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Long-term operational modal analysis of a steel-concrete composite bridge

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ABSTRACT

Selected results collected in the continuous dynamic monitoring of a steel-concrete composite bridge are reported in the paper. The investigated bridge belongs to Autostrada Pedemontana Lombarda (APL), a motorway aimed at optimizing the road connection between Milan, Monza, Como and Varese (Lombardy, Northern Italy). After a concise description of the bridge and its monitoring system, the paper presents and discusses the dynamic characteristics identified in preliminary tests and verified at the beginning of the continuous monitoring. Subsequently, the focus is moved on the data collected over approximately eight months, with particular attention to the influence of environmental parameters on the variations of natural frequencies and mode shapes. It is further noticed that the strategy adopted for the OMA-based health assessment of the bridge will be extended to various bridges managed by APL, as part of a project funded by the Italian Government.

Keywords: Ambient vibration test, Automated OMA, Composite bridge, Environmental effects, Structural Health Monitoring

1. INTRODUCTION

A large part of Italian infrastructures is "very dated". Beyond the historical bridges, erected more than a century ago, many bridges and viaducts in Italy date back to the decades immediately following World War II, when the highway crossing the entire Italian peninsula from North to South was built. Those ageing infrastructures are often characterized by inherent fragility, that might be accentuated by seismic or exceptional events.

To address the risk associated to infrastructure networks, a well-defined management framework was recently defined by the Italian Government; such a framework includes the systematic cataloguing and inspection of each bridge to establish clear priorities of intervention. In addition, to enhance the bridges safety within the main national road network, great attention is currently paid to dynamic monitoring and OMA-based strategies of Structural Health Monitoring (SHM) and a National Program started in 2022, aimed at the installation of monitoring systems on many Italian bridges. Within this context, various bridges belonging to Autostrada Pedemontana Lombarda (APL), a motorway serving various provinces of the Lombardy territory, were selected for the installation of dynamic monitoring systems.

The paper focuses on the results collected during the first months of dynamic monitoring of Olona West bridge [1]. The bridge crosses the Olona river in the province of Varese and the deck consists of a continuous steel-concrete composite girder supported by three RC piers and abutments. After a brief description of the bridge, the dynamic characteristics of the structure are presented: those characteristics, assumed as references in the modal tracking, were estimated in preliminary ambient vibration tests (March 2023) and verified during continuous monitoring. Subsequently, the effects of environmental and operational variability during several months of monitoring are highlighted, with the temperature significantly affecting all natural frequencies, whereas no remarkable changes of mode shapes were observed.

2. BRIDGE DESCRIPTION

The investigated infrastructure, denoted to as Olona West bridge (Fig. 1a) in the following, is a steel-concrete composite bridge that crosses the Olona River in the province of Varese (Lombardy region, Northern Italy). The bridge, having an overall length of 242 m (Figs. 1 and 2), consists of four spans of different lengths (55 m + 66 m + 66 m + 55 m) and is characterized by a slightly curvilinear plan.

The steel-concrete composite deck is supported by two concrete abutments (S1 on the Solbiate side and S2 on the Mozzate side, Fig. 2) and three piers (P1-P3, Fig. 2), with each pier consisting of two solid shafts with circular cross-section of 2.50 m diameter and height varying between 10.70 m and 12.35 m. All the bearing devices are elastomeric seismic isolators, characterised by: (a) appropriate dissipative capacities, (b) low horizontal stiffness to guarantee the decoupling between the horizontal motion of deck and piers/abutments and (b) high vertical rigidity to support vertical loads.

The roadway platform (Fig. 1b) varies in width between 17.12 m on abutment S1 and 14.70 m on abutment S2 and includes one pedestrian sidewalk 2.70 m wide.

