

Stress ribbon & arch pedestrian bridges

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ABSTRACT: Stress-ribbon bridges consist of very slender concrete deck segments placed over bearing cables in the shape of a catenary. These bridges are characterized by successive and complementary smooth curves that blend into the environment. A disadvantage of the classical stress-ribbon type structure is the need to resist very large horizontal forces at the abutments, which determines the economy of that solution in many cases. For that reason, two new self anchored structural systems that combine the stress-ribbon with the arches have been developed. In the first one the stress ribbon is supported by an arch, the second one combines a curved stress ribbon with a curved flat arch.

1 INTRODUCTION

Stress-ribbon bridges consist of very slender concrete deck segments placed over bearing cables in the shape of a catenary. Prestressing the deck segments stiffens the structure, providing stability to the cables. These bridges are characterized by successive and complementary smooth curves – see Fig.1.



Figure 1 : Lake Hodges Pedestrian Bridge

The curves blend into the environment and the curved shape, the most simple and basic of structural solutions, clearly articulates the flow of internal forces. The main advantage of these structures is their minimal environmental impact because they use very little material and can be erected without falsework or shoring, which could disturb the natural environment. Because there are no bearings or expansion joints, the bridges require only minimal long-term maintenance. The bridges built in the Czech Republic and in the USA were discussed in a paper presented at the International Bridge Conference in Pittsburgh in 1999 (Strasky J. 1999). Problems connected with the design and construction of the stress-ribbon structures and a survey of such bridges built all over the world is presented in (Strasky J. 2005).

Usually the deck of stress ribbon structures is assembled of precast segments of a double tee cross section that is stiffened by diaphragms at joints. The bearing and prestressing cables are situated in troughs made in edge girders (Strasky J. 2005). Local bending moments that originated in the stress ribbon deck near supports are resisted by a cast-in-place saddles designed as partially prestressed members.

An excellent example of this type of the structure is the Lake Hodges Pedestrian Bridge recently completed in San Diego – see Fig1. This, so far the longest stress ribbon bridge, has three continuous spans of equal span length of 100.58m. The sag in all spans is 1.41 m (Sánchez A. et al. 2008).

Experience with performance of bridges built so far and parametric dynamic analyses have proved that the stress ribbon deck can be even lighter. Therefore we have developed a new type of the cross section formed by slender slab that is carried and prestressed by external cables - see Fig.2. The stress ribbon is assembled of precast segments from high strength concrete; the external cables are formed by monostrands that are lead in stainless pipes. At supports, the pipes are composite with the stress ribbon deck and create a composite member that is able to resist a positive bending moment originating there - see Fig.3.



Figure 2 : Segments on external cables



Figure 3 : Stress ribbon & Pier table

2 STRESS RIBBON BRIDGES SUPPORTED OR SUSPENDED ON ARCHES

A disadvantage of the classical stress-ribbon type structure is the need to resist very large horizontal forces at the abutments, which determines 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 or is suspended on an arch – see Fig.4 and 5. 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.

The stress-ribbon structure supported by the arch was carefully analyzed and tested at the Brno University of Technology. Then the studied system was applied to a design of four bridges that have been built in the Czech Republic. A stress-ribbon structure suspended on two inclined arches was applied in the design of the 92-meter-long McLoughlin Bridge built in Portland, Oregon.

2.1 Structural system

The development of the self-anchored stress-ribbon structure supported by an arch is evident from Fig.4. It is clear that the intermediate support of a multi-span stress-ribbon can also have the shape of an arch (see Fig.4a). The arch serves as a saddle from which the stress-ribbon can rise during post-tensioning and during temperature drop, and where the center "band" can rest during a temperature rise.

In the initial stage, the stress-ribbon behaves as a two-span cable supported by the saddle that is fixed to the end abutments (see Fig.4b). The arch is loaded by its self weight, the weight of the saddle segments and the radial forces caused by the bearing tendons (see Fig.4c). After post-tensioning the stress-ribbon with the prestressing tendons, the stress-ribbon and arch behave as one structure.

