Railway Road Bridge in Novi Sad – Design and Erection

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Summary

The bridge is situated on the major international electrified railroad line No 2 (Belgrade-Budapest) and designed for to railway tracks (160 km/h), two road lanes and two footpaths, with the total width of 31,5 m. The bridge structure consists of four structures: two approach composite bridges at the banks and two steel tied network arch bridges over the river. The spans are 27,0 +177,0 + 3,0 + 219,0 + 48,0 m, totally 474,0 m in length. The heights of arches are 34,0 m and 42,0 m respectively. The arches and ties, as well as the girders of the approach spans, are steel box girders. The decks of the arch bridges are the composite reinforced concrete slabs with thickness of 300 mm. The launching itself is very complex and unique, in both analysis and construction. The arch bridges are fully assembled on the banks and launched by platforms and skids over the bank and by barges over the river, to the final position on piers.

Keywords: Railway road bridge, tied arch bridge, steel bridge structure, composite bridge structure, dynamic analysis, erection, launching.

1. Introduction

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

Fig. 1: Location of the bridge

Terms of Reference [1], composed by investor - Serbian Railways includes the following basic requirements:

- Bridge location: Location of the old bridge (1961-1999);

- Traffic across the bridge: 2 tracks + 2 traffic lanes + 2 footpaths;

- 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, *Fig. 4*;

- Bridge accessories: Water pipes 2 x Φ 610 mm; Power and telecommunication cables; Power cables and accessories for the electrification of the railroad, for the public illumination, illumination of the interior of the structure and decorative illumination, for the navigation signals (for ships and airplanes); Traffic signalization of the road and railway; Safety barriers; Carriageway drainage pipes;

Fig. 2: Bridge in Novi Sad. Visualization

- Foundation: Supporting of the new bridge onto the existing fundaments as much as possible;

- Design codes: key code Ril 804:2003, [3] and related to that code series DIN-Fachbericht 101 to 104 Edition 2009, i.e. appropriate codes series EN 1991, EN 1992, EN 1993, EN 1994 and EN 1998 in actual editions.

