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Evaluation of Dynamic Characteristics of Masonry Arch Bridges: Linking Full-Scale Experiment and FEM Modeling

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Abstract The paper presents calculated and experimentally determined dynamic characteristics of masonry arch bridges. Two bridges were considered: the road viaduct at Zaborow and the bridge at Kamienica Dolna (South Poland). Finite element models were built considering all parts of the structures: arch, spandrel walls, fill, soil-structure interaction. For verification of calculations *in situ* investigations of dynamic characteristics of bridges were conducted. As a basic ways of realization of dynamic loads impulse load (drop of a lorry wheels from a threshold) as well as kinematic excitation (train passage under the viaduct) were applied. For determination of natural frequencies power spectral density function and transfer function of measured signals were applied. Basing upon the recorded vibrations the value of logarithmic decrement of damping was evaluated. The results of measured and calculated natural frequencies were compared. With regard to the degree of complexity of structures the differences between experimental and computational results can be accepted.

Keywords: Masonry arch bridge, dynamic characteristics, in situ dynamic investigation

Introduction

Masonry arch bridges built by the end of the XIXth are frequently exploited up till now in the road system all over the world. Adaptation of the roadways and pavements to the increased traffic is the basic problem conditioning further functioning of these objects in the road network. Another problem lies in occurrence of new types of dynamic loads excited by passages of heavy vehicles or other dynamic loads resulting from vibrations of ground (high speed train passages, mining shocks). Answering the question: how harmful these new types of loads are for the existing objects? often requires in situ investigations of bridges. In dynamic analysis measurements are usually applied for checking theoretically determined dynamic characteristics of objects: natural frequencies, modes of vibrations and damping (Cantieni et al. 1995, Cunha et al. 2005).

Correct recognition of dynamic characteristics of the object permits a proper interpretation of the results of further investigations of structure response to dynamic loads. Studies on problems of dynamic characteristics calculations and their experimental verification of masonry arch bridges shown in this paper were linked with the program of adaptation of these objects to increased road traffic with preservation of their monumental character. This task required linking full-scale experiments with finite element modeling of objects.

Structural Properties of Investigated Bridges

Full-scale experiment and finite element method modeling were carried out for two stone arch bridges functioning up till now in the road network of South Poland. The first of these objects is a road viaduct in Zaborow over a railway line Rzeszow-Jasło and the other one is a bridge in Kamienica Dolna on the road Pilzno-Jaslo (Fig. 1).

The viaduct at Zaborow is constituted of a stone arch of a span length 9.20 m and width 8.30 m. The arch was constructed of sandstone blocks on lime mortar. The thickness of arch is 0.55 m in the viaduct keystone and 0.65 m in the abutments. The spandrel walls were built of sandstone 0.60 m thick. Access to the viaduct leads by earth embankments. The whole object is in poor condition. The mortar underwent degradation what caused loosening of wall fragments.


Figure 1: The road viaduct at Zaborow (left) and the bridge at Kamienica Dolna (right)

The bridge at Kamienica Dolna was built in 1860. A stone arch was constituted of sandstone blocks at that time. The structure, however, underwent principal changes being subjected to consequent renovations and adaptations to the requirements of increasing loads from road traffic. At present a stone-concrete arch of 11.0 m length and 8.7 m height. The thickness of the arch in the key stone equals 0.6 m, and in the abutments 0.85 m. The spandrel walls are 1 m thick. The bridge has wing walls 0.4 m thick as well.

Material parameters necessary for calculations were obtained from investigations carried out during reconstruction of the bridge at Kamienica Dolna.

Use was also made of data available in papers (Boothby 2001, Fanning and Boothby 2001). The authors of these papers give the intervals of values of material constants of particular structural elements of stone bridges obtained from in situ investigations: arches, spandrel walls, wing walls, fill and the co-operating ground. In Table 1 material data of the viaduct Zaborow and the bridge at Kamienica Dolna are given.