The shape and initial stresses in the stress-ribbon and in the arch can be chosen such a way that the horizontal forces in the stress-ribbon H_{SR} and in the arch H_A are the same. It is then possible to connect the stress-ribbon and arch footings with inclined compression struts that balance the horizontal forces. The moment created by horizontal forces $H_{SR} \cdot h$ is then resisted by the $\Delta V \cdot L_p$. In this way a self-anchored system with only vertical reactions is created (see Fig.4d).

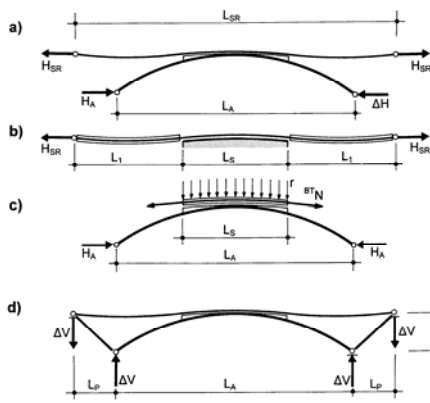


Figure 4 : Stress ribbon supported by arch

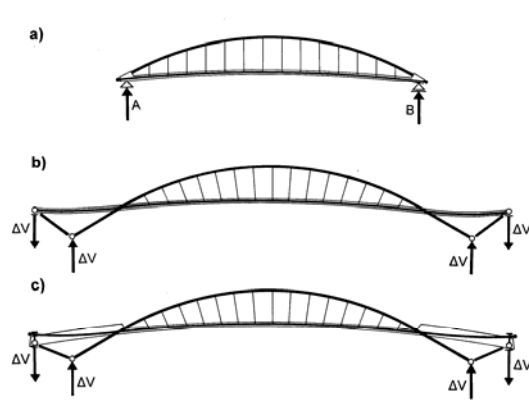


Figure 5 : Stress ribbon suspended on arch

It is also obvious that the stress-ribbon can be suspended from the arch. It is then possible to develop several self-anchored systems - see Fig.5. Fig.5a shows an arch fixed at the anchor blocks of the slender prestressed concrete deck. The arch is loaded not only by its self weight and that of the stress-ribbon, but also with the radial forces of the prestressing tendons. Fig.5b shows a structure that has a similar static behavior as the structure presented in Fig.4d. Fig.5c shows a similar structure in which the slender prestressed concrete band has increased bending stiffness in the portion of the structure not suspended from the arch.

2.2 Model test

The author believes that a structural system made up of a stress-ribbon supported by an arch increases the potential application of stress-ribbon structures. Several analyses were undertaken to verify this. The structures were checked not only with detailed static and dynamic analysis, but also on static and full aeroelastic models. The tests verified the design assumptions and behavior of the structure under wind loading that determined the ultimate capacity of the full system.

The model tests were done for a proposed pedestrian bridge across the Radbuza River in Plzen, Czech Republic. This structure was designed to combine a steel pipe arch having a span length of 77 m and the deck assembled of precast segments. The static physical model was done in a 1:10 scale. The shape is shown in Figs.6 and 7. The test has proved that the analytical model can accurately describe the static function of the structure both at the service and ultimate load.

Results of the tests were utilized in a design of following structures.

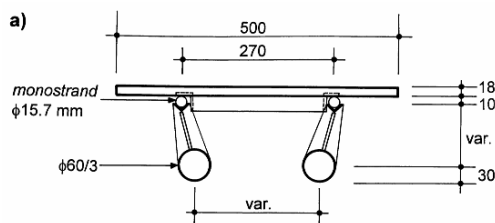


Figure 6 : Static model – cross section



Figure 7 : Ultimate load

2.3 Olomouc Pedestrian Bridge, Czech Republic

The bridge crosses expressway R3508 near a city of Olomouc. The bridge is formed by a stress-ribbon of two spans that is supported by an arch (see Fig.8). The stress-ribbon of the

length of 76.50m is assembled of precast segments 3.00 m long supported and prestressed by two external tendons (see Fig.9).

