DOI: 10.3217/978-3-99161-057-1-163

Monitoring the dynamic sensitivity of the Solkan footbridge to user-induced excitation

Mirko Kosič[1, ORCID 0000-0001-8543-8009], Doron Hekič[2, ORCID 0000-0001-5667-9129], Izabela Joanna Drygala[2, ORCID 0000-0003-2051-0318]
[1]Slovenian National Building and Civil Engineering Institute (ZAG), Dimičeva ulica 12, 1000 Ljubljana, Slovenia
[2]Cracow University of Technology, Faculty of Civil Engineering, Warszawska 24, 31-155 Krakow, Poland
email: mirko.kosic@zag.si, doron.hekic@zag.si, izabela.drygala@pk.edu.pl

ABSTRACT: This paper presents a comprehensive monitoring study of the dynamic sensitivity of the Solkan footbridge in Slovenia, with a focus on its response to user-induced actions. An extensive ambient vibration measurement campaign was carried out, during which 26 triaxial accelerometers were strategically deployed along the bridge to capture its modal characteristics in all three spatial directions. The structure's dynamic response was monitored under both regular pedestrian traffic and elevated loading conditions during a local marathon event, allowing for the assessment of its behaviour across a broad spectrum of real-world scenarios. Preliminary measurements revealed reduced pedestrian comfort, primarily due to resonance effects resulting from bridge–user interaction. The study highlights the importance of field-based dynamic assessments in diagnosing performance issues and informing mitigation strategies. The findings contribute to the advancement of resilient and dynamically efficient design and maintenance practices for pedestrian bridges.

KEY WORDS: Modal model validation; Footbridges; Ambient vibrations; Dynamic sensitivity; User-induced excitation.

1 INTRODUCTION

Pedestrian footbridges are particularly challenging structures to design due to their pronounced susceptibility to dynamic issues resulting from bridge–user interaction [1]. These interactions can lead to serviceability concerns such as excessive vibrations, which in turn affect user comfort and, in some cases, may even raise long-term durability concerns [2] [3]. Addressing these challenges requires going beyond conventional static checks and incorporating advanced dynamic analyses aimed at identifying and mitigating resonance-related problems [4].

Current standards and guidelines provide recommendations for the frequency ranges typically excited by pedestrians and runners and require dynamic analysis when a bridge's natural frequencies fall within these ranges [5-8]. The critical frequency range for vertical vibrations is between 1.5 and 3.5 Hz, while for horizontal vibrations, it is between 0.5 and 1.5 Hz [5]. According to Sétra guidelines [6], resonance risks are particularly high for vertical vibration frequencies between 1.7 and 2.1 Hz, and for horizontal vibration frequencies between 0.5 and 1.1 Hz. To prevent resonance, the fundamental frequencies of footbridges should ideally exceed these ranges. However, achieving this is often challenging in lightweight and flexible structures, such as suspension or cable-stayed footbridges. Therefore, detailed dynamic assessments are essential to ensure acceptable levels of pedestrian comfort. For instance, Eurocode [7,8] mandates dynamic analysis for footbridges with predominant vertical frequency below 5 Hz and horizontal frequency below 2.5 Hz.

Given the complexity of structural dynamic response, post-construction measurements are crucial to verify performance in real-world conditions. Ambient vibration testing, combined with operational modal analysis (OMA), offers a non-invasive and effective means of identifying a bridge's dynamic characteristics [2]. These data can be used to calibrate numerical models and support robust methodologies for evaluating and improving dynamic performance.

In addition to typical service conditions, there is growing recognition of the need to monitor the structural response of footbridges under extreme user-generated actions, such as dense crowds, synchronized movements, or dynamic events like running or jumping. Long-term dynamic structural health monitoring (SHM) enables the detection of changes in modal properties, transient amplification effects, and possible structural degradation under such rare but critical loading scenarios. Integrating SHM strategies into bridge management enhances safety, informs maintenance decisions, and supports the development of resilient infrastructure that can withstand both everyday usage and exceptional dynamic demands.

This paper investigates the dynamic behaviour of a pedestrian footbridge spanning the Soča River in Slovenia, which has shown reduced pedestrian comfort during regular use. The bridge's dynamic response and its sensitivity to user-induced excitation are evaluated through an experimental monitoring campaign utilising strategically placed triaxial accelerometers [9].

