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Steel tied network arches across the Danube

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Railway Road Bridge in Novi Sad – Steel tied network arches across the Danube

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Abstract. The Railway road bridge in Novi Sad is situated on the international railroad Belgrade-Budapest. The bridge is designed for two railway tracks (with design speed of 160 km/h), two road lanes and two footpaths. The bridge structure consists of four structures: two approach composite bridges at the banks and two steel tied network arch bridges over the river and transition structure between two arches. The spans are 27.0+177.0+3.0+219.0+48.0 m, totally 474.0 m in length. The rises of arches are 34.0 m and 42.0 m respectively. The width of the bridge is 31.440 m. The arches and ties, as well as the girders of the approach spans, are steel box girders. The decks of all bridge structures are the composite reinforced concrete slabs with thickness of 300 mm, locally 400 mm. The launching was very complex, in both analysis and construction. The arch bridges were fully assembled on the banks and launched by skids over the bank and by pontoons over the river, to the final position on piers. The bridge was designed fully according to European standards and additionally – according to requirements of German codes DIN-Fachbericht 101 to 104 Edition 2009 and Deutsche Bahn Richtlinie 804, Edition 2003. The bridge is, despite of heavy loads and structural complexity, very rational in steel volumes and construction costs as well. The bridge is also, with the arch span of L = 219 m, the bridge with the longest span in the world in the category of tied network arch bridges with two rail tracks. The bridge is open to rail traffic at 7th April 2018.

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1. Introduction

The New Railroad Bridge across the Danube River in Novi Sad is situated on the location of the old concrete road railway bridge – destroyed in air strikes in 1999, on the major international electrified railroad line No 2 Belgrade – Budapest, over the Danube, *figure 1*.

The contractor for the bridge construction is Spanish-Italian consortium AZVI-Taddei-Horta Coslada. The list of participants is given in section 6.

Figure 1. Location of the Bridge in Novi Sad.

Terms of Reference, composed by Serbian Railways includes the following basic references:

- Bridge location: location of the old bridge (1961-1999);
- Traffic across the bridge: 2 tracks + 2 traffic lanes + 2 foot-cycling paths;
- Structural system, as urban planning condition: steel arch structures over the river;
- Maximum line (train) speed: passenger trains – 160 km/h, freight trains – 120 km/h;
- Maximal vertical acceleration: $a_v \leq 1.3$ m/s^2;
- Road and rail: rail tracks axes distance = 4.20 m, road lanes = 2 x (3.50+0.35) m;
- Bridge accessories: water pipes deck drainage system, accessories and equipment for electrical power, telecommunications, illumination (public, intern and decorative), navigation signals (for ships and airplanes), traffic signalization of the road and railway, road safety barriers;
- Foundation: supporting of the new bridge onto the existing fundaments as much as possible;
- Design codes: key code Richtlinie 804:2003 [2] and related to that code series DIN-Fachbericht 101 to 104 Edition 2009 [3] to [6], i.e. appropriate codes series EN 1991, EN 1992, EN 1993, EN 1994 and EN 1998 in actual editions. Alpha factor for railway traffic load is 1.0.

2. Bridge structures

2.1. General

Essential general data about the Railway Road Bridge in Novi Sad from design [1], *figure 2*:

- Track alignment: according to the traffic solution of traffic line management – satisfying the requirement for the as short as possible connection with the existing traffic line and securing of navigation clearance under the bridge;
- Structural system: Four independent structures as simple beams, left bank approach bridge 25.30 m, main (river) bridges 177.00 and 219.00 m; right bank approach bridge 45.30 span;
- Position of the piers: Position of the axis *3* (axis of the middle pier in the Danube), is done according to the requirement that the pier should be positioned centrically onto the existing foundation of the old bridge. Positioning of the axes *2* and *4* of the designed bridge is done bearing in mind the positions of the existing foundations, position of the piers required by

the conditions of proper institution and structural raster of the bridge structure (as *n* x 3000 mm). The piers distances *1-2-3-4-5* are: 27.00 + 178.50 + 220.50 + 48.00 m;

- Main bridge dimensions: total length is 474.00 m; bridge width between the outer edges of the masks is 31.440 m; spacing of the ties axes is 23.50 m, *figure 3*.