Table 1: Material properties of the viaduct at Zaborow and the bridge at Kamienica Dolna

	Viaduct at Zaborow				*Bridge at Kamienica Dolna*			
	Arch	Spandrel walls	Fill	Asphalt	Arch	Spandrel walls	Fill	Asphalt
Elasticity modulus E [GN · m^{-2}]	5.0	4.0	1.5	1.8	15.0	12.0	1.5	2.0
Poisson ratio ν [-]	0.22	0.22	0.20	0.18	0.22	0.22	0.20	0.18
Mass density ρ_m [kg · m^{-3}]	2500	2500	2300	2000	2600	2600	2400	2100

Analytical Determination of Natural Frequencies

In calculation of frequencies and modes of vibrations use was made of finite element models in which all parts of bridges, i.e. stone arch, spandrel walls and fill were taken into regard. Interaction of structures and earth embankment on which access roads to the viaduct lead was taken into consideration. For calculations of dynamic characteristics of bridges the ABAQUS program was used.

Fig. 2 presents four modes of vibrations of the viaduct at Zaborow. It should be noticed that the spectrum of natural frequencies is very compact. This fact causes some difficulties in identification of consequent frequencies during in situ investigations, since the dynamic response of the structure is composed of all modes.

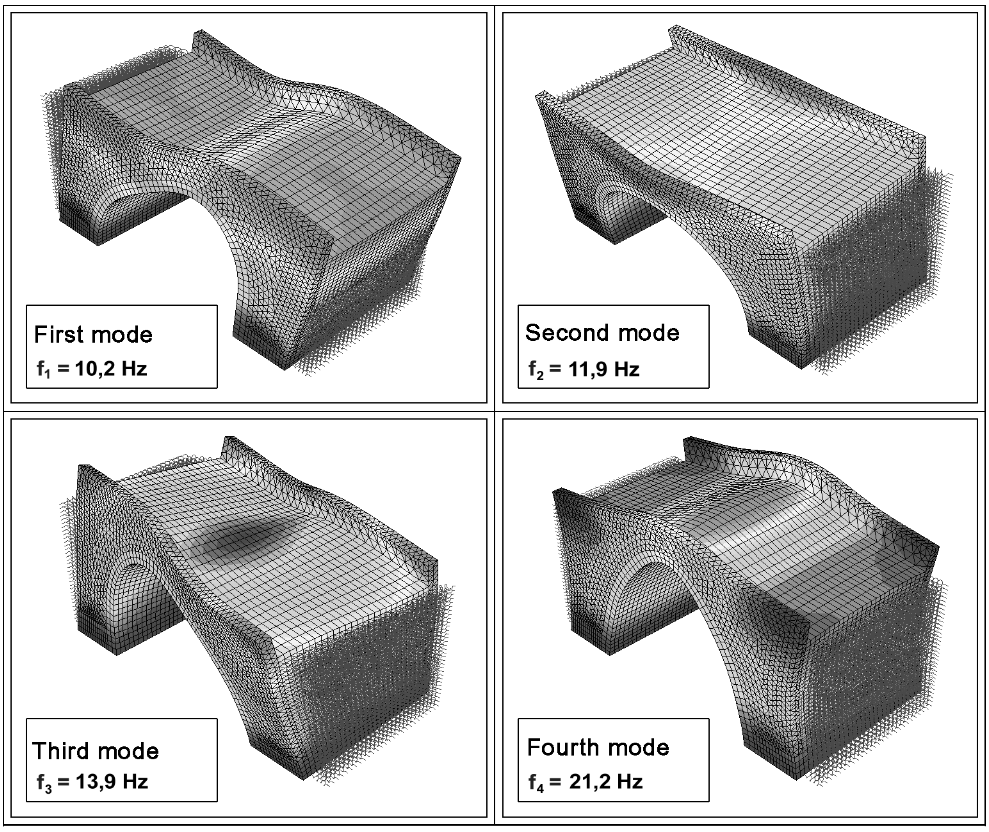

Figure 2: Frequencies and modes of free vibrations of the viaduct at Zaborow

Experimental Determination of Natural Frequencies

Authors of experimental determination of dynamic characteristics of masonry bridges present various ways of dynamic load realization serving at determination of frequencies, modes of free vibrations and damping (Rebelo et al. 2005, Sepe et al. 2005).