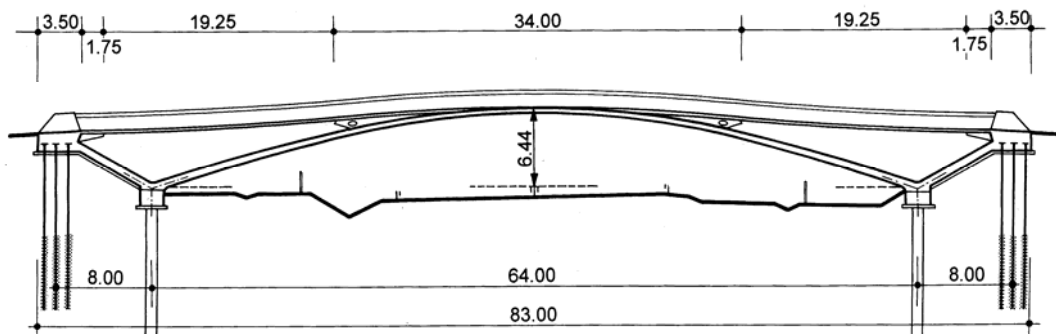


Figure 8 : Elevation

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 70MPa. 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 steel pipes are connected to the deck segments by bolts located in the joints between the segments - see Fig.2. At the abutments, the tendons are supported by short saddles formed by cantilevers that protrude from the anchor blocks. 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.

Although the structure is extremely slender, the users do not have an unpleasant feeling when standing or walking on the bridge.

The bridge was built in 2007.



Figure 9 : Completed structure

2.4 Pedestrian Bridge across the Svatka River in Brno, Czech Republic

Another such bridge was built across the Svatka River in a city of Brno, Czech Republic. 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 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 represents a logical solution - see Fig.10.

