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New Troja Bridge in Prague – Concept and Structural Analysis of Steel Parts

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Abstract

The aim of this paper is to describe the concept and structural analysis of the steel parts of "New Troja Bridge" in Prague. The bridge with the main span length of 200,4m crosses Vltava River will serve for tramway, car and pedestrian traffic. The bridge is a simply supported bowstring-arch bridge with two twins of inclined network type webs. The paper presents philosophy of analysis, construction process of steel parts, influence of the phases of the construction, stability assessment of the arch and basic results of dynamic analysis.

Keywords: bridge; bowstring-arch; prestressing; FEM analysis; construction stages

1. Introduction

As a part of the concept of internal urban circuit in Prague the new bridge over Vltava River was required near the outlet of "Blanka" tunnels in Troja. The winning structural and architectural solution was designed by author team: Mott MacDonald CZ (Jiří Petrák, Ladislav Šašek) and Roman Koucký, architektonická kancelář (Roman Koucký, Libor Kábrt). The bridge is a part of the Prague urban area thus its architectural face is very important comparing to highway bridges out of the city perimeter. In the phase of detail design documentation, Excon project team started to cooperate on the project as a subcontractor of Mott MacDonald for the design of structural steel parts of the bridge. The concrete parts were completely designed by Mott MacDonald. Later the workshop drawings of bridge structural steel parts and part of temporary steel structures have been also carried out. During the designing process, professionals of Metrostav as a main contractor of the construction cooperate and commented the nascent documentation and contributed thus to design which fits better to supplier's technological possibilities and improved in some aspects future bridge.

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New Troja Bridge consists of two adjacent spans – the main span 200,4m which over cross the river and the minor span (40,35m), spanning the floodplain of Vltava on the Troja side. The minor span is simply supported beam bridge entire made of prestressed concrete. However, in the paper we focus only on the main span – simply supported bowstring-arch.

Fig. 1. Architectural visualization of New Troja Bridge in Prague

2. Structural solution

It is a bowstring-arch type bridge, straight in plan. Span is 200,4m, rise approx. 20m. Arch has steel box section with multiple webs. Near the mid span, the cross section is wide and flat. Towards the arch ends it becomes higher and wider however in the part called “trousers” the cross section divides into two “legs” to allow the tramway go through. The grade used for longitudinal steel sheets is S420ML, diaphragms are of S355ML. More detailed description of steel parts is in [1].

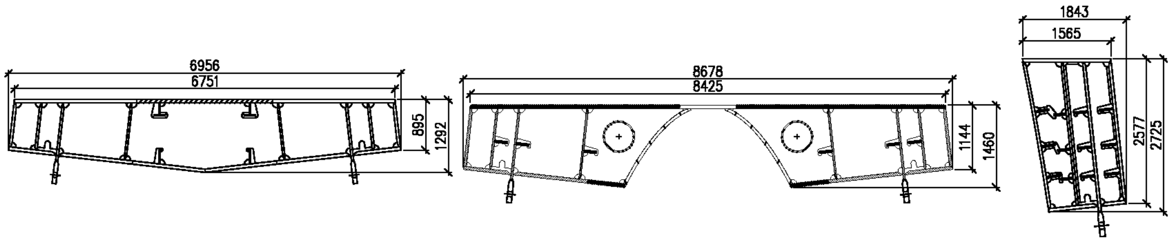


Fig. 2. Cross sections of arch (a) near the mid-span; (b) in the “trousers” part; (c) one “leg” near the arch end

Two inclined plans of tension bar networks connect the arch with two steel-concrete composite main chords. However, the function of the arch tie is taken by all prestressing cables in the deck and in the composite. Steel parts of the composite chord are thus in compression and bending because they are compressed with adjacent concrete and they also serves as a support for transversal concrete beams (via steel connecting parts cast partially into the transversal beams).

The approx. 30m wide deck of the bridge is a concrete slab 280mm thick, prestressed in both longitudinal and transversal direction. This slab is supported by transversal precast concrete 500mm wide beams with variable height. Spacing of transversal beams is 4000mm and they are connected to the above-mentioned chord. Above the bearings, the transversal beams are substituted for monolithic one. Concrete used is C50/60 (slab) and C70/85(transversal beams).

End of the arch is the steel shell with shear studs filled with self-compacting concrete (C80/95). Shear linkage between the monolithic transversal beam and the end arch part is provided.

Bridge is supported by four spherical bearings with fix point in Troja

3. Global analysis

3.1. Models

Static analysis was carried out on common models for steel and concrete parts. Steel parts were analysed in two FEM models - one with beam type elements and second with shell type elements. Phases of the construction corresponding to the construction process preferred by main contractor of the bridge including prestressing procedures have been taken into account as they affect strongly stress distribution and deformation of structure. The Scia Engineer 2009 software was used for the bridge analysis. Some crucial nodes were modelled separately, more in details, using either Scia or Nastran software.