2 METHODOLOGY

2.1 Bridge description

The Solkan footbridge is a single-span cable-stayed suspension structure crossing the Soča River in Slovenia with total span 120.0 m (see Fig. 1). It features an open-section steel deck suspended from two main parabolic steel cables anchored on both riverbanks. The main cables are supported by two steel A-shaped pylons mounted on reinforced concrete abutments. Vertical hangers, spaced at 6.0-meter intervals, connect the deck to the main cables. The deck is additionally laterally and longitudinally stabilised by a parabolic cable anchored to the abutments, along with four straight bracing cables attached at one-quarter of the span length from each end. The deck is

DOI: 10.3217/978-3-99161-057-1-163

supported at both ends by four elastomeric bearings, two of which allow for longitudinal movement to accommodate thermal expansion.

The material of the pylons is S235 steel according to EN-1993-1-1, while the material of all deck members is S355 steel. The cables are constructed with high-strength steel ropes with tension strength f_u = 1500 MPa and modulus of elasticity E = 165 GPa. The cross-section and material characteristics of the bridge are summarized in Figure 1. Footbridge over the Soča River (Slovenia).

Table 1.

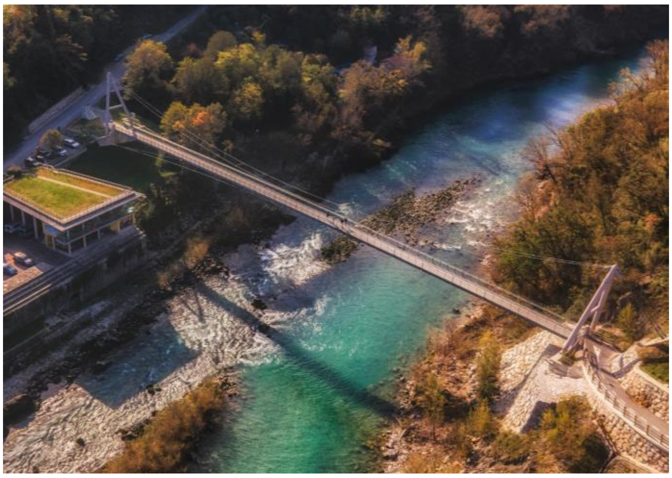


Figure 1. Footbridge over the Soča River (Slovenia).

Table 1. Characteristics of footbridge's structural parts (*FLC* – Full Coil Rope, *OSS* – Open Spiral Strands, *D* - Outside diameter, t_w - Wall thickness)

Element	Property	Material
Main cables	FLC, D = 72 mm	High-strength steel
Hangers	FLC, D = 16 mm	High-strength steel
Stabilising parabolic cables	FLC, D = 60 mm	High-strength steel
Stabilising straight cables	FLC, D = 38 mm	High-strength steel
Connecting cables	OSS, D = 12 mm	High-strength steel
Pylon (legs)	Circular hollow section, D/t_w = 355/10mm	S235
Pylon (traverse)	Hollow circular section, D/t_w = 254/10 mm	S235
Long. girders	IPE400	S355
Trans. girders	IPE270	S355
Bracing diagonals	IPE200	S355

2.2 Concept of investigation

The experimental campaign aimed at investigating the bridge's dynamic characteristics and its sensitivity to user-induced loads was conducted in November 2024. The measurements included:

- ambient vibration measurements,
- controlled pedestrian loading tests to assess its dynamic performance under user-induced excitation,
- monitoring of the bridge's response during a marathon event, to evaluate its behaviour under dense, real-world extreme pedestrian traffic.

Under controlled pedestrian loadings, the program included pedestrian sweeps, running, and synchronized marching tests with both small and large groups. This methodology allowed for evaluating the structure's general susceptibility to user-induced excitations.

Overall, the investigation was guided by two primary objectives:

- identification of the structure's modal properties,
- evaluation of the bridge's dynamic sensitivity to user-induced excitation.

3 MODAL MODELS

3.1 Monitoring setup

The footbridge's reference modal model was established based on experimental data obtained through ambient vibration measurements. For this purpose, the acceleration response of the bridge was recorded at multiple control points distributed across the structure. In total, 26 accelerometers were used in the campaign. Measurements were taken in all three global directions at each control point, with a sampling rate of 500 Hz. The sample of the measured acceleration signals consists of 1 hour of ambient vibration data. A representative control point with a tri-axial accelerometer is depicted in Figure 2.

Figure 2. Representative control point.

