Monitoring Reinforced Concrete Arch Bridges with Operational Modal Analysis

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Abstract. The paper presents the first results of the vibration-based Structural Health Monitoring strategy implemented on the historic *Brivio* bridge, within a joint research between Lombardy Region and Politecnico di Milano aimed at defining guidelines for the monitoring of key infrastructures. The bridge at study, dating back to 1917, crosses the Adda river and consists of three reinforced concrete tied arches. Due to its position, the *Brivio* bridge represents a crucial node for the vehicular traffic of the local road network. Firstly, documentary research, visual inspections, geometric survey, mechanical characterization of materials, and multiple dynamic tests are performed. The information collected on-site is then used to develop and calibrate a FE model of each arch. Once those preliminary activities are completed, a monitoring system is installed including 8 seismometers per span and 1 temperature sensor. The collected data are transferred in real time to a dedicated workstation and stored in separate files of 1 h, that are automatically processed using a multi-level procedure developed in the Matlab environment.

Keywords: Bridge · Historical constructions · Operational modal analysis · Structural Health Monitoring · Continuous monitoring

1 Introduction

Recent joint research between Politecnico di Milano and Regione Lombardia focused on the definition of criteria and guidelines for maintaining and managing roadway infrastructures [1–3]. Firstly, a risk-based prioritization methodology was developed at a regional scale; subsequently, recommendations for implementing Structural Health Monitoring (SHM) strategies on different structural typologies were provided. Nine bridges were then identified for the validation of the proposed approach. The present paper focuses on the application of a SHM strategy based on Operational Modal Analysis (OMA) to one of the selected structures: the 100-years-old bridge connecting the small towns of Brivio and Cisano Bergamasco (Fig. 1).

The *Brivio* bridge (Fig. 1) crosses the Adda river about 50 kmNorth-East of Milan. The bridge was the subject of previous studies [4] in 2014–2015. Starting from 2020, an extensive program of documentary research and on-site tests was carried out and a continuous dynamic monitoring system was installed.

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After a brief description of the bridge and of preliminary investigation of the structure, the main results of the first 5 months of dynamic monitoring are presented and discussed. More specifically, full details are given on the following activities: (i) documentary research; (ii) minor destructive tests (MDT); (iii) multiple dynamic tests; (iv) FE modelling and updating; (v) dynamic monitoring and data analysis.

Fig. 1. The *Brivio* bridge: view from the downstream of Adda River on the Lecco side.

2 The *Brivio* Bridge: Documentary Research, On-Site Tests, and FE Modelling

The 100-years-old *Brivio* bridge (Fig. 1) is a historical tied-arch RC bridge, crossing the Adda river on the route between Leccoand Bergamo. Despite the age of construction, the bridge still represents a crucial node for the vehicular traffic of the local road network.

The *Brivio* bridge is 132.0 m long and consists of three tied arches, spanning about 44.0 m each, two piers – whose foundations are built in the riverbed – and two end abutments. The deck of each arch is 9.05 m wide, for two traffic lanes and two pedestrian walkways, and consists of a cast in place RC slab supported by two longitudinal beams that are hung from each arch with 16 RC hangers. Each span is in principle symmetric with respect to its middle longitudinal and transverse planes. For the sake of clarity, from now on, the spans are numbered starting from the Lecco side.

The bridge – designed by the Italian engineer Giuseppe Banfi [5] – was built between June 1912 and May 1917. During the first documentary research, performed in the archives of the Brivio municipality, the original design documents were retrieved, and in particular: the blueprints, the static calculation of the arches, the reinforcement details, the specifications on construction materials, and the adopted code regulation. However, despite the accurate description of the bridge included in the design documents, variations in the dimension of some structural members were observed on site. Consequently, a second historical research was performed in the archives of the National Roadway Authority (ANAS) and highlighted the occurrence of a series of subsequent interventions: (i) during the 1980s, a general strengthening of the bridge was performed; (ii) at the end of the 1990s, the bearings were substituted; (iii) in 2014, the pier on the Bergamo side was strengthened.

