UDK 624.2

DYNAMIC SENSIBILITY OF CABLE STAYED FOOTBRIDGES

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Introduction

There is a necessity of increasing the amount of experimental tests on footbridges for gaining better insight into the problem of the dynamic behaviour of bridges for pedestrians. It is also important to verify numerical models and to develop present knowledge of footbridge dynamics.

Problem of comfort has become important recently, because many light and dynamical susceptible footbridges were designed. The possibility of exceeding the acceptable levels of structure vibration can be a reason for closing or restricting its serviceability. Nowadays there is no unanimity about comfort of pedestrian criteria. In many countries (including Poland) there are no codes or other regulations concerning estimating dynamic properties of footbridges. Comfort criteria usually refer to acceptable levels of amplitudes of displacement A or acceleration a [1].

Cable stayed footbridges are particularly susceptible to vibrations, because of their long spans and slender, light and flexible decks. The results of field testing of four footbridges with various types of decks and various spans are presented here.

Research realisation

The research program consisted of live loads and vandal dynamic loading of footbridges (Tab.1). Live loads tests examined influence of various kinds of pedestrian activity to a footbridge behaviour. It included: walking, synchronized walking, running, synchronized running, fast running and cycling. There was also different amount of people in each loading scheme. The live load was used to simulate regular pedestrian traffic on the bridge and to obtain its dynamic response. Influence of additional mass, from concrete slabs placed on the footbridge during the test, was also analysed. Vandal excitation consisted of rhythmical half-crouching, jumping and pulling cable stays or handrails. Half-crouching and jumping people were standing in the position of maximal vertical deck displacement for each mode (accordingly to the results of computational modal analysis). The main aim of the vandal excitation of vibration was to check structure's behaviour during malicious loads (analyse the response of the structure) and to verify computational model of footbridge and values of the natural frequencies.

***Table 1** – Loading schemes and its symbols*

Kind of vibration inducing	Type of excitation	Excitation symbol
vandal (deliberate)	half-croaching	HC-1…HC-*n*
	jumping	J-1…J-*n*
	cable stayes pulling	SP-1…SP-*n*
	handrail pulling	HP-1…HP-*n*

Kind of vibration inducing	Type of excitation	Excitation symbol
exploitation (undeliberate)	„free" walking	W-1…W-*n*
	synchronized walking	SW-2…SW-*n*
	„free" running	R-1…R-*n*
	synchronized running	SR-2…SR-*n*
	fast running	FR-1…FR-*n*

n – number of people in each test

NOPTEL OY PSM200 laser-based system was used to record the displacement of various parts of structures under dynamic and static load. The system is based on a laser diode transmitter (placed on stable point outside footbridge) and a position-sensitive detector (placed on a footbridge). The electronics inside the receiver continuously measure the centroid position of the laser beam (with sampling frequency of 50 Hz and sensitivity 0.2 mm) and supply data on its horizontal (x) and vertical (y) coordinates continuously to a PC computer. The maximum operating distance is about 300 m and the ambient temperature range from –20 to +500°C [2].

Zlotnicka footbridge in Wroclaw

Superstructure of the footbridge consists of two span continuous steel deck supported by twenty four cable stays type 2T15 connected to a steel pylon (Fig. 1) [3]. The deck composes of two steel tube girders Ø323.9/12.5 mm, connected by steel cross beams HEB 140 mm with spacing 2.00 m. Six longitudinal beams made of HEB100 with spacing varying from 0.40 to 0.50 m are placed on the cross-beams and 12 mm thick steel plate is welded to these beams. All steel elements are made of 18G2A steel (with strength of 280 MPa). The walk width is 3.00 m.

