# SEARCH FOR THE TRUE STRUCTURAL SOLUTION

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## Abstract

The author is convinced that the true architectural solution of bridges is given by their true structural solution. The best structural solution should be some particular form inherent in the constraints of the site itself which best accomplish the function of bridging the site. The task of the structural designer is to discover and realize that form in a way that is economical and efficient. This structural form is appropriate only when the design uses the inherent structural and material characteristics of the form to advantage. Of course, a bridge structure must be safe, should invite to use, be comfortable for the user, and should be designed and constructed to human scale

Each conceptual design should advance or enhance our understanding of the arts and sciences of engineering. Structural solutions should in some way lead to the development of new details, new processes of construction, or new applications of engineering technology.

The above design philosophy will illustrated on the following structures built in Europe and in the USA which conceptual design was developed by the author:

Shell Wildlife Overpasses, Urban Bridge across the River Morava in a city of Olomouc, Urban Junctions in Cities of Ostrava and Banka Bystrica, Long Motorway Viaducts, Cable-Stayed Bridge across the River Odra, Multi-span Extradosed Viaduct built in Povazska Bystrica, Self Anchored Suspension Bridge built across the River Ebro, Multi-span Arch Bridges built in Redmond and Eugene, Oregon, Stress Ribbon and Self-anchored Suspension Pedestrian Bridges built in San Diego, Self-Anchored Stress Ribbon & Arch Pedestrian Bridges built in cities of Olomouc and Brno, Cable-Stayed Pedestrian Bridges built in Eugene, Oregon, Self-Anchored Arch Pedestrian Bridges built in cities of Casky Tesin and Ceske Budejovice.

New studies of arch and cable supported structures performed at the Brno University of Technology will be also presented.

# 真の構造ソリューションの探求

## 要　旨

著者は，橋梁における真の優美性は真の構造ソリューションから生まれると確信している。最も優れた構造ソリューションは，建設地点の地形などの条件から自然に生まれるもので，場所と場所を結ぶという機能を最も優れた手法で実現するものである。構造設計者の責務はその最適構造を経済的かつ効率的な手法で発見し，理解することである。この構造様式は，使用する構造や材料の特徴，優位性を活かして初めて適切なものとなる。もちろん，橋梁構造物は安全性，使用性，快適性が確保されなければならないし，設計・施工の合理性も追求すべきである。

コンセプトデザインは我々のアートや科学技術の理解を進歩させ，向上させるものである。構造ソリューションは，様々な手法で新しい構造詳細や施工方法の開発を促進し，新技術の適用を推進するものである。

上記の設計哲学は著者が設計した下記のヨーロッパ，アメリカにおけるコンセプトデザインに明確に現れている。

Shell野生動物横断路，Olomouc市のMorava川を横断する都市内橋梁，Ostrava市とBanka Bystrica市における都市内ジャンクション，長大自動車専用道の高架橋，Odra川を横断する斜張橋，Povazska Bystricaに建設された多径間連続エクストラドーズド橋，Ebro川を横断する自碇式吊橋，RedmondとOregon州Eugeneの間に建設された多径間連続アーチ橋，San Diegoに建設された吊床版と自碇式吊橋を組み合わせた歩道橋，Olomouc市とBruno市の間に建設された自碇式吊床版とアーチ構造を組み合わせた歩道橋，Oregon州Eugeneに建設された斜張橋形式の歩道橋，Casky TesinとCeske Budejovice間に建設された自碇式アーチ歩道橋

なお，Brno工科大学で研究されている新しいアーチと吊形式の構造についても紹介する予定である。

# SEARCH FOR THE TRUE STRUCTURAL SOLUTION

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## 1. INTRODUCTION

At present time the designing of bridges has becoming more and more difficult. On the one hand ambitious structures using non-effective structural systems designed by star architects are built; on the other hand common bridge engineers are forced to design so called the most economical solutions. And, if public ask for a better solution, the designers are required to add some kind of architectural treatment that would improve the solution. The public funding agencies like to know, how much they are paying for so call *beauty*.

That policy is ineffective and misguided, because it is based on a fundamental misunderstanding of the relationship between structural and architectural bridge design. Architecture is not some kind of treatment *added to*, or *performed on* the structural design of a bridge. Really, the architecture of the bridges has to be developed from the true structural solution and design has to emphasize the beauty of effective structures.

