Assessment of pedestrian comfort and safety of footbridges in dynamic conditions: case study of a landmark arch footbridge

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The objective of this paper is to present results of dynamic tests of an arch span of the footbridge in Wronki near Poznań in Poland and clearly summarize them. The investigated footbridge, with asymmetrical arch and the main span 90.0 m long, is an example of original architecture and interesting structural solutions.

The topic of the dynamics of footbridges is a very important research problem. Such structures are very often sensitive to vibrations caused by pedestrians traffic. The recent literature on the subject contains many works on the assessment of the pedestrian comfort [1-5] and, less frequently, safety in relations to dynamic conditions.

The subject of this paper is a footbridge in Wronki near Poznań, the structure of which was examined in static and dynamic proof load tests [6]. The main aim of these tests was an assessment of pedestrian comfort and safety of the footbridge. The structure with asymmetrical arch and the main span 90.0 m long constitutes an interesting example of a design solution [7, 8], which might be a landmark of one of the biggest cities in Poland. Characteristic of the investigated footbridge, a range and results of the dynamic tests are described in this paper.

Characteristic of the investigated footbridge

The footbridge was designed as consisted of two structural parts. The first one, located over the main current of the Warta River, is the arch structure (Fig. 1.). The deck is made of an orthotropic plate with steel cantilevers and a box main girder, which is a tie-beam of the arch. The deck is connected to the asymmetrically inclined arch with plate girder hangers and steel rods. In side spans of this part of the structure, the deck is a reinforced concrete slab supported on steel cantilevers.

The second part of the footbridge (Fig. 2.) is situated over inundation area of the river and is constructed as a beam structure, made of steel I-bar beams, braced by crossbeams. In a connection place of both parts of the footbridge the deck is widened. The idea of this solution was to create an observation deck.

The total length of the footbridge is 206.40 m. The spans in the first part (arch part) are 2.75 + 22.70 + 90.00 + 20.22 m long, whereas in the second one (beam part): 18.44 + 25.20 + 19.30 m. The width of the footbridge is equal to 3.00 m. Structural steel type S355, structural concrete C40/50 and reinforcement steel BSt500S/B500Sp was used.

The decks of both parts are connected with a hinge. Due to this fact and also different static schemes (arch over the main current of the Warta River and multi-span beam over the inundation area of the river), in dynamic investigations both parts of the structure are treated independently. This paper presents only the tests results of the arch part of the structure.

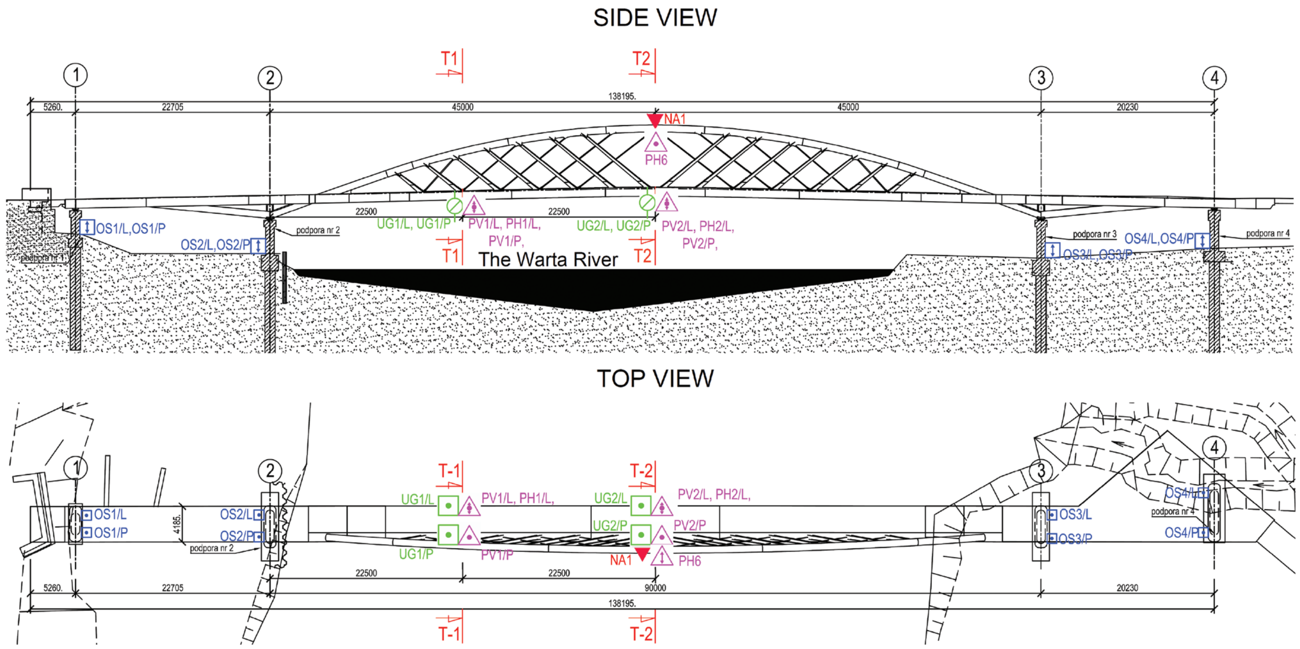
Fig. 1. View of the structure over the main current of the Warta River (Photos credit: Eurovia).