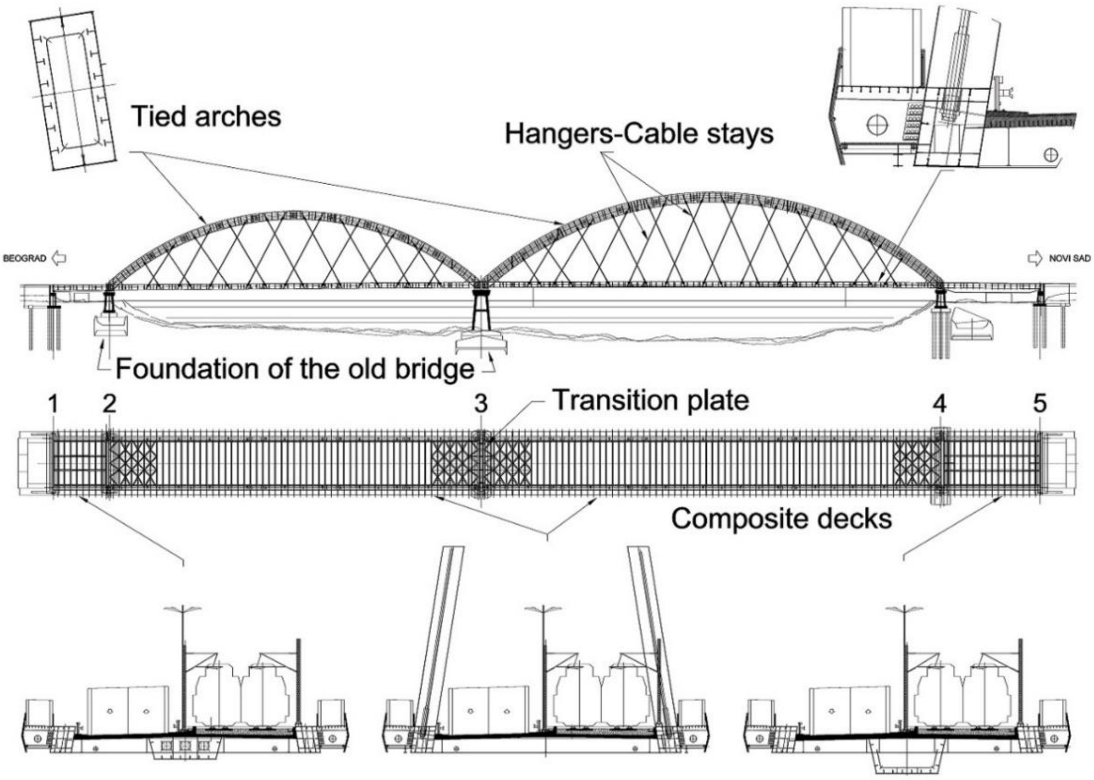


Figure 2. Layout of the bridge structure.