The measuring system was composed of twelve MonoDAQ-E-gMeter MEMS accelerometers and fourteen IOLITEi-3xMEMS-ACC accelerometers, both connected with EtherCAT cables to an industrial PC running the DewesoftX acquisition system. Both types of sensors are triaxial accelerometers, featuring low-noise performance (96 dB dynamic range and 25 µg/√Hz spectral noise density), integrated data acquisition, and EtherCAT connectivity. The MonoDAQ-E-gMeters were mounted on aluminium plates and were attached to the deck's transverse girders via magnets, while the IOLITEi-3xMEMS-ACC were attached to steel tripods and were placed directly on the bridge deck.

DOI: 10.3217/978-3-99161-057-1-163

Data acquisition and initial processing were carried out using DewesoftX software, which enabled signal recording, real-time analysis, and visualization. The collected data were subsequently exported for further analysis in FlexPro, Simcenter Testlab (LMS Test.Lab), and Dewesoft Artemis OMA, supporting both time- and frequency-domain evaluations.

3.2 Experimental modal models of the footbridge

Based on data collected during ambient vibration monitoring, the modal models of the footbridge were extracted using methods belonging to two main methodological groups that are strongly oriented towards OMA, namely [9]:

- Frequency Domain Decomposition (FDD),
- Stochastic Subspace Identification (SSI).

Accordingly, the following approaches were compared: Enhanced Frequency Domain Decomposition (EFDD), Curve-fit Frequency Domain Decomposition (CFDD), Unweighted Principal Component (SSI-UPC), and Extended Unweighted Principal Component (SSI-UPCX). Figure 3 presents an example of data recorded in the mid-span of the footbridge during ambient vibration testing, shown in the time-frequency domain. The experimental modal models were validated using the Modal Assurance Criterion (Eq. 1), with the AutoMAC matrix employed for this purpose [10].

$$MAC_{ij}(\psi_i^A, \psi_j^B) = \frac{(\{\psi_i^A\}^T\{\psi_j^B\})^2}{(\{\psi_i^A\}^T\{\psi_i^A\})(\{\psi_j^B\}^T\{\psi_j^B\})} \quad (1)$$

The modal models obtained from different identification techniques are summarized in Table 2. Figure 4 illustrates the 3D AutoMAC matrix for the SSI approach, and Figure 5 provides a comparison of the damping ratio estimates across the various methods.

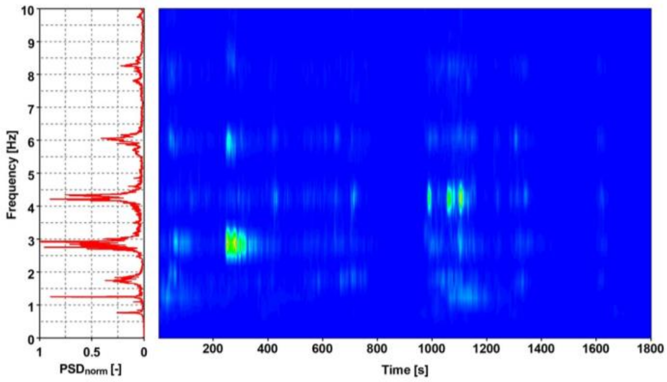


Figure 3. Acceleration and frequency time histories for ambient vibration (mid-span, vertical direction).

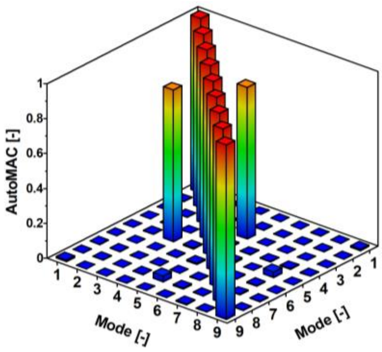


Figure 4. AutoMAC matrix for SSI OMA.

Table 2. Natural frequencies of the footbridge obtained with different OMA techniques.

