

TROJA BRIDGE IN PRAGUE

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SUMMARY

The daring decision by the city authorities in Prague to commission a 200-m-span network arch bridge to cross the Vltava River has resulted in a slender and graceful steel-composite transportation structure. The elegance of the bridge mainly results from both the ratio of the rise to the span of the arch, accounting for its slenderness of 1:10, and the ratio of the overall height of the arch to its span, which is 1/180. The dense network of hangers make it possible to achieve these ratios by improving the strength and rigidity of the structure.

Keywords: *Steel and concrete structure, prestressed, network arch, design, bridges.*

1. INTRODUCTION

The new Troja Bridge in Prague is built as a part of the city ring road. In March 2006, the Prague City Hall announced the public architectural design competition for the conceptual design of the new combined city bridge over the Vltava River in Troja district. 20 competing designs participated in the competition. The first prize was awarded to the design of the authors' team consisting of Ladislav Šašek, Jiří Petrák from Mott MacDonald CZ, s.r.o., and Roman Koucký and Libor Kábrt from Roman Koucký architektonická kancelář s.r.o. The Troja Bridge is the largest bowstring network arch-type bridge with a concrete deck in the world and is one of the most important bridges in the Czech Republic.



Fig. 1. *View of the bridge.*

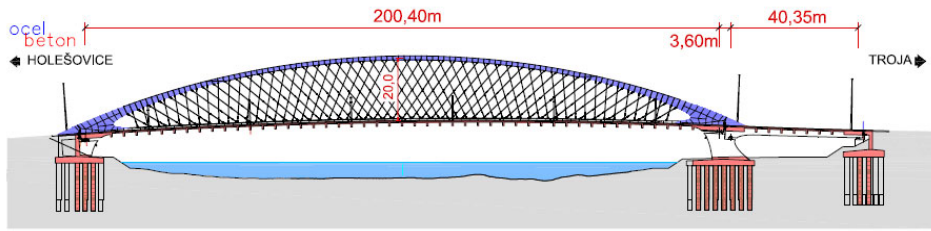


Fig. 2. Longitudinal section.

The bridging is formed by a pair of separate structures which are separated with an expansion joint over a pillar situated on the Troja bank. The main span over the Vltava River is designed as a simple supported steel bowstring network arch with a concrete deck with a span of 200.4 m. The connected inundation span on the Troja side is designed as a simple supported double-beam construction with a span of 40.35 m of a monolithic prestressed concrete. The bridge structure is founded on deep-drilled piles with a diameter of 1.5 m and the load-bearing structures are supported on reinforced concrete substructure with calotte bearings. The bridge with a total width of 34.38 m (between railings) is structurally divided in individual lanes for different modes of transport. In the centre, a double-track tram line is situated on a separate body and two double-lane roads and pavements for pedestrians and cyclists are situated symmetrically on the bridge sides.

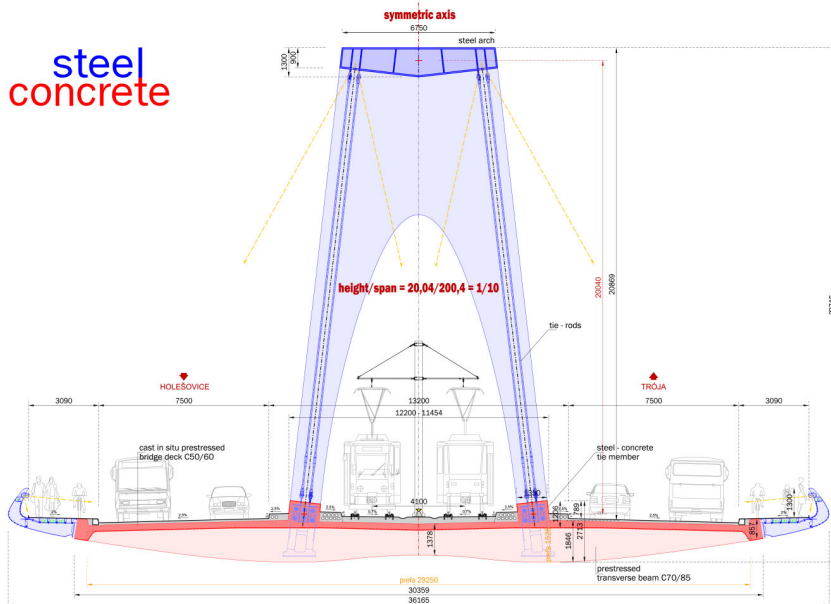


Fig. 3. Cross-section.