Fig. 2. View of the structure over the inundation area of the Warta River (Photo credit: left, Eurovia).

Photos from the author's archive with the exception of Fig. 1. and Fig. 2a.

Range of dynamic investigation

The research campaign consisted of a large number of tests and included normal live loads and vandal actions to the footbridge. Normal live loads tests examined the influence of various kinds of the pedestrian activity on the footbridge's behaviour as: walking, jogging or fast running. The pedestrian comfort was assessed in this type of schemes.



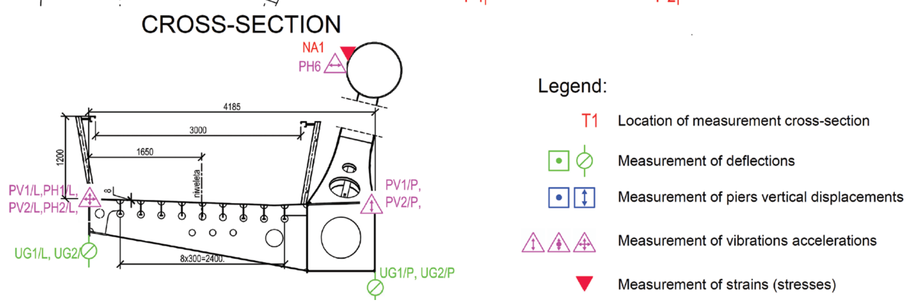


Fig. 3. Scheme of location of measurements devices (arch part of the structure) [7] – side view, top view and cross-section of the footbridge (PV – measurement of vertical vibrations, PH – measurement of horizontal vibrations, NA – measurement of strains).

Vandal type of excitation consisted of synchronized walking or running and rhythmical half-crouching. The main aim of the vandal live loads was to check structure's safety and behaviour in the extreme dynamic conditions. Forty pedestrians took part in dynamic tests.

The purpose of dynamic investigations was to identify natural frequencies of the footbridge and compare them with results obtained from a computational model. Moreover, it was to register accelerations of the deck and compare them with recommended accelerations limits, as well as to register strain of the arch and evaluate safety of the structure in conditions of dynamic vibrations.

According to the proof load test project [7] several schemes of vibrations excitations were implemented:

Scheme D1 – identification of natural frequencies of the structure;

Scheme D2 – walking of a group of pedestrians;

Scheme D3 – synchronic walking of a group of pedestrians with a step frequency 1.90 Hz (path rate was controlled by using of a metronome);

Scheme D4 – synchronic walking of a group of pedestrians with a step frequency compatible with natural frequencies of the footbridge;

Fig. 4. Walking and running of a group of pedestrians with a free path rate.