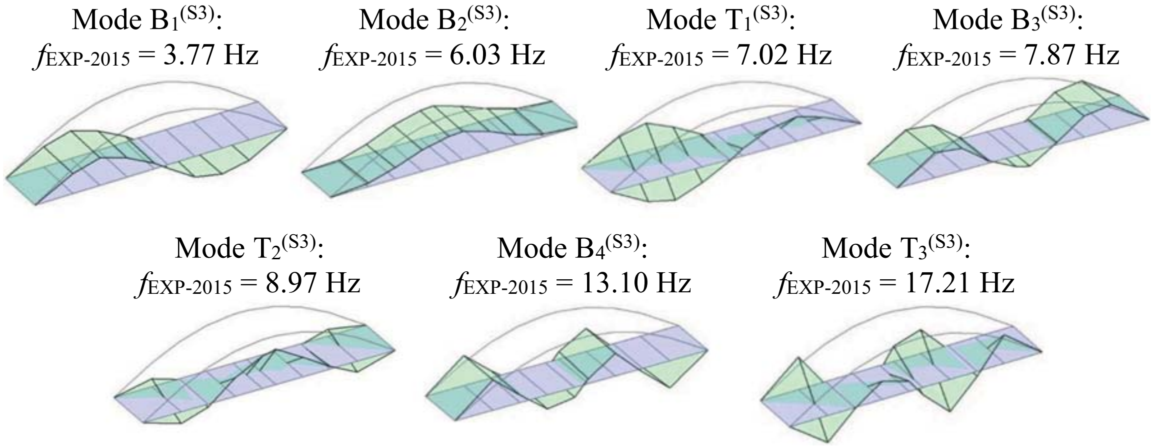
The mechanical properties of the concrete elements of the bridge were evaluated from laboratory tests on cored samples. Overall, the mechanical characterization of the concrete materials was performed by coring arches, hangers and deck in 24 different positions. The cored samples were distributed along the structure to obtain a homogeneous representation of the mechanical properties of the different structural elements of each span. The samples extracted from arches and hangers were subjected to ultrasonic pulse velocity and compression tests to estimate the compressive strength and the elastic modulus. A detailed description of the results of the tests is reported in [3].

Multiple Ambient Vibration Tests (AVTs) were performed to evaluate the dynamic characteristics of the bridge. The first tests were carried out in June 2014 (Span 1 and Span 2) and September 2015 (Span 3), with the air temperature ranging between 30 °C and 35 °C. Subsequently, the test was repeated in March 2020, with the air temperatures varying between 12 °C and 15 °C. During both tests, the (vertical) dynamic response of the structure in operational conditions was recorded in 16 measuring points for each span. The modal identification of the recorded acceleration (2014 and 2015 tests) and velocities (2020 test) was performed by applying the Frequency Domain Decomposition (FDD) technique [6]. Overall, 7 vibrations modes were identified for each span in the frequency range of 0–20 Hz. Table 1 shows the comparison between the identified natural frequencies during the subsequent AVTs (2014–2015 and 2020): the results suggest that natural frequencies tend to increase with decreased temperature.

Subsequently, a FE model of each span was developed [3]. Beam elements are used to represent arches, hangers, and beams, whereas shell elements are used to model the concrete slab. The following boundary conditions are adopted at the opposite ends of each span: (i) the transverse deformation of the longitudinal main girders is prevented; (ii) vertical and longitudinal translational springs are introduced to simulate the vertical deformability of pier/abutment and the possible interaction between contiguous spans, respectively. The uncertain parameters of the model were then updated using the identified natural as targets. Particularly the following parameters were optimized: Young's modulus of arches (E_{A}), hangers (E_{H}), deck lattice grid (E_{DG}), and deck slab (E_{DS}), and the stiffness k_L of the longitudinal springs.

Table 1. Comparison of the identified natural frequencies in the AVTs of 2014/15 and 2020.