2. BRIDGE DESIGN ASSUMPTIONS

A symmetrical arch structure traditional for Prague bridges in various forms was selected based on a static analysis. An effort to reach minimum structure height over the level line of the bridge was decisive. All this with the necessity to cross the bridge with a single span in mind. Land on both banks is axially asymmetric and is determined in detail through many complex relations. Location of the bridge could not be changed as it was impossible to adjust the complex height arrangement. The unprecedented demands on the width of the bridge also encouraged the solution. The complex assignment called for a special static-structural, and also architectural and geometric solution of the construction. The architecture of the Troja Bridge is determined through ideal conditions and mutual proportions of all factors: statics, structure stiffness, geometry, details, materials and colours. The shapes of the arch and deck slab were naturally predetermined and arise mainly from their static functions but they also correspond with the bridge architecture. The linked bow-sting arrangement of suspensions (web-like net) of the arch bridge allows uniform load distribution and thus reduces local stresses of the arch and deck slab. The arch and deck are subject to a minimum longitudinal bending stress. It was possible to design a very subtle structure while reducing the rise of arch due to the selected static system of the network arch. The ratio of the rise and arch span 1/10 and the ratio of the construction height of the arch and its span 1/183 are the basic parameters determining the elegance of a flat arch bridge. The arch shape was also determined with requirements regarding its stability. Arch structures tend to lateral buckling.

In the arch plane, the buckling is prevented through stiff webs formed by the hangers and out of the arch plane, the buckling is prevented through the shape of the flat box cross-section that is stiff in a horizontal direction. The hangers act as a thin but stiff web acting in tension. Thus, the construction of the bridge acts simultaneously as tied-arch and as a plate girder. The steel arch forms its upper flange and the prestressed concrete deck the lower flange.

3. CONSTRUCTION OF THE MAIN BRIDGE SPAN

3.1. Prestressed Deck

The deck slab consists of prefabricated cross-beams, a monolithic slab and a steel-concrete composite arch tie members. The slab thickness varies from 0.280 to 0.314 m. The slab is prestressed crosswise and lengthwise. The central tram lane is lined with steel-concrete composite tie members (with internal prestress) who separate the road area and the tram body. The arch tensile forces in the deck are eliminated with longitudinal prestress and the slab is thus only subjected to compression. Use of the prefabricated cross-beams allowed for a significant acceleration of the construction progress and reduction of temporary supports while meeting the demanding requirements on accuracy and quality. The bridge slab is made of C50/60 XF2 concrete and the tie members are made of C50/60 XF4 concrete. As illustrated in crosswise arrangement.

The cross-beams are suspended on the steel part of the arch tie members through bolted joints and are made of post-stressed concrete C70/85 XF2 (SUSPA prestressing system).

The steel part of the arch tie members has three main horizontal sheets and two vertical sheets which together form a member with working name Omega. The steel suspensions elements of cross-beams are bolted to cross-braces as well as diagonals of the temporary

truss structure. Gusset plates are welded to vertical sheets on the upper surface for hangers. Omega is made of S420 NL and S 420 NL + Z25 sheets of thickness from 25 to 90 mm.



Fig. 4. Longitudinal prestress of the bridge slab.



Fig. 5. Arch tie members.

End cross-beams of the deck are coupled with steel arch feet which are filled with high-strength self-compacting concrete of C80/95 strength class.

The longitudinal prestress of the bridge slab and arch tie members is a coherent prestress made of cables consisting of 7 to 37 strands and of cables consisting of 4 to 19 strands (crosswise prestress) performed with the highest degree of protection against circulating current PL3. The electrically insulated cables are placed in plastic ducts and are

monitored (enable measurement of the resistance at any time during the lifetime of the structure). This ensures maximum durability of this basic load-bearing system.

3.2. Steel Arch

The slender steel arch with arise of 20 m is unique in its size and design solution. In the central part, the arch has a flat box pentagonal cross-section with a height from 0.9 to 1.3 m. In the quarters of the span, it splits towards the edges in two closed quadrangular box cross-sections to meet the spatial arrangement of the clearance profile of the tram body. The shape of the steel arch was also governed by static requirements of the same stiffness and cross-sectional area along its entire length while maintaining a constant steel sheet thickness. The width of the hollow cross-section on the top of the arch is 6.9m, the cross-section expands in width and height to be divided in two independent parts which are anchored in feet in a concrete end cross-beam. The arch cross-section is reinforced with a series of internal walls. The four internal longitudinal walls optimally transfer the load from hangers to the entire cross-section, the other walls provide the construction stiffness. The thickness of the upper and lower sheet is 60 mm, the thickness of longitudinal side walls is 50 mm. The internal longitudinal walls are only 40 mm thick, the crosswise diaphragms are 25 mm thick. The foot parts are filled with concrete interacting with the steel parts which are secured by the spikes and braces. The width of sheets for the anchoring of the prestress cables is 80 mm. In the arch, longitudinal sheets are made of SL420 ML material while the other parts and foot parts are made of basic S355 NL material.