For experimental verification of dynamic characteristics of bridges the following sources of vibration were applied: impulse load – drop of lorry wheels from a threshold 5 cm high, located at ¼ of the bridge span, kinematic excitation – train passage under the viaduct (only at Zaborow, see Fig. 1). On the viaduct structure four measurement points were located (Fig. 3). Points A and B are on the piers directly above the ground, points C and D are located in the keystone of the bridge and in ¼ of the span respectively. In every point accelerators were placed in the horizontal direction paralleled to the axis of the viaduct (X) and in the vertical direction (Z).

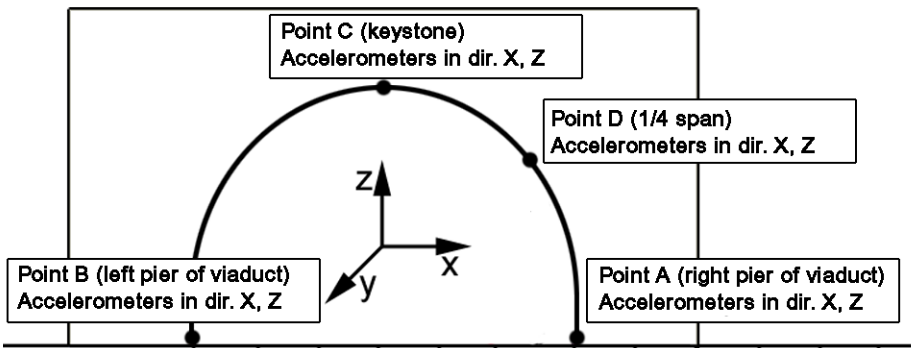

Figure 3: Location of measurement points on the viaduct structure

The spectral analysis of time traces of vibrations excited by lorry wheels drop onto the bridge surface permitted determination of natural vibration frequencies of the viaduct. The first natural

frequency obtained from power spectral density (PSD) function of signal presented in Fig. 4 equals 9.9 Hz.

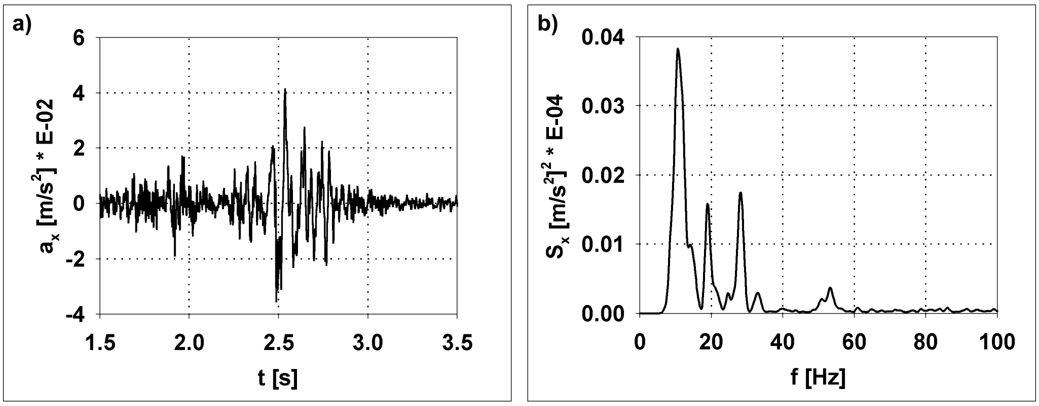

Figure 4: Accelerations of vibrations in point C in horizontal direction (X) from lorry wheel drop from the threshold: (a) time traces, (b) PSD function

In the analysis of vibrations excited by train passage under the viaduct the frequency of natural vibrations was determined by use of the complex transfer function H(f) of the signals recorded in measurement points A ad C. The modulus of transfer function shows the maxima at values corresponding with the natural frequencies.