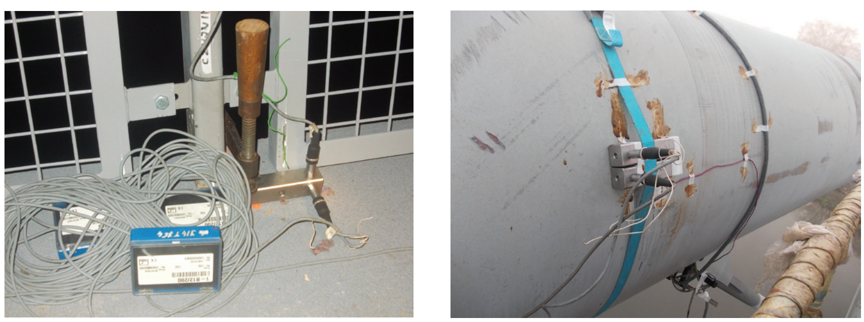


Fig. 5. Accelerometer B12/200 – measurement of vertical and horizontal accelerations of the deck (on the left) and measurement of horizontal accelerations of the arch (on the right).

Scheme D5 – running of a group of pedestrians;

Scheme D6 – synchronic half-crouching of a group of 10 pedestrians.

Accelerations of vibrations were measured in points PV1, PV2, PH1, PH2 and PH6, whereas in a point NA1 strain was measured (measurements points are presented in Fig. 3.).

Walking and running schemes were carried out in groups of 10, 20, 30 and 40 pedestrians, according to investigation

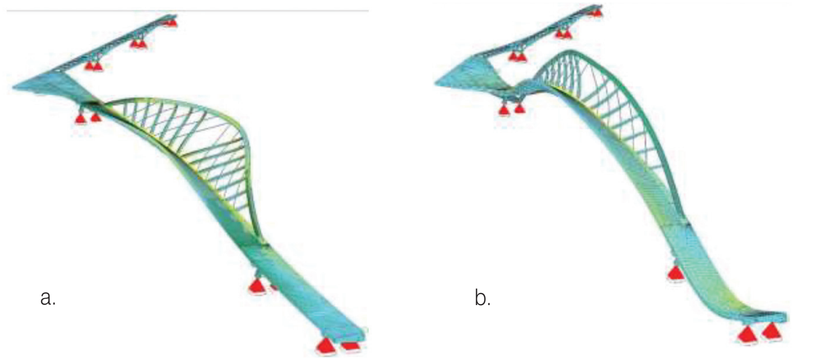


Fig. 6. Modal shapes of the deck in the arch part: a. the first modal shape (f = 1.57 Hz), b. the second modal shape (f = 2.13 Hz) [7].

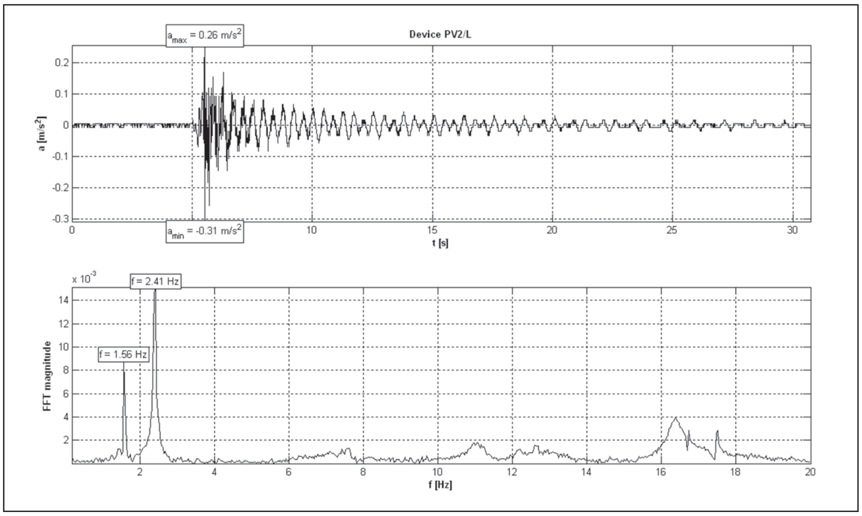


Fig. 7. Identification of the 1st and the 2nd frequency of the footbridge (scheme D1).