	Span 1 (S1)		Span 2 (S2)		Span 3 (S3)	
Mode id:	f_{2014} (Hz)	f_{2020} (Hz)	f_{2014} (Hz)	f_{2020} (Hz)	f_{2015} (Hz)	f_{2020} (Hz)
B_1	3.821	3.821	4.126	4.138	3.772	3.796
B_2	6.018	6.018	6.055	6.189	6.030	6.152
T_1	7.178	7.324	7.471	7.581	7.019	7.275
B_3	7.666	7.766	7.813	8.057	7.874	8.032
T_2	9.009	9.143	9.399	9.558	8.972	9.204
B_4	13.06	13.28	13.55	13.82	13.10	13.42
T_3	17.02	17.33	17.61	18.05	17.21	17.54



Mode $B_1^{(S3)}$: $f_{\text{EXP-2015}} = 3.77$ Hz

Mode $B_2^{(S3)}$: $f_{\text{EXP-2015}} = 6.03$ Hz

Mode $T_1^{(S3)}$: $f_{\text{EXP-2015}} = 7.02$ Hz

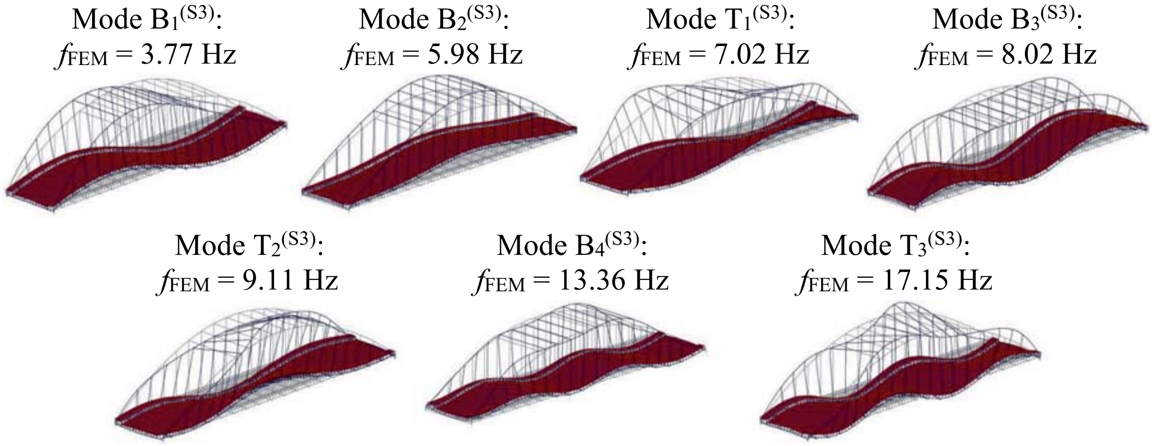
Mode $B_3^{(S3)}$: $f_{\text{EXP-2015}} = 7.87$ Hz

Mode $T_2^{(S3)}$: $f_{\text{EXP-2015}} = 8.97$ Hz

Mode $B_4^{(S3)}$: $f_{\text{EXP-2015}} = 13.10$ Hz

Mode $T_3^{(S3)}$: $f_{\text{EXP-2015}} = 17.21$ Hz

Fig. 2. Span 3 (S3): vibration modes identified during the 2015 AVT.



Mode $B_1^{(S3)}$: $f_{\text{FEM}} = 3.77$ Hz

Mode $B_2^{(S3)}$: $f_{\text{FEM}} = 5.98$ Hz

Mode $T_1^{(S3)}$: $f_{\text{FEM}} = 7.02$ Hz

Mode $B_3^{(S3)}$: $f_{\text{FEM}} = 8.02$ Hz

Mode $T_2^{(S3)}$: $f_{\text{FEM}} = 9.11$ Hz

Mode $B_4^{(S3)}$: $f_{\text{FEM}} = 13.36$ Hz

Mode $T_3^{(S3)}$: $f_{\text{FEM}} = 17.15$ Hz

Fig. 3. Span 3 (S3): vibration modes of the optimal (updated) model.

Figures 2 and 3 show the experimental and numerical vibration modes of Span 3 (S3), respectively. The accurate correlation obtained from the updating procedure is also illustrated in Table 2: the maximum discrepancy in terms of natural frequencies is equal to 4.00%, 6.82% and 1.98% for the three different spans, respectively. Finally, Table 3 shows the comparison between the structural parameters obtained from the available characterization of materials (MDT) and the identified ones (OPT, optimal models).