The author is still convinced that the true architectural solution of bridges is given by their true structural solution. The best structural solution should be some particular form inherent in the constraints of the site itself which best accomplish the function of bridging the site. The task of the structural designer is to discover and realize that form in a way that is economical and efficient. This structural form is appropriate only when the design uses the inherent structural and material characteristics of the form to advantage. Of course, a bridge structure must be safe, should invite use, be comfortable for the user, and should be designed and constructed to human scale

Criteria of aesthetics are perhaps somewhat more subjective when evaluating structural concepts for bridge designs. However, architects and engineers generally agree that the whole structure and structural members forming the bridge should express by their shape the flow of internal forces through the structural system, which is integrated into the surrounding social, historical/time, technological and physical environments.

From our point of view as structural designers, we believe that each conceptual design should advance or enhance our understanding of the arts and sciences of engineering. Structural solutions should in some way lead to the development of new details, new processes of construction, or new applications of engineering technology. But we have to be aware that the structures should be always designed and constructed to a human scale.

The above design philosophy is illustrated on the following structures for which the author had an opportunity to develop their conceptual design.

## 2. WILDLIFE OVERPASSES, CZECH REPUBLIC

For motorways' animal crossings, a new structure formed by two continuous shell arches that are supported by an intermediate support situated in the motorway median have been developed – see Fig. 1. The shell structure is continuously widened in the plan and smoothly link up the side embankments. To enable design these structures also in areas with poor geotechnical conditions, a self-anchored structural system that stresses the footings only by vertical forces has been developed. The arch horizontal force is resisted by prestressed ties (stress ribbons) that are situated above the shells.

Fig. 1 - Wildlife Overpasses

Eliminating the abutments and substituting the wings by a continuously widened shell enables the design of structures naturally connected with surroundings. So far two structures have been built.

## 3 - VIADUCT KNINICE, CZECH REPUBLIC

In several projects of the total length of 2 x 2.635 m = 5.270 km a prestressed concrete deck formed by a spine girder with large overhangs was applied. For span lengths up to 45 m a solid cross section is still economical. To transfer the mass to supports, the girder has a variable depth from 2.60 to 1.40 m and a haunch's shape is formed by a fourth degree parabola. The arrangement of the structure in the transverse direction follows the arrangement in the longitudinal direction. The deck is supported by narrow piers that are continuously widened and link up the curved overhangs. The transverse widening of the piers and the deck has also a shape of a fourth degree parabola. The simple and clean shape of the deck enables span-by-span construction utilizing under-slung movable scaffolding formed by two steel girders situated outside of the spine girder.

An excellent example represents Viaduct Kninice on the motorway D8 near the German border – see Fig. 2. The bridge is formed by two parallel bridges of the deck's length of 1,027 m and 1,077 m. The decks of both bridges are formed by continues structures with a typical span of 42 m.

Fig. 2 - Viaduct Kninice

Fig. 3 - Bridge across the Rybny Potok

## 4 – BRIDGE ACROSS THE RYBNY POTOK, CZECH REPUBLIC

If the motorway bridges the valley at a height higher than 40 m, it is more efficient to carry both motorway's carriageways by one superstructure that is supported by piers situated in the bridge axis. This solution was applied in a construction of the prestressed concrete bridge across the Rybny Creek on the freeway D8 – see Fig. 3. The 31.80 m wide bridge is formed by a continuous box girder of seven spans with span lengths from 34 to 58 m. The deck is formed by a relatively narrow 7.80 m wide and 4.20 m deep box girder with large overhangs that is supported by narrow piers of the shape of the letter H. The bridge was incrementally launched into the design position.

The structure has a simple and clean shape that has a minimum impact on the landscape. The large overhangs optically lightened the structure, while the open shape of the piers gives the structure lightness and creates a play of shadows. One bridge enabled the speeding up of the construction and brought the economy of the crossing.

## 5 – VIADUCT ACROSS THE HOSTOVSKY VALLEY CREEK, SLOVAKIA

The structural and aesthetic advantages of the one structure were also utilized in a design of the prestressed concrete viaduct that was built across the Hostovsky Valley Creek on Expressway R1 in Slovakia. The deck of a total length of 975 m and a width of 25.66 m is formed by a narrow box girder of width of 6.50 m that is additionally widened by overhangs cast in the formwork supported by precast slab struts – see Fig. 4. The box girder with spans from 33 to 69 m has a variable depth from 4.00 to 2.60 m. The bridge was progressively erected both in the longitudinal and transversal direction. At first, the basic box girder was cast in a formwork suspended on an overhead