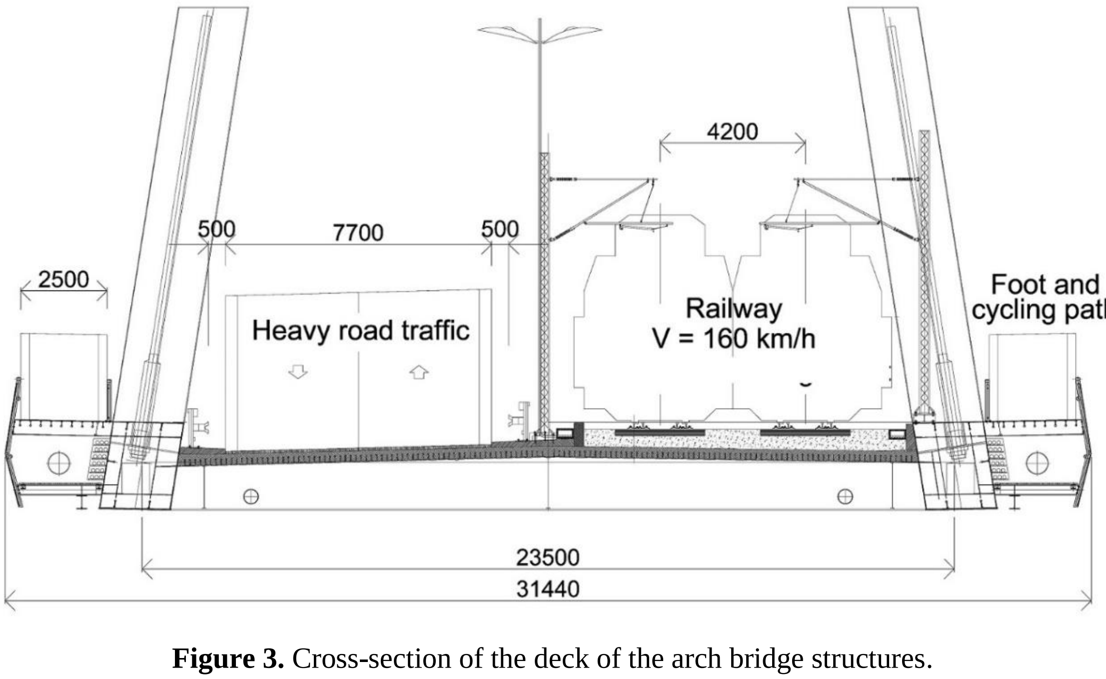


Figure 3. Cross-section of the deck of the arch bridge structures.

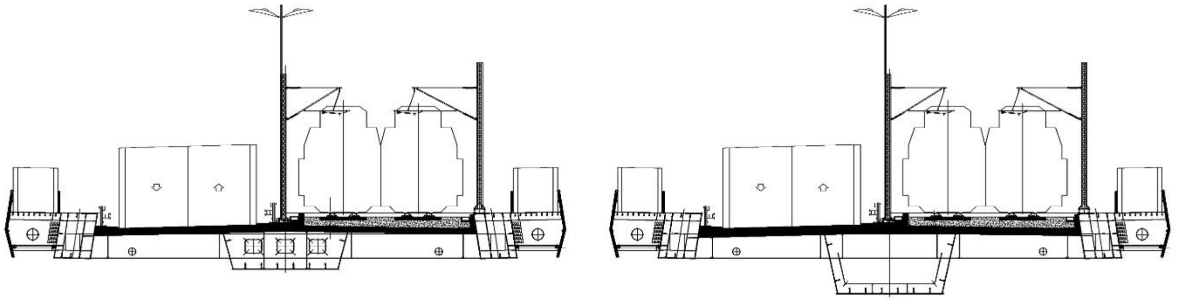


Figure 4. Cross-sections of the approach bridge structures *1-2* and *4-5*.

The choices and decisions in the design process were influenced by: elements of the Terms of Reference, design codes requirements, the requirements of rational erection and the need to achieve the optimal quantity of structure material.

Alignment of railway, and hence the location of the bridge structure was adapted according to the navigation clearance of the Danube River under the bridge. Also technical requirements for the design of railway and connection to the existing railway tracks on both banks were considered. The ballast depth is min 350 mm.

The transversal slopes of bridge deck are 2.5% and 1.5% which corresponds to conditions of drainage, both road and rail respectively, *figures 3 and 4*.

Structural materials:

- Structural steel grades are S355 mainly and in very limited areas of the nodes arch/tie is S460 applied, with thickness constraints according to the terms of Richtlinie 804:2003 [2] and DIN-Fachbericht 103:2009 [5]; the maximal plate thickness is 50 mm;
- The concrete deck slab is casted in situ, with concrete class C35/45 according to EN 1992-1-1:2004 and DIN-Fachbericht 102:2009 [4]:
- Headed studs are Ø25 x 200 mm according to EN ISO 13918:1998 and EN ISO 14555:1998;
- Reinforcement bars are from steel B500C according to EN 10080:2005;
- The hangers of arch bridges are parallel strand cables with the ultimate (nominal tensile) strength f_u = 1860 N/mm^2.

The structure and hangers are painted in signal white (RAL 9003) which reduces influence of thermal actions on the bridge structures.

2.2. Main bridges

The main bridge structures are tied arches with hangers in network arrangement.