Mode*	Frequency [Hz]			
	FDD	CFDD	EFDD	SSI
1V	0.574	0.570	0.569	0.571
2V	0.764	0.764	0.765	0.770
3H	0.847	0.843	0.843	0.844
4V	1.052	1.054	1.054	1.053
5H	1.096	1.096	1.097	1.098
6T	1.145	1.144	1.145	1.142
7V	1.743	1.740	1.741	1.735
8T	1.819	1.804	1.804	1.818
9V	2.202	2.196	2.201	2.194

V – vertical; H – horizontal; T - torsional

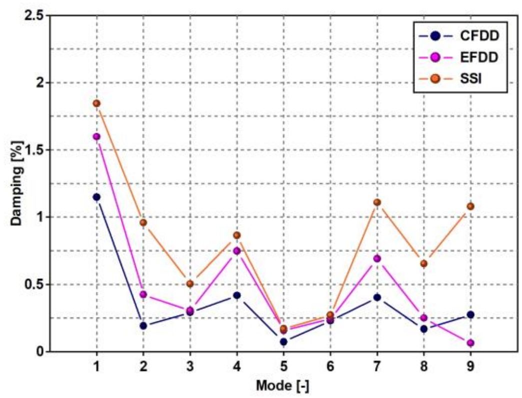


Figure 5. Damping ratios for the identified modes.

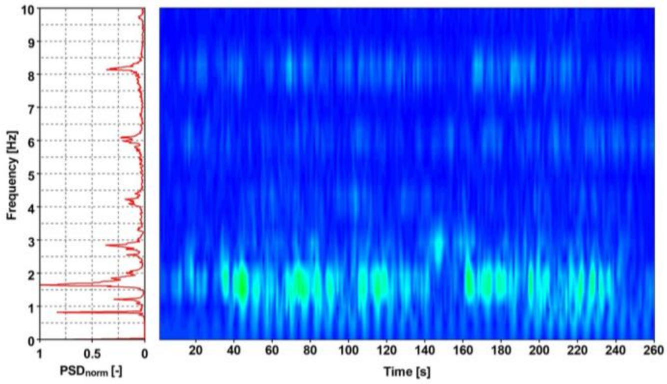
4 SENSITIVITY OF THE BRIDGE TO USER-INDUCED EXCITATION

4.1 Controlled pedestrian loading tests

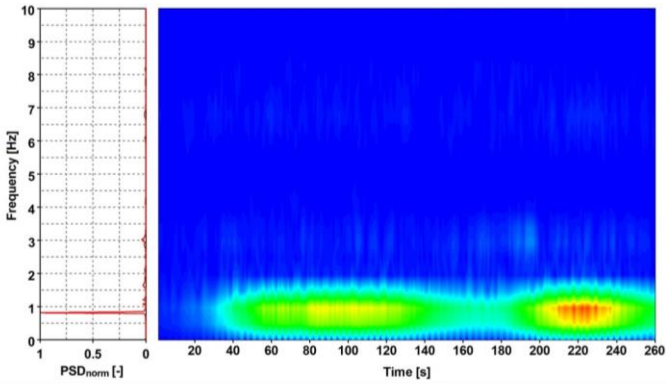
The primary objective of the field tests involving pedestrians and runners was to evaluate the footbridge's susceptibility to resonance effects. Therefore, a series of experiments was carried out, during which various dynamic scenarios were considered, including walking and synchronized group movement, to identify critical excitation frequencies and assess the resulting vibration levels in different structural locations. The responses were evaluated using acceleration and frequency time histories obtained from Short-Time Fourier Transform (STFT) analysis with a window size of 0.54 s and 50% overlap.

DOI: 10.3217/978-3-99161-057-1-163

Based on dynamic responses, a series of resonant frequencies induced by various human activities were observed. In the random walk case, the dominant response frequency in the horizontal direction was 0.84 Hz (see Fig. 6b). This resonance was exciting by walking-induced dynamic loading at a frequency of 1.64 Hz in the vertical direction, as shown in Fig. 6a. This suggests that the excitation falls within the resonance range of the first horizontal mode, which also contributes to the vertical response, particularly evident in the 7V mode (see Tab. 2). The excitation frequency (1.64 Hz) corresponds to approximately 95% of the mode's natural frequency (1.74 Hz). This is a significant observation, as both the 1.64 Hz and 0.84 Hz components originate from the same pedestrian passage, corresponding to the vertical and horizontal components of the walking-induced forces, respectively.



(a)



(b)

Figure 6. Acceleration and frequency time histories for random walking (mid-span) for vertical (a) and (b) horizontal direction.

