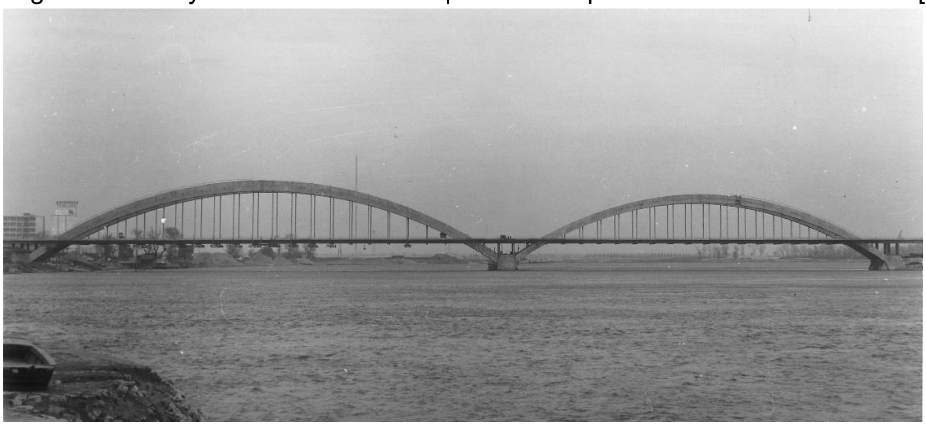

Figure 1. View of the bridge over the Danube in Novi Sad [4]

2. DESCRIPTION OF BRIDGE STRUCTURES

The road-rail bridge over the Danube in Novi Sad was located on the route of the main international thoroughfare Belgrade – Budapest, which represented the shortest connection between Central Europe and the Middle or Near East. The bridge also played a significant role in the national context, as it connected the fertile regions of Vojvodina with the rest of Serbia. Additionally, it was crucial to the transportation, economic, and industrial development of Novi Sad.

Before World War II, traffic was carried over two separate bridges – one for road and one for rail – both of which were destroyed during the war. A temporary solution after World War II was a steel truss road-rail bridge, built on the site of the demolished structure. However, its construction, adapted for combined traffic, resulted in difficult and slow traffic flow.

The construction of a new bridge was conceived as the foundation for a comprehensive solution to the railway junction and port area in Novi Sad. The bridge spanned the Danube at a location with a pronounced river bend, in the port zone, and since it was situated in the city center, it had to meet both aesthetic and urban planning requirements.

2.1. The bridge project

The total width of the regulated Danube riverbed in the area of the planned bridge, in accordance with urban planning, traffic, and industrial conditions, was 340.0 meters. The minimum navigable profile provided for a width of 190.0 meters at zero water level (elevation 71.76 m), and 210.5 meters at maximum water level (elevation 78.76 m). The vertical clearance of the navigable profile at high water levels was 6.0 meters. In addition, a secondary navigable profile of smaller dimensions was planned for upstream towing.

The bridge was designed for railway traffic, with the top edge of the deck placed at an elevation of 88.05 meters. The structure also had to span streets 15.0 meters wide on both the Novi Sad and Petrovaradin sides.

The total length of the structure between the end supports, including the river and the riverside streets with sidewalks, was 466.45 meters. It was divided into four segments: two main spans and two riverside approach structures.

The main navigable channel was spanned by an arch with a span of L = 211.0 meters, while the remaining part of the riverbed was spanned by an arch with a span of L = 165.75 meters. The floodplain structure on the Petrovaradin side was a simple beam with a span of 26.0 meters and an overhang of 2.72 meters, while the Novi Sad side had a continuous girder with spans of 10.0 + 20.0 + 10.0 meters and an overhang of 3.50 meters.

The width of the roadway slab was 20.15 meters, with pedestrian walkway expansions at the points where the bridge intersected with the arches. The clear width between the arches was 14.05 meters – of which 4.40 meters were allocated to the railway profile and 9.0 meters to the roadway. The inspection walkway had a width of 1.0 meter, while the usable width of the pedestrian paths was 5.15 meters.

