A Study on Live Load Effects in Railway Backfilled Arch Bridges

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Abstract. The problem of the arch barrel deformation in railway backfilled arch bridges caused by their typical service loads is analyzed. The main attention is paid to vertical or radial displacements of the characteristic points of the arch barrel. In the study, results of deflection measurements carried out on single- and multi-span backfilled arch bridges during passages of various railway vehicles are used. On the basis of such results empirical influence functions of displacements are being created. In the next step, the results are utilized to estimate bending effects within the arch.

The paper includes different solutions based on measurements of displacements in various points and directions for cases of single as well as multi-span bridges. It presents a potential of the proposed methodology as an effective tool of comprehensive calibration of numerical models of such bridges on the basis of field tests carried out under any live loads. This method may comprise an important element of multi-step assessment procedures for masonry arch bridges.

Keywords: Backfilled arch bridge · Field testing · Numerical analysis · Influence line · Finite Difference Method

1 Introduction

1.1 The Concept of Field Testing

A relatively simple approach proposed in this work to bridge performance monitoring which enables its further numerical static simulation is based on a study on deformations of the arch barrel under traffic actions considered as quasi-static loads. In case of railway bridges, that kind of analysis can be especially effective taking into account symmetry and regularity of the exploitation load scenarios.

The methods related just to measurements of structure's displacements on site has an important advantage which is a possibility to carry out the tests during regular exploitation of bridges – without any disturbance to the traffic [1]. Even if the displacement measurements are limited to a few points on a structure, the obtained results can provide comprehensive information on the structural response to many independent loading cases. Besides, simultaneous recording of displacements in a few points may additionally provide more complete information on the internal effects within the structure, like

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bending effects of the arch. Thus, in this manner such tests may be an efficient calibration tool of bridge numerical models (like those presented in [2] or [3], including also damaged ones [4]) verifying them in a global way.

The measurements of displacements are typically carried out at intrados of the arch barrels [5]. On this basis, influence lines of these displacements are being created [6]. From the variation of the curvature of the arch one can additionally get bending moments. In the analysis the elastic response of the structure is assumed which predicts return to the initial state after passage of a live load along the bridge. Such an assumption is however not satisfied in the analysis of the ultimate load where nonlinear behavior occurs and the structure's deformation becomes irreversible.

Effects of various railway vehicle types crossing a bridge at different speeds are controlled and registered what provides more reliable and more comprehensively verifying data which may be used in a calibration process of the bridge model. The presented testing campaigns are carried out for passages of vehicles at relatively low velocities, therefore the dynamic effects are small and the loads may be treated as quasi-static. Generally, in case of backfilled arch bridges with large mass and damping ratio and especially those with very low or no piers the dynamic influences on their load carrying capacity are relatively limited [7, 8].

1.2 Analyzed Structures

The tests are performed on bridges shown in Fig. 1 located in three towns in Lower Silesia, Poland: Oleśnica, Świdnica and Strzegom. They are, single-, twin- and multi-span structures, correspondingly. Basic geometrical parameters of the bridges related to the arch barrel intrados are presented in Table 1, which are: R – radius of the arch, L_0 – clear span, H – rise of the arch at the crown, B – width of the arch barrel h – depth of the arch barrel. Material of the arches and spandrel walls is also provided.

Table 1. Basic geometrical parameters of the analysed bridges.

Name	No. of spans	Material	R [m]	L_0 [m]	H [m]	B [m]	h [m]
Oleśnica	One-span	Brick	4.97	9.94	4.97	8.55	0.78
Świdnica	Two-span	Brick/stone	5.438	10.00	3.30	4.82	0.75
Strzegom	Multi-span	Plain concrete	13.385	16.64	2.887	4.08	0.71

1.3 Testing Arrangement

Measurement of displacements is carried out by means of LVDT gauges located in points of the arch barrel arranged in a different way for each bridge, which is presented in Fig. 1. In case of Oleśnica, they are distributed along one line across the arch in the mid-span. In Świdnica there are additional gauges at ¼ and ¾ of the span. Finally, for the bridge in Strzegom all gauges are located along a peripheral line of the arch every 1/8 of the span.

During the test various types of vehicles are used, including ET22 and ST44 locomotives used by Polish State Railways as well as a rail excavator.