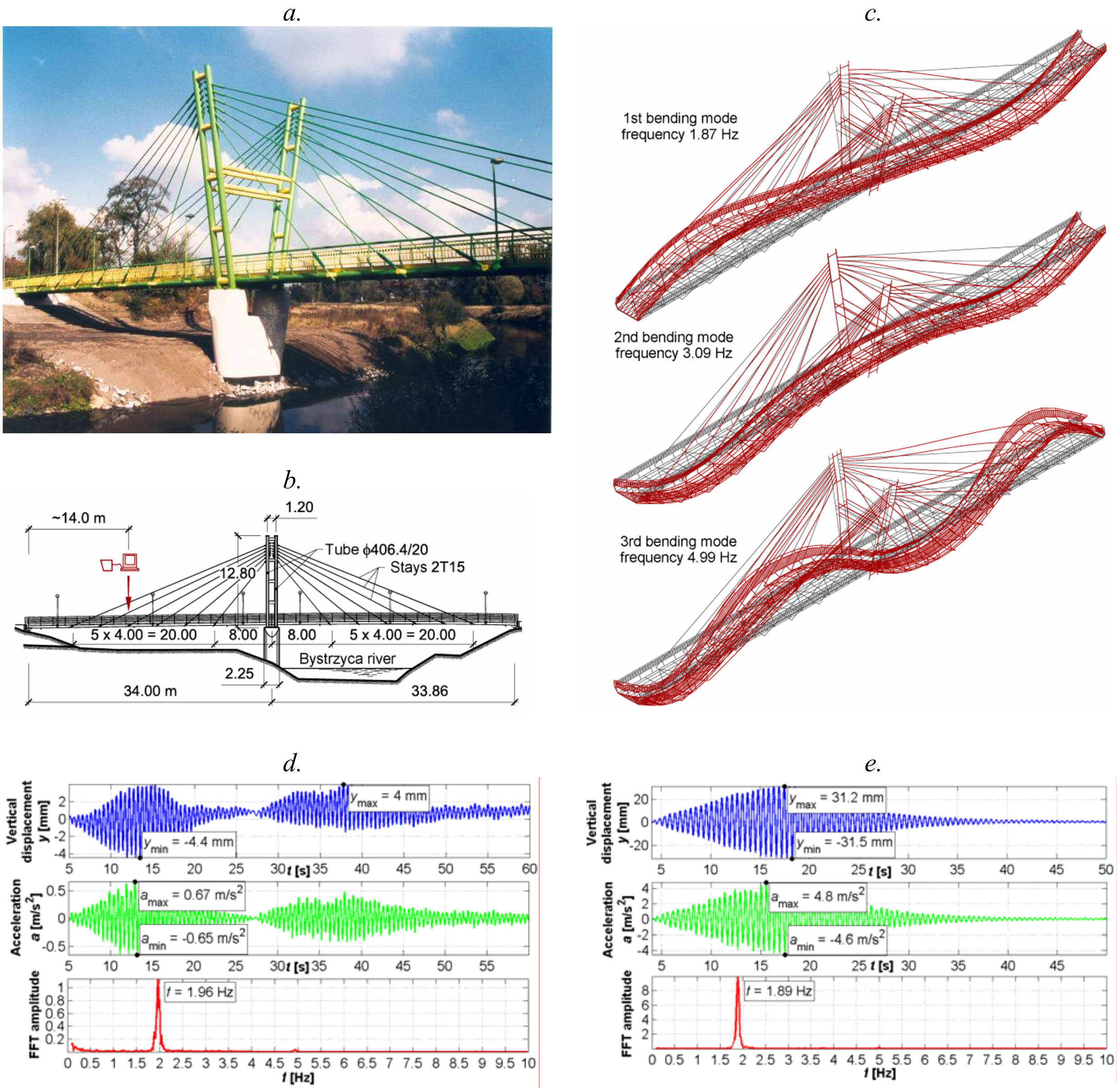
Overview of the footbridge, test results and analysis results are shown in Figure 1 and in Table 2. The computational model was very detailed and it included secondary structure elements such as handrails.