2. Bridge structures

2.1 General

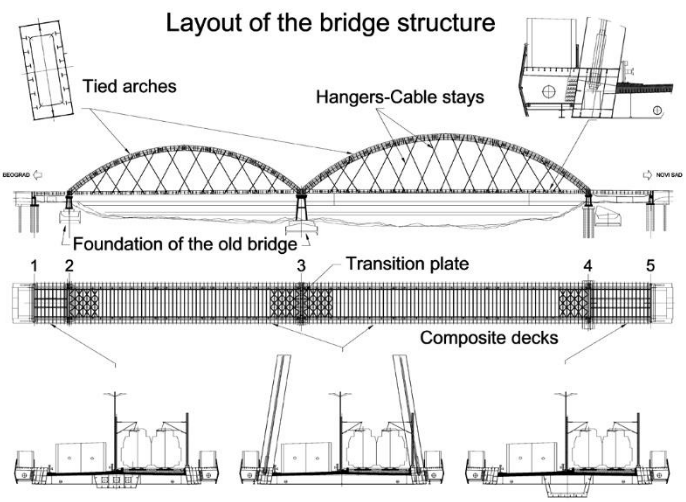

Fig. 3: Layout of the bridge structure

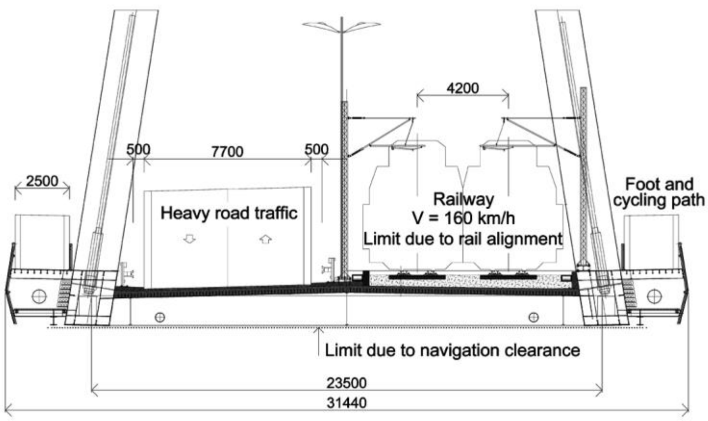

Fig. 4: Typical cross-section of the arch bridges deck

Essential general data about the Railway Road Bridge in Novi Sad, *Fig. 2*, *Fig. 3*:

- 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, *Fig. 3*: 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, *Fig. 3*: Positioning of the middle pier in the Danube, supporting the two arch bridges is according to the requirement that the pier should be positioned centrically onto the existing foundation of the old bridge. Other piers were positioned according to the bank conditions with distances between the piers *1-2-3-4-5*: 27,00 + 178,50 + 220,50 + 48,00 m;

- Main bridge dimensions: total length = 474,00 m; bridge width between the outer edges of the masks = 31,440 m; spacing of the ties axes = 23,50 m, *Fig. 3*.

The choices and decisions in the design process in the Preliminary Design and later retained in the Detailed Design [2]. were influenced by: elements of the Terms of Reference [1], design codes requirements, the requirements of rational erection and the need to achieve the optimal quantity of structure material.

Fig. 5: Bridge in Novi Sad. Visualization

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. Alignment of the new railway bridge at the highest point is about 1,10 m higher than the old one. The ballast depth is min 350 mm, which is greater than required by Ril 804:2003 [3] (300 mm).

The transversal slope of bridge deck is 2,5% and 1,5% which corresponds to conditions of drainage, both road and rail respectively.

Structural steel is S355 and very limited areas S460 with thickness constraints according to the terms of Ril 804:2003 and DIN-Fachbericht 103:2009.

The structure and hangers will be painted in signal white (*Fig. 5*) which reduces influence of thermal actions on the bridge structures.

Composite (steel-concrete) deck structure was adopted for all bridge structures (see *Fig. 3*). In comparison with the alternative solution, the steel deck structure with the orthotropic plate, the composite deck structure has the following advantages: significantly lower costs of construction, higher fatigue resistance, lower noise under traffic, significantly lower danger of freezing of the carriageway and easier maintenance. The deck slab thickness of 300 mm was adopted, as minimum required by DIN-Fachbericht 104:2009 for concrete slabs subjected to tension in arch bridges.

The concrete carriageway slab is casted in situ, with concrete class C35/45 according to EN 1992-1-1:2004, i.e. DIN-Fachbericht 102:2009. Carriageway 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. Welded headed studs shear connectors are used Φ 25 x 200 mm according to EN ISO 13918:1998 and EN ISO 14555:1998. Reinforcement of the slab is steel B500C according to EN 10080:2005.

Main longitudinal grid of 3,000 m (distance between cross beams) was set out regarding the following criterions:

- Possible bearing capacity of the deck structure cross beams, given their limited cross section height and the possible effective widths of the carriageway deck coming from the cross beams spans;

- Bending of concrete deck slab in longitudinal direction due to local action of traffic loads;

- Magnitudes of the bending moments of the tie between the hanging points.

2.2 Main bridges

The main bridge structures are tied arches with hangers in network arrangement, *Fig.3*.