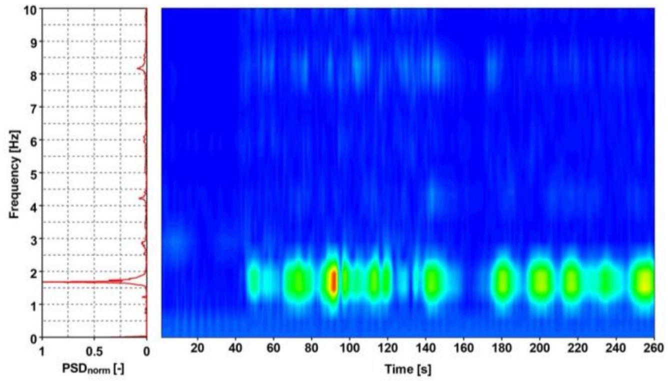


Figure 7. Acceleration and frequency time histories for marching group of people (mid-span, vertical direction).

Figure 8 presents the time-domain response recorded during the user-induced frequency sweep, ranging from 1.50 to 3.50 Hz. This was performed by three volunteers moving in synchrony, guided by a preprogrammed metronome recording. MP3 files with impulse sounds have been generated (intended to synchronize volunteers ' stomping on the bridge). Each file contains a sweep of frequencies from 1.5 Hz to 3.5 Hz, in 0.1 Hz increments (i.e., 1.5, 1.6, 1.7, ..., 3.5 Hz), with smooth transitions between frequencies (no pauses) and an approximate total duration of 385 seconds.

The Short-Time Fourier Transform (STFT) analysis, represented in terms of normalized Power Spectral Density (PSD_{norm}), revealed that several natural frequencies were excited over the course of the experiment, indicating a dynamic interaction between the excitation and the structure's modal characteristics. Notably, the most prominent response occurred in the frequency range between 0.8 and 1.70 Hz, which corresponds to the range of several resonant frequencies of the structure (3H to 7V, see Table 2). This suggests that the system exhibits a strong sensitivity to excitation near these frequencies. The largest amplification occurred at a frequency of approximately 1.2 Hz, which is close to the first torsional mode of the footbridge (6T). A clear amplification of the response in the range of resonant frequencies confirms the effectiveness of the frequency sweep in exciting the relevant modal behaviour.

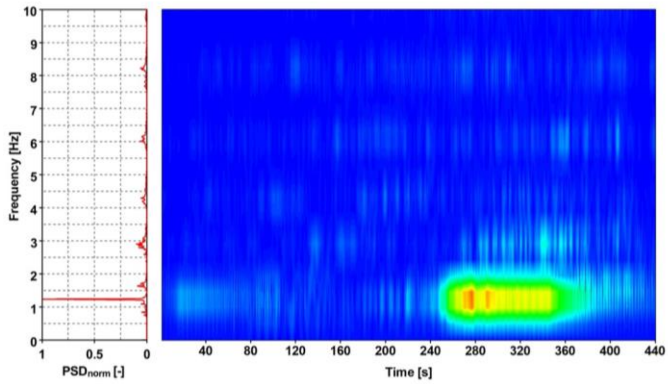


Figure 8. Acceleration and frequency time histories for user-induced frequency sweep (mid-span, vertical direction).

4.2 Footbridge's response during a marathon event

The monitoring campaign also included continuous data acquisition during a marathon, allowing for the assessment of

DOI: 10.3217/978-3-99161-057-1-163

the structure's dynamic behavior under dense pedestrian loading. Figure 9 presents the time-domain response recorded during the marathon at mid-span in the horizontal direction. STFT analysis revealed that several natural frequencies were excited during this large-scale social event, which represents an extreme loading scenario. This indicates a dynamic interaction between the excitation and the modal characteristics of the structure. The most significant response was observed at a frequency of approximately 1.10 Hz in the horizontal direction.

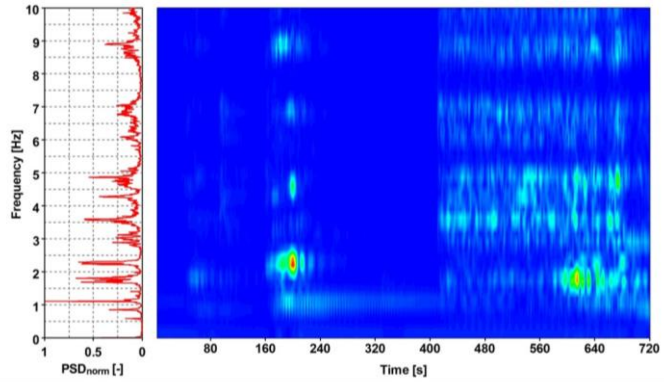


Figure 9. Acceleration and frequency time histories for marathon (mid-span, horizontal direction).

