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AN EXPERIMENTAL AND NUMERICAL ASSESSMENT OF THE DYNAMIC CHARACTERISTICS OF THE FOOTBRIDGE LOCATED OVER THE NATIONAL EXPRESSWAY DK-1

DOŚWIADCZALNE I NUMERYCZNE WYZNACZANIE CHARAKTERYSTYK DYNAMICZNYCH KŁADKI DLA PIESZYCH USYTUOWANEJ NAD DK-1

Abstract

In this paper the experimental and numerical results of dynamic characteristics (i.e. natural frequencies and modes of vibrations) of the cable-stayed footbridge, located in Czestochowa, are presented. The numerical analysis was carried out with the ABAQUS package. The i*n situ* tests methodology and the results are also presented on the basis of the spectral analysis of vibrations caused by a group people jumping. The theoretical and experimental results are in good agreement as far as both the natural frequencies and eigenmodes are concerned.

Keywords: footbridges, dynamic characteristics of footbridges, in situ experiments

Streszczenie

W artykule przedstawiono charakterystyki dynamiczne (postaci i częstotliwości drgań własnych) podwieszanej kładki dla pieszych zlokalizowanej w Częstochowie uzyskane na drodze teoretycznej jak i eksperymentalnej. Analizę numeryczną konstrukcji przeprowadzono z wykorzystaniem programu ABAQUS. W trakcie badań *in situ* zarejestrowano przebiegi czasowe drgań wymuszonych przez podskoki grupy ludzi. Analiza spektralna przebiegów pozwoliła na wyznaczenie charakterystyk dynamicznych kładki. Uzyskano dobrą zgodność częstotliwości i postaci drgań wyznaczonych teoretycznie i eksperymentalnie.

Słowa kluczowe: kładki dla pieszych, charakterystyki dynamiczne kładek, badania in situ

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1. Introduction

Pedestrian bridges are objects of public infrastructure which are designed to allow their users to pass over an obstacle [1, 3]. It is important to note that the application of advanced technology, calculation and materials gives engineers the opportunity to create footbridges that are more slender, lighter and longer than bridges designed for cars or trains [3]. Because of this, in a vast majority of cases, footbridges have the lowest natural frequency, which coincides with the frequency of pedestrian steps (whether walking or running). Such situations are very dangerous because resonance phenomena can occur [3, 4].

In the contemporary history of bridge construction, one of the most publicized examples is Millennium Bridge located in London. From the day of its opening on 10 June 2000, the bridge exhibited very dangerous tendencies that attracted the attention of scientists, including more than 1000 articles and 150 broadcasts in the media around the world [3].

The first step in the analysis is to determine the dynamic characteristics of the structure. There are two ways to do it: numerical and experimental [2].

In this paper, the comparison of both the experimental and the numerical results of dynamic characteristics (i.e. frequencies and modes of natural vibrations) of the existing footbridge are presented.

2. Basic geometry and material data of the analysed footbridge

The dynamic characteristics were determined for an existing two-span footbridge located in Czestochowa, Poland. The primary purpose of the structure is to allow pedestrians to cross over the national expressway DK-1. It was designed according to the technical requirements demanded of footbridges (PN-85/S-10030). The cross-section of the footbridge span is shown in Fig. 1, whereas the side view of the structure and its main dimensions are presented in Fig. 2. In both figures the locations of accelerometers, used for the *in situ* experiment, are also presented.

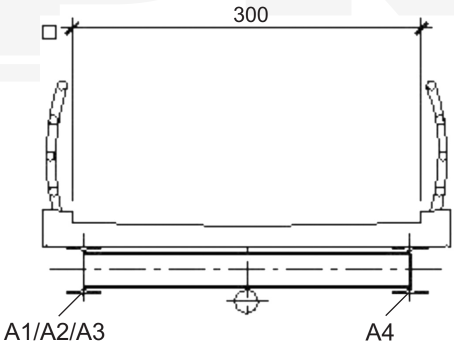

Fig. 1. The cross-section of the footbridge span along with the locations of sensors (A- accelerometer)

