Arch Bridges
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RESEARCH OF CONCRETE ARCH BRIDGES UP TO 1000 M IN SPAN

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Abstract. *In the Engineering Department of the Faculty of Civil Engineering of the University of Zagreb a research and the experimental studies of possibilities of high strength concrete applications in bridge construction have been carried on. The development of RPC material should bring a significant advancement in the field of building large structures. However, the material of such a high compressive strength makes possible and also requires different ways of designing. In this paper, there are shown the structural and technological aspects of an arch bridge construction of 750 m and 1000 m in span, made of RPC concrete.*

1 INTRODUCTION

The whole century is behind us during which engineers designed the structures with the materials that were evolving, more or less, as regards an increase of strength and other significant properties. Along with the improvement of materials, there came also to the evolution of structural design and technologies of construction. A very appreciable revolution happened too concerning the structural calculations by use of computers. It helped to build the structures, which construction steps could not be followed by classical methods of calculation until then. A great technological development did not go around the field of high-strength materials either. In the last decade, a particular attention among builders drew a composite material based on Portland cement, called Reactive Powder Concrete (RPC). This material can reach the compressive strengths from 200 to 800 MPa. Now, the builders are faced with the task of making the most of the new material.

The design solutions for the arches of 500 m, 750 m and 1000 m in span have been elaborated. The present study gives a survey of the arch of 1000 m in span only.

2 ARCH OF 1000 M IN SPAN

2.1 Longitudinal disposition

The structure is conceived as prefabricated and is executed like a monolith due to the heavy weight of segments. The weight of an arch segment of the bridge, 5 m in length, amounts to 5.61 MN, therefore, the segments are heavy to handle. The flatness of the arch is chosen in the ratio 166.67/1000=1/6 (Fig. 1).

Except the bridge foundations and abutments, all bearing elements of the structure are made of RPC by concreting in situ. The structure performs after the Ist stage concrete and the joining by prestressing is executed only at working joints, at 5 m intervals.

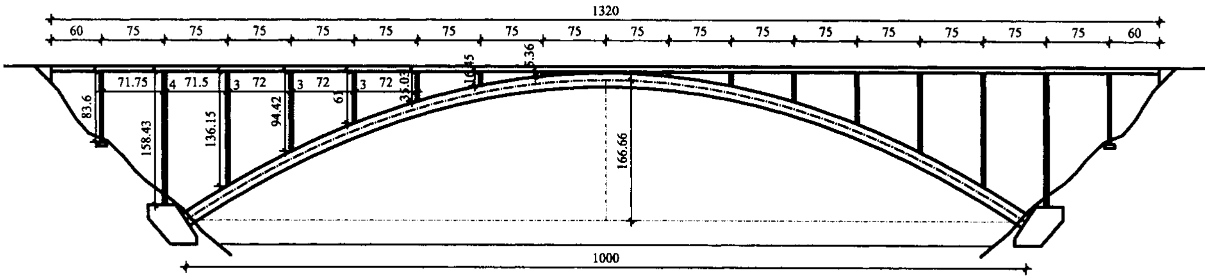

Figure 1: Longitudinal section

2.2 Arch

The arch cross-section is octagonal in shape, of constant outside dimensions along the span (Fig. 2). The thicknesses of the lower and the upper slab change linearly from the arch abutment (100 cm) to the second pier above the arch (25 cm). The ratio between the width and the height of the arch is 33/16.5=2. Every segment has transversal diaphragms 30 cm thick, as the slenderness of slabs and webs would be less than 1/30. The weight of one segment is 5609 kN.