Table 2. Comparison between the experimental frequencies ($f_{\mathrm{EXP\text{-}2014/15}}$) and the corresponding frequencies of the optimal ($f_{\mathrm{FEM\text{-}OPT}}$) FE models.

	Span 1 (S1)			Span 2 (S2)			Span 3 (S3)		
Mode id:	$f_{EXP\text{-}2014}$ (Hz)	f_{FEM} (Hz)	*DF* (%)	$f_{EXP\text{-}2014}$ (Hz)	f_{FEM} (Hz)	*DF* (%)	$f_{EXP\text{-}2015}$ (Hz)	f_{FEM} (Hz)	*DF* (%)
B_1	3.82	3.78	1.19	4.13	3.85	6.82	3.77	3.77	–
B_2	6.02	6.00	0.34	6.06	6.06	–	6.03	5.98	0.92
T_1	7.18	7.14	0.60	7.47	7.27	2.75	7.02	7.02	–
B_3	7.67	7.97	−3.94	7.81	8.13	−4.10	7.87	8.02	−1.79
T_2	9.01	9.37	−4.00	9.40	9.51	−1.14	8.97	9.11	−1.48
B_4	13.06	13.36	−2.33	13.55	13.57	−0.11	13.10	13.36	−1.98
T_3	17.02	17.02	–	17.61	17.41	1.11	17.21	17.15	0.37

$DF = 100 \times (f_{\mathrm{EXP}} - f_{\mathrm{FEM}})/f_{\mathrm{EXP}}$

Table 3. Optimal (OPT) values of the updating parameters and comparison with the available mechanical characterization (MDT).

	Span 1		Span 2		Span 3	
Parameters	MDT	OPT	MDT	OPT	MDT	OPT
E_A (GPa)	34.77	34.00	33.34	37.00	36.46	35.12
E_H (GPa)	28.09	31.97	36.00	32.00	25.07	28.48
E_{DG} (GPa)	–	28.51	–	27.26	–	29.77
E_{DS} (GPa)	–	25.07	–	29.50	–	26.83
k_L (kN/m)	–	1.70×10^6	–	1.25×10^6	–	1.26×10^6

3 SHM Methodology

The SHM methodology adopted for the *Brivio* bridge is based on a multi-level procedure developed in the MATLAB framework and aimed at the early detection of structural anomalies by using both the cleansed natural frequencies and the changes in mode shapes (Fig. 4). In detail, the developed procedure involves the following steps: (i) preliminary pre-processing of the raw data; (ii) automated identification of modal parameters; (iii) removal of environmental/operational effects from the natural frequencies; (iv) identification of the onset of damage using both the changes in mode shapes and the cleansed natural frequencies (within the framework of classic novelty analysis).