Basic characteristics of arch structures:

- Span and rise: Bridge *2-3*: L/H = 177,0/34,0 m = 5,21; Bridge *3-4*: L/H = 219,0/42,0 m = 5,21;

- Main structural system acts a spatial structure, arches + transversal arch connecting beams + ties + hangers + cross beams + concrete deck plate;

- Box cross-sections dimensions of arches: Bridge *2-3*: 4,00x2,00 m; Bridge *3-4*: 4,90x2,00 m;

- Cross-sections dimensions of ties: box 2,55x2,00 m, footpath cantilever b = 2,90 m;

- Deck slab: t = 300 mm and t = 400 m at the ends – in bracings zone;

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

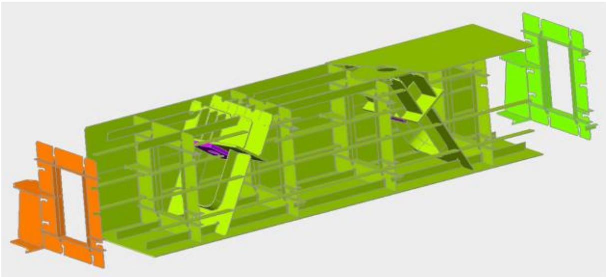

Fig. 6: Structural details of the tie

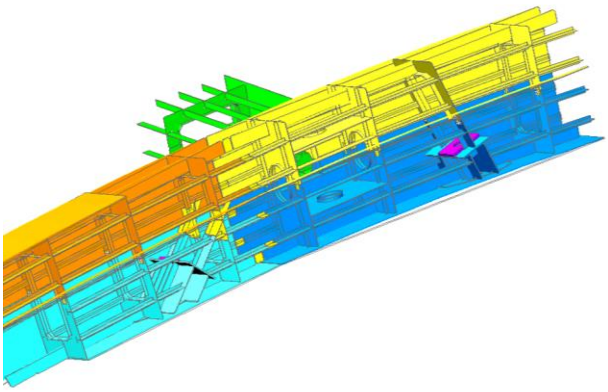

Fig. 7: Structural details of the arch

The sizes of the cross-sections and the rises of the arches *2-3* and *3-4* were determined by the alternative analysis of the most critical design requirement – compliance with the requirement of the sum of rotations of the supports in the axis *3* as one of the serviceability limit state criteria. In addition, the analysis showed that the extension of the rise has an insignificant influence to the deflection reduction. The designed dimensions of the arches cross-sections are practically the largest possible rational dimensions for the box cross section of steel arches.

Width of the arches and ties is 2,00 m. It was obtained satisfying the following criterions:

- Global and local stability of the arches;

- Required widths of diaphragms inside the arches and ties and openings within them planned as passage for the maintenance;

- Required widths of the arches and ties at the supports that need to be in accordance with necessary dimensions of bearings considering large reaction forces and deformations.

Cable stays were decided for composition of the hangers upon the selection between the cable stays or rigid steel compression elements. The advantages of the cables to the rigid steel compression elements are as follow:

- No need for the splice joints (the hangers' lengths are up to 42 m);

- Significantly higher fatigue resistance;

- More efficient possibility of damping the vibrations coming from the action of the traffic and wind;

- More adequate finishing of the surfaces bearing in mind aero elastic stability.

Network arrangement of hangers guaranties very rigid arch structure, far more rigid in comparison to arches with vertical hangers. The hangers are in two planes at the axis distance of 300 mm and not connected at cross points.

2.3 Approach bridges

The structure of approach spans *1-2* and *4-5* (*Fig. 8*) consists of three girders, connected transversally by cross beams. The side girders are steel structures, shaped as ties of arch bridges for sake of visual compliance. The middle girder is a composite beam.

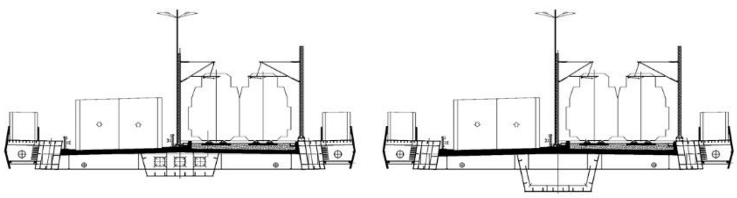

Fig. 8: Cross-sections of approach spans 1-2 and 4-5

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

2.4 Erection of arch bridges

Erection of arch bridges *2-3* and *3-4* consists of two global operations: assembling and launching. *Fig. 9* presents nine main stages of the erection of the arch bridge *3-4*, (principally the same method is applied at other arch bridge, bridge *2-3*):

