53rd CONFERENCE ON EXPERIMENTAL STRESS ANALYSIS
Český Krumlov, Czech Republic, June 1–4, 2015

The Reliability Verification and the Actual Dynamic Behavior Assessment of an Existing Footbridge

E. Fanfulová [1], T. Plachý [1], M. Polák [1,*]

[1] *Czech Technical University in Prague, Faculty of Civil Engineering, Department of Mechanics, Thákurova 7, 166 29 Prague, Czech Republic*

[*] *polak@fsv.cvut.cz*

Abstract: The dynamic experimental and theoretical analysis that is described in this paper was focused to the footbridge across Vltava River in Prague which was built in 1984. The footbridge was evidently sensitive to dynamic excitation by passing pedestrians since its putting into operation. Moreover during its existence the substantial part of the footbridge was overflowed by two great floods in August 2002 and June 2013 and an evident damage on the deck was found by a visual inspection after the second flood. At first the experimental modal analysis was performed. Secondly the dynamic load test focused to the footbridge vibrations caused by different groups of pedestrians was carried out. It was found out the deck vertical vibrations exceed the pedestrian comfort limit in some situations. Based on comparison of evaluated modes of natural vibrations with the appropriate ones from previous experiments, it was confirmed that the detected damage caused the partial variation of dynamic footbridge behavior.

Keywords: Dynamic Analysis; Experiment; Vibration; Comfort Limit; Damage.

1 Introduction

The footbridge across Vltava River in Prague was built in 1984. Four dynamic tests were performed regularly during the lifetime of the footbridge in 1984 before its commissioning, in September 1997 [1], in November 2010 and in June 2013 [2] which were similar to each other and to the experimental modal analysis that is described in the paper.

The footbridge was evidently sensitive to dynamic excitation by passing pedestrians since its putting into operation. It became known between users as footbridge that vibrates considerably and many of them has tried to get vibrate the footbridge deck.

Moreover, during existence of the footbridge the substantial part of it was overflowed by two great floods in August 2002 and June 2013. An evident damage on the deck was found by a visual inspection after the second flood and the subsequently realized experimental modal analysis [2] found out the partial variation of dynamic footbridge behavior. An analogous problem with reliability verification of a similar footbridge damaged by a great flood was also solved on the footbridge in Přerov [3].

The basic objective of the realized dynamic experimental and theoretical analysis [4] that is described in the paper was the reliability verification and the actual dynamic behavior assessment of the investigated footbridge. The basic objective was divided into two partial ones.

At first the experimental modal analysis was performed that was focused mainly on verification of the results and consequent conclusions from the experiment realized in June 2013 [2].

Secondly the dynamic load test concentrated to the footbridge vibrations caused by different groups of pedestrians was carried out.

2 Description of the Investigated Footbridge

The footbridge across Vltava River in Prague (see Fig. 1) is made from the prestressed concrete. The bearing structure is the stress ribbon bridge with three spans 85.5 m, 96.0 m and 67.5 m (see Fig. 1). The footbridge deck is composed from precast segments DS – L and DL – Lv that are made from concrete B500 (see Fig. 2) and from the monolithic saddle which are located upon both of two intermediate piers (see Fig. 1 and Fig. 2).

Fig. 1: The overview on the investigated footbridge.

Fig. 2: The bottom view on the footbridge deck.

3 Description of the Dynamic Experiment Arrangement

3.1 The Experimental Modal Analysis

The ambient vibration technique was used for determination of basic natural frequencies and modes of the footbridge deck by the experimental modal analysis. The vibrations were observed in vertical and horizontal direction on the upper face of the footbridge deck in a net of chosen deck points that contained 48 points divided to 24 cross sections with 2 points in each one. 8 cross sections were placed in the 1st span 9 ones in the 2nd span and 7 in the 3rd span.