Table 2 *– Results of measurement*

Type of activity	Scheme	f_1 [Hz]	f_2 [Hz]	f_3 [Hz]	A [mm]	a [m/s^2]
calculations		1.87	3.09	4.99	–	–
vandal	HC-4	1.89			31.4	4.80
	HC-4	1.88			35.7	5.40
in normal conditions	W-1	2.02			2.2	0.39
	W-2	2.0			4.2	0.72
	W-4	1.96			4.2	0.67
	W-6	1.86			5.2	0.77
	SW-2	1.97			4.0	0.69
	SW-4	1.93			9.3	1.50
	SW-6	1.97			10.2	1.70
	R-1	2.15			3.7	0.75
	R-2	1.95	2.75		1.7	0.55
	R-4	1.96			2.4	0.64
	SR-2	2.0	2.44		2.7	0.75
	SR-4		2.56		3.1	1.0
	FR-4			3.27	8.9	3.80

The first vertical mode was excited by synchronized half-crouching of four people (vandal load). Maximum amplitudes of vibrations reached 35.7 mm for displacement and 5.40 m/s^2 for accelerations, what represents a significant level of vibrations. Large horizontal transverse vibrations of the street lamps located on the footbridge were noticed with amplitudes up to 10 cm. The deck vibrations were large but it is not necessary to satisfy the comfort criteria during the vandal excitation of vibrations.

It is important to take the location of the footbridge (in a park area) and its regular loads into consideration during assessment of its dynamic behaviour. It was observed that no more than 10 people (usually one or two pedestrians) were using the footbridge. In those conditions the comfort criteria were fullfilled for the regular service of the footbridge.



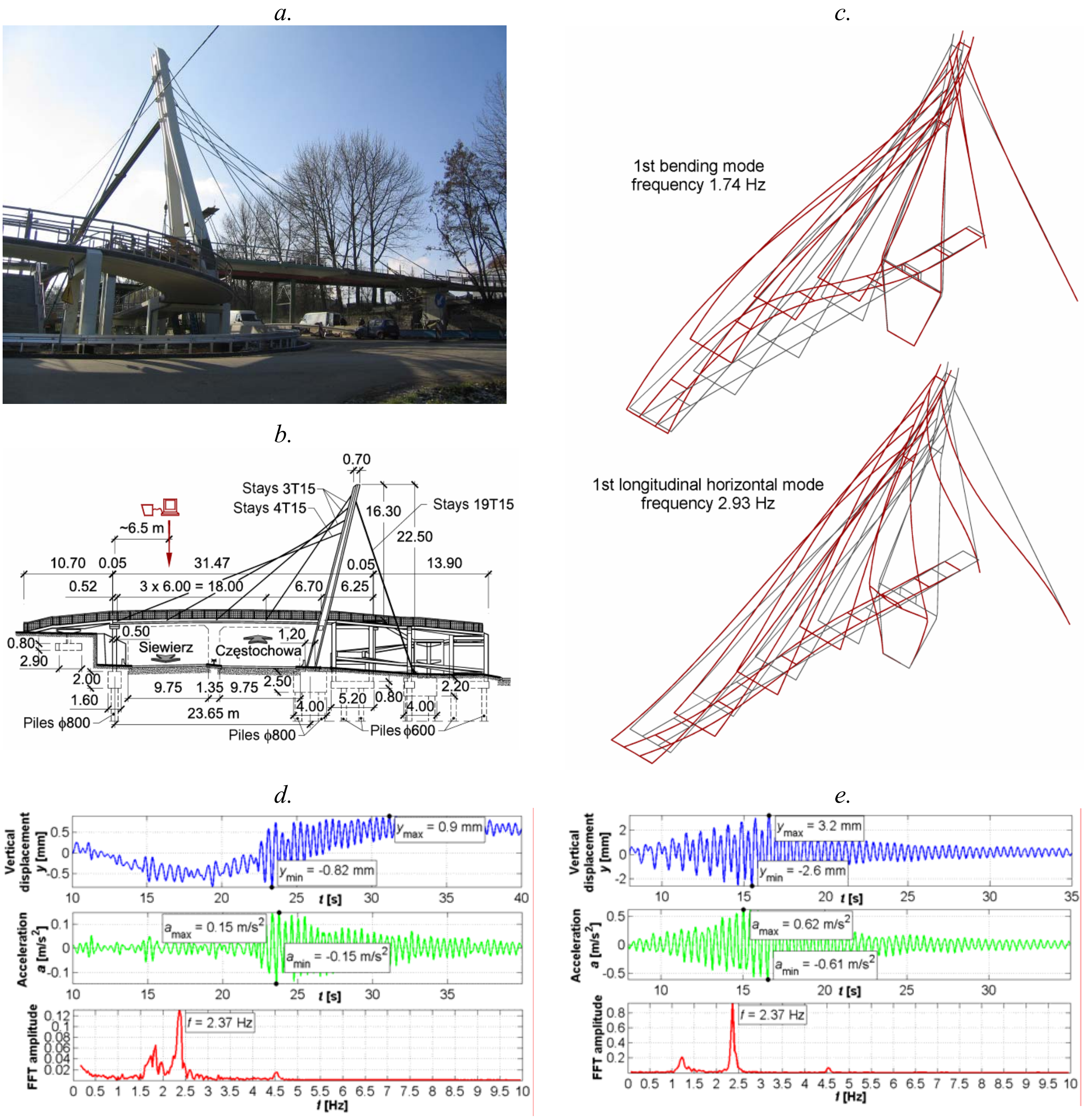
a – photo of the structure, b – view of the structure, c – calculated modes, d – results of measurement for scheme W-4, e – results of measurement for scheme HC-4.