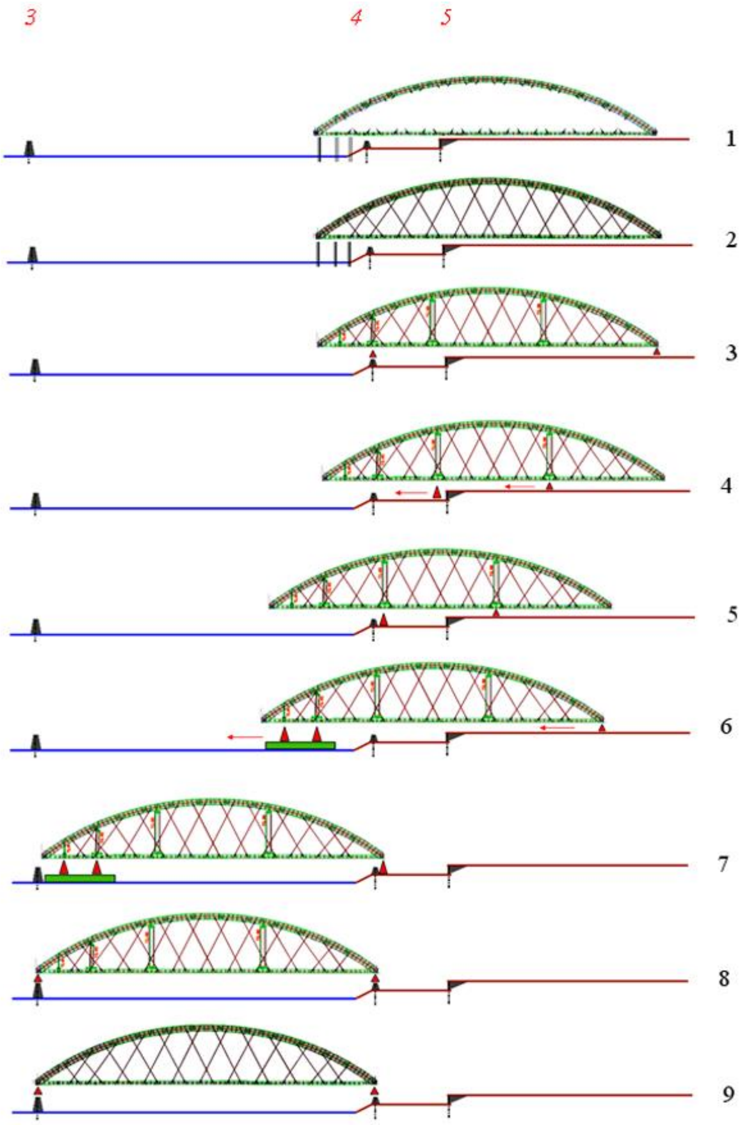

Fig. 9: Structural details of the arch

Phase 1: Assembling of the steel structure (ties, cross beams, arches) at the site on the riverbank.

Phase 2: Installation of hangers (cable stays).

Phase 3: Installation of temporary columns for launching (TCL). The whole system bridge structure + TCL is enough rigid for next phases of launching; transfer of supports to Pier 4 and under the bridge structure axes *4* (*BS-4*).

Phase 4: Transfer of supports to platforms and skids in the central zone of the bridge structure.

Phase 5: Transport to end position near Pier 4.

Phase 6: Transfer of supports to barges and at *BS-4*.

Phase 7: Transport over the river and across the bank to the end position near Pier *3*.

Phase 8: Positioning of the bridge structure to the final position on bearings on piers *3* and *4*.

Phase 9: Dismantling of temporary columns for launching.

Phase 10: Concreting of deck plate.

Phase 11: Installation of ballast, rails, asphalt layer, and various equipment and accessories on the bridge.