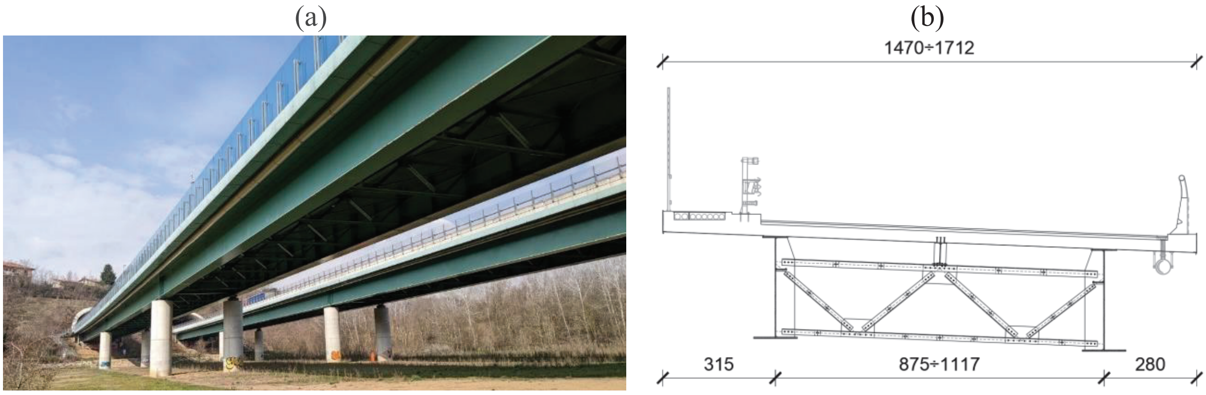


Figure 1. (a) View of the Olona West bridge and (b) typical cross-section of the deck (dimensions in cm).

3. DYNAMIC CHARACTERISTICS OF THE BRIDGE

Ambient vibration tests (AVTs) were performed on the investigated bridge [1] on March 7th, 2023, with the twofold objective of estimating the modal behavior and designing the dynamic monitoring system to be installed in the structure.

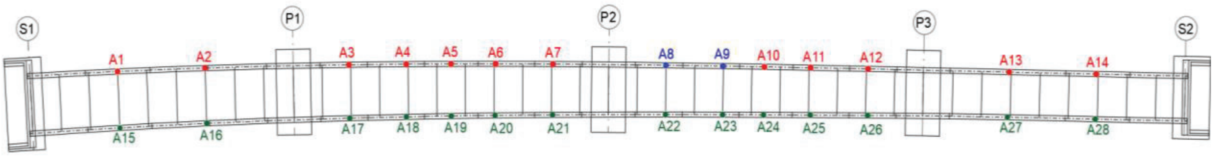


Figure 2. Measurement points adopted during the preliminary tests (Setup 1 is in red, Setup 2 is in green, and the reference sensors are in blue) and the continuous dynamic monitoring.

The dynamic responses induced by road traffic, wind and micro-tremors were recorded in two sensors' layouts (Fig. 2) to identify the lower natural frequencies and to describe the associated mode shapes at 28 measurement points belonging to the opposite ends of the deck cross-sections. The first set-up (see the red points in Fig. 2) was carried out in the morning with both lanes active, whereas in the second set-up (see the green points in Fig. 2) only one lane was open to traffic. It should be noticed that the permanent monitoring involves the same cross-sections investigated in the preliminary tests, with the 28 measurement points, denoted as A1-A28 in Fig. 2, being moved from the deck to the lower flanges of the main steel girders.

For each set-up of the preliminary test, two datasets of 2700 were recorded and data were sampled at 200 Hz. After low-pass filtering and decimation, the application of the Frequency Domain Decomposition (FDD) [2] technique allowed to identify 6 bending modes (B_1-B_6 in Fig. 3) and 3 torsion modes (T_1, T_2 and T_4 in Fig. 3) in the frequency range 0-8 Hz. Figure 3 shows that, after the installation of the monitoring system, a larger number of normal modes was identified.

4. CONTINUOUS DYNAMIC MONITORING AND RESULTS

4.1. Continuous dynamic monitoring strategy

As previously stated, the sensors' layout illustrated in Fig.2 was adopted for the continuous monitoring as well: the equipment installed in the bridge consists of 28 MEMS accelerometers and 2 temperature sensors and has been active since May 20th, 2024.

The monitoring strategy herein applied involves the following steps: (a) Preliminary pre-processing of the raw data; (b) Automated modal parameter estimation and tracking; (c) Checking the mode shapes invariance; (d) Removal of environmental and operational effects from the natural frequencies; (e) Novelty detection.