The total length is 46.9 m, with the lengths of the spans 21.1 and 25.8 m. The width of the footbridge is 3.5 m. The primary structural system of the footbridge consists of steel girders (I-section HEB 400) located at a distance of 2.8 m and connected by crossbars (I-section HEA

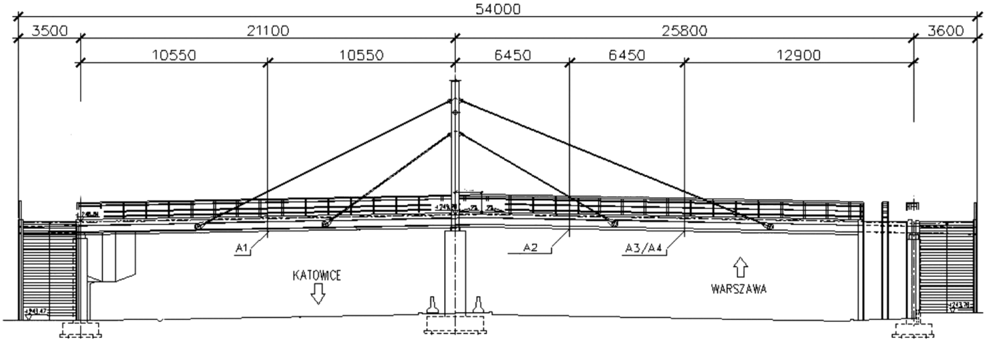

Fig. 2. The side view of the footbridge along with the locations of sensors (A – accelerometer)

300). The main girders are integrated with a concrete deck by steel bolts. The thickness of the deck varies from 0.17 to 0.20 m. The superstructure has been suspended (4 trusses on both sides of the deck) from a pylon 13.20 m high situated above the middle support. The pylon is constructed of steel pipes with a diameter 457 mm and concrete inside. The trusses (type ASDO M42) are hinged to the pylon and to the deck. Three supports are constructed as reinforced concrete pillars with a cross section of 1.0 x 1.2 m and 0.8 x 0.8 m for the middle and the extreme pillars, respectively.

The modulus of elasticity of steel was taken as 210 GPa. The Poisson's ratio was assumed to be 0.29. The material data of concrete were assumed: the modulus of elasticity at 39 GPa, the Poisson's ratio at 0.17 and the mass density at 2500 kg/m^3.

3. Experimental determination of dynamic characteristics of the footbridge

For an experimental determination of the dynamic characteristics of the footbridge, an impulse load – a jump by a group of nine people – was applied as a vibration source. The footbridge was equipped with sensors (accelerometers) arrayed vertically (see Figs 1 and 2). The natural frequencies of the structure were assessed on the basis of the spectral analysis of the registered time history of the vibrations caused by the jump.

The time history of accelerations registered by sensor A1 is shown in Fig. 3a. The amplitude-frequency spectra calculated from the time histories of accelerations recorded by sensors A1, A2, A3, A4 are presented in Fig. 3b. It can be observed from the spectral analysis of all signals in Fig. 3b that the first, second and third natural frequencies equaled 2.7, 4.9 and 6.2 Hz, respectively.

The mode shapes associated with the obtained natural frequencies have also been detected from the registered signals. The analysis of the first mode shape is presented in Fig. 4. To abstract the accelerations associated with the first natural frequency a bandpass filter with the lowest frequency of 2.4 Hz and the highest frequency of 2.9 Hz was used. The filtered time histories of accelerations registered by sensor A1 located on the first span and by sensor A3 located on the second span are compared in Fig. 4a. Then, the comparison of the accelerations registered by sensor A3 and situated on the opposite sides of the second span is illustrated in Fig. 4b. It should be noted that the accelerations of the first and the second span are out of phase (sensors A1 and A3), whereas the accelerations of both sides of the deck (sensors A3 and A4) are almost identical.

