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To cite this article: Jan Trenz *et al* 2020 *IOP Conf. Ser.: Mater. Sci. Eng.* **960** 042070

IOP Conf. Series: Materials Science and Engineering **960** (2020) 042070 doi:10.1088/1757-899X/960/4/042070

Experimental model of plan curved footbridge supported by arch

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Abstract. The new type of plan curved structure with the upper deck has been developed within the research of arch structures. The paper describes the process of the research and the design of the physical model in scale 1:10 built for testing of the structure type. The design of the structure has been based on observation of static and dynamic behaviour of arch structures of various radii of plan curvature. Internal forces, deformations and natural modes were monitored for different methods of the design. At first, a simplified method of designing plan curved structures with arch situated in the bridge axis has been investigated and the behaviour of structures designed in accordance with this method has been studied. It has been discovered that simplified method can be used for design of structures with plan curvature radius of 250 m or higher. After investigation of other design methods, the method based on inversion of suspension cable has been chosen for further development. The method has been improved with processes that allow the application for plan curved structures. The result is a plan curved structure supported by a spatial arch. The geometry of the arch corresponds with ideal thrust line of the arch for given permanent loads. The composite structure with steel arch of span of 60,0 m with radius of plan curvature of 37,5 m has been designed and analysed thoroughly in MIDAS Civil software. The behaviour of the calculation model has been compared with behaviour of physical model in scale 1:10 that has been built in laboratory of the Faculty of Civil Engineering of BUT. Results have demonstrated that calculations and measurements correspond.

1. Introduction

Arch structures with the upper deck can be very rarely seen among plan curved footbridges (see [1]). It is not clear why architects and bridge engineers omit this structure type. The reason can be the construction difficultness or the absence of a universal design approach for determination of ideal shape of these arch structures. The research team from the Faculty of Civil Engineering of the Brno University of Technology has decided to examine them thoroughly in theory and build a physical model in scale 1:10 to verify presumed behaviour of such structure.

2. Investigation of arch shape

Before the actual construction of the physical model, it was essential to determine the shape of the investigated structure so the arch is subjected mostly by axial force and only minimal or no bending moments. In the first phase, the shape was determined by simplified method based on bending of straight structure with arch situated in the deck axis around theoretical cylindrical surface (see figure 1). The influence of various curvature radii was investigated on arch footbridge of total length of 60 m. The structure consisted of composite deck and steel arch that were connected by steel struts. The arch was connected with the deck in its crown as well. Both arch and deck were fixed into the supports. Internal forces, deformations and natural modes of structures with radii of plan curvature of 500 m, 250 m, 100 m, 50 m and 25 m were investigated and compared (together with reference straight structure). The comparison has demonstrated that the method of simple bending of straight structure is applicable for radius of 250 m or higher; with higher plan curvatures, the influence of bending moments is very high compared to axial compressive force and the main load bearing element is rather curved beam than the arch.

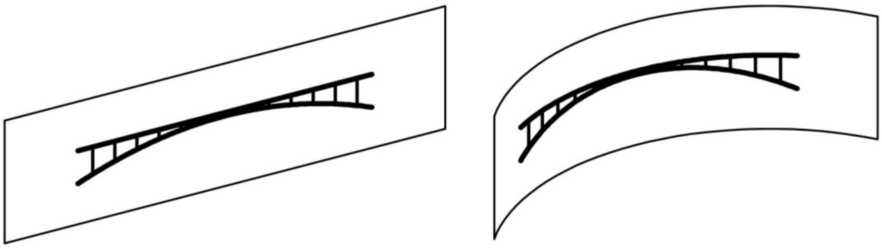

Figure 1. Principle of bending of straight structure around a cylindrical surface.

More convenient method for design has been sought. Among the others such as analytical method, incremental method or old empirical method (more appropriate for vault bridges), the method of inversion of suspension cable (see figure 2) has been chosen and modified for possible application for plan curved structures. The footbridge with radius of plan curvature of 37,5 m and span of 60,0 m has been designed. The total plan camber of the deck has been 15,0 m.