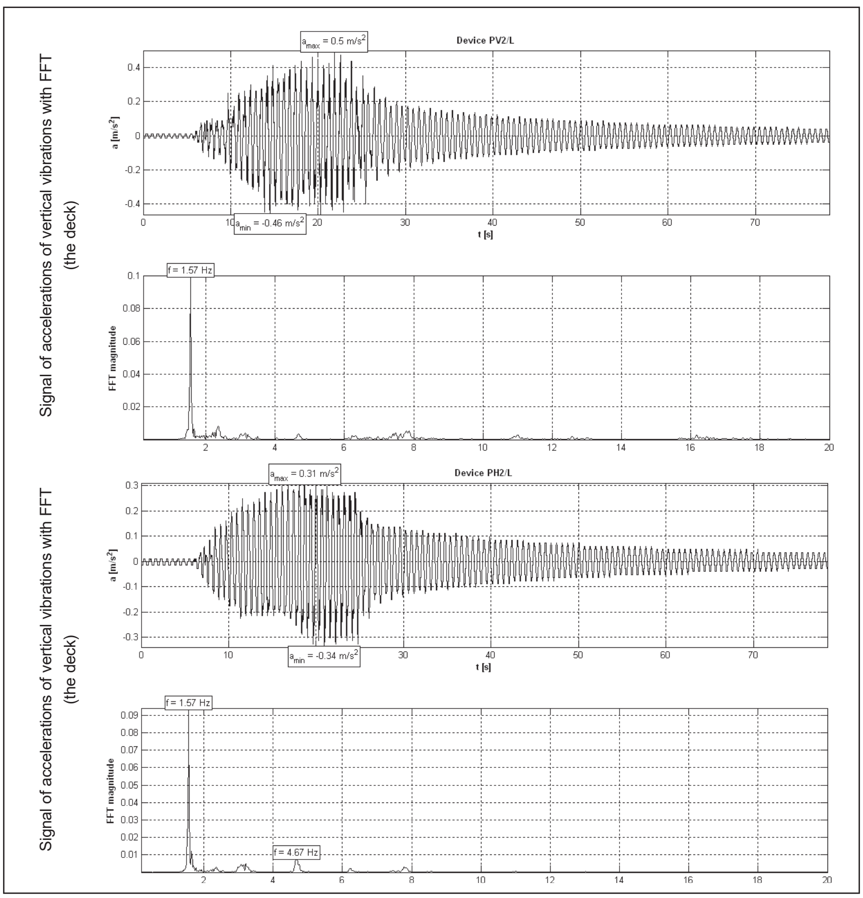


Fig. 8. Inducing of vibrations by half-crouching with frequency f_1 (the deck).

Table 1. Calculated and identified frequencies of deck's vibrations.

Frequency	Calculation	Investigation
f_1 [Hz]	1.57	1.56
f_2 [Hz]	2.13	2.41

procedures [9-11]. Examples of schemes are presented in Fig. 4.

Accelerometers by HBM Hottinger Baldwin Messtechnik GmbH (type B12/200), with SPIDER8 amplifier and CATMAN software (version Express 4.5), as well as electric resistance wire strain gauges were used for the tests of the footbridge (Fig. 5.).

Identification of vibrations frequencies

The first two determined in the proof load test project [7] modal shapes with calculated corresponding frequencies are presented in Fig. 6. The computational model of the structure was prepared in the SOFiSTiK software as a 3D model, discretized by 7373 nods and 10295 elements (beam and shell type) [7]. The MES model was described in [8] and proper, advanced methods of such type, untypical footbridges computational modelling, as well as simulations of vibration effects caused by pedestrians can be found e.g. in [12-17].