Fig. 1. "Zlotnicka" footbridge

Footbridge in Wrzosowa near Czestochowa

The footbridge is a two-span structure with spans 24.70 and 6.00 m. Deck thickness is 0.35 m and it is constant over its length. Superstructure is made of C50/60 concrete and supported by a concrete pylon with eight (four pairs) cable stays type 3T15 and 4T15.

Pylon is stabilized by two stays type 19T15. Span is also supported by reinforced concrete piles (cross-section of 0.50x0.50 m), a beam which connects legs of the pylon and on the concrete wall (0.50x2.70 m) on the opposite side (Fig. 2). The width of walk is 3.00 m and total width of the deck 3.60 m.



a – photo of the structure, b – view of the structure, c – calculated modes, d – results of measurement for scheme W-20, e – results of measurement for scheme J-8.

Fig. 2. Footbridge in Wrzosowa:

First two vertical modes were identified at 1.73 and 2.37 Hz (values similar to the calculated ones – see Fig. 2 and Tab. 3). “Free” walking and synchronized walking was realized by a group of 20 people. “Free” walking excited second vertical mode, and synchronized walking – first vertical mode of the deck. Synchronized running and fast running of 20 people excited second mode, comfort criteria were not satisfied in this case. First and second modes were induced during deliberate excitation by jumping of 8 people. For such case there are no comfort criteria, but the test results showed that the footbridge has very good dynamic behaviour even during vandal loads.

***Table 3** – Results of measurement*

Type of activity	Scheme	f_1 [Hz]	f_2 [Hz]	A [mm]	a [m/s^2]
calculations		1.74	2.93	–	–
vandal	J-8		2.37	2.9	0.62
	J-8	1.65	2.37	2.9	0.55
in normal conditions	W-20		2.37	0.8	0.15
	SW-20	1.73		1.0	0.14
	SR-20		2.37	3.7	1.0
	SR-20		2.49	3.5	1.10
	FR-20		2.63	3.5	1.10

The dynamic testing was also carried out during static proof loads of the footbridge. It allowed to record deck vibration during significant increasing of deck mass, that was realized by concrete slabs placed by a crane on the deck. These slabs were removed rapidly so to get quick unloading of the deck. The results showed increase in the frequency value of footbridge vibration due to unloading (see Tab. 4). The higher the additional mass of the deck was, the lower the frequency of vibrations, but change in the frequency value was only 0.17 Hz for the mass change of 14.62 t.