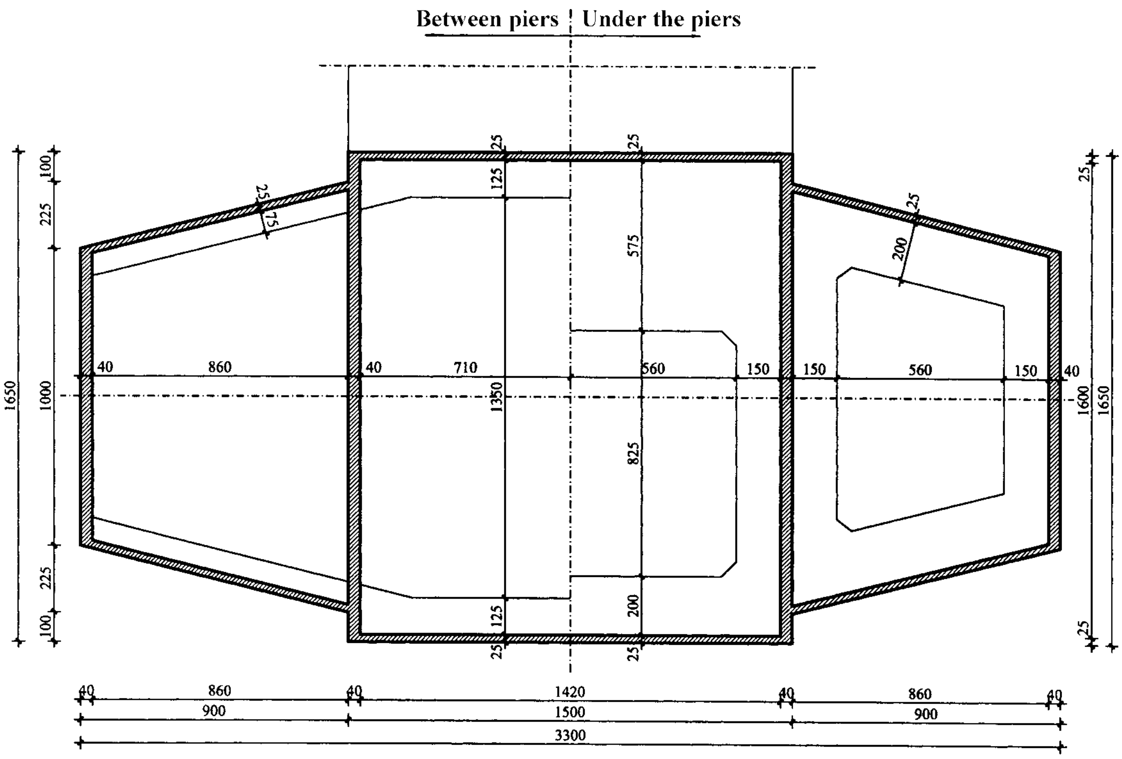

Figure 2: Cross section of arch

2.3 Piers

The piers above the arch and approach system are single boxes, rectangular in shape (Fig. 3). They are concreted in moving formwork in the segments of 5 m in length. The weight of one segment amounts 1388 kN.

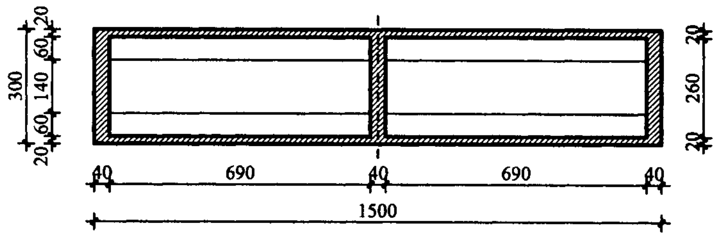

Figure 3: Cross section of pier

2.4 Beam

The beam is of a trapezium cross-section (Fig. 4). The cross-section with four webs, 40 cm thick, is constant along the span. At the segment ends, there are performed the transversal diaphragms, 30 cm thick, in order to satisfy the span-thickness ratio h/t=4.7/0.20=23.5<30. The beam spans are 75 m. The ratio between the height and the span is 1/12, what is optimal for the execution by incremental launching.