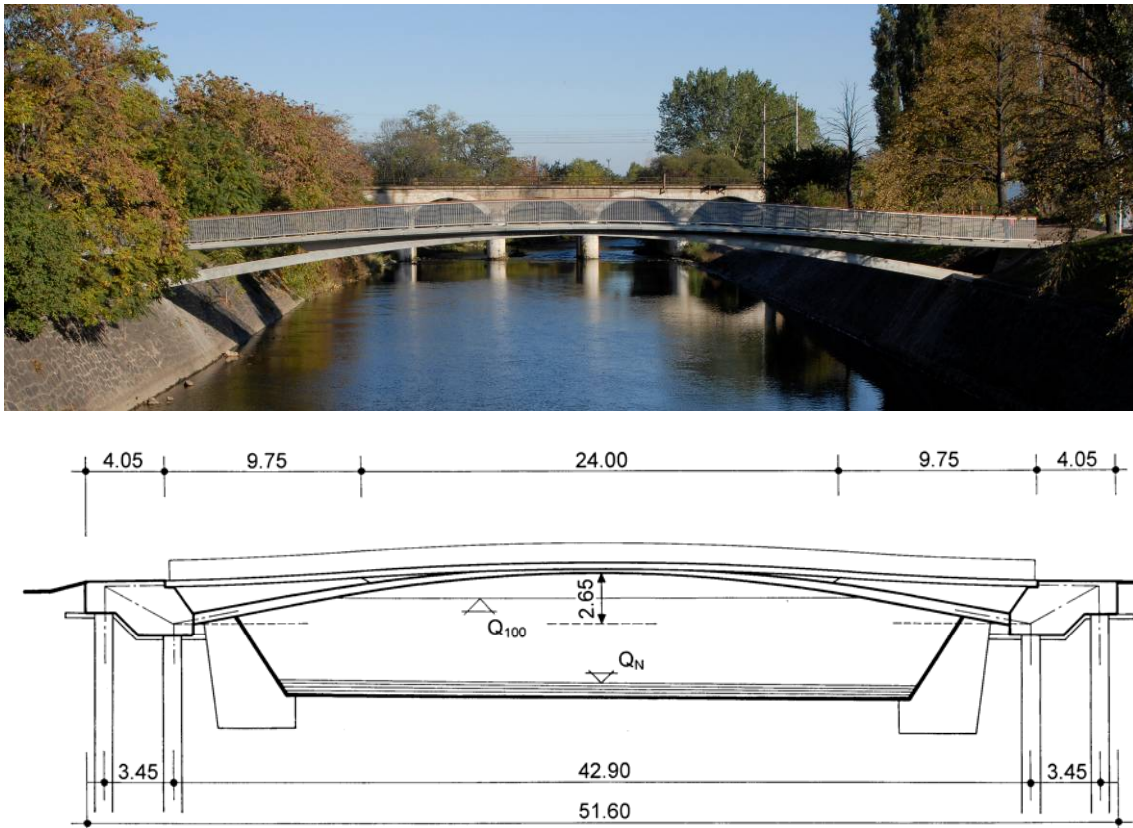


Figure10 : Completed bridge and elevation

Since the riverbanks are formed by old stone walls, the end abutments are situated beyond these walls. The abutments are supported by pairs of drilled shafts. The rear shafts are stressed by tension forces, the front shafts are stressed by compression forces. This couple of forces balances a couple of tension and compression forces originating in the stress ribbon and arch. The arch span $L = 42.90$ m, its rise $f = 2.65$ m, rise to span ratio $f/L = 1/16.19$. The arch is formed by two legs 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. 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.

Although the structure is extremely slender, and first bending frequencies are close to 2 Hz, the users do not have an unpleasant feeling when standing or walking on the bridge.

The bridge was built in 2007.

2.5 McLoughlin Boulevard Pedestrian Bridge, Portland, Oregon, USA

The McLoughlin Boulevard Pedestrian Bridge (see Fig.12) is a part of a regional mixed-use trail in the Portland, Oregon metropolitan area. The bridge is formed by a stress-ribbon deck that is suspended on two inclined arches. Since the stress- ribbon anchor blocks are connected to the arch footings by struts, the structure forms a self-anchored system that loads the footing by vertical reactions only (see Fig.5c). The deck is suspended on arches via suspenders of a radial arrangement; therefore, the steel arches have a funicular/circular shape.

The stress-ribbon deck is assembled from precast segments and a composite deck slab. In side spans, the segments are strengthened by edge composite girders. The deck tension due to dead load is resisted by bearing tendons. The tension due to live load is resisted by the stress-ribbon deck being prestressed by prestressing tendons. Both bearing and prestressing tendons are situated in the composite slab. The bearing tendons that were post-tensioned during

the erection of the deck are formed by two bundles of 12 by 0.6" diameter strands that are protected by the cast-in-place slab; deck prestressing tendons are formed by six bundles of 10 by 0.6" diameter tendons that are grouted in ducts.



Figure 11 : Suspension of the deck



Figure 12 : Completed bridge

Edge pipes and rod suspenders make up part of the simple hanger system – see Fig.11. The suspenders connect to "flying" floor beams cantilevered from the deck panels to provide the required path clearance. The edge pipes contain a small tension rod that resists the lateral force from the inclined suspenders on the end of the floor beams. Grating is used to span the gap between the edge pipe and the deck panels.

Construction of the bridge commenced in March, 2005, and was completed in September, 2006.

3 CURVED STRESS RIBBON & FLAT ARCH BRIDGES

Recently, several noteworthy curved pedestrian bridges, which decks are suspended on their inner edges on suspension or stay cables, have been built. However, curved stress ribbon and/or flat arch bridges have not been built so far. Therefore we have decided to study these structures analytically and verified their function on a static model.