The research results analysis showed that footbridge is not dynamicly susceptible. Good dynamic behaviour was proved by values of amplitudes of vibration and acceleration within the acceptable limits.

***Table 4** – Results of measurement*

Type of activity	Number of slabs	Mass [t]	Frequency [Hz]
last slab putting	10	16.65	2.20
removing a slab	9	15.53	2.20
removing a slab	8	14.40	2.20
removing a slab	7	13.28	2.21
removing a slab	6	12.15	2.27
removing a slab	5	10.13	2.27
removing a slab	4	8.10	2.30
removing a slab	3	6.08	2.33
removing a slab	2	4.05	2.33
dropping a slab	1	2.03	2.37

Footbridge in Pszczyna

The footbridge deck is made of reinforced concrete C50/60 and deck thickness is 0.30 m. The span is supported by eight (four pairs) cable stays type 2T15 to the concrete stand (pylon) with four legs and founded on two reinforced concrete piles (with rectangular cross section of 0.70 by 0.70 m) (Fig. 3). The main span is 25.90 m, the walk width 3.0 m and total deck width 3.52 m.

There were no live load tests provided into research program, only malicious inducing of vibrations. First three natural frequencies were identified at 1.78, 2.06 and 2.37 Hz (values differed from calculated ones – see Fig. 3 and Tab. 5).

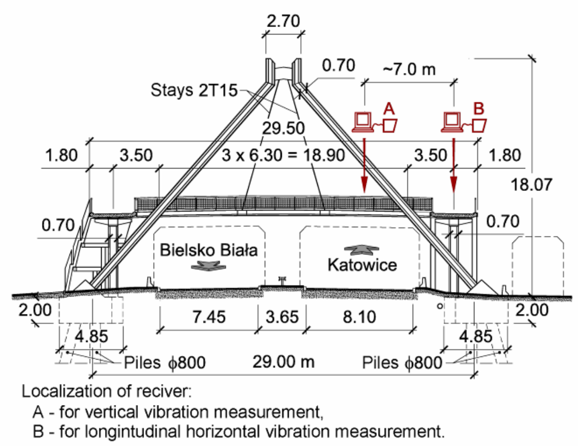
***Table 5** – Results of measurement*

Direction of displacement	Scheme	f_1 [Hz]	f_2 [Hz]	f_3 [Hz]	A [mm]	a [m/s^2]
vertical	calculations	2.34	2.97	5.14	–	–
	HC-16			3.43	2.0	0.75
	HC-16		2.33		1.5	0.51
	HC-16		2.0		2.2	0.74
	HC-16		2.06		1.5	0.33
	HC-16	1.78		3.45	1.6	0.64
horizontal	calculations	–	–	–	–	–
	HC-16	2.12			0.5	0.10
	HC-16	2.07			0.7	0.13
	HC-16	2.03			0.5	0.09

The longitudinal horizontal vibration of the deck was noticed, because of low stiffness of concrete piles supporting the span. The structure turned out to be susceptible for inducing longitudinal horizontal vibration. The measured frequency of that vibration was 2.07 Hz, its amplitudes 0.7 mm and acceleration 0.13 m/s^2 – according to [1] these values are acceptable. Selected records of measured vertical vibrations, calculated accelerations and Fourier transform of displacement are shown on Figure 3. Good dynamic behaviour was proved by sufficient values of amplitudes of vibration and acceleration. The dynamic response of footbridge under regular conditions would be smaller, so the comfort criteria would be satisfied with more spare.

a.

b.



