EXPERIMENTAL AND NUMERICAL STUDY ON DISPLACEMENTS OF MASONRY BRIDGES UNDER LIVE LOADS

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SUMMARY

The problem of the arch barrel deformation in masonry railway bridges generated by their typical service loads is analysed. Attention is paid to displacements of characteristic point of the structure i.e. vertical deflection of the arch crown section. In the study results of deflection measurements carried out on two masonry arch bridges during passages of various typical Polish locomotives are used. On the basis of the measurement results empirical influence functions of displacements are being created. In the next step, taking into account various speeds of locomotives generating the measured deflections, the empirical influence lines are developed. Finally, obtained results are used in calibration of Finite Element models of the bridges. Careful comparison of the experimental and numerical outcomes presents potential of the proposed procedure to be an effective tool of comprehensive calibration of masonry bridge numerical models on the basic of field tests carried out under live loads.

Keywords: *Masonry arch bridge, field testing, influence lines, numerical analysis, Finite Element Method.*

1. INTRODUCTION

Masonry arch bridges are complex structures characterised by many parameters having an important influence on their mechanical behaviour being however sometimes difficult to determine. These technical parameters cover both the material properties of the structural components (precisely defined in diverse laboratory tests only) as well as their geometrical characteristics including those hidden by the backfill and inaccessible for the direct measurements. Therefore a reasonable structural analysis of the masonry bridges becomes a demanding and time-consuming task in case of no technical data on the structure available.

A simpler solution to the problem may be a careful study on the structure deformation under live loads. Especially in case of the railway bridges the that kind of analysis can be effective taking into account regularity of the exploitation load scenarios. The main idea of the approach is related to measurements of the structure displacements on site and its important advantage is a possibility to carried out the tests during regular exploitation of bridges – without any disturbance to the traffic [1]. Even if the displacement measurements are limited to a single point of the structure, like the midspan arch deflection controlled within this study, the obtained results can provide comprehensive information on the structural response to many independent loading cases. Thus, in this way that kind of tests may be an efficient tool of a masonry bridge model calibration verifying it in a global way.

The proposed analysis is presented in two case studies of railway arch bridges with a similar structure. Effects of various railway vehicle types cross them running with different speed are controlled and recorded what actually provides more reliable and more comprehensively verifying data used in further calibration process.

2. EXPERIMENTAL ANALYSIS OF MASONRY BRIDGE DISPLACEMENTS

2.1. Analysed structures

In the analysis two similar single-span brick railway bridges are considered (Fig. 1) with structure, technical condition and age representative for the bridges in this part of Europe [1]. Both of them are located along Polish railway line no. 281: in Oleśnica and Milicz. The bridge in Oleśnica have semi-circular arch barrel with intrados radius R = 4,97 m and thickness h = 0,78 m (assumed theoretical span length L_t = 10,72 m). The bridge in Milicz is differing with intrados radius R = 6,0 m and thickness h = 0,80 m (thus L_t = 12,80 m). The structures have the same width equal to B = 8,55 m and both are dating back about 1875 [2].

Fig. 1. *Analysed bridges during the tests: a) in Oleśnica, b) in Milicz.*

2.2. Applied live loads

Among all types of rail transport vehicles a locomotive has the most regular, invariable in time and easy to determine loading parameters including values of axle loads and spaces between the axles. Wagons of trains can be more diverse regarding these parameters. Therefore only effects of locomotive’s actions crossing the bridges are considered within the presented study. The applied locomotive types and their technical parameters are presented in Tab. 1 and described in Fig. 2 for a representative vehicle.