Basic characteristics of arch structures:

- Spans and rises: bridge *2-3*: *L*/*H* =177.0/34.0m=5.21; bridge *3-4*: *L*/*H* =219.0/42.0m =5.21;
- Main structural system acts as a spatial structure, arches + transversal arch connecting beams + ties + hangers + cross beams + concrete deck plate;
- Box cross-sections dimensions of arches: bridge *2-3*: 4000x2000 mm; bridge *3-4*: 4900x2000 mm;
- Cross-sections dimensions of ties: box 2550x2000 mm, footpath cantilever length *b*=2.90m;
- Hangers: cable stays as 55 parallel strands; each cable is with the magnetic sensor on the reference strand (randomly selected strand); the cable sensors for registering of actual cable stays axial forces are the part of monitoring system of the bridge structure; the number of hangers at the arch bridges – 2x18 and 2x22;
- Deck slab: *t* =30cm and *t* =40cm at the ends – in bracings zone; three layers of reinforcement bars in longitudinal direction and two layers in transversal direction,(*figure 8*);

- Supports: 2 x 3 bearings at system axes. Longitudinal and transversal displacements are restrained at central bearings in axis *3*, (*figure 6*).

About the main structural designing decisions and most important structural analysis results see the details in the references [7], [8] and [9].

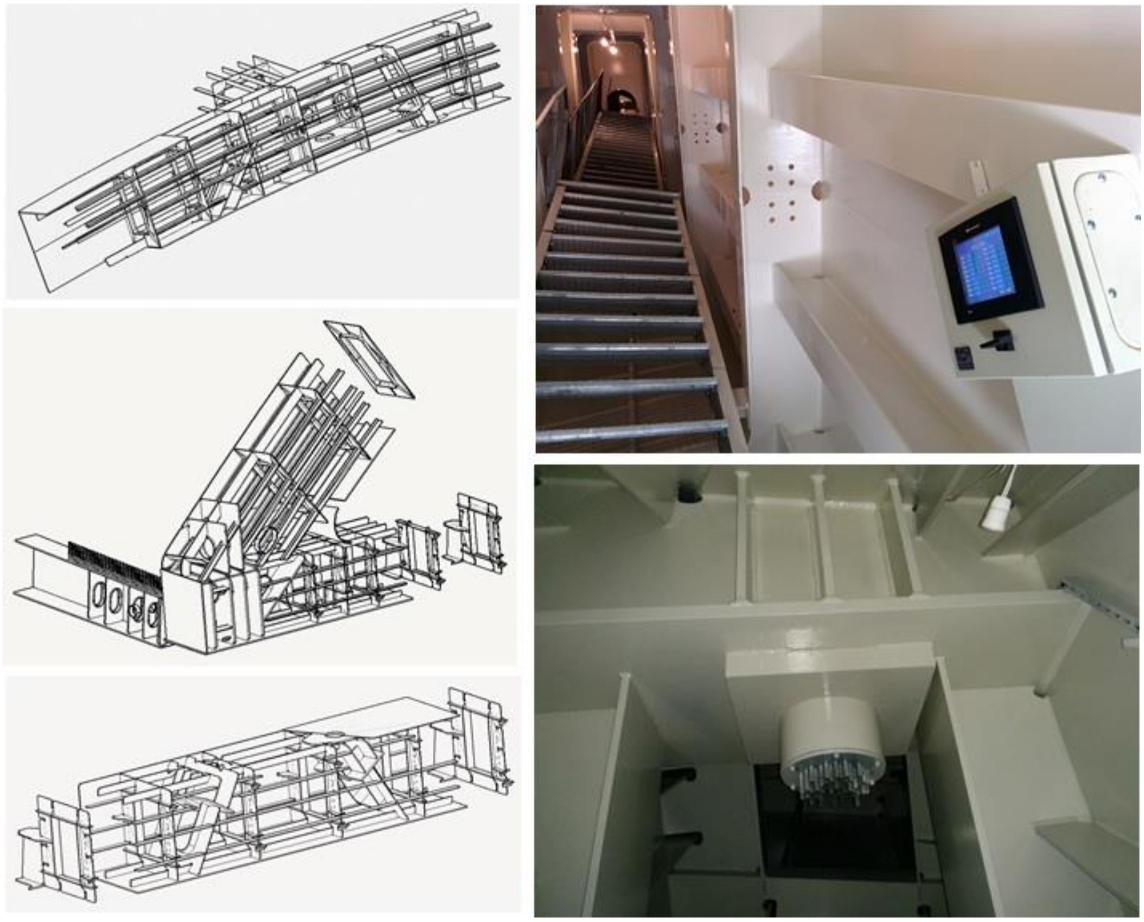


Figure 5. Fragments from 3D-Workshop drawings and interior of arch and tie.