The vibrations were measured by four seismic piezoelectric accelerometers Type 8344 Brüel & Kjær. The measurement system Pulse and Front-end 3050-B-040 Brüel & Kjær were used for data acquisition and data analysis. The arrangement of the experimental modal analysis was very similar to the experiment performed in June 2013 [1] for the purpose of the possibility to compare in detail the results from both experiments.

Tab. 1: The selected experimentally obtained natural frequencies of the footbridge from October 2014.

natural frequency No.	value of the natural frequency [Hz]	description of the corresponding mode shape
(1)	0.50	1st vertical bending mode shape (see Fig. 4)
(2)	0.64	2nd vertical bending mode shape (see Fig. 5)
(3)	0.94	3rd vertical bending mode shape
(4)	1.01	4th vertical bending mode shape
(8)	1.58	bending mode shape (see Fig. 6)
(9)	1.79	bending mode shape
(10)	2.05	1st torsional mode shape (see Fig. 7)
(11)	2.19	bending mode shape
(12)	2.33	2nd torsional mode shape
(13)	2.41	bending mode shape
(14)	2.50	bending mode shape
(15)	2.89	bending mode shape

3.2 The Dynamic Load Test

The force vibration of the footbridge deck was studied during the second part of the experiment that was caused by different groups of pedestrians. The footbridge deck vibrations were observed by a normal pedestrian traffic, walks of two pedestrians (see Fig. 3) and actions of vandal groups for example. All walks of two pedestrians and actions of vandal groups were synchronized at resonance with some natural frequency of the deck (see Fig. 3) the attention was focused on the footbridge natural frequencies around 2.0 Hz especially.

Fig. 3: The walk of two pedestrians synchronized at resonance with the ninth natural frequency 2.05 Hz.

The force vibrations were observed in three deck points only (see Fig. 3). Two points were placed in the cross section in the middle of the main footbridge span where the vertical vibrations were observed in both points and the horizontal ones in one point. The third point was situated at the quarter of the main span and in this one the vertical vibrations were investigated only. The same measurement system, device and transducers, were used as by the experimental modal analysis.

4 The Basic Evaluated Results

4.1 The Experimental Modal Analysis

Twenty natural frequencies and corresponding mode shapes were evaluated by experimental modal analysis in the frequency range from 0.5 Hz to 5.0 Hz. The program ME'Scope was used for off line evaluation of the footbridge modal characteristics. The selected experimentally obtained natural frequencies are stated in Tab. 1.

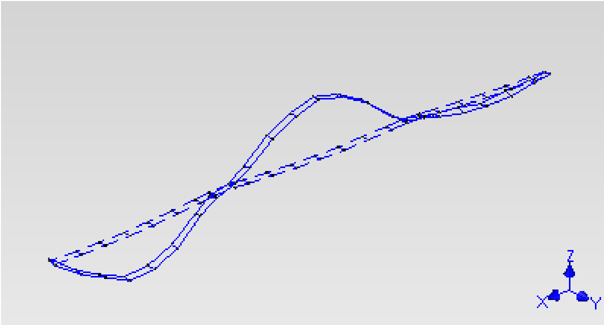

Fig. 4: The 1st measured natural mode shape of the footbridge, $f_{(1)} = 0.50$ Hz.

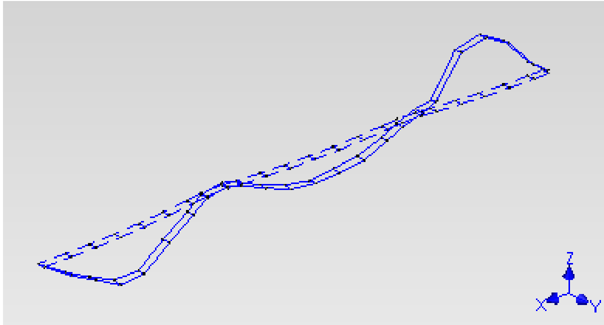

Fig. 5: The 2nd measured natural mode shape of the footbridge, $f_{(2)} = 0.64$ Hz.