5 CONCLUSIONS

Based on the presented study, several key conclusions were drawn. Within the frequency range of 0–2.50 Hz, nine vibration modes were successfully identified. Among them, two modes belonged to the commonly recognized critical set for footbridges, including one vertical (1.74 Hz) and one horizontal mode (0.84 Hz), which suggests sensitivity of the bridge to user-induced excitation. Notably, both modes were excited by a single pedestrian passage, making the response particularly concerning. This is further amplified by the fact that the random walk scenario, responsible for triggering both modes, is the most frequent type of loading expected during regular bridge use. A high level of consistency was achieved across all developed modal models, with a mean error of less than 2%, confirming the reliability of the applied identification techniques.

The analysis of dynamic responses revealed a dominant resonant frequency of 1.64 Hz under both random walking and marching activities, indicating a strong excitation associated with the vertical component of pedestrian loading. Additionally, during random walking, a significant response was observed at 0.84 Hz, which corresponds to the horizontal component of the same excitation. These results demonstrate that human-induced vibrations can simultaneously activate multiple modal components of the structure. Furthermore, during the marathon event, extreme horizontal vibrations were recorded, to the extent that participants were unable to continue running across the footbridge. This highlights the severity of the dynamic response under real, large-scale crowd loading. The use of user-induced frequency sweeps during experimental testing proved to be an effective method for capturing a wide range of vibration modes and natural frequencies.

These findings underscore the importance of considering both vertical and horizontal components of pedestrian-induced loading in the dynamic analysis, design, and safety assessment of footbridges. The observed variation in identified modal parameters across different load scenarios highlights the need to account for uncertainty in vibration-based evaluations. Future research should address this aspect more systematically by following established best practices in pedestrian bridge monitoring and incorporating statistical methods to quantify confidence levels in the extracted modal data.

ACKNOWLEDGMENTS

The authors would like to acknowledge the support of the Municipality of Nova Gorica (Slovenia), Rok Mesar from the company Dewesoft (Slovenia), and Prof. Chiara Bedon, Marco Fasan and Michele Dilena from the University of Trieste (Italy) in the execution of the field measurements. The first and second authors would like to acknowledge the support of the Slovenian Research Agency, obtained through Research core funding No. P2-0273 and Infrastructure funding I0-0032.

REFERENCES

[1] H. Bachmann, 'Lively' footbridges – A real challenge, in: Proceedings of Footbridge 2002, 2002.

[2] C. Bedon, I.J. Drygala, J.M. Dulinska, D. Jasinska, Application of optimized spring–mass–damper pedestrian load models for vibration assessment of footbridges: numerical and experimental investigation of a cable-stayed system, Archives of Civil and Mechanical Engineering, 25 (2025), 86.

[3] X. Wei, J. Russell, S. Živanović, J.T. Mottram, Measured dynamic properties for FRP footbridges and their critical comparison against structures made of conventional construction materials, Composite Structures, 223 (2019), 110956.

[4] C. Moutinho, A. Cunha, E. Caetano, J.M. Carvalho, Vibration control of a slender footbridge using passive and semiactive tuned mass dampers, Structural Control and Health Monitoring, 25 (2018).

[5] International Organization for Standardization, ISO 10137:2007(E) – Bases for design of structures – Serviceability of buildings and walkways against vibrations, ISO, Geneva, Switzerland, 2007.

[6] SÉTRA, Assessment of Vibrational Behaviour of Footbridges under Pedestrian Loading. Technical Guide, Technical Department for Transport, Roads and Bridges Engineering and Road Safety, Paris, France, 2006.

[7] CEN, Eurocode 1: Actions on structures – Part 2: Traffic loads on bridges, European Committee for Standardization, Brussels, Belgium, 2003.

[8] British Standards Institution, BS NA EN 1991-2: UK National Annex to Eurocode 1 – Actions on structures – Traffic loads on bridges, BSI, London, UK.

[9] Structural Vibration Solution (SVIBS). ARTeMIS Modal. Operational Modal Analysis. Online: https://www.svibs.com/operational-modal-analysis/

[10] D.J. Ewins, Modal Testing: Theory, Practice and Application, 2nd edition, Research Studies Press Ltd., Philadelphia, PA, USA, 2000.