Table 1. *Technical parameters of the locomotives used in the tests.*

Bridge	Locomotive type	Axle load *P* [kN]	Bogie type	Space between bogies *d* [m]	Spaces between axles [m]		
					a	***b***	***c***
Oleśnica	ET22	200	Co'Co'	10,30	1,75	2,720	6,80
Milicz	ET22	200	Co'Co'	10,30	1,75	2,720	6,80
	EU07	196,2	Bo'Bo'	8,55*	3,05*	2,317	5,50
	E31	203	Co'Co'	10,95	2,40	1,525	6,15
	Dragon	202,2	Co'Co'	10,50	1,95	2,965	6,60

* 4-axle locomotive

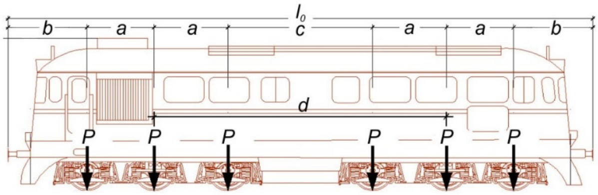

Fig. 2. *Dimensions of a representative locomotive.*

2.3. Testing procedure

The applied testing procedure is based on measurements of the arch barrel deflection during passages of the locomotives across the bridge [3]. Results of deflection measurements used within the study were collected by means of various types of gauges including LVDT gauges, laser distance sensor and microradar equipment (see [4]). The controlled points are located on intrados of the arch barrel in the midspan (crown cross-section). An example of the recorded deflection for the bridge in Milicz during passage of a train (with ET22 locomotive) is shown in Fig. 3.

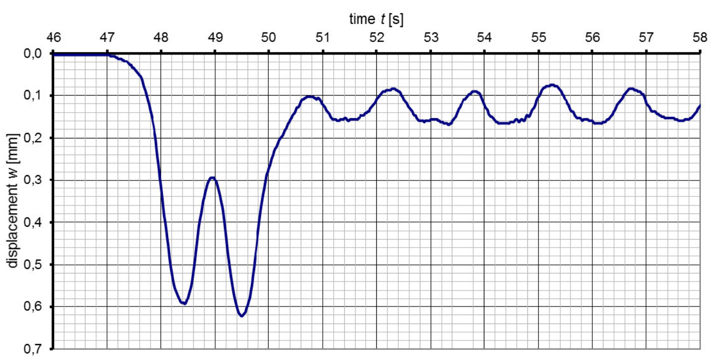

Fig. 3. *An example of the recorded deflection of the arch crown cross-section during passage of a train (with ET22 locomotive) across the bridge in Milicz.*

In the figure specific moments t_1 = 48,4 and t_2 = 49,5 seconds can be indicated when the front and the rear locomotive bogie axes correspondingly are over the arch crown section. Effects of individual three axles of each bogie is invisible due to dispersion of the loads within the track and the bridge structure. Deflection $w(t_2)$ of the arch is also influenced by the first wagon, thus it is higher than $w(t_1)$. Therefore for the further calculation the first branch of the diagram only is taken into account.

Location of the locomotive on the bridge is determined by coordinate x, defined as a distance of the front bogie axis (reference axle) from the arch midspan cross-section (see Fig. 4 and Fig. 5). In case of 6-axle locomotives when x = 0 the reference bogie is located centrally over the arch midspan and both remaining axles of the bogie are in the distance a (to the left and right) from it. The other bogie is in the distance d from the midspan what corresponds to the asymmetrical position (A). For $x = d/2$ both bogies are equally distant from the midspan and the locomotive takes the symmetrical position (S). On the basis of the time difference $t_2 - t_1$ and the distance between bogies the average speed of the locomotive crossing a bridge can be evaluated – what is given in Tab. 2.

Table 2. *Characteristics of locomotive's passages across the bridges.*

Bridge	Passage	Locomotive type	$t_2 - t_1$ [s]	v [m/s]
Oleśnica	V11	ET22	0,95	10,8
Milicz	V10	ET22	1,03	10,0
	V13	EU07	0,66	12,9
	V16	E31	0,70	15,6
	V20	Dragon	0,53	19,8

3. EMPIRICAL INFLUENCE FUNCTIONS OF DISPLACEMENTS

Taking into account the speed of the locomotive one may transform the diagram $w(t)$ (like the one in Fig. 3) into the diagram $w(x)$. Exemplary diagrams of this type are given in Fig. 4 and Fig. 5 which can be further used to create empirical influence functions of the arch crown deflection $\xi(x)$. For this purpose constant axle load values P given in Tab. 1 for each case are assumed. Accordingly, a general relationship between the arch crown deflection $w(x)$ and ordinates $\xi(x)$ of the influence function corresponding to the location of the locomotive axles is expressed by a formula:

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

where: x – location of the locomotive reference axle against the arch midspan section, x_i – location of the consecutive locomotive axles i against the reference axle, n – number of locomotive axles.