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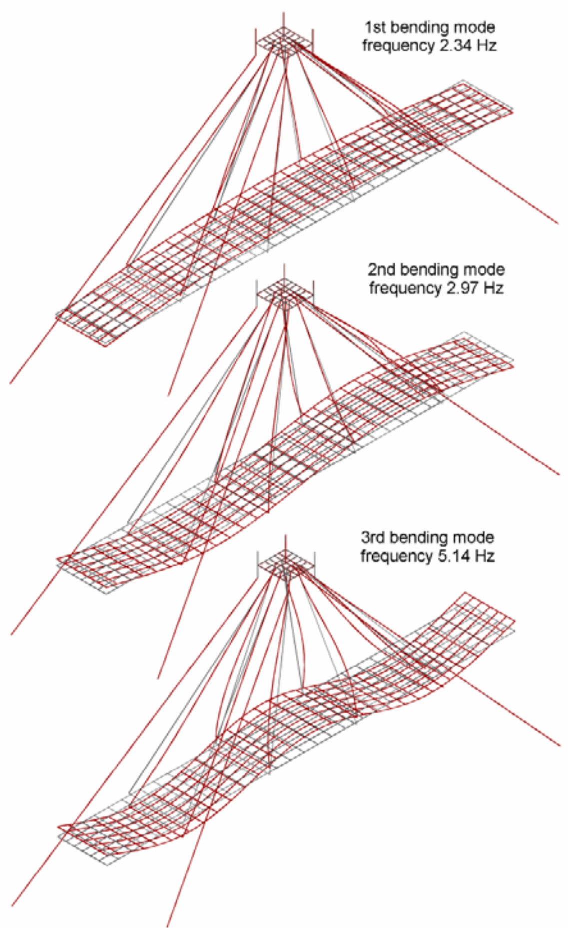

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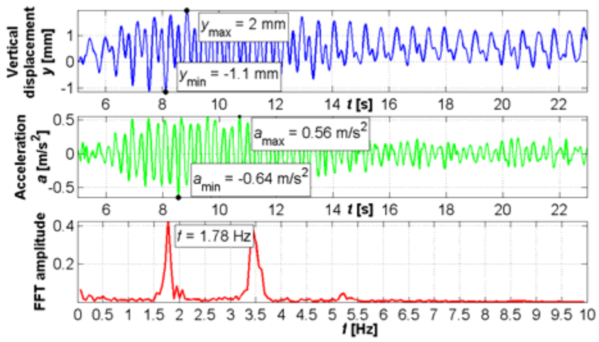

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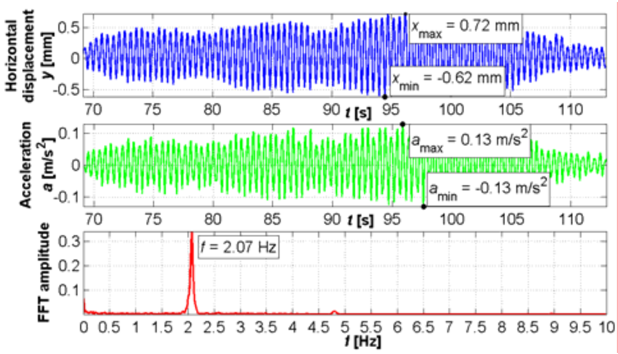


a – photo of the structure, b – view of the structure, c – calculated modes, d – results of measurement for scheme HC-16, e – results of measurement for scheme HC-16.

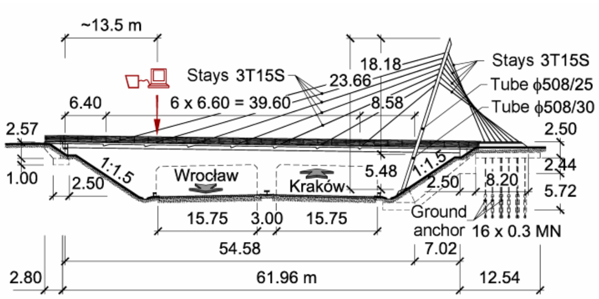
Fig. 3. Footbridge in Pszczyna

Footbridge in Ruda Slaska

The footbridge spans are 54.58 and 7.02 m, the walk width is 3.00 m. The span consists of two beam girders (0.88 m high) connected by a 0.18 m thick slab. Whole deck is made of C40/50 concrete and is prestressed by two cables type 13T15S. The two span deck is supported by 14 cable stays type 3T15S, connected to a steel pylon. The deck is also fixed to the abutment near pylon and supported by fixed bearings at the pylon and unidirectional bearings at the second abutment, as shown in Figure 4 [4].

a.

b.