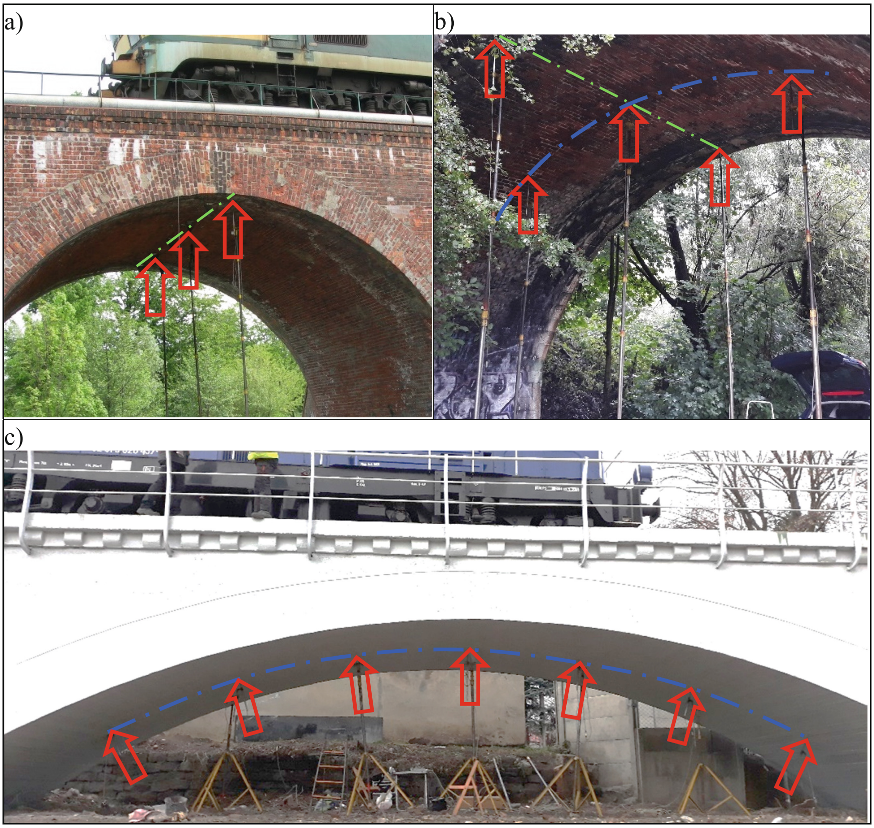

Fig. 1. The arrangement of LVDT gauges in measurements on bridges in: a) Oleśnica, b) Świdnica, c) Strzegom

2 Influence Line of Displacement

2.1 Single-Span Bridge

For the single-span bridge from transformation of direct measurement results of displacements in the mid-span recorded in the time domain $w(t)$ a function $w(x)$ can be received. In the paper, x is assumed as the distance between the middle force of the front locomotive bogie and the crown section. Generated in this this way and averaged from three points located in the mid-span $w(x)$ function for the bridge in Oleśnica is presented in Fig. 2. The diagram $w(x)$ can be further used to create the empirical influence function of the arch crown deflection $\xi(x)$. Accordingly, a general relationship between the arch crown deflections $w(x)$ and ordinates $\xi(x)$ of the influence function corresponding to the location of the successive locomotive axles (with load values P and location x_i) is expressed by the formula:

$$w(x) = P\sum_{i=1}^{n}\xi(x + x_i) \tag{1}$$

To find the values of the influence function $\xi(x)$ a progressive calculation procedure is applied starting from the point $x = x_0$, for which the whole measured deflection is equal to $w(x_0)$ while for all the previous points laying at least in the distance a (corresponding to distance to the next axle) from x_0 it is equal to $w(x_0 - a) = 0$. In case of a single locomotive crossing a bridge a confirmation of the influence function $\xi(x)$ correctness can be the agreement between diagram $w_\xi(x)$ calculated according to Eq. (1) backward from $\xi(x)$ with the diagram of the directly measured deflections $w(x)$ – as it is presented also in Fig. 2.

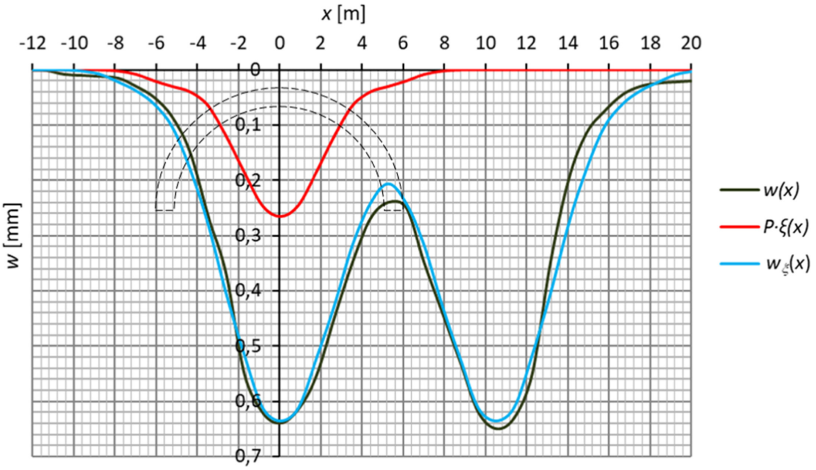

Fig. 2. The measured $w(x)$ deflection variation from the passage of ET22 locomotive and calculated $w_\xi(x)$ from the influence function $\xi(x)$ (presented rescaled by force P) for the bridge in Oleśnica