2.2. Arc of span L=211.0 m

The structural system of the main span consisted of a fixed (encastre) arch with a span of L = 211.0 meters and a rise-to-span ratio of f/L = 1/6.5. The moment of inertia varied – decreasing from the crown toward the supports, where it increased sharply. The rise of the arch was 32.50 meters, while the axial spacing between the arches was 16.55 meters.

The arch had a box cross-section, with a height of 4.50 meters at the crown, tapering to 3.20 meters at the supports. The height-to-span ratio ranged from h/L = 1/47 to 1/66. The width of the arch above the roadway was constant at 2.50 meters, while below it widened to 4.70 meters. The side walls of the cross-section were 25 cm thick, while the top and bottom slabs varied from 62 cm to 1.20 meters. The section was reinforced and additionally radially prestressed.

The structural analysis included compensation of stress states in the arch using hydraulic presses at the dry crown joint to account for viscoelastic and plastic deformations, while the final closing of the crown was performed after the installation of the hangers.

Most of the roadway was suspended from the arch using hangers with an octagonal cross-section, with 15 cm sides, made of prestressed concrete (Figure 2). The transverse girders were prefabricated, also made of prestressed concrete.

Figure 2. Pre-assembled hangers at the place of manufacture [4]

The rest of the structure consisted of secondary transverse girders, four longitudinal girders, the roadway slab, and cantilevers with pedestrian walkways. Except for the walkway, all elements were constructed on site. The roadway slab was cross-reinforced, with expansion joints located above the piers and at mid-span (Figure 3).

Figure 3. Track plate and secondary supports [5]

The arches were connected by a truss bracing system made of prefabricated elements, which were prestressed and formed a unified structure (Figure 4). For stability under lateral loads, a box-shaped stiffening element was provided beneath the roadway, which, together with the lower parts of the arches, formed a closed frame.

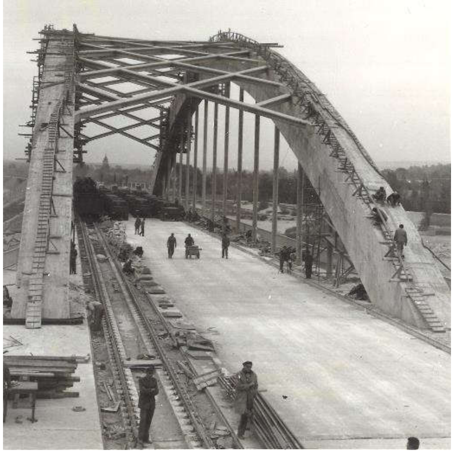

Figure 4. The design of the arch with a lattice connection [5]

The scaffolding for the large arch had to be designed to meet navigation requirements, allowing a 100.0-meter-wide passage for ships during the bridge construction (Figure 5). On the other hand, the high speed and depth of the river, as well as the potential for significant ice flows, required scaffolding with as few supports in the river as possible. To meet these conditions, a five-span scaffolding structure was designed. Two of the spans were composed of military prefabricated steel structures with a span of 23.0 meters, and the central span of 108.0 meters consisted of four two-hinged arches made of prefabricated reinforced concrete elements, connected by transverse girders and prestressed crossed diagonals. The auxiliary supports were founded on prestressed concrete piles with cross-sectional dimensions of 35 x 35 cm and a length of 17.0 meters.

The scaffolding was designed to carry only about 40% of the weight of the arches, which required the arches to be concreted in three phases. After the first phase, the lower ring had to be prepared using hydraulic presses to carry the load of its own weight and, together with the scaffolding, the load of the subsequent phases. In this way, an economical and lightweight scaffolding system was designed.