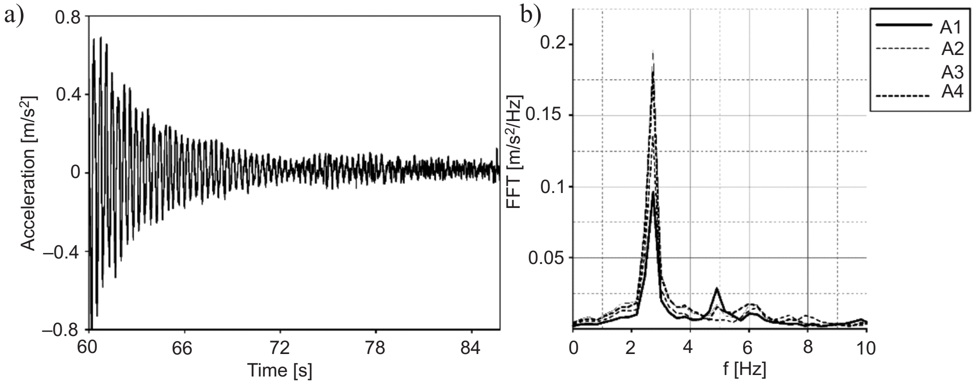

Fig. 3. (a) Time history of accelerations registered by sensor A1; (b) amplitude-frequency spectra calculated from the time histories of accelerations recorded by sensors A1, A2, A3, A4

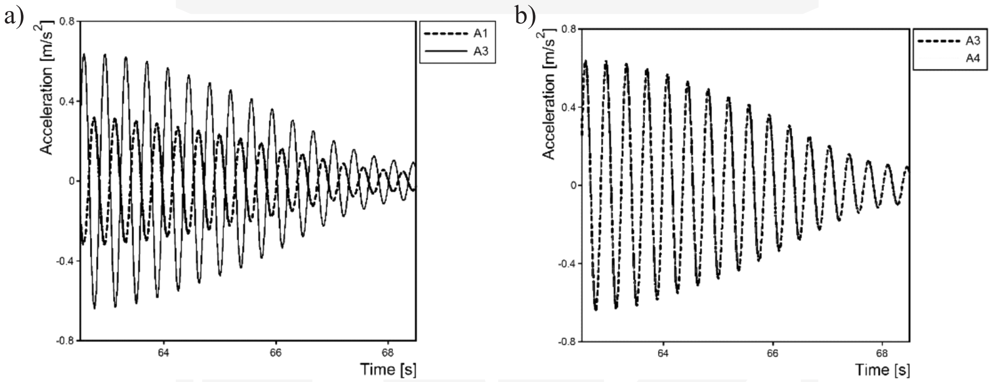

Fig. 4. Comparison of accelerations (filtered to 2.4-2.9 Hz) recorded by sensors: (a) A1 located on the first span and A4 located on the second span; (b) A3 and A4 located on the opposite sides of the deck on the second span

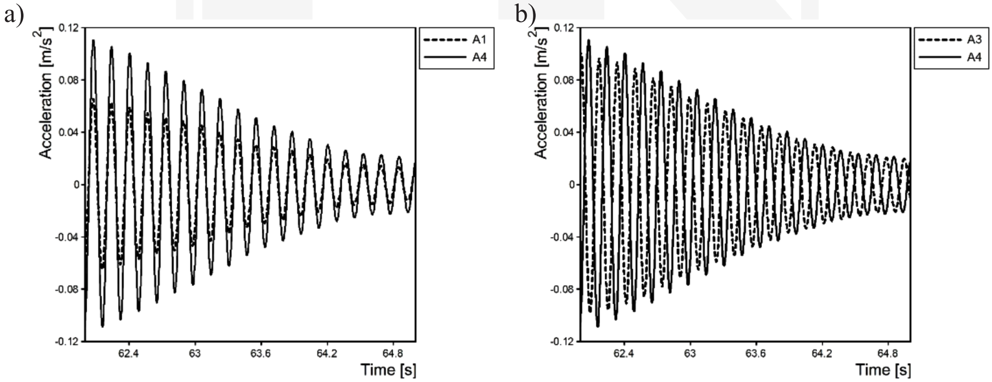

Fig. 5. Comparison of accelerations (filtered to 5.9-6.3 Hz) recorded by sensors: (a) A1 located on the first span and A4 located on the second span; (b) A3 and A4 located on the opposite sides of the deck on the second span

A similar analysis was carried out for the second and third mode shapes. The acceleration histories recorded by sensors A1, A3 and A4, filtered around the second natural frequency 4.9 Hz, are all in phase. Finally, the analysis demonstrated that the acceleration histories recorded by sensors A3 and A4, filtered around the third natural frequency 6.2 Hz, are out of phase (see Fig. 5).