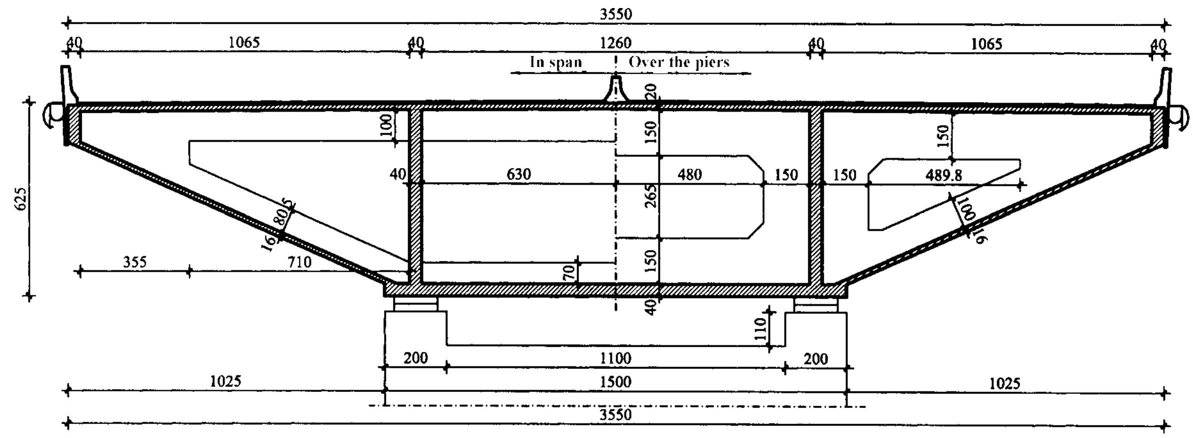

Figure 4: Cross section of beam

In order that the arch is loaded symmetrically, the beam is executed by symmetric incremental launching from both sides of the bridge. The nose length is 40 m and the weekly steps are 25.0 m in length. The weight of one segment is 3206 kN. During the incremental launching of the beam, there are tensile stresses of 12 MPa appearing at the arch abutments. The amount of external prestressed steel bars at working joints (Fig. 5) is determined from the condition that all joints are to be under a minimum pressure of -1.5 MPa. In distinction from the beam, the arch and pier segments as compressive elements are interconnected by deformed reinforcing bars with threads.

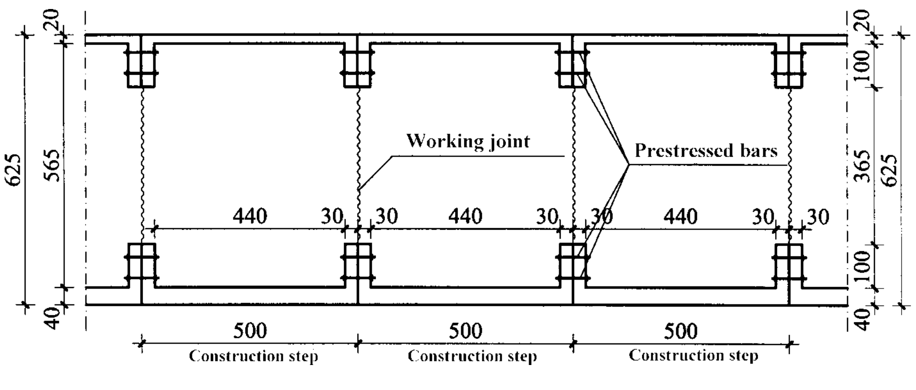

Figure 5: Longitudinal section of beam

2.5 Arch execution

The arch is constructed by a cantilever method by making a temporary truss, in which the lower elements and the piers are under compression and the diagonals and the upper elements are under tension (Fig. 6). In order to increase the truss height and to reduce forces, on the pier tops there are executed temporary steel columns 30 m high. The segments are made monolithically. The arch consists of 2 x 107 segments, each 5 m long, and the final segment 3 m in length.