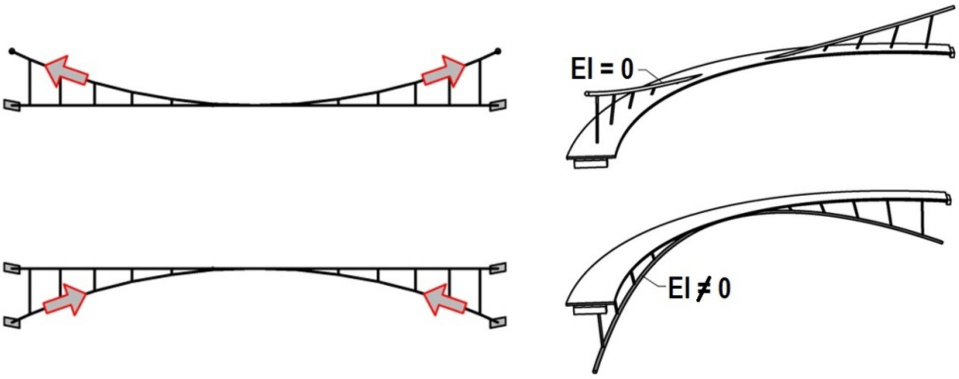

Figure 2. Method of inversion of suspension cable – in plane (left) and in space (right).

The principle of the method of inversion of suspension cable is based on the design of suspension structure of sag equal to the rise of the designed arch. The flexible cable is subjected only to tensile axial forces. If the initial shape of the cable is inverted under the deck and elements of cable replaced by elements of the arch, then with similar boundary conditions the arch should be subjected only to axial compressive force. The four-step algorithm has been developed for finding the optimal shape of the spatial arch, whose shape hasn't corresponded to any traditional mathematical function. Then the final structure has been subjected to detailed analysis with various positions of variable loads.

After the analysis, the structure has been scaled down to 1:10. This structure has been built and tested. The aim was to verify the outcomes from calculation model. It was necessary to include the influence of the ballast load of total weight of nine times of structure's self-weight. According to Model similarity theory, it is requisite for obtaining similar stresses in original structure and in the physical model. The total weight of 2627,0 kg of ballast load has been suspended on the physical model (see figure 3).

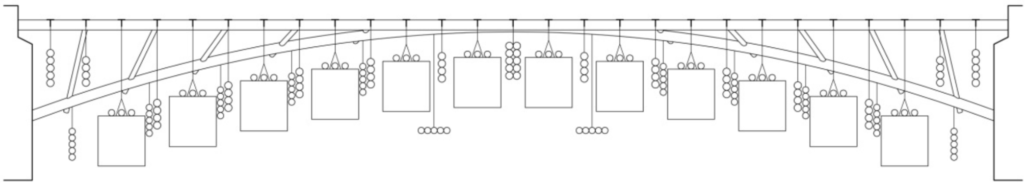

Figure 3. The scheme of ballast load – rectangular concrete blocks and round steel pipes

3. Building of the physical model

The model has been built in laboratory of Institute of metal and timber structures of Faculty of Civil Engineering. Since the possibilities of anchoring of the structure inside of laboratory were limited, the model has been designed as twin-bridge, with the deck supported by an arch on one side and deck suspended on the arch on the other side. In that case, both parts were balanced and it was possible to test two different structures at the same time. The principle is shown in figure 4, visualization of the model is presented in figure 5. Design of the lower arch structure is not the subject of this paper (for more information see [2] or [3]).