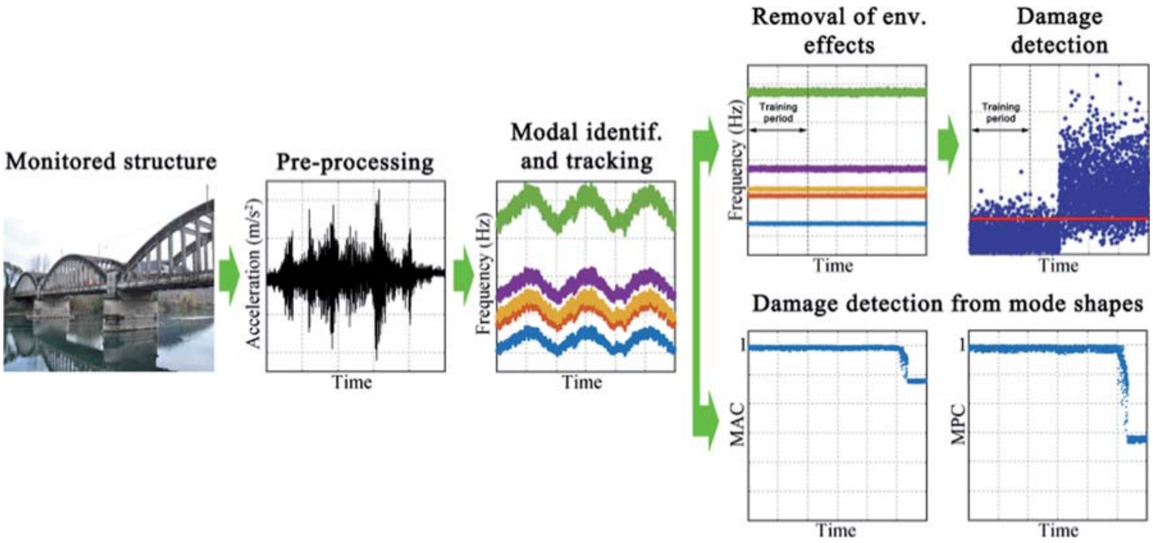


Fig. 4. Schematic of the SHM methodology adopted for the Brivio bridge.

Every hour the measured velocities are transmitted to Politecnico di Milano and the pre-processing is immediately performed. Firstly, the signal attenuation in the low-frequency range is compensated by deconvolving the raw data according to the sensor technical data and the manufacturer recommendations. The root means square of the recorded velocities is then evaluated for each span separately. Subsequently, low-pass filtering and decimation are applied, reducing the sampling frequency from 100 Hz to 50 Hz. The processed signals are assembled for each span on a hourly basis – namely, 3 new files containing 8 columns with 3600 × 50 samples – and stored in local archives and online database for the subsequent analysis.

The modal parameters are separately evaluated for each span, as it was performed in the preliminary AVTs. Accordingly, the pre-processed signals are evaluated with a fully automated procedure based on the covariance driven Stochastic Subspace Identification (SSI Cov) algorithm [7] developed in a previous research [8]. Firstly, the modal parameter estimation is performed, and every hour natural frequencies, mode shapes, and damping factors are identified. At this stage, mode shapes variations are evaluated through the well-known Modal Assurance Criterion (MAC) [9], and the mode complexity is estimated by using the Modal Phase Collinearity (MPC) [10]. It should be noticed that the MAC values are calculated with respect to a reference mode shape identified in the first few days of monitoring.

Since the mode shapes are not significantly affected by environmental and operational changes, Fig. 4 exemplifies that sharp changes of MAC and MPC can be used to directly detect the onset of structural anomalies (without any removal of environmental and operational effects). On the contrary – as shown in Fig. 4 and widely reported in the scientific literature – the natural frequencies of concrete structures are highly influenced by environmental and operational conditions. Therefore, the removal of these "mask" effects is needed to detect the onset of structural anomalies from the frequency data. To this purpose, the calibration of a regression model – based on the Principal Component Analysis (PCA) – is ongoing during a training period of about 8–10 months: at the present stage, the monitoring system of the *Brivio* bridge is still recording data for the training period.

As long as the structure exhibits a regular behavior without any anomalies, the PCA-based regression model can predict the evolution of natural frequencies. Once an anomaly occurs, the variations in the natural frequencies are detected using a control chart, such as the Hotelling multivariate control chart based on the T^2 statistic [11]. Hence, the T^2 statistic is computed using the discrepancy between the predicted and identified natural frequencies (i.e., the prediction errors or residuals), and the upper control limit is evaluated during the training period (Fig. 4).

4 Description of the Monitoring System

The dynamic monitoring system of the *Brivio* bridge is entirely based on the SARA SS45 seismometers, namely, electro-dynamic velocity transducers. The use of these sensors is becoming more popular in Civil Engineering [12, 13] due to the high sensitivity (78 V/ms^{-1}), the null power demand, and the cost to performance ratio.