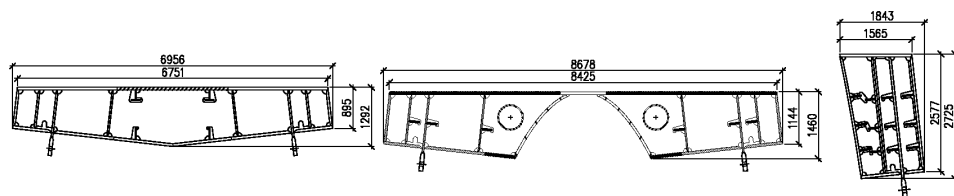


Fig. 7. Cross-sections in the centre, in 1/4, and on the edge of the arch.

All joints of the airtight construction are designed to allow non-destructive inspection of load-bearing welds from the outer surface of the cross-section. The arch was produced in Horní Počernice (Metrostav) and in Slané (MCE) in parts weighing 43 to 83 t, approximately in the same scope.

Hangers on both sides of the bridge always form two planes, a total of 200 pieces of hanger rods were used and produced by Macalloy with rolled threads M76, M85, M100, and M105 of material with yield strength of 520 MPa. The special turnbuckles with high resistance to fatigue verified with fatigue testing were developed for this project.

4. CONSTRUCTION PROGRESS

The construction progress started with a stage assembly of the temporary truss structure for incremental launching, the upper part of which was made of steel part of the arch tie member. Suspensions of the prefabricated concrete cross-beams were bolted to cross-

braces of the truss structure. In this way, a grid structure was developed which was launched over the river in sections of 16 m. The whole structure with a length of 200 m was launched in approximately 2.5 months in the spring of 2011. Furthermore, end cross-beams were concreted. Before concrete work, the arch feet had to be fitted which are coupled with the end cross-beam.



Fig. 8. Incremental launching of the temporary truss structure with cross-beams.



Fig. 9. Incremental launching of the temporary truss structure with cross-beams.

After concreting of the end cross-beams the construction continued with filling of arch feet with high-strength self-compacting concrete followed by stage concreting of the bridge slab, again in sections of 16 m. The crosswise prestress was activated immediately after the concreting of individual parts of the slab. Upon completion of the slab concrete work, the coupled steel-concrete composite tie members of the arch was concreted in sections. The longitudinal prestress of the bridge slab and arch tie members was activated in 3 steps. The first third of the longitudinal prestress was introduced in the structure upon completion of concrete work on the main bridge span. The prestressed deck slab was used as a platform for assembly of the steel arch.

During the pre-assembly of the steel arch structure, towers were built on the deck of PIŽMO system which was used for its assembly. Concurrently, in the centre of the deck in the place of the future tram line a track was built that was used to transport progressively the individual parts of the steel arch which were welded into larger units.



Fig. 10. Assembly of the outer edge parts.

The hydraulic trucks were used to transport the steel parts. The individual parts of the steel arch structure were welded into units in length of approximately 1/3 of the arch. The assembly started with one third of the arch on the Troja side with its lifting at the arch foot and connecting to the pivot on the supportive structure at the foot. Then the part was lifted at the free end to the required height and subsequently welded to the arch foot. After that, it was possible to dismantle the spatial supportive structure with the pivot. Similarly another third of the arch was lifted on the Holešovice bridge side. The central part of the bridge arch was lifted as the last one. All lifting operations were performed using bar suspensions and hollow hydraulic cylinders. The weight of the outer arch parts is approximately 720 t while the central part weighs approximately 680 t.



Fig. 11. Assembly of the central part of the arch.

Upon complete welding, the arch became self-supporting and it was lowered from the PIZMO temporary towers while the arch deformations, temporary supports in the river and the stresses in the load-bearing structure of the bridge were monitored. After dismantling of the temporary supports, the assembly and prestress of the final bridge hangers could start. The hangers prestress was optimised so that under no load condition the tensile forces disappear from the hangers and to prevent the arch from introduction of opposing forces and deformation to the forces and deformation resulting from the steel arch lowering from the temporary supports, lowering the entire construction and removal of the temporary truss structure. Forces in tie members were measured with strain gauges in the full bridge configuration providing a continuous online access to data with the Internet.