2.2 Multi-span Bridges

In case of bridges with two or more spans the procedure to obtain the influence line of displacement is the same as for the single-span structure but the resulting diagrams have partially different shape. For the crown section both the $w(x)$ and $\xi(x)$ functions get negative values (displacements upwards) which is related to positions of the load in adjacent spans. This effect is presented in Fig. 3 in the case of the bridge in Świdnica for the crown section (K) as well as for points at ¼ (A) and ¾ (B) of the first span.

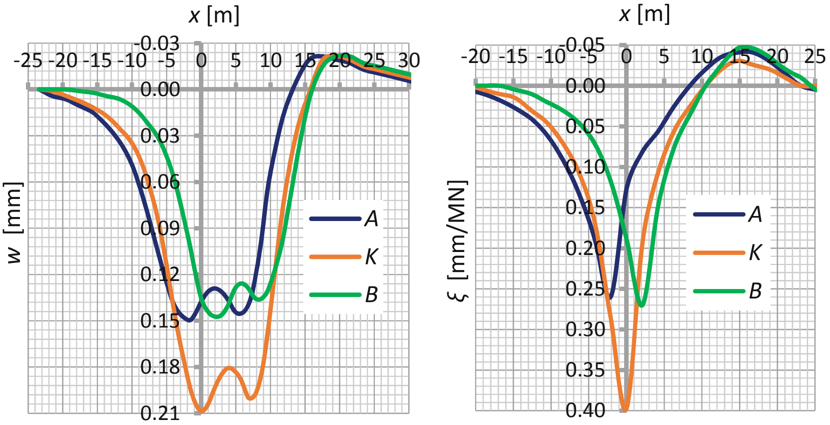

Fig. 3. Results for the bridge in Świdnica: a) deflection variation $w(x)$ under ST44 locomotive and b) influence lines of deflection for points A, K and B

3 Estimation of Bending Effects in Masonry Arches

When displacements are measured at several points located along the circumferential line of the arch intrados, it is possible to estimate the change in the radius of curvature [9]. For this purpose, the *Finite Difference Method* [10] and displacements in radial direction (consistent with the arch radius R) are used. Thus, for the central point K, the curvature κ is obtained from Eq. (2) with the parameters explained in Fig. 4:

$$\kappa = \frac{1}{s^2}\left\{r_A - \left[2 - \left(\frac{s}{R}\right)^2\right]r_K + r_B\right\} \tag{2}$$

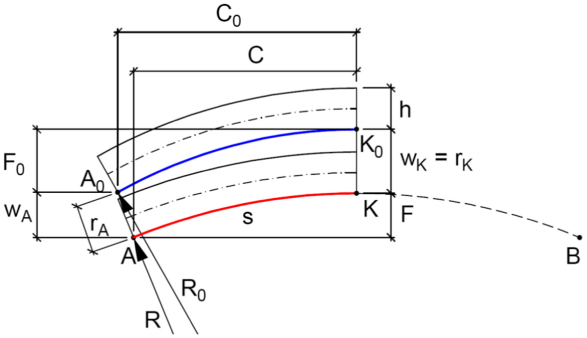

Fig. 4. Diagram of deformation of the arch segment at the crown

Then, the curvature κ may be used to calculate bending moment values taking into account the flexural stiffness (EI) of the arch, according to formula:

$$M(x) = EI \cdot \kappa(x) \tag{3}$$

The bending moment may be calculated as well for any other point along the arch treated as the middle one (K) provided that displacement results in all three points (A, K and B) are available.

Exemplary results are presented in Fig. 5 for the multi-span bridge in Strzegom which is loaded with a rail excavator. For this case diagrams $w(x)$ are obtained for six points (0–5) every 1/8 of L_0 and on this basis the functions $M(x)$ are calculated for intermediate points (1–4) – assuming flexural stiffness $EI = 6045$ MNm^2.