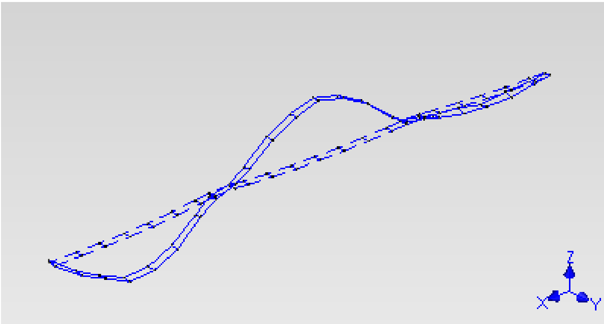

Fig. 6: The 8th measured natural mode shape of the footbridge, $f_{(8)} = 1.58$ Hz.

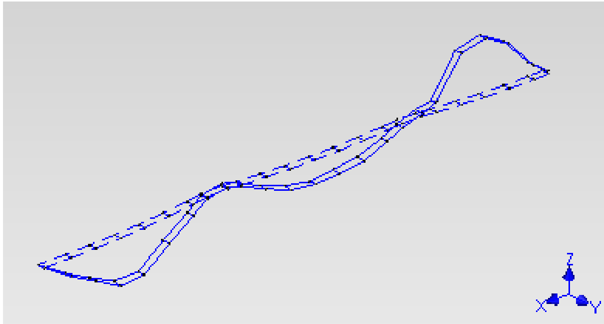

Fig. 7: The 10th measured natural mode shape of the footbridge, $f_{(10)} = 2.05$ Hz.

4.2 The Dynamic Load Test

As shown in the previous chapter, the basic natural frequencies of the footbridge are relatively low and these ones would not be possible to excite effectively by dynamic effects of synchronized pedestrians or vandals therefore the experiment was focused on to get vibrate the footbridge deck with the higher natural frequencies from the eighth to the fifteenth natural frequency. The selected experimentally obtained maximum peak accelerations of the footbridge deck are stated in Tab. 2.

The footbridge damping that was evaluated from observed free damped vibrations was relatively low for a presstresed concrete structure. The logarithmic decrement value of approximately 0.04 or respectively the damping ratio of 0.6 % was obtained.

4.3 The Results Comparison with the Previous Experiments

The comparison of the selected natural frequencies which were evaluated in October 2014 with the appropriate ones obtained by the similar previous experimental modal analyses [1,2] is shown in Tab. 3. The natural frequencies of the footbridge decreased slightly over its service years as it is evident from Tab. 3. However the natural frequencies measured in June 2013 [2] were lower than appropriate ones from October 2014. This fact was investigated theoretically and it was detected on the theoretical model of the footbridge that this fact was

Tab. 2: The selected maximum vertical acceleration of the footbridge deck observed during the dynamic load test.

observed quantity	normal pedestrian traffic [m·s^{-2}]	synchronized walk of two pedestrians at 2.05 Hz [m·s^{-2}]	synchronized walk of two pedestrians at 2.89 Hz [m·s^{-2}]	action of the vandal group at 1.58 Hz [m·s^{-2}]	action of the vandal group at 2.05 Hz [m·s^{-2}]
peak value	0.52	0.88	0.73	1.86	2.83

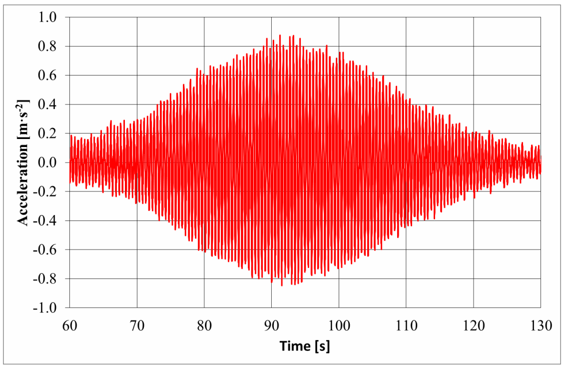

Fig. 8: The vertical acceleration time record that was measured at the middle of the main span by the synchronized walk of two pedestrians at 2.05 Hz there and back again.