Optimised process was prepared for assembly and prestress of hangers using linear programming. After installation of all hangers the dismantling of the temporary truss structure started through interruption of the lower string in the four pre-defined locations. Subsequently, the second third of the longitudinal prestress was performed and the entire main section of the bridge was lowered from sliding bearings on temporary supports – it remained supported only on the final bearings. The bridge slab dropped approximately 150 mm as expected in static calculations and all hangers were activated through the dead weight of the deck. After lowering the load-bearing structure, a complete dismantling started of the temporary truss structure and other structures in the river. Subsequently, the second stage of the hangers prestress was performed during which extreme deviations of the project forces were removed and the projected redistribution of the inner structure forces was introduced.

4.1. Loading Test

The evaluation of the static loading test proved that the flexible and permanent deflections are within the limits of the standard provisions. Deformation shapes during the test loading showed no abnormalities. In asymmetric loading stages, a slightly higher torsional rigidity of the structure and brackets was evident which is a positive phenomenon. Dynamic load test confirmed the calculated values of the structural shapes and frequencies. Deviations from the calculated values were within the recommended standard values. It can be concluded that measurements confirmed the correctly selected calculation model with regard to normal variations resulting from the different side conditions and material properties in theoretical and actual conditions. The test also confirmed that the measured accelerations of the bridge vibrations caused by the cars crossings do not exceed values which the pedestrians would experience as uncomfortable in a long-term perspective. Static and dynamic tests proved the expected technical properties of the bridge and low sensitivity to dynamic excitation of transport.

4.2. Accessories

The Troja Bridge represents a unique structure including a number of advanced solutions of its equipment. Operationally proven expansion joints of Freyssinet were used for the first time in the Czech Republic. Drainage of the road and pavements in the entire length of the bridge and on supports is secured with kerb drainers Envirodeck by Pipeline & Drainage System. Ltd. Double-track tram line in the central part of the deck passes the bridge on a floating monolithic reinforced concrete slab. The slab is separated from the load-bearing construction with an elastomeric anti-vibration mat with thickness of 23 mm. Traction poles and safety steel angles are anchored to the slab. Continuous welded

rails are designed for the bridge. Rail expansion devices are placed on the supports behind the load-bearing structure.

4.3. Corrosion Protection

Various coating systems are used to protect steel structure with regard to corrosion load according to TP 84. Generally, a coating system can be characterised as a set of first coat with a high content of zinc, two prime coats and finish coat in the shade of white colour. Corrosion protection is enhanced by additional layers or hot-dip galvanising in exposed areas.

4.4. Bridge Monitoring

The original structural design utilising the material options and a complex construction process requires the operations to be controllable, the possibility to verify the bridge behaviour and if the structure is built according to the design assumptions. Therefore, the structure was monitored during the entire construction. It consisted of geodetic monitoring and tension measurements on the bridge structure using the integrated strain gauges. The geodetic monitoring was used during sliding and a very precise inspection of the position and shape of all the bridge parts during assembly. Tension was measured on the supportive truss structure, in the concrete deck, in the arc and forces on all the suspensions under the monitoring programme during construction. A long-term bridge monitoring programme after its completion assumes measurements in the deck, arch and selected bridge hangers and allows to predict their lifetime.

5. BRIDGE ARCHITECTURE

Gradual shaping of the entire substructure corresponds to the basic shape of the bridge arch. All shapes of all parts are inseparably linked together. Shapes of the left bank support and central pillar (visually right bank support) are only similar, not identical – the “cut-out” heights from the terrain level are the same as well as the basic shape. The entire bridge looks like a unified, almost symmetrical whole due to the same concept and shape of the longitudinal cross-section (cross-beams and slab shapes) and other identical details of railing and other bridge equipment. All minor construction elements as well as the bridge equipment (cross-beams under the deck, pavements and railing brackets, trolley and lightning poles) are always perpendicular to the level line of the deck, not vertical – they form an integral part of the arch and do not draw attention to its tilt. Great attention was paid to bridgeheads and especially to the bridge lower views which is crucial for perception of the whole from both (future) riverfronts – respect of all shapes allowing to see the “invisible” construction parts from below. All the bridge shapes correspond to not only the bridge in the final stage but also to the production and assembly. All curved surfaces are linear.