The bridge will be equipped with bridge monitoring system for monitoring of stresses, deformations, vibrations and accelerations of various bridge components during launching and exploitation.

3. Structural analysis

Structural Analysis has been prepared entirely in accordance with the design codes given within the Terms of Reference [1] and in Tender Documents. The most sophisticated analysis methods were used comprising: finite elements second and even, in some cases, third order theory, material nonlinearity, buckling analysis with imperfections, time-history analysis of real trains. The scope of basic assumptions is following:

Structural analysis software: Sofistik as the lead one, TOWER and SAP partially.

Structural models: Approach spans fully in finite elements (*Fig. 10*), arch bridges as beam models (*Fig. 11*). The concrete slab was modelled with shell finite elements coupled in composite action with cross beams.

Major structural details, (node arch-tie-cross beams, anchorage structures in arches and ties, central fixed supports on Pier 3) were modelled using finite elements models.

Rail traffic loads: LM71, SW/2. Road traffic loads: LM1, LM4.

Fatigue loads: LM71/One track and LM3.

Rail traffic loads for dynamic analysis: Train Type 2 and Type 5.

Wind: Data from Republic Hydrometeorogical Service of Serbia, basic wind speed $v_{b,0}$ = 21 m/s.

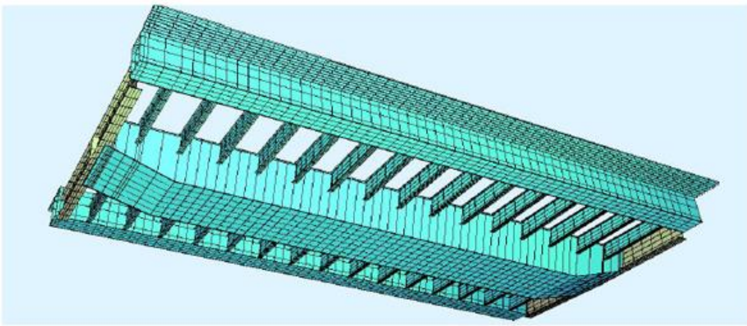

Fig. 10: Structural model of the approach bridge 4-5

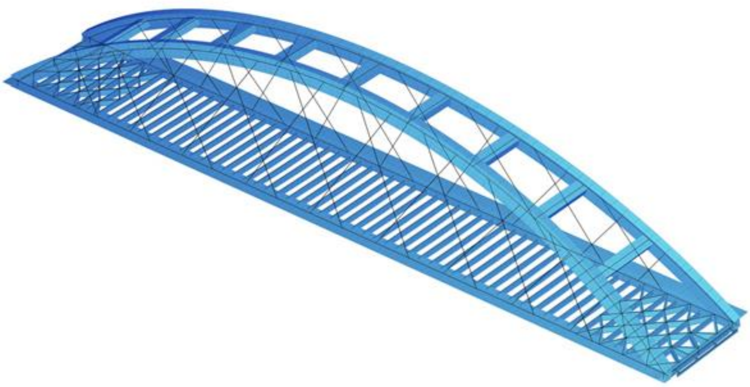

Fig. 11: Structural model of the arch bridge 3-4

Thermal actions: On basis of $T_{Air,min}$ = -24°C, $T_{Air,max}$ = +37°C.

Seismic actions: Data about seven appropriate earthquakes were obtained from the report made by Seismological Survey of Serbia.

Combinations of actions: ULS acc. to EN 1991-2:2003 and DIN-Fb 101:2009, with dominant variable action as railway or road traffic load, temperature, or wind action.

General design method: Elastic-elastic method, for steel and composite structural components.

Static analysis:

- For each relevant ULS and SLS-combination;

- Dynamic factor Φ for each specific structural component;

- Camber calculation: combination: $G + 0{,}25Q$, Q = LM71/one track + LM1;

- Seismic analysis: combination: G + 0,20LM1 + 0,30LM71/one track, with foundations modelled with spring elements with elastic properties in three orthogonal directions. Analysis was made as multi-modal response spectrum analysis and time history analysis;

- Local stability – buckling: according to reduced stress method;

- Global stability of arches: according to General method and Second Order Theory.