The continuous monitoring system of the *Brivio* bridge (Fig. 5) includes 8 (vertical) mono-axial seismometers for each span – overall, 24 devices – and 1 temperature sensor. Taking advantage of the symmetry of the structure and its dynamic characteristics (Fig. 2), the seismometers are installed on the upstream side of the bridge (Fig. 5). Each group of 8 sensors is wired to a 24-bit digitizer and the digitizers are connected to one UMTS modem for data transfer. Every hour, a binary file for each sensor is created, and it is sent to Politecnico di Milano for data processing. The structural response to ambient and operational excitations is continuously recorded at a sampling frequency of 100 Hz, and datasets of 3600 s are collected. The data files received from the monitoring system are then managed in a multi-level procedure developed in the MATLAB framework (Fig. 4).

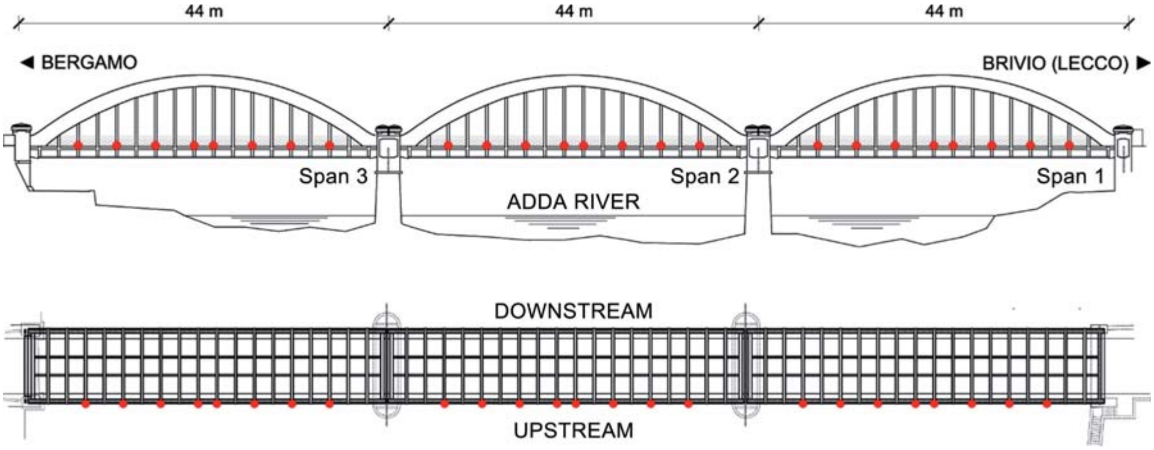


Fig. 5. Sensor layout of the dynamic monitoring system installed on the *Brivio* bridge.

5 Monitoring Results

This section summarises selected results obtained in the dynamic monitoring of the *Brivio* bridge. The Span 3 is used to exemplify the obtained results for a period of 5 months, from 01/10/2020 to 01/03/2021. During this time period, 3624 1-h datasets were collected and automatically processed to identify the modal parameters and track their evolution.

Regarding the measure of the environmental parameters, Fig. 6 presents the evolution of the outdoor temperature measured with the temperature sensor installed on the bridge. The maximum and minimum recorded temperatures in the selected period are equal to 21.3 °C and −2.0 °C, respectively.

During the selected time period, 7 vibration modes are continuously identified in the frequency range 0–20 Hz. The evolution of natural frequencies is shown in Fig. 7. In addition, mode $B_2^{(S3)}$ and mode $T_1^{(S3)}$ are selected to exemplify the frequency-temperature correlation (Fig. 8). As expected, the natural frequency increases with the decrease of temperature for all the identified vibration modes. In addition, all frequencies exhibit a clear increase below 0 °C.

Due to the relatively dense sensors setup, the mode shapes variations are also investigated. Figure 9 illustrates the time variation of mode shape – expressed in terms of the MAC factor – for mode $B_2^{(S3)}$ and mode $T_1^{(S3)}$. As expected, the mode shapes are approximately time-invariant. It is worth mentioning that a similar time invariance is also obtained for the MPC measures of mode complexity.