5.1. Materials and Colours

Materials, finish and colours form an integral part of the entire architectural effect of the bridge. The cold white arch steel structure including steel bars of the hangers. The steel consoles bearing the pavements have the same colour. Substructure (supports, a pillar but also all the staircases) consisting of the steel arch structure is made of reinforced

concrete as well as the “ribbed” deck slab suspended on the arch. All concrete is light, architectural with visible formwork which is just as the division of prefabricated parts designed in a geometric order of the bridge and its modular system. The prefabricated and monolithic parts of the structure have different and contrasting finish – prefabricated is completely smooth and monolithic is rough. All other parts of load-bearing and non-bearing structures show their material in essence. Railing panels are made of aluminium expanded metal; drainers are made of grey plastic. Lightning and trolley poles follow in their grey colours the concept outside the bridge structure. Black roads and tram line rails are in a similar contrast to the entire structure. As if they were only “passing” the bridge. The overall variety of individual road area colours and individual structure part colours is enhanced with different bridge lightning colours which distinguish mainly the deck plane with white colour underside and the area on the bridge with the arch in yellow colour.



Fig. 12. Basic colour design.

5.2. Lighting

And last but not least, it was important to follow the light. Especially the light under the unusually wide deck. Sun and artificial bridge lightning create an endless number of impressions and moods. The artificial bridge lightning is a distinctive aesthetic element. The artificial bridge lightning is divided into several lightning systems:

- Road lightning embedded in the steel arch – spacing of lights of 3.6 m,
- Lightning of the railing sills lights the road and pavement – spacing of 8 m,
- Lightning embedded in the railing lights the railing steel structure – spacing of 1 m,

- Lower lighting of the construction consists of four narrow-beam headlamps placed under the deck, in pairs on pillars light the underside of the bridge.



Fig. 13. Artificial bridge lighting.

6. CONCLUSION

Metrostav, a.s. the general contractor of the bridge mastered the complex assembly and technologically demanding combination of prestress concrete and steel structure technologies in high quality. The Troja Bridge is an exceptional structure in its architectural design and technical parameters. The implementation team dedicated maximum effort in ensuring that the emerging structure was designed and built safely and also met the requirements of a modern engineering design. Therefore, particular attention was paid to durability and long-term lifespan of the structure. Innovative but proven technologies and materials were used. In addition to the load-bearing structure, great emphasis was laid on functionality, quality and visual aspects of the other bridge parts as well.

The Troja Bridge is very important and courageous bridge construction utilising yet unusual interconnections of structural elements consisting of a steel arch and a prestressed concrete deck slab connected with a net of hangers. The layout and shape of the bridge with a span of 200.4 m creates the world's unique design.

Troja Bridge Awards:

- 1) Czech Chamber of Chartered Engineers and Technicians Engaged in Construction Award 2014;
- 2) Tekla BIM Awards 2014 – the winner of the “Steel Structures” category;

- 3) Hills Milenium Award 2015 – Institution of Engineering Designers GB – Ladislav Šašek;
- 4) AWARD OF EXCELLENCE – The European Steel Design Awards 2015 – European Convention for Constructional Steelwork (ECCS);
- 5) The Engineering Academy of the Czech Republic Award 2015 for “The project of the new bridge over the Vltava River in Prague”;

Construction Participants:

- Troja Bridge authors’ team: Jiří Petrák, Ladislav Šašek, Roman Koucký, Libor Kábrt
- Detailed Design: Mott MacDonald CZ, Ladislav Šašek Chief Engineer, Petr Nehasil, Jan Loško, Vojtěch Hruška, Aleš Lubas
- Architecture and 3D coordination: Roman Koucký architektonická kancelář, Roman Koucký, Libor Kábrt
- Steel structure Designer: Excon, Vladimír Janata, Dalibor Gregor
- Bridge Contractor: Metrostav a.s., Project Management: Alexandr Tvrz, Zdeněk Račan, Petr Koukolík
- Project preparation: Robert Brož, Vladimír Hájek, Pavel Guňka
- Construction Manager: IDS a.s., Josef Kalíšek, Luděk Fuchs, Jiří Plachý
- Incremental launching of the bridge and assembly parts handling: Metrostav a.s., Tomáš Wangler, Jiří Lukeš
- Steel manufacturer: Metrostav a.s., Jindřich Hátle, Ladislav Pokorný, Josef Olenič, Leoš Gurný
- MCE Slaný a.s., Jan Svoboda, Vladan Michalík