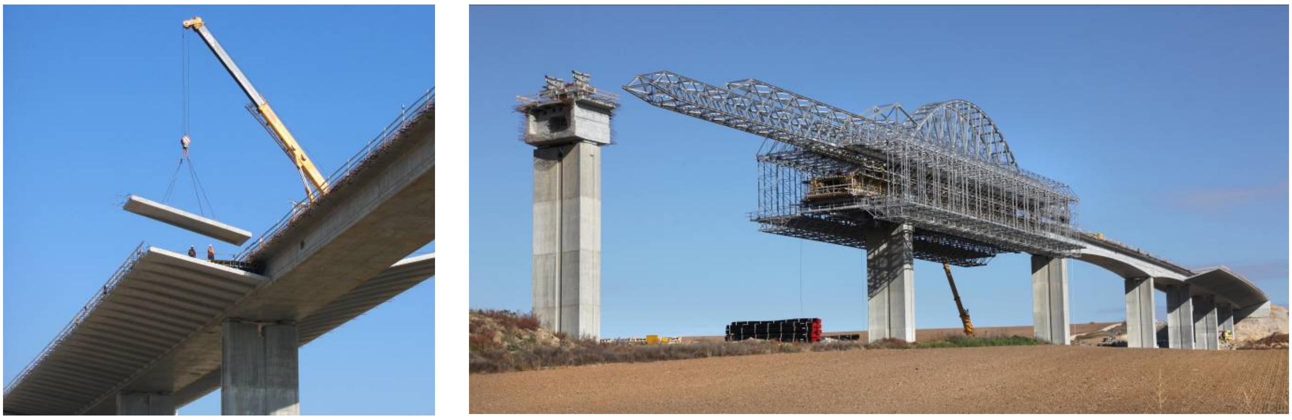

Fig. 4 - Viaduct across the Hostovsky Valley Creek

launching gantry, then the precast slab struts is erected and the overhangs are cast. The launching gantry formed by a truss tied arch utilized so called *Organic Prestressing*. During the girder's casting, the tension in the tie was gradually increased.

While the box girders and piers have smooth surface, the slab struts are stiffened by ribs that create a play of shadows and consequently optically lightened the structure.

## 6 MAPLE AVENUE BRIDGE, REDMOND OREGON, USA

An arch by its own shape naturally expresses an effort to bridge the obstacle. For the dead load a correctly designed arch is stressed by compression stresses. Therefore, it can be light and transparent. Recently we participated in a design of two concrete arch bridges built in the USA. The Maple Avenue Bridge provides an east-west link for the city of Redmond across Dry Canyon, which bisects the city. The canyon is a scenic natural feature, providing open space and recreation to local citizens. It was a desire to design a bridge that blends with its beautiful natural surroundings – see Fig. 5.

Fig. 5 - Maple Avenue Bridge, Redmond

The bridge of three equal spans of length of 64 m is formed by two arch ribs supporting a double tee deck. The girders and arch ribs have the same width; the intermediate supports of octagonal cross section are narrower. The arch ribs are not stiffened by any transverse ribs. A direct connection of the arches with the girders creates a clear and readable structural system that emphasizes the static function – arch and girder. The omitting of transverse ribs not only optically lightens the structure but also, by the creation of transverse ductile frames, increases the seismic resistance.

## 7 - WILLAMETTE RIVER BRIDGE, EUGENE, OREGON, USA

A successful realization of the Redmond Bridge has helped getting a project of another arch bridge that is being

Fig. 6 - Willamette River Bridge, Eugene

built in the city of Eugene, Oregon, USA. The interstate freeway I-5 crosses the Willamette River, a local highway, a railroad and a junction ramp on north bound and south bound bridges of lengths of 604.9 m and 536.1 m – see Fig. 6. These bridges replace original bridges built in fifties of the last century

The main bridge is formed by two arch spans of length 118.9 and 126.8 m. The deck that is formed by two girders and deck slab is stiffened by precast cross beams; the arches are formed by two ribs without any bracing. The approach bridges are formed multi-cell box girders of a variable depth that has the same perimeter as the arch deck. The substructure has a similar architectural and structural arrangement as the arch columns.

The bridge was erected progressively. At first, the arch ribs with the crown precast cross beams were cast. After the jacking, the midspan joints were cast. Then the columns were erected and longitudinal girders with the transverse cross beams are cast. After that the deck slab is cast.