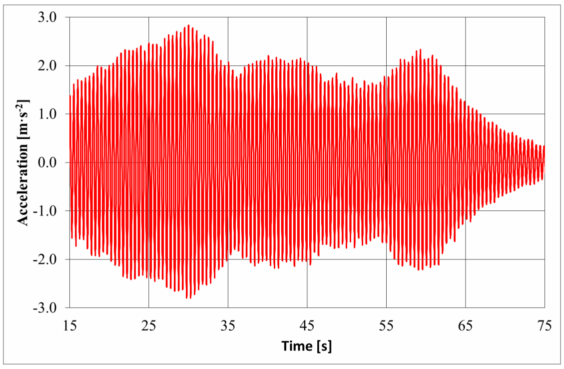

Fig. 9: The vertical acceleration time record that was measured at the middle of the main span by the action of the vandal group at 2.05 Hz.

Tab. 3: The comparison of the selected evaluated natural frequencies of the footbridge with the ones obtained by the previous experiments realized in June 2013 [2], November 2010 and September 1997 [1].

	natural frequency No.				
experiment	(1) [Hz]	(2) [Hz]	(3) [Hz]	(4) [Hz]	(9) [Hz]
September 1997	0.53	0.65	0.93	-	1.63
November 2010	0.51	0.66	0.92	1.04	1.62
June 2013	0.47	0.63	-	0.97	1.53
October 2014	0.50	0.64	0.94	1.01	1.58

very probably caused by large temperature difference about 25 °C of the footbridge bearing structure between the experiments.

It was stated in [2] that the similarity of the natural mode shapes measured in 2010 and in 1997 was high. On the other hand, some differences were found out between the natural mode shapes from 2013 and 2010, especially in the area where the evident damage was found on the deck, which is located approximately in the middle of the first span. It was confirmed that similar differences were detected between natural mode shapes from 2014 and 2010. The detected damage on the deck also after its partial repair caused the partial variation of dynamic footbridge behavior.

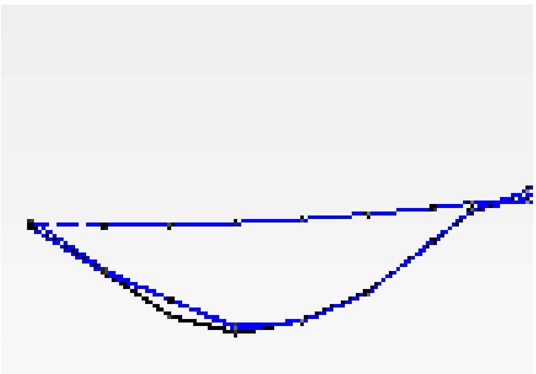

Fig. 10: The comparison of the 1st natural mode shapes of the footbridge measured in 2010 (black) and 2014 (blue) in the area of the 1st span.

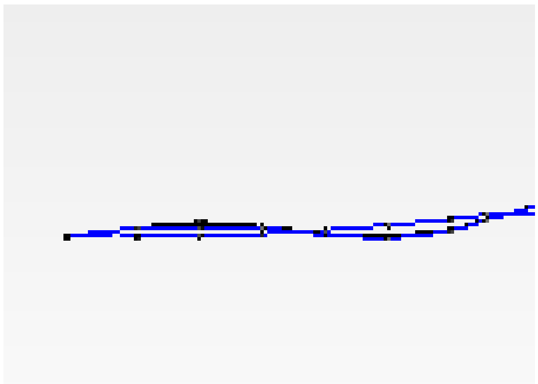

Fig. 11: The comparison of the 4th natural mode shapes of the footbridge measured in 2010 (black) and 2014 (blue) in the area of the 1st span.