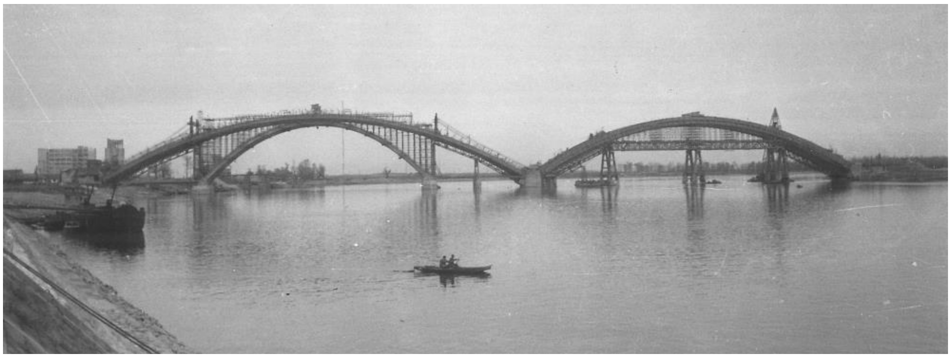

Figure 5. Scaffolding display during the construction of the arches [5]

The 108.0-meter-span arch scaffolding for the large opening was assembled using the cantilever method with a floating crane that had a lifting capacity of 50 tons and a lifting height of up to 35.0 meters. Individual prefabricated elements, weighing between 16.5 and 24.0 tons, were hinged to one another and held in place with cables over pylons and anchors until the arch was positioned in its final design alignment. Afterward, the hinged joints were concreted, and the arch was definitively tensioned transversely (Figure 6).

The supports for the two-hinged arch scaffolding were constructed on-site as box structures reinforced with ribs.

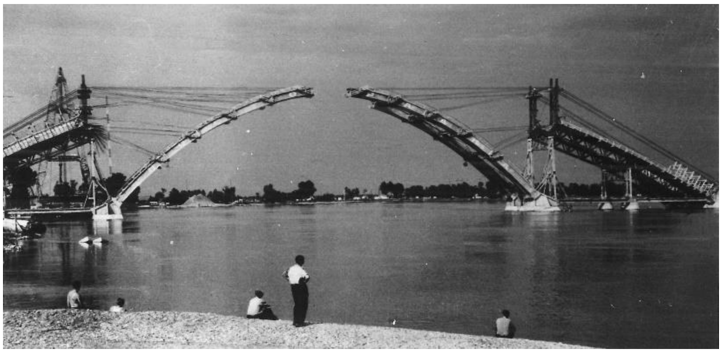

Figure 6. Installation of arched scaffolding of a large arch [5]

2.3. Arc of span L=165,75 m

The arch with a span of L = 165.75 m had the same slenderness ratio f / L = 1 / 6.5 as the larger arch. The rise of the arch was 26.50 m, and the axial spacing between the arches was 16.55 m. The arch structure was built as a closed box section of variable height – at the crown, the height was 3.63 m, gradually decreasing to 2.60 m at the supports. The height-to-span ratio ranged between h / L = 1 / 46 and 1 / 64.

The width of the arch above the roadway was constant at 2.20 m, while below the roadway it widened towards the supports to a maximum of 4.20 m. The side walls of the section had a constant thickness of 25 cm, while the thickness of the top and bottom slabs varied from 50 cm at the crown to 90 cm near the supports.

The arch was reinforced in both longitudinal and transverse directions, and the side walls were additionally radially prestressed.

The roadway structure was suspended from the arch by vertical hangers with an octagonal cross-section and 15 cm side length, made of prestressed concrete. The hangers were designed as prefabricated elements, partially prestressed at the production site and additionally prestressed during connection to the arch and the transverse girder.

A smaller portion of the roadway was supported on reinforced concrete piers with a rectangular cross-section, located above the river pier. The transverse girders were also prefabricated, made of prestressed concrete, and designed as simply supported beams. The rest of the roadway structure consisted of secondary girders, four longitudinal girders, the roadway slab, and sidewalk cantilevers. Most of these elements were constructed on site, except for the prefabricated parts of the pedestrian walkway. The cantilevers and secondary girders were made of prestressed concrete, while the remaining elements were made of reinforced concrete.