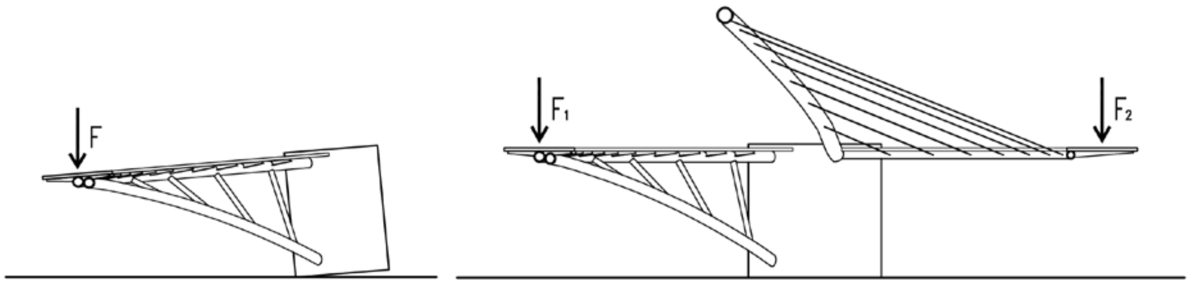

Figure 4. Principle of balancing of two structures – instable model (left) and balanced model (right).

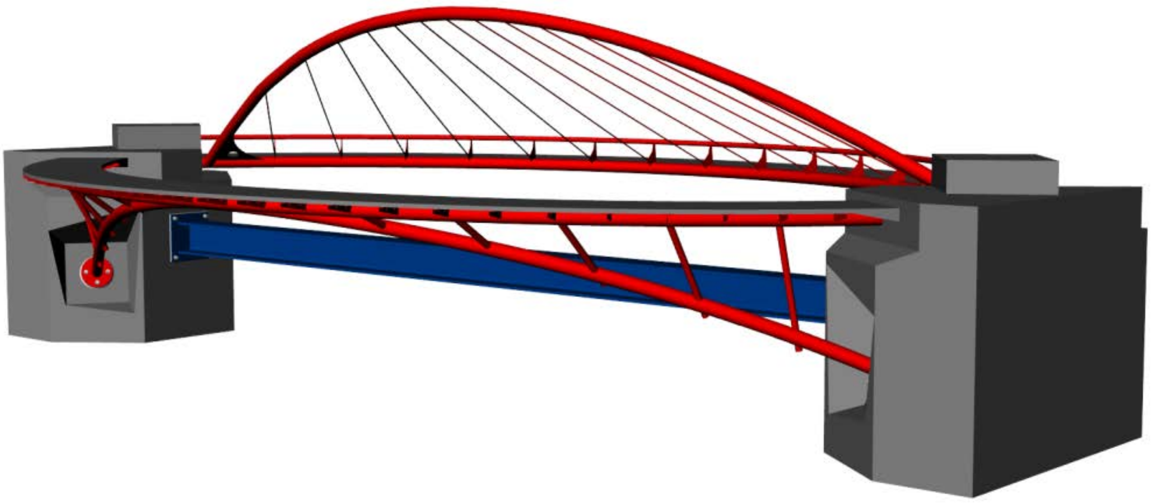

Figure 5. Visualization of the physical model (without ballast load)

Theoretical span of the steel structure was 6,0 m. It was anchored to reinforced concrete blocks of shape of an irregular hexagonal prism (see figure 5 and figure 6). The arch has been bolted to concrete blocks; the deck pipe has been anchored through steel anchor block that has been embedded into the concrete after anchoring.

Figure 6. Concrete block Z1 and reinforcement cage of block Z2

The model has consisted of composite deck, steel arch and steel struts. The deck has consisted of pipe ø70/5 of structural steel S355, bended into plan arch of constant radius of 3,75 m. The length of the pipe between steel anchor blocks was 7,8 m. There were 27 intermediate T-shaped steel crossbeams of variable cross-section of steel plate of 4 mm thickness welded into the pipe in constant distance of 250 mm. The web of each crossbeam has been provided with holes for suspension of ballast load. Steel 1 mm thick plate has been welded on the top of crossbeams, making up a U-shaped trough. It served as formwork for concrete part of the deck – concrete slab of dimensions of 450 x 20 mm. The connection between concrete slab and steel trough has been provided through bolted nuts M8/4.6 in regular grid.