Fig. 5 shows time traces of accelerations in horizontal direction (X) in point A (right pier of the viaduct) and in point C (keystone). The transfer function |Hx(f)| of these signals presented in Fig. 6 shows first maximum at the frequency of 11.25 Hz. This result is in good agreement with value of the first frequency of free vibrations determined with previous experimental method.

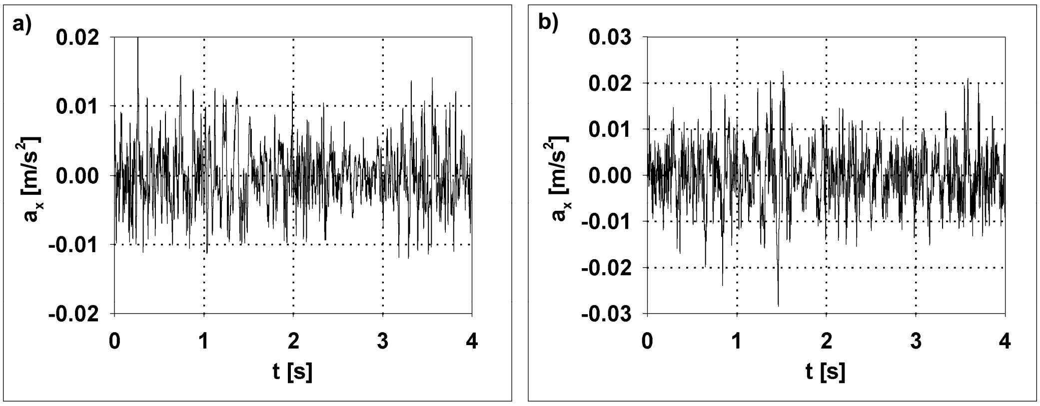

Figure 5: Time traces of accelerations from train passage recorded in horizontal direction (X): (a) in point A (right pier), (b) in point C (keystone)

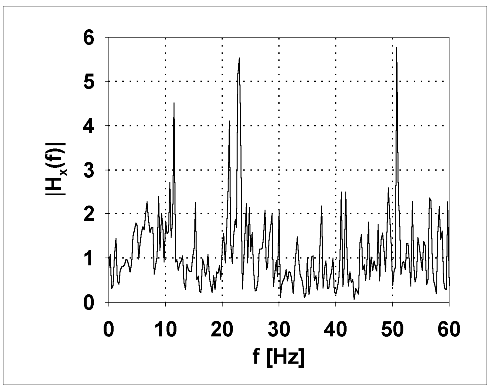

Figure 6: Transfer function modulus, $|H_x(f)|$, of signals in points A and C in horizontal direction (X)

A similar investigations were performed in the case of the bridge at Kamienica Dolna. Frequencies of natural vibrations of the viaduct at Zaborow and the bridge at Kamienica obtained in result of measurements and determined by calculations are compared in Table 2.

Table 2: Comparison of calculated and experimentally determined natural frequencies of the viaduct at Zaborow and bridge at Kamienica Dolna

		Frequency [Hz]					
		Viaduct at Zaborow			Bridge at Kamienica Dolna		
		f_1	f_2	f_4	f_1	f_2	f_4
Measured	Impulse load (lorry)	9.9	12.1	-	8.65	16.00	17.50
	Kinematic excitation (train)	11.25	-	23.0	-	-	-
Calculated		10.2	11.9	21.2	8.72	15.15	17.00

A comparison of natural frequencies measured by use of various methods and calculated shows their good agreement. Considering the degree of structures complexity (Ellick and Brown 1994) as well as necessity of adoption of some data from literature, the existing differences reaching 12% between the results obtained from experiments and calculations can be accepted.