The longitudinal girders were designed as continuous girders with fixed supports, with transverse load distribution based on the grillage system. The roadway slab was cross-reinforced, with expansion joints located above the piers of the bank structure and at mid-span.

The scaffolding for the smaller arch was designed using prefabricated “Kohn” and “Rotwagner” structures, with four spans (Figure 5). Three auxiliary supports were designed to be founded on prestressed concrete piles, with lengths of 15.0 and 17.0 m and cross-sectional dimensions of 35 x 35 cm. One foundation contained 10 and another 14 piles.

2.4. Approach inundation constructions

On the Petrovaradin side, the approach inundation structure was a simply supported beam with a span of 26.0 m and an additional cantilever of 2.72 m in length. It was constructed as a concrete slab supported by ribs, which also formed cantilevers. Installation ducts were placed beneath the slab. This structure was monolithically connected to the arch and transmitted all vertical and horizontal loads.

On the side of Novi Sad, the approach inundation structure was a continuous girder, consisting of three segments with spans of 10.0 + 20.0 + 10.0 m, and an additional cantilever of 3.50 m. In terms of structural design, it was similar to the Petrovaradin side, but it accounted for the possibility of larger thermal displacements. For this purpose, bearings allowing movement in both directions were installed at the first support, while the remaining supports were designed as sliding bearings in the longitudinal direction.

3. BRIDGE CONSTRUCTION TECHNOLOGY

Construction of the bridge began in 1957, with the organization of the construction site on the left bank of the river, which is navigable only during exceptionally high water levels. Additionally, this bank is well connected to external land and water communications.

3.1. Supports

The left riverbank pillar was constructed on-site and then lowered to the designated level through caisson excavation. Since the area near the foundation, where the slab was supposed to be placed to achieve the reactive thrust from the soil, had poor-quality soil (silty clay), a deeper excavation was carried out. After that, the slab was cast and lowered to the designated level using a hydraulic elevator. To consolidate the ground behind the slab, mechanical compaction of sand and gravel in layers was performed, and part of the natural sandy material was reinforced with "Franki" system piles.

The right riverbank pillar was constructed in a similar way to the left one. The difference was that, at the location where the support was to be placed, a stone embankment island was first created, using a mix of stone rubble and dredged sand as part of the future riverbank regulation. Then, the caisson was constructed along with the slab. After that, the caisson excavation was carried out, and the caisson was lowered to the intended level.

The middle (river) pillar was constructed about 100 meters upstream on the left bank, and, after dry excavation, was lowered to the depth of the riverbed. Then, the channel was connected to the river flow, and the caisson was transported to the pillar location using caisson barges. This construction method was adopted due to the great water depth at the river pillar (10.0 meters at average water level), ensuring safer and faster work.

The caisson was made with reduced sections and pre-stressed elements, so during the caisson transportation phase, it weighed 3200 tons, out of the 6000 tons it weighed when it was lowered to the riverbed.

3.2. Concreting of the arches

The concreting of the arches began with the creation of the first ring (phase one). Once the lower ring in the crown received the load from its own weight through hydraulic presses, the viscoelastic and plastic deformations were partially compensated. Therefore, the upper ring was concreted independently from the lower one. Once the viscoelastic and plastic deformations were similarly compensated for the upper ring, the two rings were connected (phase three). To ensure secure bonding of the concrete during all three phases, the side walls were pre-stressed with radial cables.

The concreting of the individual phases was done in slabs of 10 to 15 meters in length, with an interspace of 1.5 meters. These interspaces were later concreted to eliminate the initial deformations due to shrinkage of the concrete.

The main reinforcement for the arches, Č 37 with a diameter of 32 mm, was welded in contact up to half the length of the arches, then manually transported and placed in the formwork. The concrete was prepared on the bank or floating structures, and lifted into place by a crane. After the concreting of the arches was completed, the wind bracing was assembled using a light mobile wooden scaffold.