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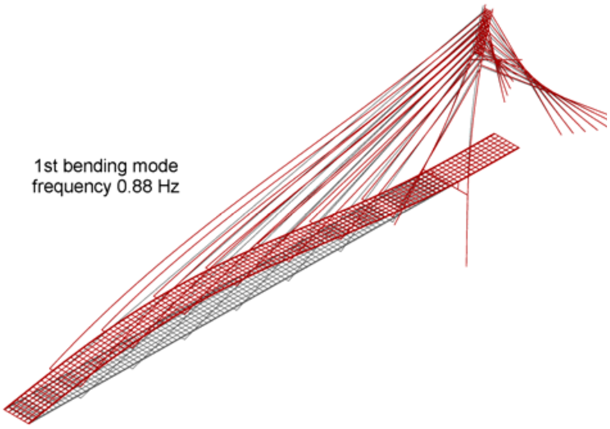

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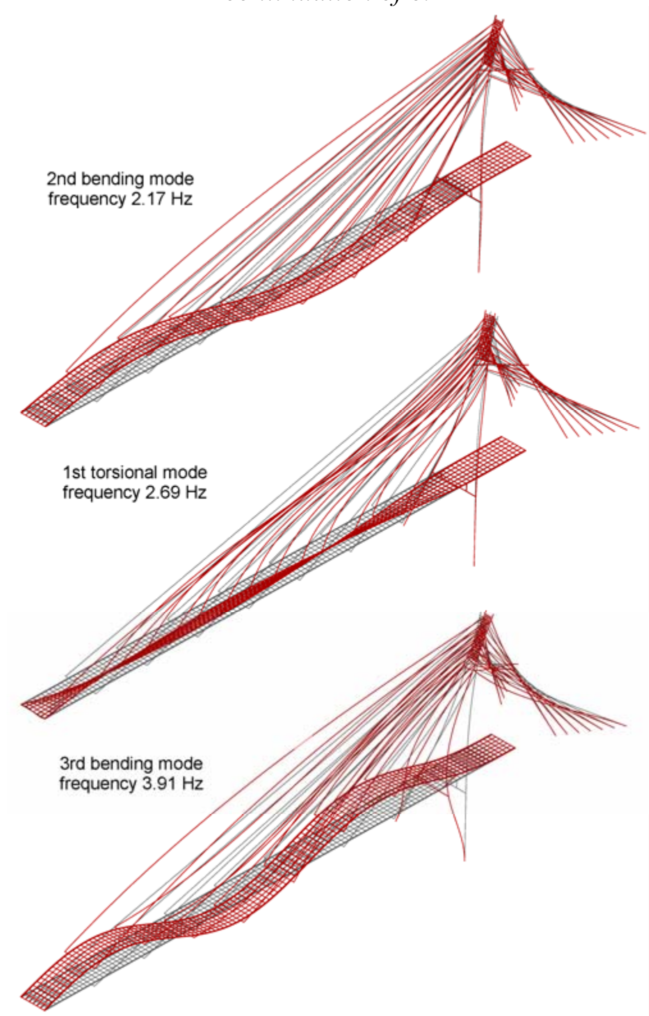

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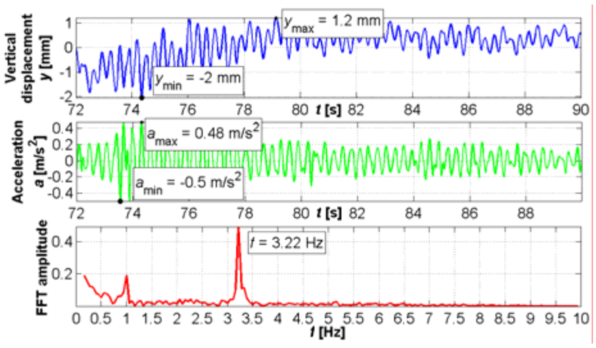