The acceleration response is continuously measured at a sampling frequency of 200 Hz, and a dataset containing only vertical accelerations is created every hour. Before performing the operational modal analysis, the signals of each dataset are down-sampled to reduce the sampling frequency from 200 Hz to 20 Hz (after applying a low-pass filter with a cutoff frequency of 10 Hz).

The modal parameter estimation (MPE) and the modal tracking (MT) were automatically performed using the MATLAB software package DYMOND [3], which implements the covariance-based Stochastic Subspace Identification (SSI-Cov) algorithm [4]. In more details, the automated MPE procedure initially makes use of damping ratios and modal complexity [5] to detect and remove some spurious poles from the stabilization diagram; subsequently, poles exhibiting comparable characteristics in terms of frequencies and mode shapes are clustered within each dataset. After each MPE, the identified modes are tracked in time and the properties monitored for SHM purposes are natural frequencies, damping ratios, the modal deflection of each instrumented node, the Modal Assurance Criterion (MAC) [6], and the Mean Phase Collinearity (MPC) [5], quantifying the complexity of mode shapes.

Since the bridge dynamic response is continuously collected in a reasonably well distributed measurement grid (28 channels of data), the mode shapes invariance is firsltly checked for anomaly detection and localization.

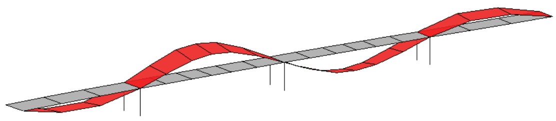
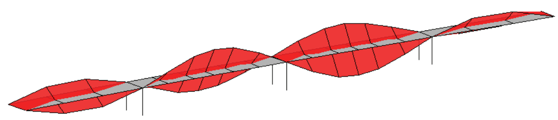
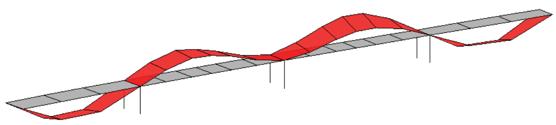
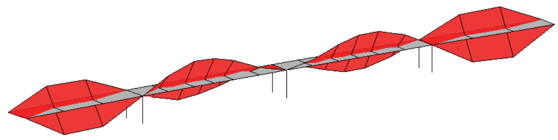
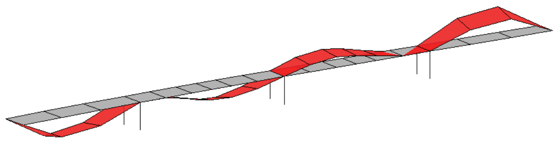
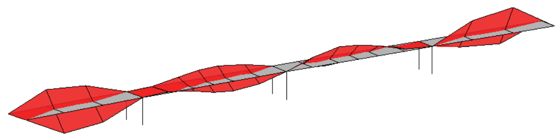
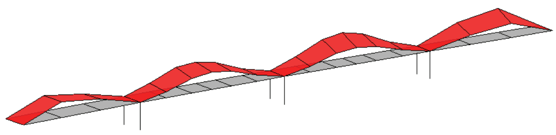
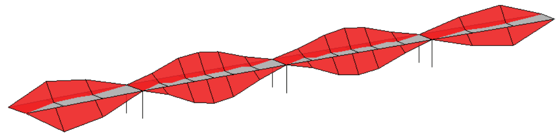
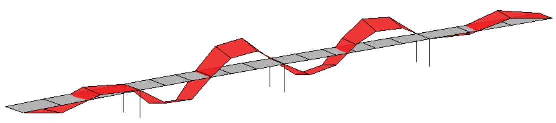
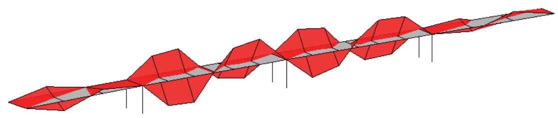
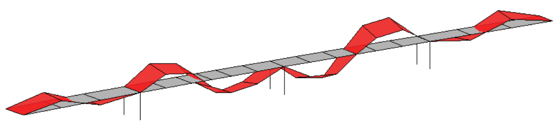
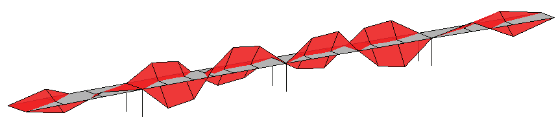
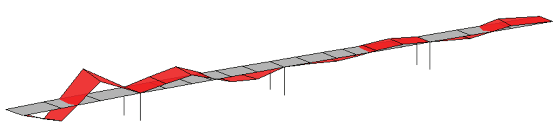
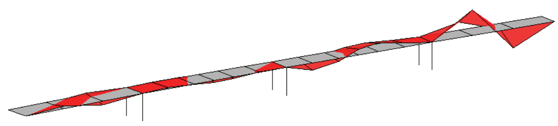
Mode B_1 07/03/2023 08/06/2024 f_{B1} = 1.416 Hz f^R_{B1} = 1.406 Hz 	Mode T_1 07/03/2023 08/06/2024 f_{T1} = 1.680 Hz f^R_{T1} = 1.664 Hz 
Mode B_2 07/03/2023 08/06/2024 f_{B2} = 1.865 Hz f^R_{B2} = 1.854 Hz 	Mode T_2 07/03/2023 08/06/2024 f_{T2} = 2.109 Hz f^R_{T2} = 2.096 Hz 
Mode B_3 07/03/2023 08/06/2024 f_{B3} = 2.412 Hz f^R_{B3} = 2.393 Hz 	Mode T_3 07/03/2023 08/06/2024 f_{T3} = – f^R_{T3} = 2.620 Hz 
Mode B_4 07/03/2023 08/06/2024 f_{B4} = 2.744 Hz f^R_{B4} = 2.726 Hz 	Mode T_4 07/03/2023 08/06/2024 f_{T4} = 2.949 Hz f^R_{T4} = 2.927 Hz 
Mode B_5 07/03/2023 08/06/2024 f_{B5} = 4.824 Hz f^R_{B5} = 4.794 Hz 	Mode T_5 07/03/2023 08/06/2024 f_{T5} = – f^R_{T5} = 5.129 Hz 
Mode B_6 07/03/2023 08/06/2024 f_{B6} = 5.547 Hz f^R_{B6} = 5.504 Hz 	Mode T_6 07/03/2023 08/06/2024 f_{T6} = – f^R_{T6} = 5.757 Hz 
Mode B_7 07/03/2023 08/06/2024 f_{B7} = – f^R_{B7} = 6.279 Hz 	Mode T_7 07/03/2023 08/06/2024 f_{T7} = – f^R_{T7} = 6.723 Hz 