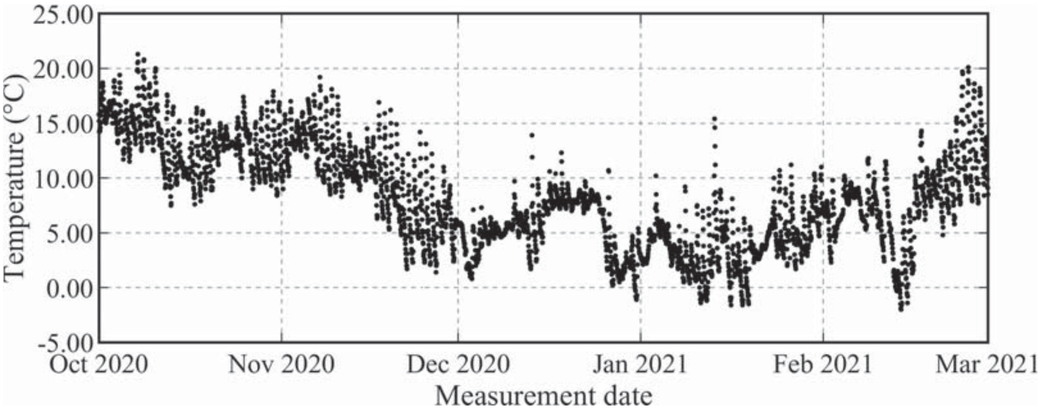


Fig. 6. Variation in time of measured temperature.

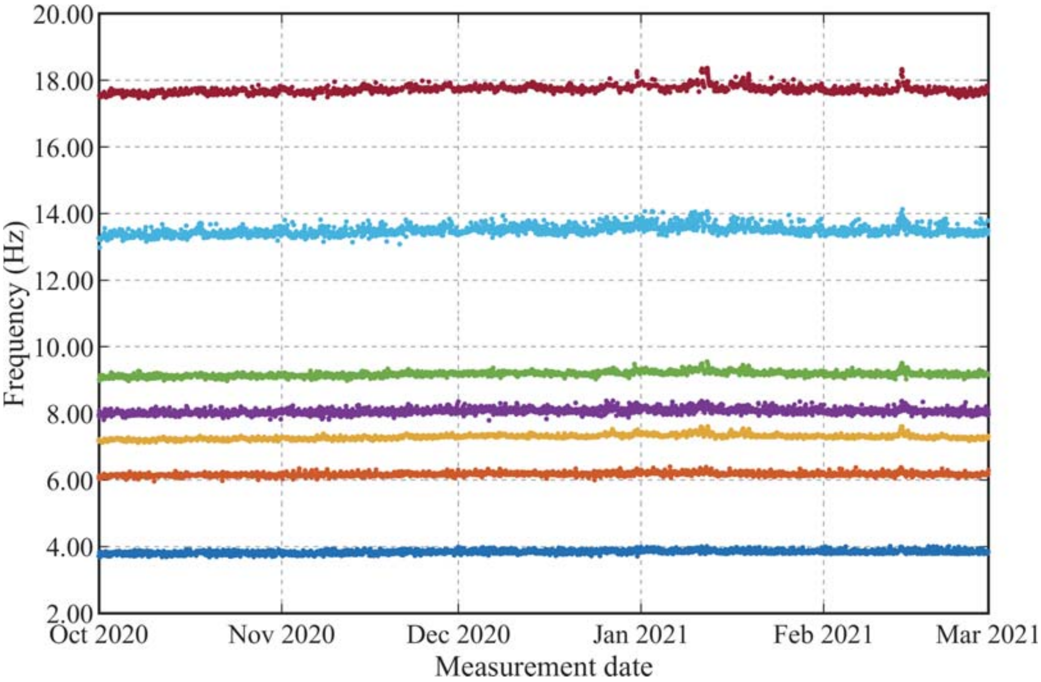


Fig. 7. Span 3 (S3): variation of identified natural frequencies.