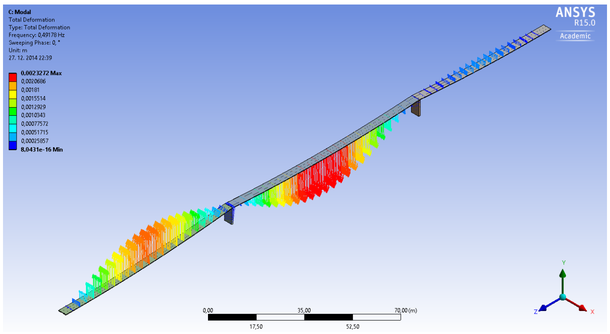

Fig. 12: The 1st theoretical natural mode shape of the footbridge model, $f_{(1)}$ = 0.49 Hz.

Fig. 13: The damage detected on the deck after its partial repair.

5 Conclusions

The footbridge across Vltava River in Prague became known by its sensitivity to dynamic excitation by passing pedestrians since its putting into operation. The performed experiment that is described in the paper confirmed that the footbridge deck vertical vibrations exceed the pedestrian comfort limit 0.7 $\mathrm{m{\cdot}s^{-2}}$ in some situations. The deck vibration level under normal pedestrian traffic was relatively low, the maximal observed acceleration was 0.5 $\mathrm{m{\cdot}s^{-2}}$. However, two pedestrians walking with pacing frequency in resonance with the ninth natural frequency of the first torsional mode induced the maximal footbridge deck acceleration 0.9 $\mathrm{m{\cdot}s^{-2}}$. The deck response to the extreme effect of the vandal groups was substantially higher, it attained the maximal vertical acceleration 2.8 $\mathrm{m{\cdot}s^{-2}}$ in the extreme load case in which the tenth natural frequency of the first torsional mode shape was excited by vandals.

The lowest determined natural frequencies and mode shapes were compared with the ones obtained by the similar previous experiments [1,2]. It was found out the natural frequencies of the footbridge decreased slightly over the years (see Tab. 1). Although the natural frequencies measured in June 2013 were lower than the appropriate ones from October 2014. It was detected on the theoretical model that this fact was very probably caused by large temperature difference about 25 °C of the footbridge structure by the experiments. However, based on comparison of evaluated modes of natural vibrations with the appropriate ones from previous experiments it was confirmed that the detected damage on the footbridge deck caused the partial variation of dynamic footbridge behavior.

Acknowledgement

This paper has been supported by the Technology Agency of the Czech Republic – Competence Centers under No. TE01020168 Centre for Effective and Sustainable Transport Infrastructure.

References

[1] M. Pirner, O. Fischer, Studijní dynamická zkouška lávky v Praze – Troji (in Czech) (Experimental Dynamic Study of the Footbridge in Prague - Troja), expert report (1997), Institute of Theoretical and Applied Mechanics Academy of Sciences of Czech Republic, Prague.

[2] M. Polák, T. Plachý, J. Máca, Experimental Modal Analysis of the Footbridge across Vltava River in Prague Damaged by Flood in June 2013, Applied Mechanics and Materials 617 (2014), 3-6, doi: 10.4028 /www.scientific.net/AMM.617.3.

[3] T. Plachý, M. Polák, Experimental Modal Analysis of the Footbridge across Bečva River in Přerov, in proc.: Proceedings of the 50th Annual Conference on Experimental Stress Analysis (EAN 2012) (2012), ed. M. Růžička, K. Doubrava, Z. Horák, Czech Technical University in Prague Faculty of Mechanical Engineering, Prague, 327–332.

[4] E. Fanfulová, Ověření skutečného dynamického chování a spolehlivosti stávající lávky pro pěší (in Czech) (Verification of the Reliability and Real Time Dynamic Behavior of an Existing Footbridge), diploma thesis (2014), Czech Technical University in Prague Faculty of Civil Engineering, Prague.

[5] T. Plachý, M. Polák, Damage Detection and Localization on Reinforced Concrete Slabs Based on Modal Analysis, in proc.: 22nd Danubia-Adria Symposium on Experimental Methods in Solid Mechanics DAS 2005 (2005), ed. L. Collini, University of Parma / Ingegneria Industriale, Parma, 247-248.