## 8 – URBAN VIADUCT IN POVAZSKA BYSTRICA, SLOVAKIA

The freeway D1 crosses the city of Povazska Bystrica, Slovakia on several viaducts. The biggest one that has a total length of 968 m is formed by a continuous girder of ten spans of length 34.2 + 48.8 + 70.8 + 6x122 + 68 m – see Fig. 7. The deck is formed by a single cell box girder with large overhangs supported by precast struts. In the bridge axis the deck is suspended on seven low, 14 m tall pylons. The stays have a semi-radial arrangement. The girder is supported by four pot bearings situated in two rows on H-shaped piers formed by two mutually connected inclined columns. The suspended spans were progressively cast, segment by segment, in seven symmetrical cantilevers. The neighboring cantilevers were mutually connected by mid-span segments and by consequent prestressing.

Multi-span Extradosed Bridge formed by the single box girder with large overhangs supported by V shaped struts supported by transparent supports expressed the dynamic of present time. The bridge was well accepted both by professional and by public.

Fig. 7 – Urban viaduct in Povazska Bystrica

## 9 BRIDGE ACROSS THE ODRA RIVER AND ANTOSOVICE LAKE, CZECH REPUBLIC

Fig. 8 – Bridge across the Odra River and Antosovice Lake

Near a city of Ostrava the freeway D47 crosses the River Odra and Antosovice Lake on a twin bridge of the total length of 589 m. Due to a limited clearance, the deck of the structure had to be as slender as possible. Since the bridge is situated in a nice recreation area, it was necessary to design a structure of high aesthetic value that can become a symbol of the new freeway. Therefore a cable stayed structure suspended on one single pylon was accepted - see Fig. 8. The bridge crosses the river in a skew angle of $54^0$. The freeway's axis is in a plan curvature of 1500 m that transits into the straight line and it is in a crest elevation with a radius of 20,000 m.

The span length is from 24.5 to 105.0 m. The main span bridging the Odra River is suspended on a 46.8 m high single pylon. Since the stay cables have a symmetrical arrangement, the back stays are anchored in two adjacent spans situated on the land between the river and lake. The stay cables have a semi-radial arrangement; in the deck they are anchored at a distance of 6.07 m, at the pylon they are anchored at a distance of 1.20 m.

The decks are formed by two cell box girders of the depth of 2.20 m without traditional overhangs. The bottom slab of both cells is inclined and it is curved in the middle of girder - see Fig. 9. In the suspended spans the box girders are mutually connected by a top slab cast between the girders and by individual struts situated at distance of 6.07 m. The stay cables are anchored at anchor blocks situated at the connected slab. The struts connect the curved bottom of the girders and together with the inclined slabs create a simple truss system transferring the force from the stays into the webs. Between the stays' anchors there are circular openings at the connected slab. All piers have an elliptical cross section of the width of 4.10 m and depth of 1.60 m.

The bridge deck was cast span-by-span in two formworks suspended on two movable scaffoldings. With respect to the span length of the movable scaffoldings, temporary piers had to be built in the suspended spans. As soon as the spans adjacent to the pylon were cast, the pylon's steel core was erected and concrete fill and cover was progressively cast.

Fig. 9 – Bridge across the Odra River and Antosovice Lake

Simultaneously, the concrete struts between the girders were erected and top slab between the girders was cast and transversally prestressed. After that, the stay cables were erected and tensioned. Then the temporary piers were removed.

## 10 BRIDGE ACROSS THE RIVER EBRO, SPAIN

Fig. 10 - Bridge across the River Ebro, Spain

Prestressed concrete technology was also used in construction of the Rio Ebro Bridge. The bridge replaces a ferry that connected small cities Deltebre – Sant Jaume D'Enveja situated close to the river's estuary into the Mediterranean Sea. The arrangement of the bridge is a result of an architectural & structural competition. The client required a signature structure that, however, corresponds to a scale of these decent cities. The bridge crosses the river in a skew angle and it is in a crest elevation. The bridge forms a self-anchored suspension structure of three spans of lengths 69.00+ 112.00 + 69.00 m - see Fig. 10.

The deck of the width of 19.30 m is suspended on four suspension cables situated in the bridge axis. The torsionally stiff deck is formed by a composite four cell box. The central web of a variable depth that protrudes above the deck slab and substitute suspenders of the classical suspension structures naturally divides a local highway from pedestrian and cyclist routes. At distance of 3.00 m the steel structure is stiffened by transverse cross beams that support the composite deck slab. At the abutments the deck is stiffened by the end cross beams transferring the load from the bearings into the central webs.