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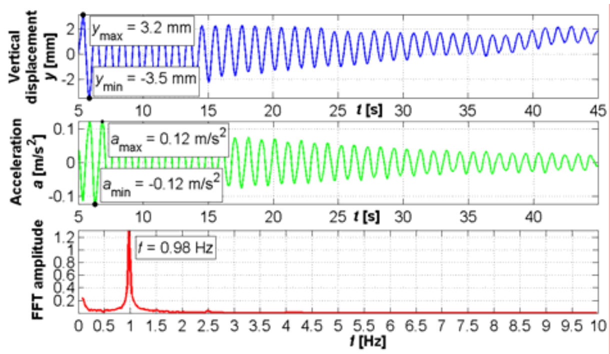

a – photo of the structure, b – view of the structure, c – calculated modes, d – results of measurement for scheme FR-6, e – results of measurement for scheme J-10.

Fig. 4. Footbridge in Ruda Slaska

First four natural frequencies were identified at 0.98, 1.92, 2.50 and 3.22 Hz (values similar to the calculated ones shown in Figure 4 and in Table 6, there are also selected results of measured vertical vibrations, calculated accelerations and Fourier transform).

Additional vibrations of cable stays (5th and 6th pair) with amplitude of 5 cm where induced by synchronized running of 10 people. The vibrations of these stays were also noticed during not very strong wind.

Vibrations of the fifth stay were maliciously induced by three person. Amplitudes of these vibrations were 5 cm and excited also third vertical mode of the deck (measured frequency was 2.57 Hz, amplitude of displacement 1 mm and acceleration 0,34 m/s^2). These deck vibration were not perceptible for pedestrians. High stays vibrations caused acoustic effect (knocking of strands to stay casing), because there was no filling inside stay casing.

The test results analysis showed that footbridge has very good dynamic behaviour. It was proved by satisfactory values of amplitudes of vibration and acceleration in all cases except of fast running of 10 people. Even vandalistic vibration excitation caused no violation of the comfort criteria.

Table 6 *– Results of measurement*

Type of activity	Scheme	f_1 [Hz]	f_2 [Hz]	f_3 [Hz]	f_4 [Hz]	A [mm]	a [m/s^2]
calculations		0.88	2.17	2.69	3.91	–	–
vandal	HC-10	0.98				7.4	0.39
	J-10	0.98				3.4	0.12
in normal conditions	SW-10		1.92			0.7	0.11
	R-5			2.53		0.8	0.27
	R-10			2.75		1.5	0.50
	SR-6	1.0		2.59		1.2	0.37
	SR-10			2.48		3.9	1.30
	FR-6	1.0			3.22	1.2	0.50
	FR-10				3.21	0.7	0.46

Summary and conclusions

From the experimental tests and calculation results the following was concluded:

- During creating a computational model of a structure, it is important to take into account some secondary structure elements (especially handrails), because they provide a substantial changes in stiffness of the deck and natural frequencies.
- Footbridges with reinforced or prestressed concrete deck have better dynamical properties (lower dynamic susceptibility).
- Comfort of usage of structures with steel deck is noticeably decreased. It is important to take into consideration dynamic behaviour of a deck during design stage.
- Influence of an additional mass on changing natural frequencies is rather low. Frequencies decreased not much during putting heavy concrete plates. Such modification of structure (by adding mass) can be reasonable for footbridges which fundamental frequency is close to 1.4 Hz (lower boundary of the unacceptable frequency range).
- It is important to provide proper stiffness of supports to eliminate a possibility of exciting longitudinal horizontal vibration of deck.

References

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[4] BILISZCZUK J. et al., *Bridge structures as landmarks along polish motorways*, FIB Symposium "Keep Concrete Attractive", Budapest, Hungary, 23-25 May 2005.