Dynamic analysis:

- Forces, deformations, dynamic factors;

- Modal analysis: Mode shapes and frequencies;

- Vertical accelerations of the structure.

SLS and traffic safety calculations, according to DIN-Fachbericht 101:2009:

- Movements of the end of the deck beyond bearings;

- Extreme angular rotations at bearings;

- Twist of the deck;

- Horizontal transverse deflection;
- Horizontal rotation of a deck about vertical axis;
- Cracks of the concrete carriageway slab;
- Passenger comfort: Vertical accelerations and deflections of deck.

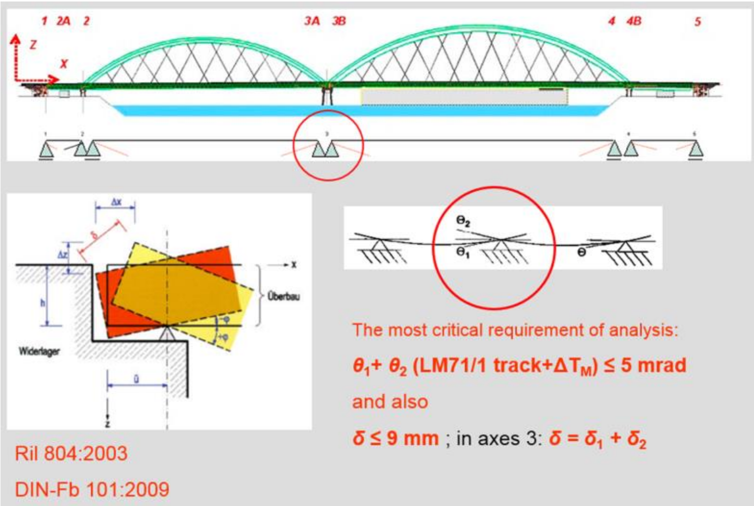

Fig. 12: Angular rotations at bearings

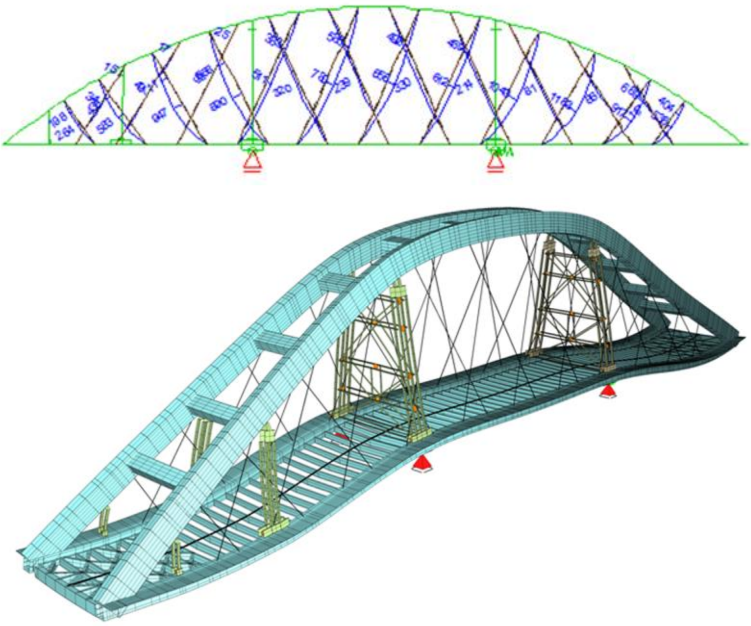

Fig. 13: Bridge 3-4 during launching in phase 4

Aerodynamic stability, according to Design Manual for Roads and Bridges BD 49/01: *Design Rules for Aerodynamic Effects on Bridges*:

- Deck: Vortex excitation, turbulence, classical flutter;

- Hangers (cable stays): Vortex shedding, galloping, flutter, rain and wind induced vibrations.