Steel arch has been made of steel pipe ø70/5 of structural steel S355. Both ends were attached with round end plates of thickness of 10 mm, each with 4 holes for anchor bolts. The arch has been connected to deck pipe by 12 struts of variable length made of steel pipe ø33,7/2,6 of S355. In the middle of the span, the arch and the deck have been connected by two welded 8 mm thick steel plates.

Figure 7. Fabrication of steel arch

The construction of the physical model took 3 months, including technological breaks. It was preceded by careful project preparation. The structure was analysed with respect to both limit states, stability and feasibility. The fabrication of the steel part was done by Brno based workshop

MBNS - International, spol. s.r.o. The pipe of the arch was bent in plane according to 1:1 scale template and then it was formed out of the plane by heating into final spatial shape (see figure 7). The structure was mounted and welded together. Concrete blocks were built in a laboratory by research team members. The formula of concrete, which has been used for the deck, was compounded by experts of Institute of Concrete and Masonry structures of the Faculty of Civil Engineering.

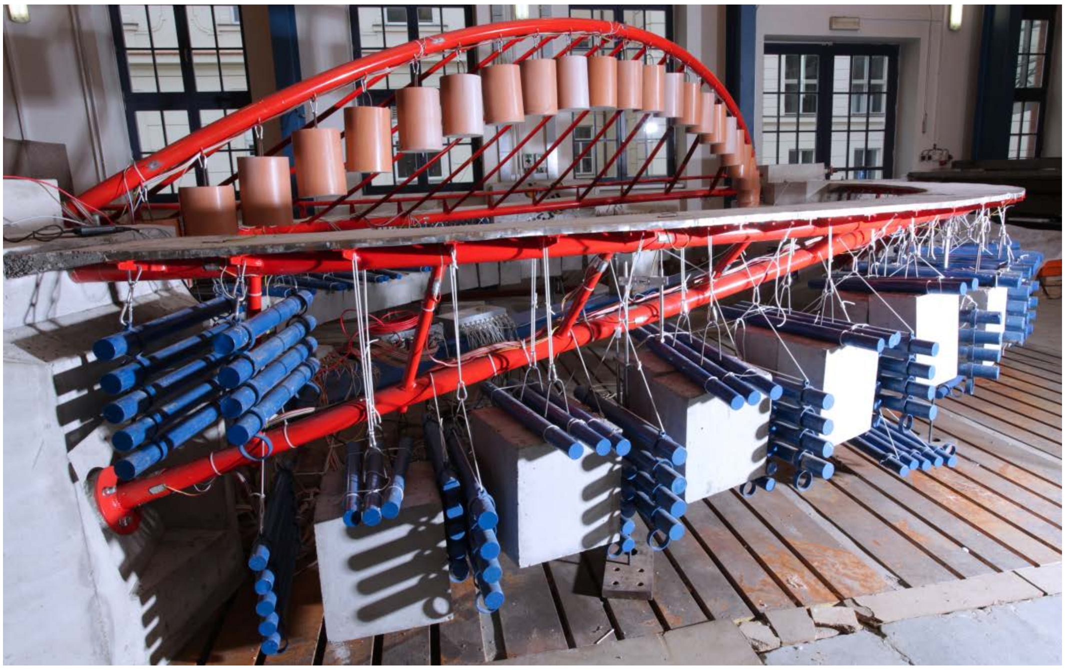

Figure 8. Physical model after the construction (lower arch part in the background)

Figure 9. Physical model after the construction (view from the inside of the model)

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4. Testing and evaluation of the physical model

The structure (see figure 8 and figure 9) has been mounted with 41 strain gauges at various positions on both steel and concrete parts and 5 deflections sensors measuring vertical deformation of the deck in the middle of the span and in both quarters of the span and vertical deformation of the arch in both quarters of its span. For testing, three positions of variable load of 4,0 kN/m^2 has been considered – load on the whole length of the deck, load on the first half of the deck and load on the middle half of the deck (see figure 10).