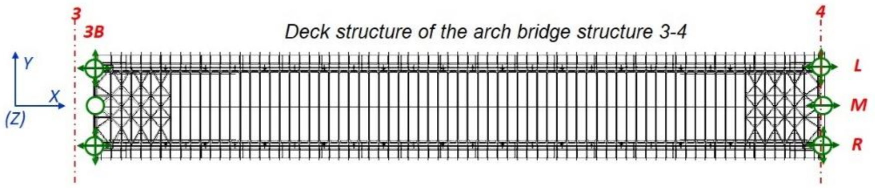
The approaching structures *1-2* and *4-5* consists of three girders (*figure 4*), connected transversally by cross beams. The side girders are steel structures, shaped as ties of arch bridges for sake of visual compliance. Side girders are also horizontally connected with the deck slab by the headed studs. The middle girder is a composite beam.

The mutual work of three girders in the grillage system is well balanced considering the eccentricities of traffic loads.

3. Some specific details of the bridge structure and construction of the bridge

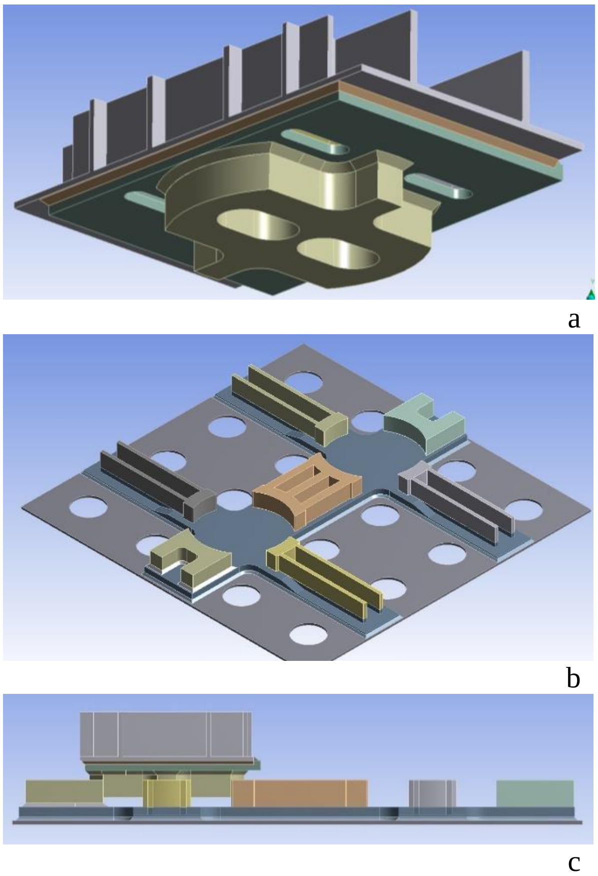
3.1. Horizontal supports on Pier 3

Central pier – pier in axis *3*, *figure 2* – is placed over residual caisson from the previous bridge (1961-1999). The dimensions of the old caisson are significant, 39.5x24.5 m in the layout and therefore capable to resist significant horizontal forces and corresponded moments from the bridge arch structures. The maximal magnitude of horizontal forces is 37000 kN per horizontal support in axes *3B*, (*figure 6*). This fact was used to design in [1] horizontal fixed supports *3A/M* and *3B/M*, longitudinally and transversally, on pier 3. Horizontal support structures are the bearings designed to transfer the horizontal forces, but not the vertical, (*figure 6*). Horizontal supports are connected to end cross beams of both arch bridge structures, transported with the bridge structures during launching and welded connected in situ after the final space tuning on the pier. The structural solution is presented in *figure 7*.



	Bearings L& R			Bearings M		
Axis	X	Y	Z	X	Y	Z
1	-	-	+	-	+	+
2A	-	-	+	+	+	+
2	-	-	+	-	+	+
3A	-	-	+	+	+	-
3B	-	-	+	+	+	-
4	-	-	+	-	+	+
4B	-	-	+	+	+	+
5	-	-	+	-	+	+

Figure 6. Bearings arrangement of the arch bridge *3B-4* and support reactions scope.



Horizontal support structure:
a) Superior part – Pin, under the end cross beam,
b) Inferior part – Pot, over the concrete pier,
c) Complete structure as Pin + Pot.
Horizontal forces tranfere from End cross beam, over the Horizontal support to the steel tube pins in concrete top beam of the central pier.