Some results from structural analysis:

- Frequencies of 1st mode of vertical vibrations of four bridge structures are respectively: $n_{1,V}$ = 4,44 Hz; 1,16 Hz; 0,96 Hz; 2,39 Hz < $n_{0,min}$ which means dynamic analysis is required;

- Dynamic analysis of four bridges: $N,V,M(\Phi\text{LM71}) > N,V,M[(1+\varphi'+\varphi'')\text{RT}]$, RT = Train Type 2, Train Type 5 (as proper for analysis);

- Vertical accelerations of the decks of four bridges (*Fig. 3*), Train Type 5, respectively: $a_v \le$ 1,0; 1,3; 0,8; 1,0 m/s^2 , which mean that good or very good user comfort is achieved;

- Vertical deflections of the deck under LM71/one track are respectively: $\delta_Z \le$ 5 mm = *L*/5060; 53 mm = *L*/3345; 65 mm = *L*/3388; 11 mm = *L*/4118 << L/800;

- Movements of the end of the deck beyond bearings (*Fig. 12*), as the sum of rotations: axis *2*: δ = 3 mm, axis *3*: δ = 4 mm, axis *4*: δ = 4 mm < 9 mm;

- Extreme angular rotations (*Fig. 12*) at bearings, required $\theta_1 + \theta_2$ (LM71/1 track+ΔT_M) ≤ 5 mrad: axis *2*: $\theta_1 + \theta_2$ = 2,3 mrad, axis *3*: $\theta_1 + \theta_2$ = 3,7 mrad, axis *4*: $\theta_1 + \theta_2$ = 3,1 mrad;

- Fatigue utilization factors of arches, ties, hangers are respectively, (fatigue loads: (LM71/one track) + (2xLM3)): $[(\gamma_{Ff}\,\Delta\sigma_{E,2})_{Railway} + (\gamma_{Ff}\,\Delta\sigma_{E,2})_{Road}\,] / (\Delta\sigma_C/\gamma_{Mf}) \le$ 0,36; 0,39; 0,68 < 1.

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 (*Fig. 9*). The hanger cable stays forces vary from tension to “compression” from step to step, *Fig. 13*. 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.

4. Conclusion

The Railway Road Bridge in Novi Sad *Fig. 14* should be finished in 2015.

The arch bridge structures are undoubtedly remarkable engineering achievement when comparing to other similar world bridges, such as Wanzhou Bridge (trussed tie arches, 360 m, two tracks), Caiyuanba Bridge (tied arches with tie as girder, 420 m, two tracks+6 lanes) in China and Fehmarnsund Bridge in Germany (tied arches, 248 m, one track + two lanes).

5. Participants

Structure: Railway Road Bridge across the Danube in Novi Sad.
Investor: Public Enterprise Serbian Railways, Belgrade.
Financing: Delegation of the European Commission to the Republic Serbia
Autonomy Province of Vojvodina
Municipality of Novi Sad
Contractor: JV AZVI S.A., Taddei S.p.A., Horta Coslada S.L
www.azvi.es, www.gruppoedimo.it/taddei

Fig. 14: Aerial view of the site. Arch 177 m, Jan. 2014

Subcontractors for designing:
Bridge structure: DEL ING DOO, Belgrade, www.deling.rs
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: Mammoet, Rotterdam, Netherland.
Bearings and expansion joints: FIP Industriale, Servazzano, Italy.
Technical control of the Detailed Design: “Kirilo Savic” Institute AD, Belgrade, Serbia.
Engineer: JV DB International and Egis International, www.db-international.de, www.egis-group.com

6. References

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[3] Ril 804:2003, DB RICHTLINIE. Eisenbahnbruecken (und sonstige Ingenieurbauwerke). Planen, Bauen und Instand halten

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