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 measured deflection is equal to $w(x_0)$, while for all previous points laying at least in a distance away from x_0, it is equal to $w(x_0 - a) = 0$. Thus, at the beginning of the analysis the initial position of the first axle load is considered as follows:

$$w(x_o) = P \cdot \xi(x_0 + a)) \tag{2}$$

From the formula (2) the function value $\xi(x_0+a)$ can be calculated taking into account $\xi(x_0) = 0$. The second function ordinate is being calculated for a point in a distance from the previous one, according to the formula:

$$w(x_o + a) = P[\xi(x_o + a) + \xi(x_o + 2a)] \tag{3}$$

When the locomotive third axle appears in the active range of the influence function the corresponding formula takes a form:

$$w(x_o + 2a) = P[\xi(x_o + a) + \xi(x_o + 2a) + \xi(x_o + 3a)] \tag{4}$$

from where the function value $\xi(x_0+3a)$ can be found, since from the previous formulas the ordinates $\xi(x_0+a)$ and $\xi(x_0+2a)$ were already calculated.

Further procedure carried out with subsequent positions of the locomotive defined by $x = x_0 + i \cdot a$ allows to find the next ordinates of the influence function $\xi(x)$.

Fig. 4 presents the shape of the deflection influence function $\xi(x)$ calculated according to the described procedure for the structure in Oleśnica on the basis of ET22 locomotive crossing the bridge itself. For the compatibility of the units with the diagrams $w(x)$ the ordinates ξ are multiplied by axle load P, treated here as a constant factor. In case of a single locomotive crossing a bridge the confirmation of the influence function $\xi(x)$ correctness should be an agreement between diagram $w_\xi(x)$ developed backward from $\xi(x)$ with the diagram of the directly measured deflections $w(x)$ – as it is presented also in Fig. 4 – according to the formula:

$$w(x) \cong w_\xi(x) = P \sum_{i=1}^{n} \xi(x + x_i) \tag{5}$$

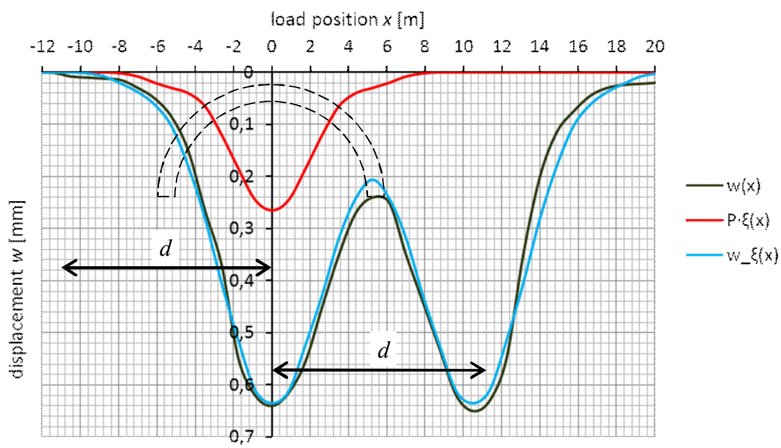

Fig. 4. Comparison of the arch crown deflections of the bridge in Oleśnica (generated by ET22 locomotive) directly measured during the tests (w(x)) and calculated ($w_\xi(x)$) from the influence function ξ(x) (presented rescaled by force P).

The lack of a prefect agreement between the diagrams $w(x)$ and $w_\xi(x)$ can arise from many reasons including: imprecision of measurements, different real axle loads, variable speed of the locomotive, various directions of the travelling vehicles (including the direction of a preceding run), nonlinear behaviour of the real structure or effects of the dynamic action of the loading vehicles [5]. It is worth to notice that the range of a half of the influence function shown in Fig. 4 is equal to about 8 m. It indicates that the action of the locomotive on the masonry arch starts when the reference axle of the vehicle is in a distance slightly lower than the clear span L from the arch crown section.