Experimentally identified frequencies are presented in Tab. 1. These frequencies were determined by analysing vibrations signals registered in a scheme D1. The example of registered signal is presented in Fig. 7. in a time and frequency domain. The scheme D1 consisted on an impulse excitation of the vibrations by a single jump of one person on the empty deck of the structure, in the anti-node zone of the modal shape.

Results of dynamic tests

Extreme accelerations of vibrations and values of strains of the arch, which were registered during dynamic proof load tests, are presented in Tab. 2.

Examples of registered signals of the deck vibrations in vertical and horizontal directions in scheme D6 are presented in Fig. 8. Signal of the arch vibrations in a horizontal direction and signal of strain registered in the same scheme by strain gauge sensor (NA1w1) is presented in Fig. 9. Signals are presented in time and frequency domain.

Discussion of results

The investigation of considered footbridge shows that very good compatibility between the results obtained using the computational model [7, 8] and results of experimental tests of the structure was achieved. Calculated natural frequency of flexural vibrations of the bridge was 1.57 Hz, while the value obtained experimentally was 1.56 Hz. This proves that the model of the structure was correct.

Table 2. Accelerations and strains registered during dynamic tests.

No.	Scheme	Description of a scheme	Number of pedestrians	Deck		Arch	
				a_V [m/s²]	a_H^D [m/s²]	a_H^A [m/s²]	ε [10^{-6}]
1	D2	Walking	10	0.16	0.05	0.13	4.56
			20	0.25	0.08	0.16	8.64
			30	0.34	0.12	0.22	12.72
			40	0.32	0.11	0.26	15.12
2	D3	Synchronic walking (f = 1.90 Hz)	10	0.30	0.09	0.20	6.00
			20	0.31	0.11	0.26	11.76
			30	0.57	0.17	0.36	16.32
			40	0.59	0.18	0.47	18.72
3	D4	Synchronic walking (f = 1.56 Hz)	10	0.25	0.14	0.61	10.56
			20	0.40	0.19	0.94	17.28
			30	0.37	0.21	0.94	19.20
			40	0.43	0.26	1.11	24.48
4	D5	Running	10	0.60	0.20	0.30	8.40
			20	0.70	0.41	0.62	13.44
			30	0.89	0.44	0.62	16.56
			40	0.81	0.40	0.67	16.08
5	D5A	Synchronic running (f = 2.41 Hz)	10	0.81	0.24	0.33	13.44
			20	1.10	0.37	0.51	16.08
			30	1.31	0.33	0.61	18.24
			40	1.35	0.41	0.68	22.80
6	D5B	Sprint	10	0.57	0.21	0.32	7.20
			20	1.09	0.40	0.83	12.48
			30	1.14	0.33	0.82	16.80
			40	1.03	0.38	0.81	14.64
7	D6A	Synchronic half-crouching (f_1)	10	0.50	0.34	1.52	21.36
8	D6B	Synchronic half-crouching (f_2)	10	1.28	0.41	0.58	20.40

Notations used in Tab. 2.:
a_V – maximum acceleration of vertical vibrations of the deck in the arch part of the structure, registered by devices PV1 and PV2,
a_H^D – maximum acceleration of horizontal vibrations of the deck in the arch part of the structure, registered by devices PH1 and PH2,
a_H^A – maximum acceleration of arch vibrations, registered by device PH6,
ε – maximum value of arch strains, registered by device NA1w1.

The pedestrian comfort was assessed in schemes simulating normal conditions on the footbridge (vibrations induced by walking, jogging or fast running without synchronization). The maximum value of the vertical vibrations acceleration induced by walking persons without synchronization was 0.34 m/s². This value does not exceed 0.70 m/s², which is generally recognized as a limit value of vibrations in relation to usage comfort on footbridges in the design codes, e.g. [18-21]. Then it may be concluded that the structure meets usage comfort. Even in case of synchronic walking the value of the maximum vertical vibrations acceleration 0.59 m/s² (scheme D3 with 40 pedestrians marching) did not exceed the comfort criteria, although by such type of excitation only the structure's safety should be ensured. The maximum value of the vertical vibrations acceleration induced by people running without synchronization was 1.14 m/s², which should be regarded as a satisfactory value [9-11].