4. Comparison of the experimental and numerical results

As a result of the numerical analysis, the natural frequencies of the footbridge were also calculated. The model was created in ABAQUS software. In Table 1 the experimental and numerical results of natural frequencies are compared. The differences between the experimental and the numerical results did not exceed 10%.

The modes of natural vibration are presented in Fig. 6. It should be noted that, in the case of the first mode, the shape obtained from the numerical analysis of the vertical displacements of the first and the second span were out of phase. In the case of the second mode, the shape the vertical displacements of both spans were in phase. In the case of the third torsional mode, the shape of both sides of the footbridge deck moved out of phase. These results are in good agreement with the experimental results registered by accelerometers located at points A1-A4.

Table 1

Comparison of experimental and numerical values of natural frequencies of the footbridge

No. of frequency	Frequency [Hz]			Description of mode shape
	Experimental	Numerical	Difference [%]	
1	2.7	2.6	3.7	Bending
2	4.9	5.0	2.0	Bending
3	6.3	6.9	9.5	Torsion

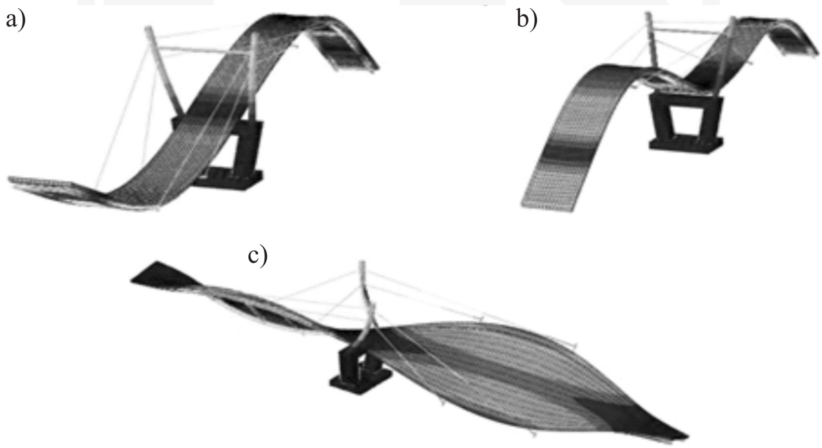

Fig. 6. Modes of natural vibrations of the footbridge: (a) first; (b) second; (c) third

5. Conclusions

In this paper the dynamic characteristics of the cable-stayed pedestrian footbridge obtained in numerical and experimental ways are presented. On the basis of the obtained results, the following conclusions can be drawn, as well as some general remarks for engineering practice:

1. The comparison of the analytical and experimental results are in very good agreement as far as both the natural frequencies and modes of vibrations are concerned. Hence, the numerical model of the cable-stayed footbridge was positively verified.
2. The obtained natural frequencies are within the range of 2.7-3.3 [3], which is typical for fast pedestrian running. Hence, the resonance phenomenon resulting in the amplification of the dynamic response may occur.

References

[1] Bilszczuk J.,W. Barcik. et al., *Design of steel footbridges,* Lower Silesia Educational Publisher House (DWE), Wroclaw 2004.
[2] Dulińska J., *Evaluation of Dynamic Characteristics of Masonry Arch Bridges: Linking Full-Scale Experiment and FEM Modeling*, Advanced Materials Research, 133–134: 605–610.
[3] Flaga A., *Mosty dla pieszych,* WKL, Warsaw 2011.
[4] Murzyn I.J, *Dynamic characteristics of cable-stayed pedestrian and cyclists footbridge 120 m long,* International Journal of Earth Sciences And Engineering, 7(1): 313–319.