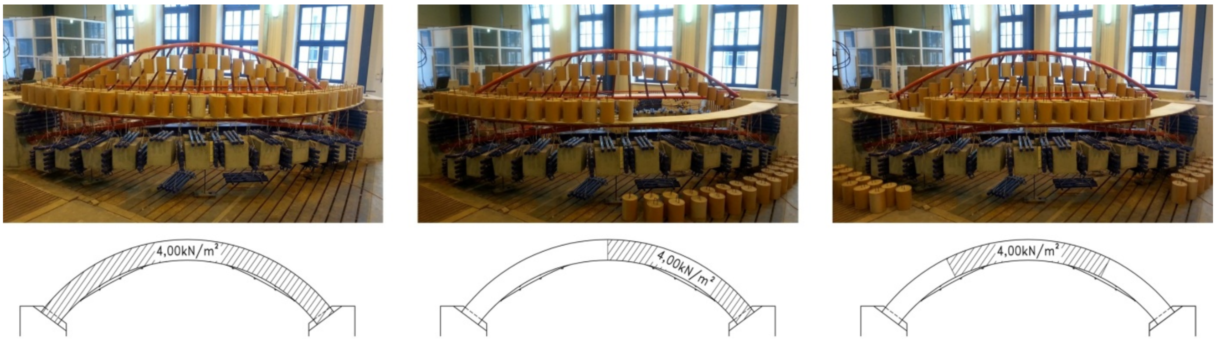

Figure 10. Three positions of variable loads

Further on the structure has been tested for the maximal possible variable load (i.e. maximal possible that could have been applied on the deck, which has been limited with the dimensions of the deck and range of available loading blocks). The structure has been loaded by 19,2 kN/m^2 on the whole length of the deck and 27,9 kN/m^2 on the first half of the deck (see figure 11). In both cases the deck has been subjected to stresses beyond the tensile strength of the concrete, even some cracks have appeared, however, the structure has endured the loads and the ultimate bearing capacity hasn't been achieved.

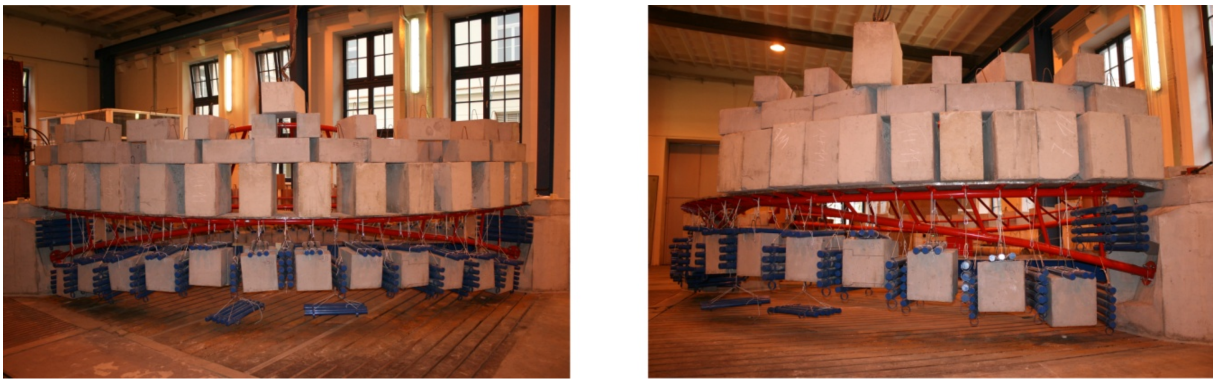

Figure 11. Two positions of variable loads for ultimate test

5. Results and discussions

Observed behaviour of the physical model of upper arch footbridge has helped with understanding of these structures and has exposed some important facts. Modelling of joints of structural elements in calculation model is essential for correct design. Comparison of vertical deformations of the structure (see figure 12) indicates that connection of struts to the steel part of the deck and to the arch (which necessitated drilling holes into each pipe and therefore weakening of the elements) caused a reduction of the overall stiffness of the structure. On the other hand, the connection of the deck and the arch in the crown has been much stiffer than in the calculation model. Therefore, the calculated and measured vertical deformations in the middle of the span are almost similar, but vertical deformations in quarters of the span differ. Consequently, the structure has the same absolute value of the deflection, but the course of the deformation curve is slightly different.