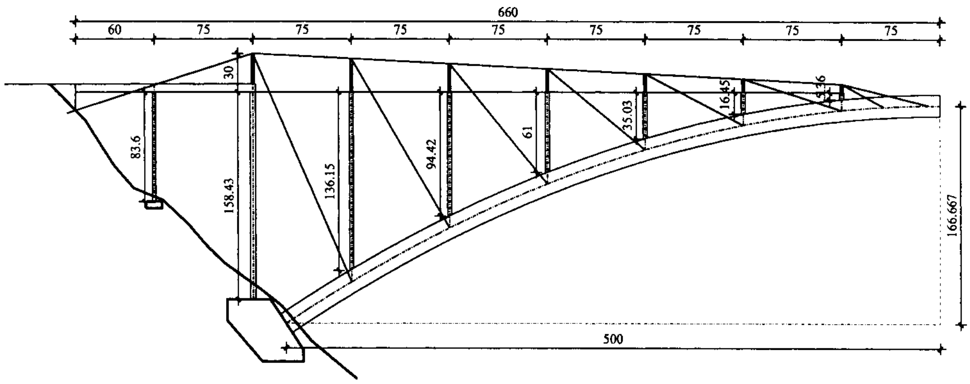

Figure 6: Last stage of arch execution

All tensile elements of the truss so designed are made of carbon wires (CFRP) that are of a considerably smaller weight (1.56 g/cm^3) and much higher strength (3300 MPa).The small weight, approximately 7 times less than the one of steel ropes for the same breaking strength, enhances transportation and handling.

The maximum force in a tie rod of the truss so designed for the execution of the complete cross-section of the arch amounts about 865 MN, depending on configuration of the ground and/or the anchor tie rod angle of inclination. In the present example, the anchor tie rod is taken at the inclination of 18º to the horizontal (Fig. 7).

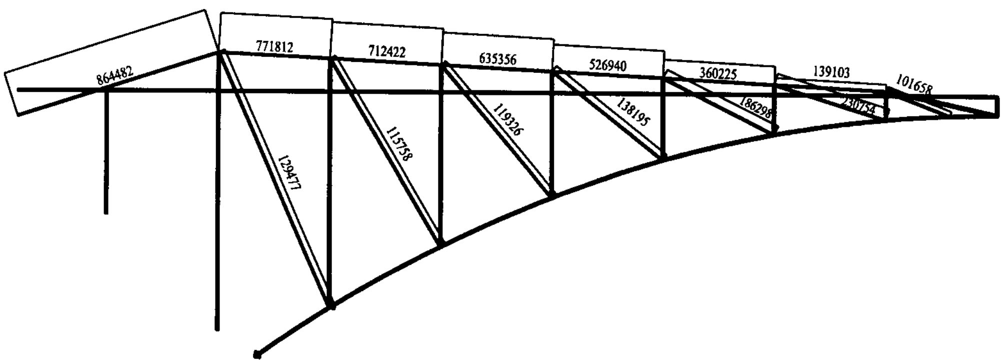

Figure 7: Diagram of longitudinal forces in tie rods at concreting the last segment of the arch in case the complete arch section is executed

The biggest forces in tie rods occur from most distant arch segments in relation to the arch abutment. Therefore, an example of the arch execution in two stages is presented. In the first stage, the complete arch cross-section is executed to the third pier above the arch, and further to the crown its central part only (Fig. 8).

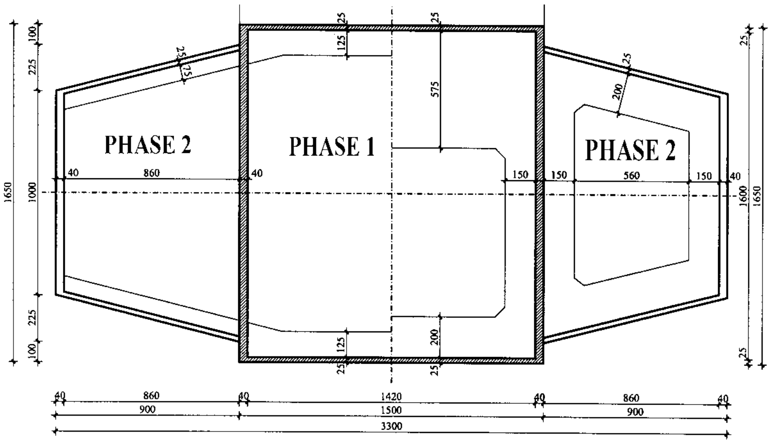

Figure 8: Arch is executed in two phases

The anchor tie rod force was reduced for 46% by such execution that is from 865 MN to 590 MN. But, compressive stresses increased for 35 %. The highest compressive stress in this case amounts -84 MPa in the arch crown (Fig. 9), requiring a better quality material of 250 MPa. The problem cannot be solved by thickening of the upper and the lower slab of the arch cross-section, because, in this way we increase also the forces in tie rods.