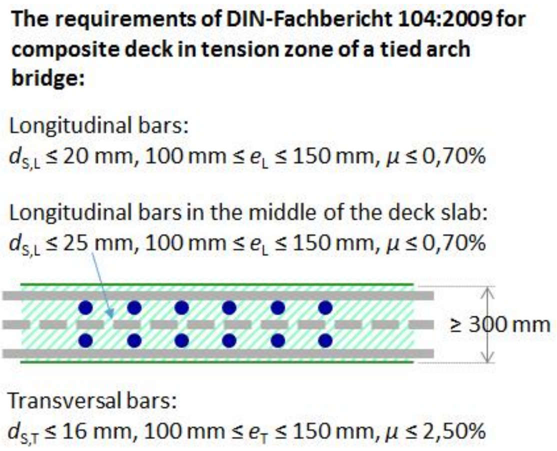
Figure 7. Horizontal support structure in the design and on the site.

3.2. Deck slab

The deck structure of all four bridge structures is the composite one, with cross beams and reinforced concrete slab. Deck slab is joined with the cross beams (transversal composite action) and with ties of arch bridges and side girders at approach spans for purpose of longitudinal and lateral composite action.

The deck structures of arch bridges are also exposed to tension forces from main structural system. Limitation of crack widths is realised thru the appropriate structural detailing of reinforcement bars, strictly according to very strong requirement of DIN-Fachbericht 104:2009 [6] for reinforced concrete deck plates of arch bridges, see *figure 8*.

Additionally, the deck plate is double protected: superior surface – water insulation methyl methacrylate resin layer; inferior surface – permanent steel formwork.



Deck reinforcement installation. The temporary columns for launching are still on place.

Figure 8. Reinforcement of concrete deck.

3.3. Launching

The launching of arch bridge structures (*figure 9*) has been realized through the movement on the banks – with skids and over the water – on pontoons. The bridge structures were reinforced with the temporary columns for launching, securing the structure to overstressing.

Figure 9. Launching of arch bridges over the Danube.

Special attention has been paid to calculation of forces and deformations of entire structure during cable stay installation as well as to erection analysis in all phases of the erection, *figure 9*. The hanger cable stays forces vary from tension to "compression" from step to step, according to changes of structural system during launching. The analysis was performed using Third Other Theory (analysis with large cable stays sags), avoiding the long iterative calculations with strait members and effective modulus of elasticity of cable stays.

3.4. Test load

The test load of the bridge (*figure 10*) is an obligation according to Serbian standard SRPS U.M1.046:1984. The tests were practised as static tests in seven phases and dynamic tests in four stages. The used vehicles were: three axle trucks of 23.5 t mass, four axle hopper-dozator wagons of 72 t and locomotives of 110 t.

In final phase of static test, the bridge structures were loaded on both road lanes and both tracks, across the whole span. For example, on the arch bridge of 219 m span, the total load was 32000 kN (3200-ton mass) of fully loaded vehicles.

Dynamic tests were performed with three coupled locomotives, with following velocities: On track No 1, *V* = 10; 55 and 80 km/h and on track No 2, (downstream side, *figure 3*) *V* = 30 km/h.

The measured deformations (displacements and support rotations), stresses and cable stays forces, vibration frequencies and accelerations (in vertical and horizontal plane) as well, were in very good correspondence to calculated values. For example – vertical displacements of four bridge structures (*figure 2*) with the spans of 25.3 m, 177.0 m, 219.0 m and 46.3 m, in the final static test phase, the values Measured/Calculated were respectively: 4.0/6.6 mm, 64.4/71,9 mm, 86.5/89.3 mm, 21.0/21.2 mm.

Figure 10. Test load of the Bridge, static and dynamic.

4. Structural materials quantities and construction costs

Quantities of structural materials for the bridge structures:

- Structural steel (for *1-2, 2-3, 3-4* and *4-5*): 300+3900+5300+700 = 10200 t
- Secondary steel structures: 400 t
- Cables, 55 parallel strands: 1000+1500 = 2500 m
- Concrete for decks: 3730 m^3
- Reinforcement: 1250 t.

The construction cost is about 55 Million EUR, (state April 2018).
The bridge is open to rail traffic at 7^{th} April 2018.