Analogical diagrams are presented in Fig. 4 for the bridge in Milicz also on the basis of ET22 locomotive passage. In this case additional influence of wagons following the locomotive is visible in the diagram $w(x)$ but practically for $x > d/2$ only. For the bridge in Milicz the range of a half of the influence function shown also in Fig. 5 is more or less equal to span length L. Besides, the first extreme of the function $w(x)$ is located for $x > 0$. It is caused by influence of both locomotive bogies on the deflection in this point related to aforementioned wide range of influence function $\xi(x)$ – in this case being wider than d (what is indicated in Fig. 5). The second extreme $w(x \approx 10{,}75$ m) is slightly higher than the first one $w(x \approx 0{,}75$ m) what is related to influence of the first wagon.

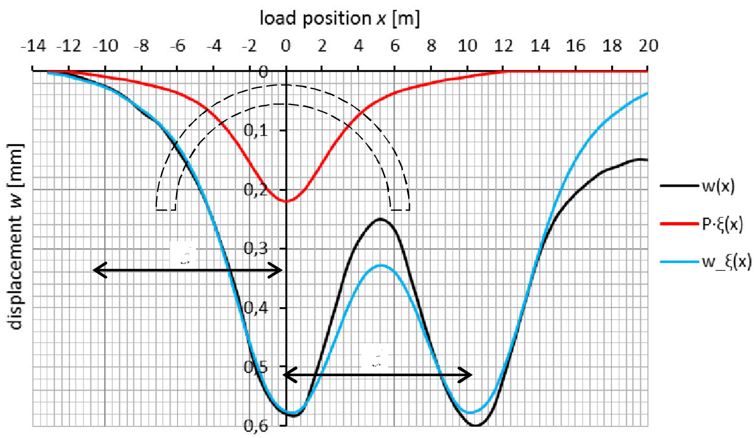

Fig. 5. *Comparison of the arch crown deflections of the bridge in Milicz (generated by ET22 locomotive) directly measured during the tests (w(x)) and calculated ($w_\xi(x)$) from the influence function ξ(x) (presented rescaled by force P).*

4. INFLUENCE LINES OF THE ARCH CROWN DISPLACEMENTS

In the structural analysis of bridge structures the influence lines of internal forces and displacements $\eta(x)$ find a common application. That kind of function is a feature of the structure which is independent of the load nature since it is determined from a single static unit force. In case of finding of the influence function of deflection $\xi(x)$ carried out within this study the deflection of the arch generated by vehicles composed of many axles travelling with various speeds are taken into account.

In Fig. 6 all influence functions of deflection $\xi(x)$ calculated according to the procedure presented in the previous chapter on the basis of deflections of the arch bridge in Milicz measured during various locomotive runs are given together.

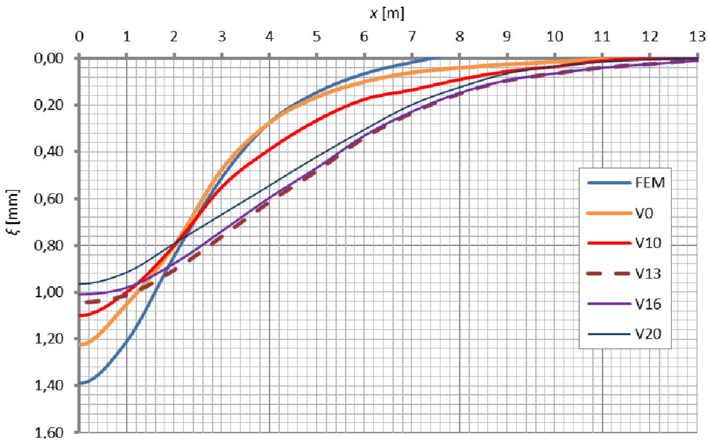

Fig. 6. *Influence functions ξ(x) of the arch in Milicz obtained on the basis of measured deflections (for various locomotive speeds V10-V20) and extrapolated (V0) – compared with calculation (FEM).*

Diagrams V10-V20 (presented in Fig. 6) calculated for the bridge in Milicz, corresponding to speeds given in Tab. 1, have different shapes which are not related to various geometry of the locomotives. The crucial feature of the diagrams is their dependence on the speed of the running locomotives. According to the results the extreme ordinate ξ_{max} equal to $\xi(x=0)$ is getting higher with the decrease of the speed v. Taking into account the previous statements the influence function of deflection $\xi(x)$ should be compatible with the influence line of deflection $\eta(x)$ when the speed of the vehicle applied during measurements is $v \approx 0$. The difference between $\eta(x)$ and $\xi(x)$ corresponding to various speeds is not caused by the effect of the dynamic vibrations (which can be treated as negligible according to diagram in Fig. 3) but most probably is related to large inertia of masonry bridges responding with some delay to the loads.