The above curved structures have to be designed in such a way that for the dead load there is no torsion in the deck. One possibility is to supplement the deck with stiff L shaped members and suspend the deck at their top portions. The cable geometry has to be designed in such a way that suspenders or stay cables direct to the deck's shear centers. This approach was also used in a design of our stress ribbon structure - see Fig.13. The structure is formed by slender deck that is supplemented by steel L frames supporting the slab. The tops of their vertical portion are connected by steel pipes in which the strands are placed. Radial forces originating in the strands during their post-tensioning load the structure – see Fig.13b. The vertical components of these radial forces balance the dead load – see Fig.13c, the horizontal components balance the dead load's torsional moment and load the structure by horizontal radial forces – see Fig.13d. Since the stress ribbon is fixed into the abutments, these forces create uniform compression in the deck.

Our design has been developed from the above approach. However, for resisting of the effects of the live load, we have to add additional cables that have very complicated arrangement. Therefore we have decided to add a torsionally stiff member of the pentagon cross section. Resulting arrangement of the structure is evident from Figs.14. The curved pedestrian bridge of the span of 45m is in a plan curvature that in pathway's axis has a radius of 45m. The maximum longitudinal slope at the abutments is 7%. Both the concrete slab and the steel girder are fixed into the anchor blocks. The external cables are situated in the handrail pipe and are anchored in end concrete walls that are fixed into the anchor blocks. Horizontal forces are resisted by battered micropiles – see Fig.15a.