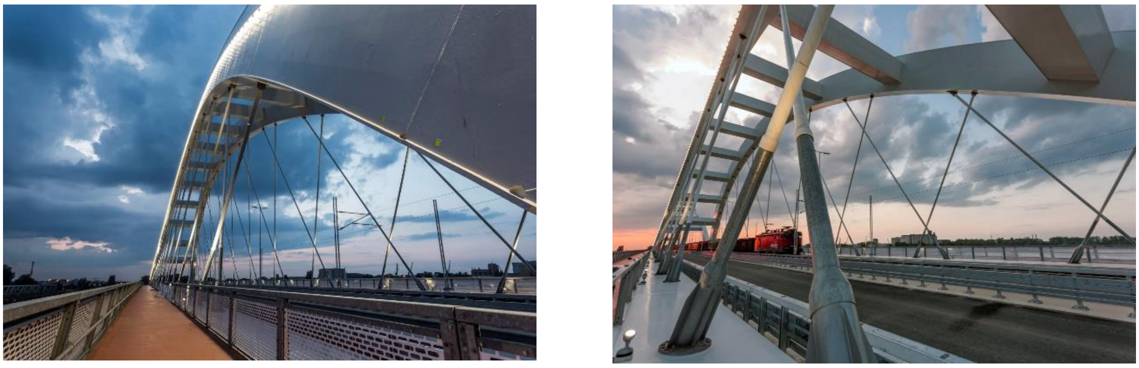
5. Conclusion

The Railway Road Bridge in Novi Sad is excellent example of high efficiency of the network arch systems for railway bridges, especially regarding very strict serviceability limit states requirements. The specific consumption of structural steel (kg/m^2 or kg/m^1 of rail track) is below the expected, statistically defined, mean values according to literature, (e.g. [10]).

The bridge itself (*figures 11 and 12*), with the arch span of L = 219 m is a bridge with the longest span in the world in in the category of tied network arch bridges with two rail tracks.

6. Participants

Structure:	Railway Road Bridge across the Danube in Novi Sad.
Employers:	Delegation of the European to the Republic of Serbia, Enterprise Serbian Railways.
Financing:	Delegation of the European to the Republic of Serbia Autonomy Province of Vojvodina Municipality of Novi Sad
Contractor:	JV AZVI S.A., Taddei S.p.A., Horta Coslada S.L.
Subcontractors for designing:	
Bridge structure:	DEL ING DOO, Belgrade, Serbia.
Foundation and piers:	ENCODE DOO, Belgrade, Serbia.
Subcontractors for construction:	
Assembling of the bridge structure:	Mostogradnja AD, Belgrade, Serbia.
Cable stays:	VSL Ltd., Poland.
Launching:	ALE Heavylift Iberica, Madrid, Spain.
Bearings and expansion joints:	FIP Industriale, Servazzano, Italy.
Technical control of the Detailed Design:	“Kirilo Savić” Institute AD, Belgrade, Serbia.
Engineer:	JV DB International and Egis International.



a b

Figure 11. Railway Road Bridge in Novi Sad
a – Footpath with parapets and masks inside; b – The cargo train on the Bridge

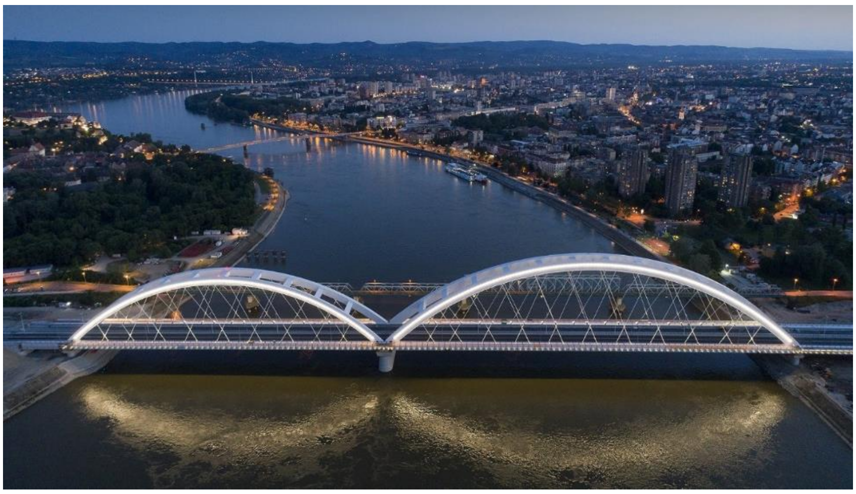


Figure 12. Railway Road Bridge in Novi Sad.

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