Anyway, separate extrapolation of ordinates of influence functions of deflection $\xi(x)$ for various speeds but for the same location x gives the influence function of deflection $\xi_0(x)$ corresponding to zero speed which is also presented as V0 diagram in Fig. 6. Such extrapolation should eliminate all unknown effects manifesting themselves in speed dependent shapes of the function $\xi(x)$ and finally give the experimentally based diagram of the influence line $\eta(x)$.

5. FINITE ELEMENT ANALYSIS

5.1. Modelling technique

Two-dimensional FE models are applied in analysis of both considered bridges representing the effective width of the structures equal to half of the total width. They are composed of a masonry arch barrel, masonry backing, soil backfill and pavement layer (see Fig. 7). The extent of the models covers the area of the soil about 20 m away from the arch to both sides to consider the most distant positions of the live loads.

The masonry arch is modelled with application of so called mezomodelling technique [6], related to direct representation of selected radial masonry joints in the model and using average (homogenized) masonry properties for the remaining area of the arch.

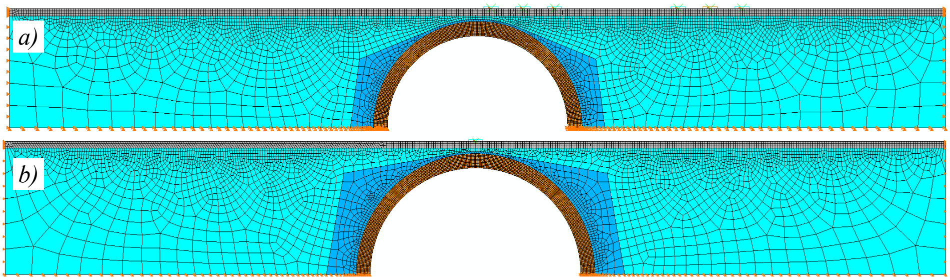

Fig. 7. FE models of the analysed bridges: a) in Oleśnica and b) in Milicz.

Defined properties of all materials are determined by means of field and laboratory testing as well as on the way of numerical calibration based on loading test results; farther details on it can be found in [4]. The live loads represent action of the locomotive axles; each axle is applied to the top of the pavement layer as a pressure uniformly distributed over a width equal to 80 cm.

Within the carried out analysis the deflection of the arch barrel intrados in the midspan is controlled. Various loading scenarios are considered including: action of a single axle located in positions along the whole model differing by 1 m – to create a numerical influence line of deflection as well as action of selected locomotives in positions corresponding to those recorded during measurements.

5.2. Results of analysis

Two essential types of the analysis results were collected and compared with the corresponding measured values:

- the influence lines of deflection in the arch midspan (presented in Fig. 6 for the bridge in Milicz) – created on the basis of individual analyses for various position of a single axle load,
- deformation of the whole structure (presented in Fig. 7 and Tab. 3) – triggered by selected positions of the considered locomotives.

The first type of results given in Fig. 6 is compared with the influence function corresponding to zero speed of a locomotive which is developed by means of extrapolation from the measurement results for various speeds. The second type shows the global response of the masonry bridges to typical railway loads represented by FE models (Fig. 7). Precise control of the calculated deformations of the arch mid-span section of the bridge in Milicz triggered by all locomotives – each located in two specific positions A and S – is presented in Tab. 3. These numerical results w_c are compared to the directly measured w_v (at a given speed) and to extrapolated w_0 deflections. The extrapolated deflections are recalculated according to the formula:

$$w_0(x) = P\sum_{i=1}^{n} \xi_0(x + x_i) \tag{6}$$

where: $\xi_0(x)$ – extrapolated influence function of deflection corresponding to zero speed (presented in Fig. 6).