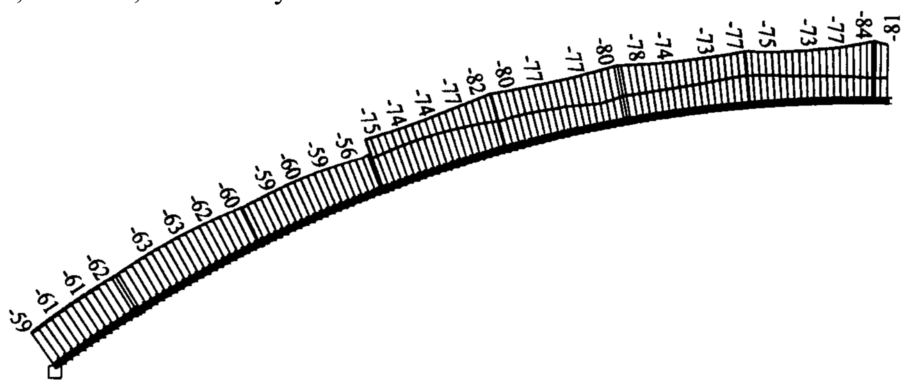

Figure 9: The envelope of the highest compressive stresses in the arch for combinations of main and additional forces in case of two stage execution of the arch

For comparison:

- On the arch land-Island of Krk, span 390 m, the supporting force amounted 60 MN, in which process the arch was executed with the middle box only (HPC)[xvii].
- On the Bakar arch, span 432 m, the supporting force amounted 78 MN, in which process the arch was held on to radial tie rods and executed without piers (RPC)[iv].
- On a semi-motorway arch with a span 500 m, the supporting force amounted 90 MN, in which process the arch was held on to radial tie rods and executed without piers (RPC)[ix].
- On the arch of 750 m in span, with a full motorway width and the truss designed similarly, the supporting force amounts 400 MN[iii].

2.6 Results of Statical Analysis

All structural calculations were performed based on allowable stresses, like in prestressed concrete, as the material is such that it performs after the Ist stage of concrete. The chosen compressive strength of RPC is 200 MPa and the bending tensile strength is 40 MPa[v]. The allowable stresses are taken in the value of 1/3 of standard strengths. For the module of elasticity 50 GPa was taken.

The arch axis was obtained by an inverted load method[vii] (Fig. 10). The problem of finding out an arch compression line is analogous to the problem of finding the equilibrium position of a catenary which is loaded with same forces, but in opposite direction.

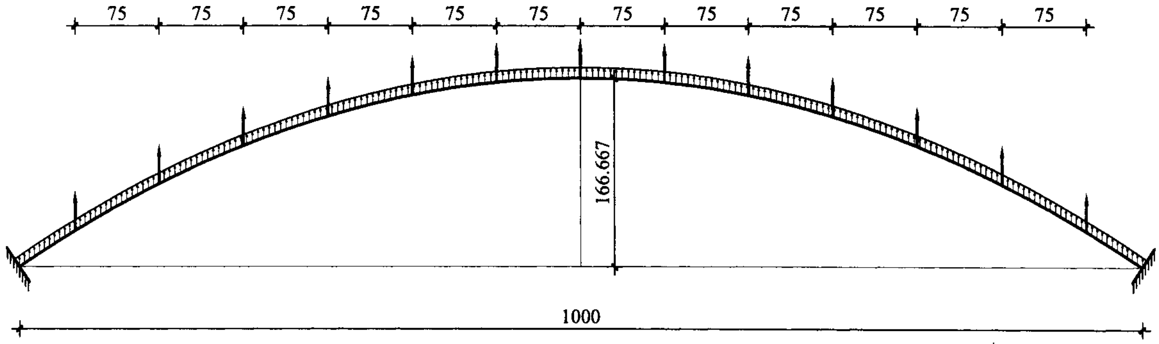

Figure 10: Inverted load method[vii].