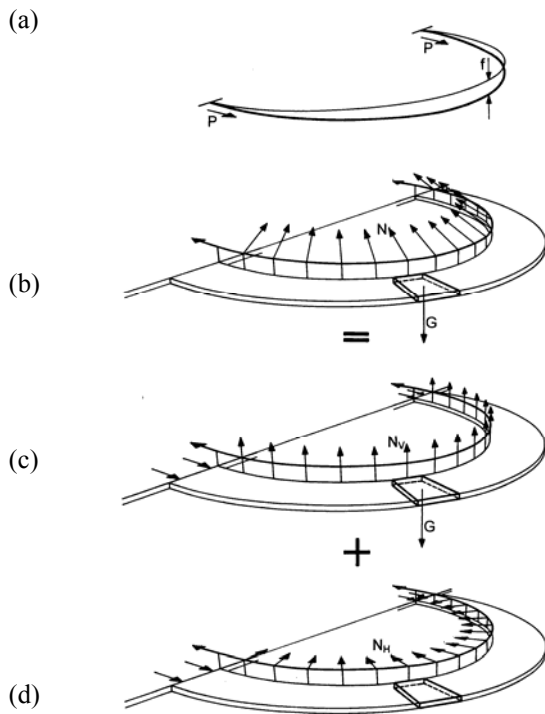


Figure13 : Curved stress ribbon

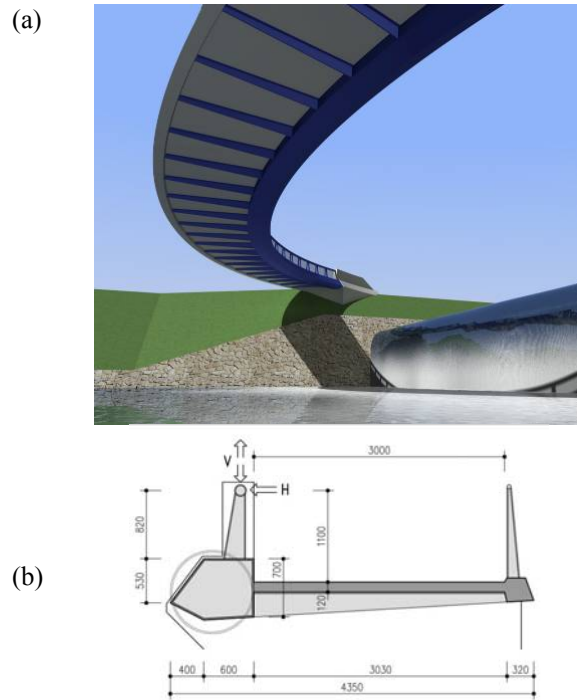


Figure14 : Stress ribbon & arch structure

The detailed static and dynamic analyses have proved that the structure is able to resist all design loads. The first bending frequency is $f_1=1.437$ Hz. The forced vibration done according to (Design Criteria for Footbridges 1988) has caused maximum acceleration $a_{max}=0.578m/s^2$ that is close to allowable acceleration $a_{lim}=0.589m/s^2$. Therefore we propose using two dampers, to be sure the pedestrians would not have an unpleasant feeling when standing or walking on the bridge.

The function of the studied structure was verified on a static model built in the scale 1:6 – see Figs.17 and 18. To reduce the longitudinal horizontal force, the curved stress ribbon was tested together with a structure formed by a curved flat arch of a similar arrangement. It is evident that actual structure can be built similarly. The horizontal force from the stress ribbon can be balanced by the horizontal force originating at the flat arch – see Fig.15b. In this way a very economic structural system can be created. The analyses according to (Design Criteria for Footbridges 1988) have proved that the dynamic behavior of the curved flat arch is similar to the curved stress ribbon structure; the first bending frequency $f_1=1.437$ Hz.

To simplify construction of the model, the steel box of the stress ribbon and flat arch was substituted by steel pipe that were fixed into the end anchor blocks. The steel pipes were produced with steel L shaped members. Their horizontal part supported the concrete slab; their vertical parts supported steel pipes in which the monostrands were placed.

To guarantee a model similarity, the curved steel pipes and transverse L members were loaded by concrete block and steel rods representing the self weight of the structure. This load was suspended on the steel structure. The live load was represented by additional concrete block and cylinders placed on the stress ribbon deck.

The construction of the model was carefully monitored. The structure was tested for 2x3 positions of the live load (see Fig.17) and for the ultimate load (see Fig.18). The live load was situated on the left side, right side on the whole length of the deck. The measured deformations and strains were in a good agreement with the results of the static analysis. At the end, the model was loaded by an ultimate torsional load that was situated along whole length of both structures. The both structures proved that have a sufficient margin of safety.

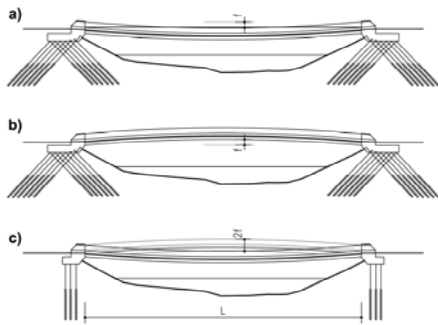


Figure 15 : Stress ribbon & arch structure

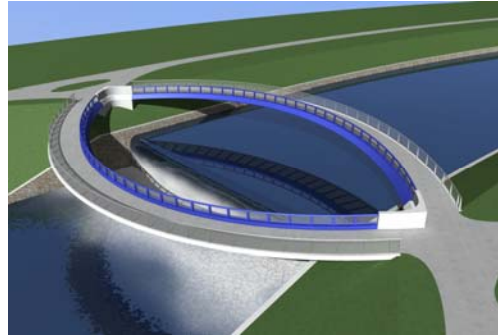


Figure 16 : Stress ribbon & arch structure



Figure 17 : Model test – Service load



Figure 18 : Model test – Ultimate load

4 CREDITS

The continuous development of the stress ribbon structures is being done at the Faculty of Civil Engineering of the Brno University of Technology with a collaboration of engineering firm Strasky, Husty and Partners, Brno. The design of the bridge utilized results of the research projects of the Czech Ministry of Industry FI - IM5/128 “Progressive Structures from High-performance Concrete”. Paper originated with the financial support of the Ministry of Education, Youth and Sports of the Czech Republic, project No. 1M0579, within activities of the CIDEAS research centre.

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