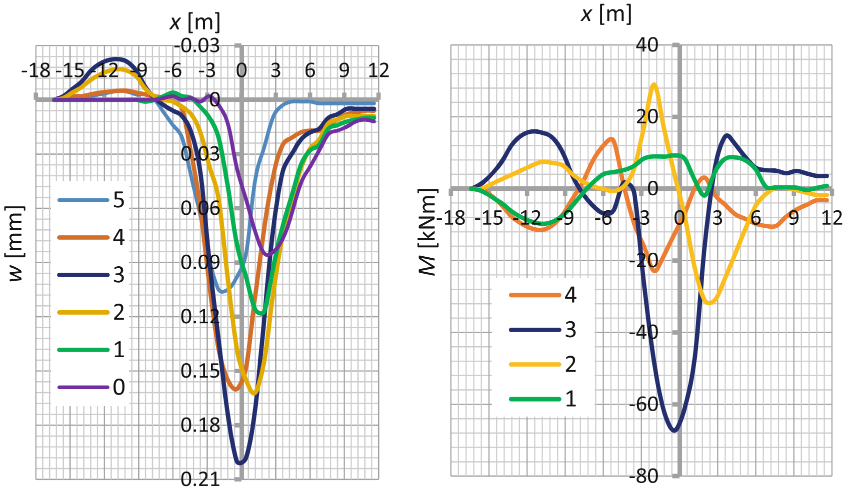

Fig. 5. Results for the bridge in Strzegom: a) deflection variation $w(x)$ in points 0–5 and b) bending moment variation $M(x)$ in points 1–4 as a function of the excavator load position

Taking into account that the measured deflection variations $w(x)$ come from the load triggered by a rail excavator with a very low axle space and therefore may be treated as a concentrated load, the diagrams are simultaneously corresponding to functions $P \cdot \xi(x)$ in the given points, where $P = 200$ kN is the total weight of the vehicle.

The diagrams of the influence line of deflection $\xi(x)$ for three following points A, K and B can be also used to create the influence lines of bending moment $\mu(x)$ for the middle point. According to Eq. (2), if the deflections w_{i} are substituted for the ordinates of influence line of deflection ξ_{i}, one can obtain the expression:

$$\mu = \frac{EI}{s^2}\left\{\xi_A + \xi_B - \left[2 - \left(\frac{s}{R}\right)^2\right]\xi_K\right\} \tag{4}$$

Additional possibility is to create charts of bending moment distribution $M(s)$ along the circumferential line of the arch triggered by a vehicle located in discrete positions. Such results are shown in Fig. 6 for the bridge in Strzegom representing effects of loading by the excavator located at x equal from −3,6 m up to −0,4 m every 0,8 m. The position of the load x [m] given in the legend of the figure, is counting from the crown section. Observing the shape of the $M(s)$ distribution the loading vehicle position may be estimated.

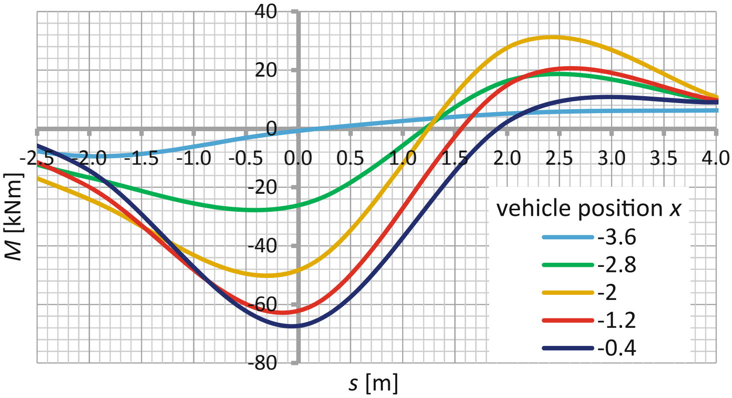

Fig. 6. Bending moment distributions $M(s)$ in the area of the arch crown section for the analysed discrete positions of the vehicle for the bridge in Strzegom

4 Conclusions

The paper deal with testing of the static effects generated by railway vehicles travelling across backfilled arch bridges. Single-track railway bridges with various number of spans are selected for the testing. For a broader discussion of the spectrum of the effects, a diverse loading vehicles in terms of geometry and axle loads are used in the case studies. Besides, a slightly different methodology of measurements and processing of their results are presented in each analysed case.

The main and fundamental effects possible to be experimentally determined are the influence lines of displacements. Additional benefit of measurements is the possibility of estimating the effects of the arch bending on the basis of displacements. These results comprise important information to structural analysis of masonry arch bridges [11] as well as may provide useful and comprehensive data e.g. for calibration of bridge numerical models related to verification of the assumed material properties, invisible geometry or in case of a 2D model its effective width.

The opportunity to get extensive information on the structure and its behavior just from measurements carried out during regular exploitation of a bridge without any disturbance to the traffic is very attractive and in many situations is the only possible solution. The proposed approach is especially useful in analysis of railway bridges undergoing very regular and easily characterized loading schemes, like those represented by locomotives. However it can be also used in analysis of road bridges. The procedure can be based as well on other mechanical effects (including both vertical and horizontal displacements or strains) in any point of a structure. This method may comprise an important element of multi-step assessment procedures for masonry arch bridges, according to those proposed in [12].

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