The structure's safety was assessed in the extreme dynamic conditions simulated by vandal type of excitation, consisted of synchronized walking or running and rhythmical half-crouching. The criterion of the footbridge load capacity in dynamic conditions were checked by comparing values of stresses measured in the dynamic tests with design values. In relation to the arch part of the structure the criterion taken into account was not exceeding values of the design stresses in the arch [7] as this structural element is the most crucial for the footbridge. The maximum value of strains was $24.48 \cdot 10^{-6}$, that corresponds to 5.0 MPa. This result is much lower than the calculated value of the stresses due to static proof load tests (in scheme U2, critical for the arch, in a measurement point NA1w1 calculated value of stresses is 32.7 MPa). These strains results lead to the statement that the safety of the structure in conditions of dynamic influences is fulfilled (including vandal actions on the structure). The safety assessment in dynamic conditions was an additional point in a general safety evaluation of the footbridge, carried out in the static proof load tests (Fig. 10.). These tests were conducted by using 4 trucks weighing 13 t each. The results of the static proof load tests are not a subject of this paper and were not discussed in the manuscript.

Summary

Analysed structure was an interesting subject for research because of the unusual design solutions and its main span length. Final structural solutions applied to the arch part of the footbridge [7, 8] provided the relevant dynamic characteristics and correct behaviour under pedestrian load. The footbridge is an example of the original architecture of the structural system which does not require the use of additional vibrations damping devices.

Assessment of the pedestrian comfort was conducted using the existing design codes [18-21]. The comfort criteria were also fulfilled considering the current technical guidelines [22, 23]. The safety of the structure in dynamic conditions was evaluated according to the own research procedures of the author [9-11].

Acknowledgments

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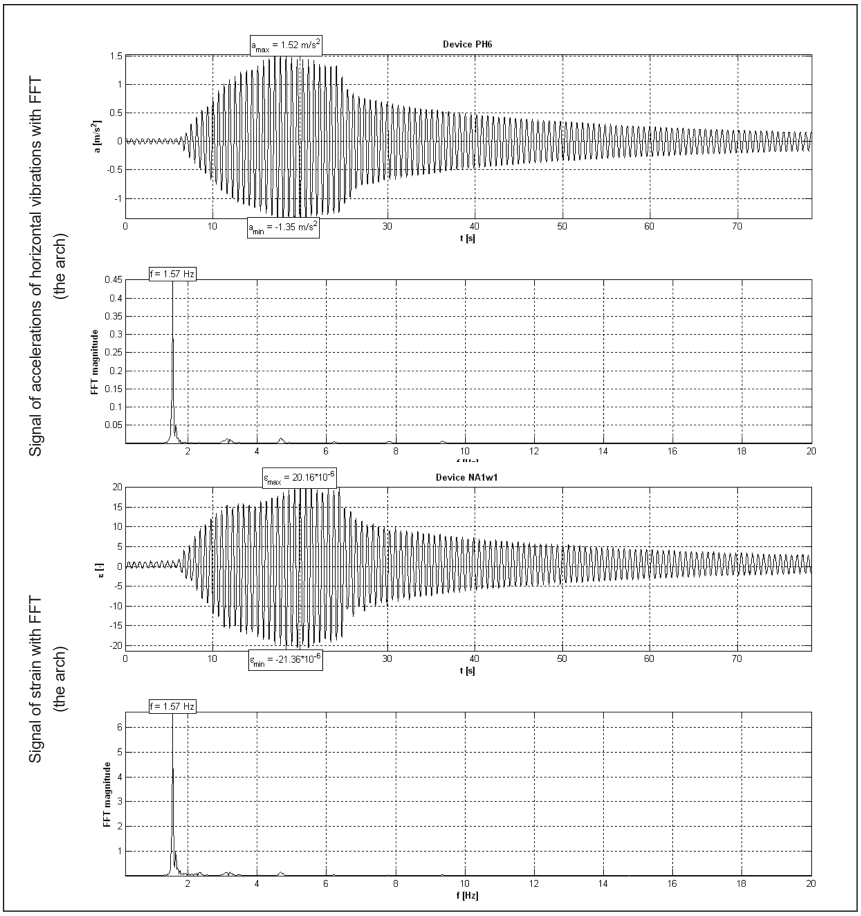