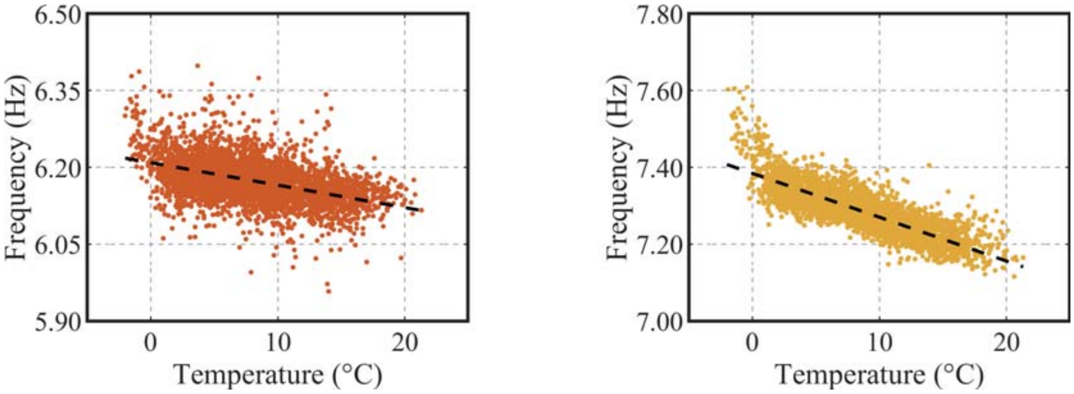


Fig. 8. Span 3 (S3): frequency-temperature correlation for modes $B_2^{(S3)}$ and $T_1^{(S3)}$.

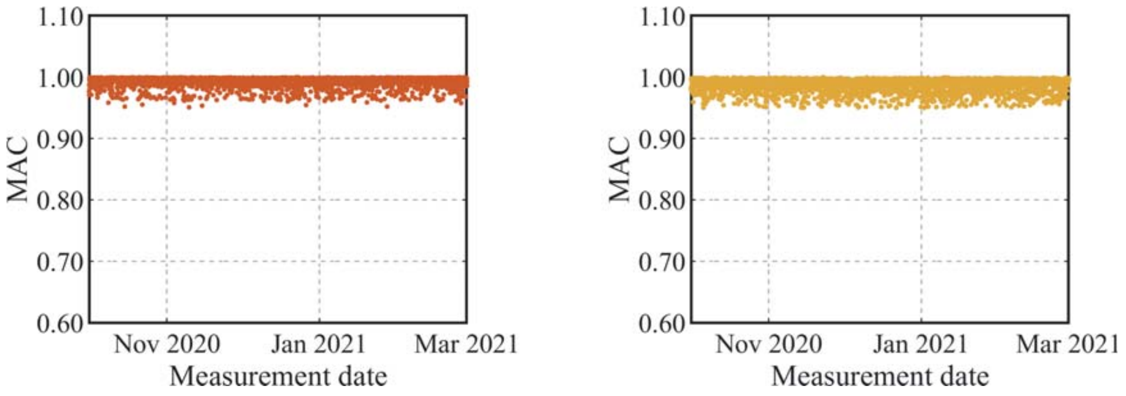


Fig. 9. Span 3 (S3): variation of MAC for modes $B_2^{(S3)}$ and $T_1^{(S3)}$.

6 Conclusions and Future Developments

The paper illustrates the OMA-based strategy adopted for the SHM of a 100-years-old bridge. The main objective of the installed monitoring system is the prompt detection of structural anomalies using both the cleansed natural frequencies (within the framework of classic novelty analysis) and the changes in mode shapes.

Based on the results obtained from the preliminary investigations and the first months of monitoring, the following conclusions can be drawn:

- During multiple preliminary AVTs, seven vibration modes are identified for each span in the frequency interval of 0–20 Hz;
- The results of two dynamic tests (i.e., 2014/15 and 2020) – performed in different temperature conditions – suggest that the natural frequencies of the bridges tend to increase with decreased temperature, whereas no remarkable difference in terms of mode shapes are detected;
- The application of effective tools for the automated operational modal analysis allows the accurate estimation and tracking of 7 vibration modes for each span;
- The air temperature is the dominant driver of the daily variations of natural frequencies of all modes;
- The mode shapes do not exhibit appreciable fluctuations driven by environmental and operational changes.

During the upcoming months, the training period will be completed, and a regression model will be established to remove the fluctuations on natural frequencies induced by temperature variations. In addition, the SHM methodology will be integrated with the optimized baseline FE model to give information on the damage location and extension.

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