The structural analysis is made for all critical stages of the execution of the arch, piers and beam launching and also for the exploitation loads. In table 1 there are given the main dead and live loads.

No	Element	Loads (kN/m)
1.	Beam weight	641.1
2.	Pier weight	261.1
3.	Arch weight	1120.1
4.	Permanent load	144.6
5.	Live load	110.7

Table 1: Loads data

The figure 11 shows an envelope of maximum compressive stresses in the arch for the combinations of main and additional forces. The whole arch is continually under compression for any loading combinations, except in one critical stage during the beam launching, and the maximum stress amounts -61 MPa in the arch crown.

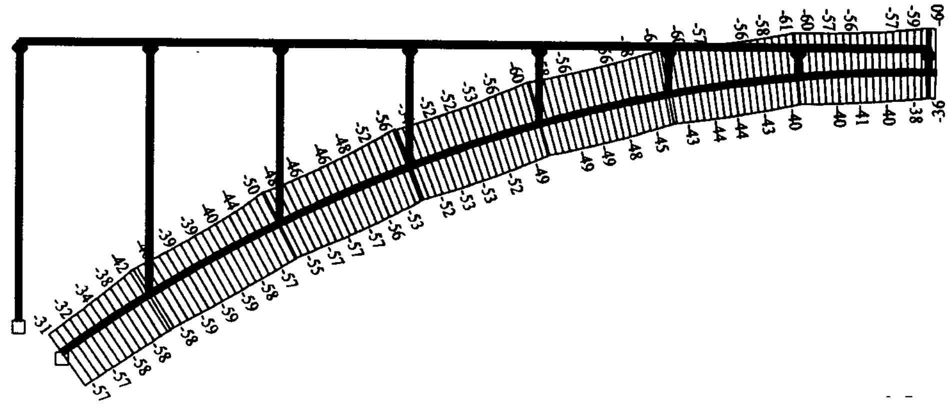

Figure 11: Envelope of maximum compressive stresses in arch for combinations of main and additional forces

The maximum deflection of the arch from a dead load and an additional dead load amounts 1352 mm (Fig. 12), thus, the ratio of the deflection and the span is 1/740, being in accordance with the relationships for concrete systems.

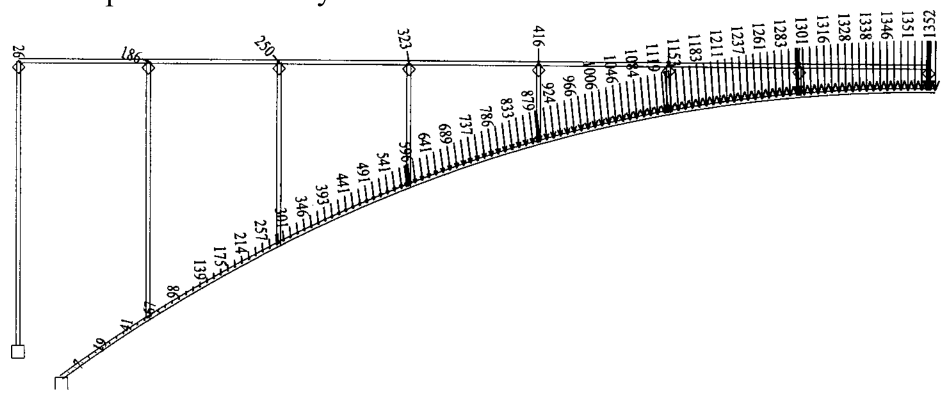

Figure 12: Total deflections of arch dead load

In the piers, the maximum compressive stress amounts -25 MPa and the tensile stress is 5 MPa (Fig. 13).