3.2. Arch global and local stability, shear lag

For the beam FEM model as a first approach, the global stability of the arch was taken into account by means of buckling factor. It was determined from linear stability calculation of the beam model and its value was 0,8 for in-plane flexural buckling. To check the stability by GNIA method, the beam model was used with the equivalent geometric imperfection with amplitude of 200mm, which is conservative value according to standards. Its shape is affine to first linear buckling mode, which is combination of first asymmetric in-plane buckling mode of simple supported arch and slight torsional deformation. GNIA proved that such an imperfection affected significantly neither arch internal forces nor the arch deformation. The value of buckling factor in plane of the arch equal 0,8 seemed to be hyper conservative.

Complete arch profile is under compression for all load combinations after its completion and removing temporary supporting towers. Therefore, the local stability of all plated parts had to be taken into account. Wide parts prone to buckling were stiffened in such a way that the effective area of stiffened part stay the same or slightly greater than the geometric area of unstiffened part. It was hence possible to check the unstiffened cross sections using their geometric characteristics and not the effective ones.

The phenomenon of shear lag is related to changing flexural moment where shear is transmitted between webs and wide flanges in which the normal stress distribution is not uniform. In the case of our arch the moments corresponding to vertical bending are minor (less than 10%) compared to axial force in the top part of the arch where central part of the flange is relatively wide. Towards the supports bending moment influence rises (up to approximately 30%) however cross section becomes rather high and narrow so the flange part between the webs is not slender enough to allow the shear lag influence the normal stress. However, the effect of shear lag was studied on shell FEM model and it proved that shear lag could be neglected.

3.3. Tension bars

First, the tension forces after whole building process were evaluated to get the initial state caused by permanent loads on the bridge taking into account the building phases which affect the force distribution in tension bars along the length of the bridge. Then the maximum and minimum forces caused by traffic were found. It was rather hard work because the extreme effect for each tendon occurs with different position and/or combination of traffic load models (loads in the lanes, walkways, tramways). Finally, the effects of temperature and wind were calculated. It has to be noticed that surprisingly the forces due to extreme traffic loads are 40 to 50% of total maximum forces in tendons. In addition, the minimum forces in tendons were analysed. Because we found several tendons with minimum forces less than approx. 100kN we have checked these combinations by geometrically nonlinear analysis and proved that the forces are redistributed to the surrounding tendons but neither these tendons nor arch are overloaded by this redistribution.

3.4. Dynamics

As an input for all further calculation, the modal analysis was carried out. The first natural frequency is 0,84Hz and corresponding shape corresponds to torsional deformation. Very near is the second natural frequency 0,88Hz with the 1st in plane bending shape. These two modal shapes are in the Fig 3. Torsional modes appear plentifully in modal analysis so it can be deduced that the structure will most probably vibrate in some combined flexural-torsional shape.

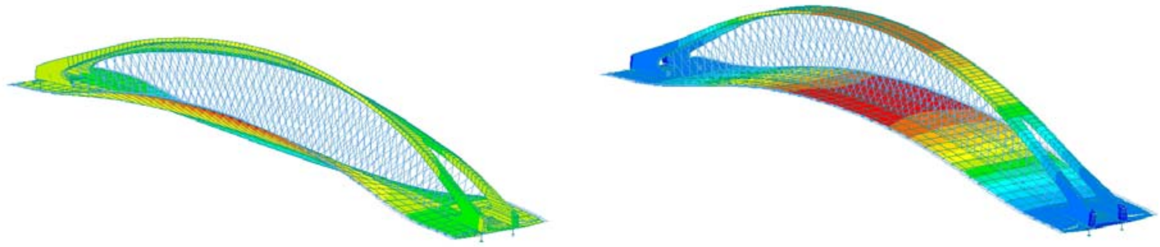


Fig. 3. (a) First modal shape (f_1=0,84Hz); (b) Second modal shape (f_2=0,88Hz)

There were three separate analyses made by subcontractors. The first one focused on vibration and acceleration caused by traffic. The crossing of lorry in different speed was modelled in dynamic model with random roughness of surface. The admissible acceleration values from pedestrians' comfort point of view were not exceeded for the speeds up to 50km/h and the values were less than 0,3ms^{-2}. Then the crossing of lorry over the obstacle defined by code was analysed and in this case, the above-mentioned limits were exceeded however, this situation can be qualified as maintenance state and investor accept overstepping of this pedestrian comfort criteria. Second analysis focused on aero elastic stability of whole bridge. According to preliminary assumption, there is no problem with aero elastic instability with this span. The third analysis deals with the question whether the tendons are sensitive to vibrate due to the vortex shedding or not. This problem depends on stiffness of tendons, axial force, boundary conditions, logarithmic decrement and there are at least two of the inputs, which are uncertain. The analysis excluded the tendons for which the critical wind speed is either too low that wind flow has not enough energy to induce vibration or too high that there is low probability to retain steady flow at this speed for significant duration. The rest of the tendons are sensitive to vibrate but additional stresses due to this vibration are not clear so it was decided to realize in-situ measurement after completion of the bridge. If the measurement will show significant growth of the stresses due to the vibration necessary construction changes in order to increase the damping or changing the modal properties will be provided.