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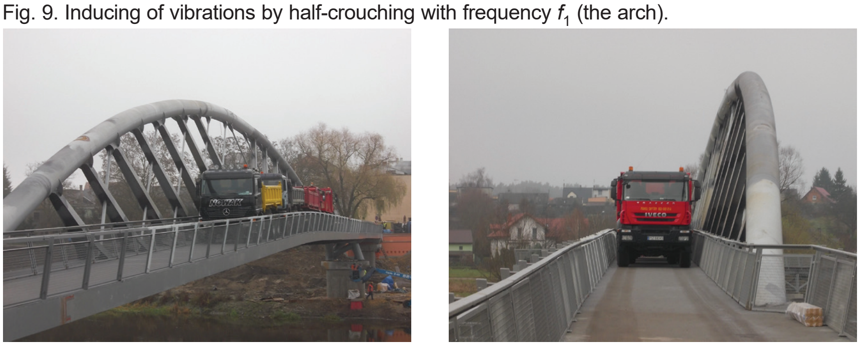

Fig. 10. Static proof load test of the structure (scheme U2).

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Abstract: The objective of this paper is to present results of dynamic tests of an arch span of the footbridge in Wronki near Poznań in Poland and clearly summarize them. The investigated footbridge, with asymmetrical arch and the main span 90.0 m long, is an example of original architecture and interesting structural solutions.
The research campaign included normal live loads and vandal actions to the footbridge. Normal live loads tests examined the influence of various kinds of the pedestrian activity on the footbridge's behaviour as: walking, jogging or fast running. The pedestrian comfort was assessed in this type of schemes. Vandal type of excitation consisted of synchronized walking or running and rhythmical half-crouching. The main aim of the vandal live loads was to check structure's safety and behaviour in the extreme dynamic conditions. The research was carried out in a large group of pedestrians – under a crowd of 40 volunteers.
Keywords: Arch Footbridge, Dynamic Behaviour, In-situ Tests, Pedestrian Comfort, Safety

Streszczenie: OCENA KOMFORTU UŻYTKOWANIA I BEZPIECZEŃSTWA KŁADEK DLA PIESZYCH W WARUNKACH ODDZIAŁYWAŃ DYNAMICZNYCH: PRZYPADEK KŁADKI ŁUKOWEJ TYPU PUNKT CHARAKTERYSTYCZNY. Celem artykułu jest przedstawienie i podsumowanie wyników badań dynamicznych przęsła łukowego kładki dla pieszych we Wronkach koło Poznania. Badana kładka o niesymetrycznym łuku oraz rozpiętości przęsła głównego wynoszącego 90 m stanowi przykład oryginalnej architektury, a także interesujących rozwiązań projektowych.
Zakres badań obejmował normalne obciążenia użytkowe oraz oddziaływania typu wandalistycznego, polegające na intencjonalnym wzbudzeniu drgań. W schematach obciążeń użytkowych normalnych symulowano typowe oddziaływanie pieszych na konstrukcję: chód, bieg typu trucht i szybki bieg. Schematy te posłużyły do oceny komfortu wibracyjnego użytkowania konstrukcji. Schematy obciążeń użytkowych wyjątkowych składały się z chodu i biegu synchronicznego oraz wymuszeń drgań półprzysiadami. Głównym celem tych oddziaływań było sprawdzenie bezpieczeństwa konstrukcji oraz jej zachowania w ekstremalnych warunkach dynamicznych. Badania przeprowadzono przy dużej liczebności grupy – pod tłumem 40 osób.
Słowa kluczowe: kładka łukowa, zachowanie dynamiczne, testy *in-situ*, komfort użytkowania, bezpieczeństwo