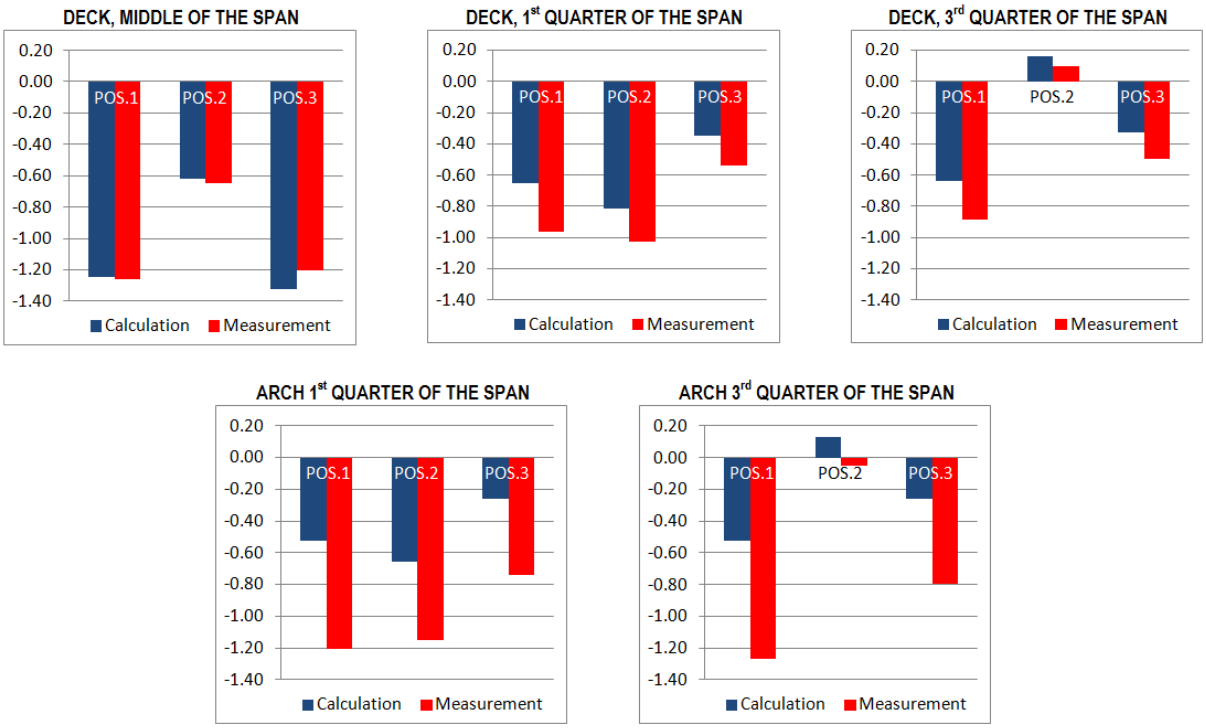

Figure 12. Vertical deformations – comparison of calculation and measurement

Another finding is that real load bearing capacity of structure of this kind is much higher than expected and required by design codes and standards. This can be helpful for bridge engineers during the process of optimization of the real structure.

The process of evaluation of the measurements hasn't been finished yet and the results from strain gauges will provide more information about the behaviour of this new type of the structure. Then results can be used for improvement of calculation models and for further research of spatial structures supported by an arch.

6. Conclusions

It has been demonstrated that it is possible to design plan curved arch bridge structure supported by spatial arch using method of inversion of suspension cable. The comparison between the calculation model and physical model in scale 1:10 has demonstrated the corresponding behaviour and therefore correctness of design approach.

Acknowledgment(s)

The paper has been published and the research intent has been performed thanks to TAČR within the research project TA02011322 "Spatial structures supported by cables and/or arches".

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