3.5. Deflection

In the analysis, we supposed that all deflection due to permanent loads are compensated by precamber of deck (approx. 250mm) and arch (400mm). Once the arch is complete and the tendons are installed the maximal precamber of deck and arch in the mid-span are of similar value of 240mm. When the bridge is finished, it should reach the theoretical designed shape. Precamber for a part of live load was not applied because of reology of the prestressed deck. The deck will deform upwards and we did not like to increase the slope for tramway which tends to upper limit values on Holešovice side.

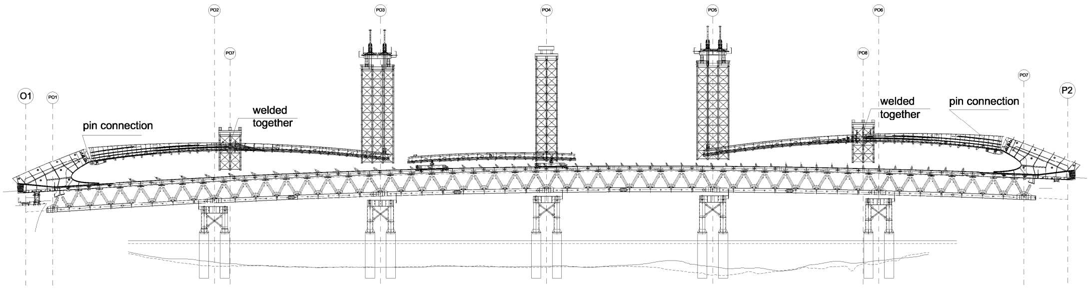
The maximum vertical in-plane deflection of the arch caused by traffic is 90mm, for temperature loads it is +/-80mm, snow has almost no influence, for wind load it is less than 20mm. Horizontal deflection due to wind and temperature are of similar magnitude – 20mm.

4. Construction process

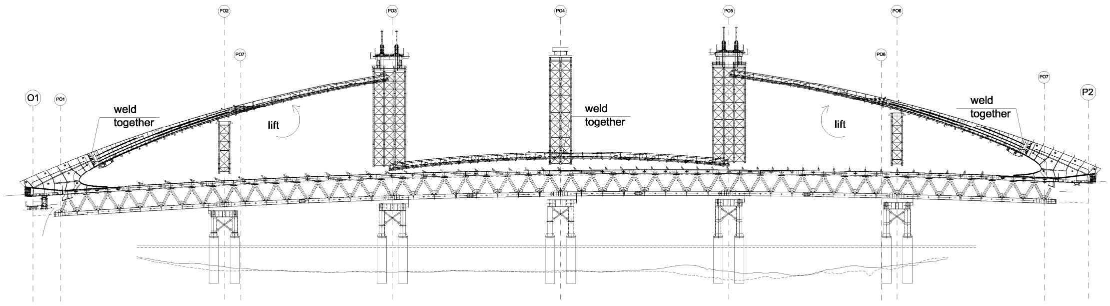
- Temporary steel truss girder whose top chord is the steel part of the future arch chord is incrementally launched from Holešovice to Troja over seven temporary supports fixed to the riverbed. The precast transversal beams of the future deck are mounted on the girder and they are launched with.

- The arch-ends are mounted on the temporary structure, which will stay cast-in. Steel arch end shells are filled with self-compacting concrete and concrete deck is casted.

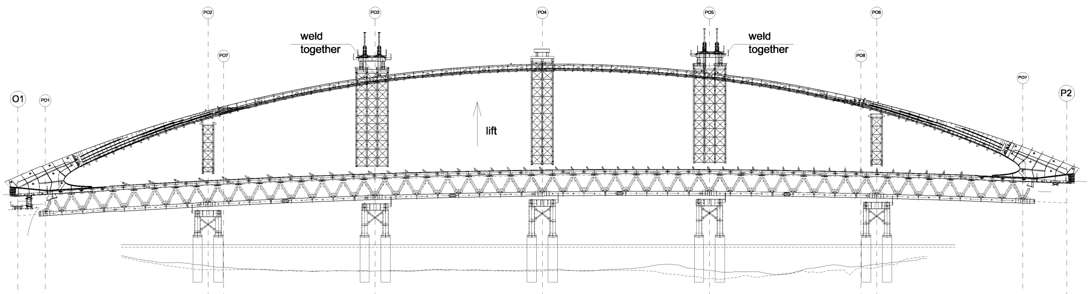
- First 1/3 of longitudinal prestressing in the deck is applied. There are five temporary towers prepared on the chord. Using the undercarriage, parts of the arch are launched on the temporary track from the banks to the deck. The outermost ends of preassembled parts are lifted to the special pin connection.



- Outermost thirds of the arch are lifted to the position. Central third of the arch is launched from both banks and welded together. Two towers are transformed to the new shape to support the lifted part.



- The central arch part is lifted and arch is closed. The temporary towers are deactivated. The tension bars (hangers) are mounted.



- Bottom chord of temporary truss is cut in four positions. Second 1/3 of longitudinal prestressing of deck is applied.
- Temporary supports in the river are deactivated. Temporary truss is step-by-step removed. Last 1/3 of longitudinal prestressing is applied.
- Steel walkway cantilevers are mounted; all other permanent loads are applied.

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