The main suspension cables are formed by four BBRV cables anchored at the end diaphragms and deviated at the saddles of the low pylons. For the construction of the side spans and piers artificial peninsulas were consecutively created at both banks. They served for drilling of 46m long piles, casting the footings and construction of the piers. Then the steel structure forming the side spans and cantilevers protruding into the main span were erected. The whole central portion of the main span of length of 61.40 m and weight of 500 tons was assembled at one bank and consequently floated and lifted into the design position.

## 11 BRIDGE ACROSS THE FREEWAY D1, CZECH REPUBLIC

The bridge that crosses the freeway D1 near a city of Bohumin is used both by pedestrians and bicycles - see Fig. 11. The bridge deck of two spans of 54.94 and 58.29 m is in a plan curvature with a radius of 220 m. The bridge is suspended on a single mast situated in the area between the freeway and local roads.

The bridge deck is fixed into the end abutments formed by front inclined walls and rear walls forming the anchor blocks. Due to heavy bicycle traffic the city of Bohumin has required to separate the pedestrian and bicycle pathways. Therefore the deck is formed by a central spine girder with nonsymmetrical cantilevers carrying the pedestrians and bicycles. To balance the load, the shorter cantilever is solid, while the longer is formed by a slender slab stiffened by transverse ribs.

The mast is formed by two inclined columns of two cell box sections that are tied by top and bottom steel plates connecting the boxes' central webs.

Fig. 11 - Bridge across the freeway D1

## 12 HARBOR DRIVE BRIDGE, SAN DIEGO, CALIFORNIA, USA

The bridge that crosses Harbor Drive and several railroad tracks connects a new downtown ballpark with San Diego Convention Center and a parking garage. The City Development Corporation (the San Diego Redevelopment Agency), needed a pedestrian structure that would also serve as a landmark for the New Downtown and was prepared to invest in aesthetic considerations. Therefore a curved suspension was accepted see Fig. 12.

The bridge that is in a plan curvature with a radius of 176.80 m forms a self anchored suspension structure suspended by the hangers on the inside of the curve. The suspended span of the length of 107.60 m is monolithically connected to stairs at both ends. The stairs of length of 13.54 and 21.97 m form part of the structural system that transfers the stresses into the abutments supported on piles. The ramp to the parking structure on the south side, as well as the elevator on the north side, is structurally independent from the deck.

The 39.80 m tall pylon, which supports the main cable, is founded on the convex side of the deck, leans over the deck, and supports the main cable on the inside of the curve. It is stabilized with two backstays and internal post-

Fig. 12 - Harbor Drive Bridge, San Diego, California

tensioning. The main cable stretches from the abutment to a deviator at the top of the stairs to the anchorage at the top of the pylon. It is made of prestressing strands encased in stainless steel pipe. The hangers are attached to the steel pipe of the main cable and to the handrail on the bottom. The top of the handrail also carries a large post tensioning cable which is anchored at the deviators at the top of the stairs This cable is overlapped by the internal cables that prestressed the stairs.

The suspended deck is formed by a non-symmetrical box girder with one side overhangs supported by ribs. The girder is prestressed not only by internal tendons situated at the top slab, but also by horizontal components of the hangers forces and by the external cables. Therefore the inner railing, in which the hangers are anchored, is a part of the structural system. The geometry of the deck, position of the anchoring of the hanger, and position of the external cable and internal tendons were determined in such a way that the horizontal forces balance the moment created by eccentricity of the suspension.

## 13 PEDESTRIAN BRIDGE ACROSS THE BORDER RIVER OLSE, CZECH REPUBLIC - POLAND

Fig. 13 - Pedestrian Bridge across the border River Olse

Prestressing cables situated at bridge edge girders that balance the dead load torsional moment was used in a design of the composite pedestrian bridge built across the border River Olse. The bridge connects two cities of Czech and Polish Tesin – see Fig. 13. The bridge of a total length of 95.40 m is in a plan curvature with a radius of 100 m and in a crest elevation. The bridge has four spans of lengths from 13 to 45 m. The deck is formed of a slender steel box girder of a non-symmetrical streamline cross section that is in the main span stiffened by one side inclined arch. The deck is fixed into the end abutments and is supported by neoprene pads on intermediate piers. To balance the torsional moment due to the dead load the deck is prestressed by radial cables situated at edge curbs. Both the girder and the arch are composite of steel and concrete. LED lights situated in the handrails and at the arch illuminated the walkway and the structure.