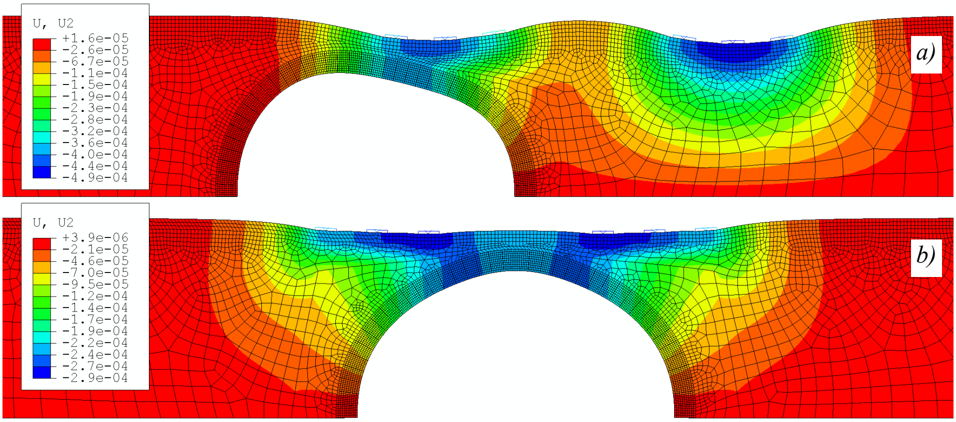

Fig. 8. *Deformation calculated in FE models: a) of the bridge in Oleśnica under ET22 locomotive, b) of the bridge in Milicz under symmetric position of DRAGON locomotive.*

Only the comparison of the calculated values with the extrapolated measured deflections (corresponding to v=0) shows good compatibility of the results while the results of direct measurements of the train passages significantly differ from the FE based calculations. The average discrepancy expressed on the percentage basis between w_0 and w_c considering all loading cases is very low being equal to $\overline{\omega}$ = -4.6 %.

Table 3. *Comparison of the measured and calculated deflections of the bridge in Milicz.*

Passage	Loco-motive position	Directly measured deflection w_v [mm]	Extrapolated measured deflection w_0 [mm]	Calculated deflection w_c [mm]	Discrepancy $\omega = (w_c - w_0)/w_0$ [%]
V10	A	0,508	0,595	0,562	-5,5
	S	0,245	0,236	0,233	-1,3
V13	A	0,375	0,385	0,369	-4,2
	S	0,256	0,274	0,261	-4,7
V16	A	0,504	0,522	0,487	-6,7
	S	0,453	0,248	0,235	-5,2
V20	A	0,509	0,573	0,536	-6,5
	S	0,410	0,240	0,233	-2,9
					$\overline{\omega}$ = -4,6%

6. CONCLUSIONS

The presented procedure of testing and analysis of masonry arch bridge deflections under live loads may be an effective method of a comprehensive calibration of bridge numerical models including verification of the assumed material properties, invisible geometry or, in case of a 2D model, its effective width.

The opportunity to get sufficient results from measurements carried out during regular exploitation of a bridge without any disturbance to the traffic is very attractive and in many situation makes the testing possible at all [1]. The proposed approach is especially useful in analysis of railway bridges undergoing very regular and easily characterised loading vehicles 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 structural point other than the midspan section presented within this work.

Calibration process carried out on the presented bridge FE models according to the proposed procedure enabled formulation of conclusions about specific mechanical features of the bridges. First, large area of the soil in the approaching zones of the bridge (reaching at least L outside the arch springing) needs to be included in the model to eliminated impact of the side boundary conditions and to enable consideration of live loads affecting the arch even from large distance. Besides, an essential meaning of the surrounding backfill properties (found to defined by very large modulus of elasticity exceeding 100 MPa) as well as the shape of the masonry backing (presented in Fig. 7) to the behaviour of the arch was discovered. Finally, an evident participation of the railway pavement in the bridge stiffness is visible which also significantly influence distribution of concentrated axle loads and therefore is indispensable in to be included in the model to provide compatibility of the numerical results with the values measured on the real structure.

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