The joint at the crown of the arch remained under pressure for about six months, until the beginning of the concreting of the secondary transverse and longitudinal supports. During this period, a significant portion of the parasitic influences was compensated, such as viscoelastic and plastic deformations, concrete shrinkage, plastic flow, and the separation of the end supports.

3.3. Construction of pavement

The suspenders and transverse supports were made on-site as prefabricated elements, transported below the bridge by floating means, and lifted and installed using a light wooden portal crane. The attachment of the suspenders to the arch and the transverse supports to the suspenders was done using pre-stressing.

After the installation of all the transverse supports, formwork was made for the longitudinal and secondary transverse supports, and concreting was carried out. Following that, the assembly of the pedestrian path elements was completed, and finally, the road slab was concreted, with simultaneous connection of the pedestrian path elements to each other and to the grillage of the main supports.

The concreting of the roadway was carried out from the ends toward the center of the structure.

4. DEMOLITION OF THE BRIDGE

On March 24, 1999, a group of NATO member countries, led by the United States, began an aggression against the Federal Republic of Yugoslavia. Under the pretext of preventing a humanitarian disaster in the territory of Kosovo and Metohija, both military and civilian targets across the country were bombed. The aggression lasted for 78 days, with the use of cluster bombs and bombs containing depleted uranium. The NATO member states sought the approval of the United Nations Security Council for military intervention, but it was not granted.

All the bridges in Novi Sad were destroyed during the aggression. The Brotherhood and Unity Bridge, better known as the Žeželj Bridge, was a target that long withstood attacks. It was destroyed on May 3, 1999, after being hit for the sixth time. Throughout the bombing, the target was the river pier, which was struck by several dozen GBU-27 projectiles.

The arch static system had inclined reaction supports that could be broken down into horizontal and vertical components. Since both ends of the arches were supported by the river pier, which was destroyed after being hit multiple times, the horizontal reaction components of the arch supports over the river pier remained in "balance," as shown in Figure 7. Therefore, after the destruction of the river pier, the arches leaned on each other, and it can be conditionally said that the arches were levitating. More accurately, the operation to destroy the bridge was unsuccessful.

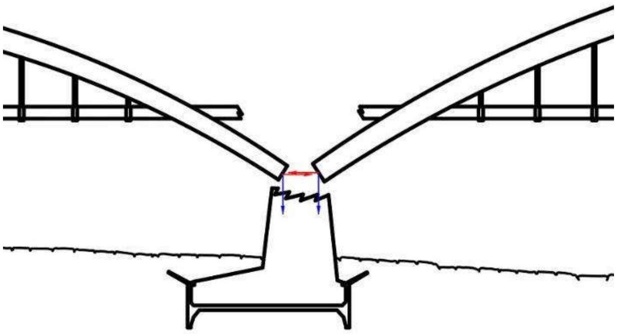

Figure 7. Schematic representation of the support of the arches after the destruction of the river column

Only after many unsuccessful hits on the river pier, the smaller arch was later targeted from the side at the crown by cruise missiles. After several consecutive lateral strikes, the smaller arch (connected by the roadway slab and tie rods) was overturned into the river as a whole, thus completing the bridge demolition mission, as shown in Figure 8.

Figure 8. Aerial photo before and after the bombing of the bridge [6]

Nineteen years later, a new steel arch bridge was built at the site of the old bridge, visually resembling the original concrete bridge.

5. CONCLUSION

The road-rail bridge over the Danube in Novi Sad was much more than an infrastructure facility – it represented a crucial point of connection not only in transportation but also in urban, economic, and strategic terms.

This bridge was the result of a carefully designed revolutionary engineering solution [7], which successfully met the complex technical, traffic, and aesthetic demands of a modern city. The method of its construction served as a model for many engineers around the world.

The construction of the bridge, made possible by the knowledge and dedication of local experts and workers, was a symbol of progress and modernization. Its existence testified to the skill, ambitions, and values of the state and society at that time.

The destruction of the bridge during the NATO aggression in 1999 not only physically interrupted vital transportation flows but also dealt a significant blow to the historical heritage of Novi Sad and Serbia.

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