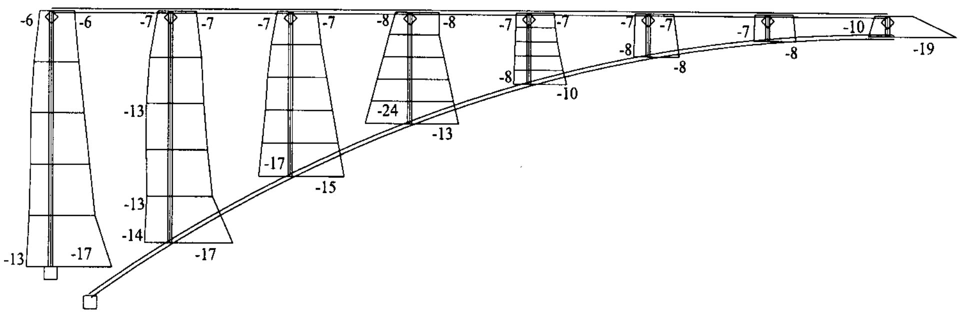

Figure 13: Envelope of maximum compressive stresses in piers for combinations of main and additional loads

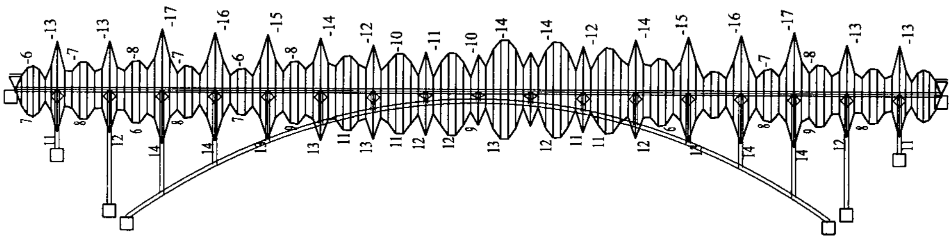

Figure 14: Envelope of maximum compressive and tensile stresses in a beam for combinations of main and additional loads

The first period of a dynamic analysis is transversal, amounting 10.3 sec (Fig. 15).

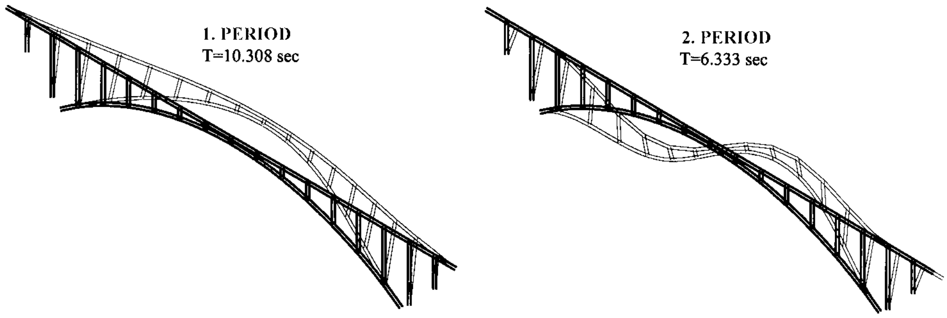

Figure 15: The first (transversal) and the second (vertical) period of dynamic analysis

3. CONCLUSION

The statical analysis is made for all critical stages of the execution of the arch, piers and beam launching and the exploitation loads. The maximum compressive stresses amount -61 MPa and are located at the places of joining with the piers above the arch and the maximum tensile stresses amount 14 MPa and are located at the middle supports of the beam. The main problem represents the magnitude of a tie rod force, which amounts 865 MN for the execution of the complete arch cross-section. The force can be reduced to 590 MN by executing the arch in two stages, yet using better quality materials or another truss shape. For the arch of 750 m in span, the anchor tie rod force amounts 400 MN for the execution of the whole cross-section.

		Arch 750 m		Arch 1000 m	
No.	Element	RPC (m^3)	(%)	RPC (m^3)	(%)
1.	Arch	22,736.	48%	50,861.	52%
2.	Pier	7,096.	15%	14,246.	14%
3.	Beam	17,648.	37%	33,849.	34%
	Total	47,480.	100%	98,957.	100%

Table 2 : The portion of individual structural parts in total RPC amount

The total quantity of RPC for the execution of all bridge elements, without the abutments and foundations, amounts $98957/(1320*35.5)=2.11\ m^3/m^2$ for the arch of 1000 m in span and $1.75\ m^3/m^2$ for the arch of 750 m in span[iii].

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