In determining natural frequencies on the basis of vibration occurring in consequence of drop of lorry wheels, the fact that car remains on the structure while the dynamic response is recorded should be taken into consideration. The additional mass on the bridge span lowers the frequency and influences the modes of free vibrations. This effect is in agreement with observations of other authors who investigated dynamic characteristics of stone arches not being under load and remaining under additional load in the middle of the span (Boothby et al. 1998). Differences between measured and calculated values may also result from simplifications applied in the finite element models in which neither cracks and losses in spandrel walls, nor changes of the elasticity modulus of the fill in dependence on compressive stresses were considered.

Experimental Determination of Damping

Basing upon the recorded time traces of accelerations caused by drop of lorry wheels from a threshold the value of the logarithmic decrement of damping δ was estimated. Fig. 7 shows time traces of accelerations in point D in horizontal direction (X) after using lowpass filter of frequency 18 Hz to separate first mode of vibration. Approximate value of the logarithmic decrement of damping δ and fraction of critical damping ξ determined of the basis of Fig. 7 equals:

$$\delta = \frac{1}{m}\ln\left(\frac{A_n}{A_{n+m}}\right) = \frac{1}{3}\ln\frac{2,3}{0,6} = 0,448, \quad \xi = \frac{\delta}{2\pi} = \frac{0,448}{2\pi} = 0,07$$

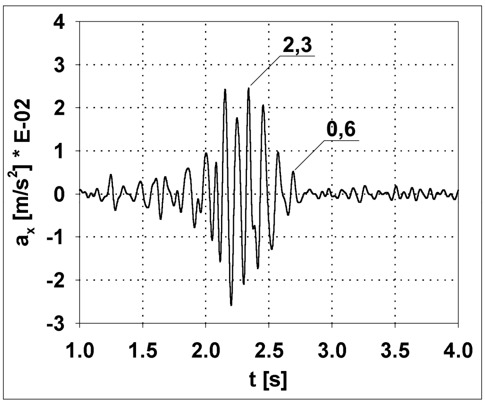

Figure 7: Time traces of accelerations in point D in horizontal direction (X)

After a number of attempts at determination of the value of the critical damping fraction on the basis of recordings of damped free vibrations in points C and D the value included in the interval 6–9% was obtained. The obtained values of the critical damping fraction are in good agreement with values given by other authors on the basis of stone bridge measurements.

Conclusions

Taking into regard the above presented analysis general conclusions can be formulated:

1. The frequencies obtained from theoretical calculations are in good agreement with frequencies obtained from experimental analysis of vibration traces.
2. Investigations confirmed that old stone bridges are structures of relatively high frequencies of natural vibrations and considerable damping, reaching 9% of critical fraction.
3. A proper recognition of elasticity constants of particular elements of the structure is especially significant for calculations of frequencies and modes of free vibrations.
4. In determining dynamic characteristics of old masonry bridge structures diagnosis of their technical state, i.e. condition of stone, mortar, damage of arch and spandrel walls, is essential.
5. The frequency spectrum in compact. The final response of the structure to dynamic actions will be composed of bending and torsional modes of vibrations in all directions.
6. Taking into regard results of full-scale experiments and analytical calculation it may be stated that the physical and finite element models of investigated structures are correct.

It should be emphasized that many of old masonry arch bridges belong to cultural heritage. The length of arch spans and the structural solutions of these objects are examples of skilful joining of utility features, beauty, and durability. Before admission of these old structures to carry contemporary types of loads, which appear in consequence of civilization progress, their individual evaluation is necessary, and in case of doubt further experimental studies should be performed. The determined vibration frequencies permit to undertake further dynamic analysis of structures considering influence of traffic loads or other dynamic influences.

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