## 14 THE LAKE HODGES BRIDGE, SAN DIEGO, CALIFORNIA, USA

The word longest stress ribbon bridge is located in the northern part of San Diego County and it is a part of the San Dieguito River Valley Regional Open Space Park - see Fig. 14. The bridge is formed by a continuous stress ribbon of three equal spans of length of 108.58 m. The sag at mid-spans is 1.41 m. The stress ribbon of the total length of 301.75 m is assembled of precast segments and cast-in-place saddles situated at all supports. The stress ribbon is fixed into the end abutments and it is frame connected with intermediate piers.

The precast segments of the depth of 0.407 m are 3.048 m long and 4.266 m wide. Each segment is formed by two edge girders and a deck slab. At joints the segments are strengthened by diaphragms. During the erection the segments

Fig. 14 - The Lake Hodges Bridge, San Diego, California

were suspended on bearing cables and shifted along them to the design position. After casting of saddles and joints between segments, the stress ribbon was post-tensioned by prestressing tendons.

The saddles have a variable depth and width. Above supports a viewing platforms with benches were created. The saddles were cast after erection of all segments in the formwork suspended on the already erected segments and supported by piers or abutments. During the erection the bearing cables were placed on Teflon plates situated on steel saddles. The horizontal force as large as 53 MN is transformed into the soil at the left abutment by four drilled shafts of a diameter of 2.70 m, at the right abutment by rock anchors.

## 15 - Bridge across the expressway R3508 near Olomouc, Czech Republic

Classical stress-ribbon type structures need to resist very large horizontal forces at the abutments, which determine the economy of that solution in many cases. For that reason, a new system that combines an arch with the stress-ribbon has been developed. The stress-ribbon is supported on an arch. The structures form a self-anchoring system where the horizontal force from the stress-ribbon is transferred by inclined concrete struts to the foundation, where it is balanced against the horizontal component of the arch.

Fig. 15 - Bridge across the expressway R3508 near Olomouc

The pedestrian bridge in Olomouc is formed by a stress-ribbon of two spans that is supported by an arch – see Fig. 15. The stress-ribbon of the length of 76.50 m is assembled of precast segments 3.00 m long supported and prestressed by two external tendons. The precast deck segments and precast end struts consist of high-strength concrete of a characteristic strength of 80 MPa. The cast-in-place arch consists of high-strength concrete of a characteristic strength of 70 MPa. The external cables are formed by two bundles of 31-0.6" diameter monostrands grouted inside stainless steel pipes. They are anchored at the end abutments and are deviated on saddles formed by the arch crown and short spandrel walls. The stress-ribbon and arch are mutually connected at the central of the bridge. The arch footings are founded on drilled shafts and the anchor blocks on micro-piles.

## 16 BRIDGE ACROSS THE SVRATKA RIVER IN BRNO, CZECH REPUBLIC

Fig. 11 - Bridge across the Svratka River in Brno

Similar structural system was used in the design of the pedestrian bridge connects a newly developed business area with an old city center. Close to the bridge an old multi span arch bridge with piers in the river is situated. It was evident that a new bridge should also be formed by an arch structure, however, with a bold span without piers in the river bed. Due to poor geotechnical conditions a traditional arch structure that requires resisting of a large horizontal force would be too expensive. Therefore, the self anchored stress ribbon & arch structure has been built. Both, the stress ribbon and the arch are assembled of precast segments from high strength concrete and were erected without any temporary towers. Smooth curves that are characteristic for stress ribbon structures allowed a soft connection of the bridge deck with both banks.

The arch span L = 42.90 m, its rise f = 2.65 m, rise to span ration f/L = 1/16.19. The arch is formed by two branches that have a variable mutual distance and merge at the arch springs. The 43.50 m long stress-ribbon is assembled of segments of length of 1.5 m. In the middle portion of the bridge the stress ribbon is supported by low spandrel walls of the variable depth. At midspan the arch and stress ribbon are mutually connected by 2x3 steel dowels that transfer the shear forces from the ribbon into the arch. The stress ribbon is carried and prestressed by four internal tendons of 12 0.6” dia monostrands grouted in PE ducts. The segments have variable depth with a curved soffit. The stress-ribbon and the arch were made from high-strength concrete of the characteristic strength of 80 MPa.

## 17. CONCLUSIONS

The presented structures utilize different architectural and structural forms that are inherent in the constraints of the site and are economical and structurally efficient. They were well accepted both the public and professional.

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