Figure 3. Dynamic characteristics identified in preliminary AVTs (07/03/2023) and reference dynamic characteristics identified at the beginning of the continuous monitoring (08/06/2024, h 16:00).

To investigate the possible onset of structural anomalies, the evolution in time of natural frequencies is examined as well with the objective of understanding and minimizing the effects of environmental and operational variability. One effective method for doing this could be through the use of cointegration analysis [7]. However, it is worth noting that, at present, the monitoring period available (i.e., from 20/05/2024 to 26/01/2025) is not yet extended enough to fully evaluating and mitigating the effects of seasonal temperature fluctuations.

4.2. Reference modal parameters and monitoring results

During the first few weeks of bridge monitoring, the normal traffic conditions allowed to successfully identifying 14 vibration modes with good identification rate. More specifically, 7 vertical bending modes and 7 torsional modes were identified: it should be noticed that the lower two series of four bending modes (B_1-B_4 in Fig. 3) and four torsion modes (T_1-T_4 in Fig. 3) are perfectly corresponding to theoretical expectations for a continuous beam with 4 spans. The dynamic characteristics summarized in Fig. 3 were obtained by applying the SSI-Cov method to the dataset collected on 08/06/2024, h 16:00 and subsequently were used as references for MT purposes.

Since the early stages of monitoring, the automatically identified frequencies exhibited clear daily fluctuations, which can reasonably be attributed to changes in temperature. The time evolution of natural frequencies in the investigated monitoring period (i.e., from 20 May 2024 to 26 January 2025) is illustrated in Fig. 4a, whereas the corresponding changes of air temperature – approximately ranging between −3°C and +37°C – are shown Fig. 4b.

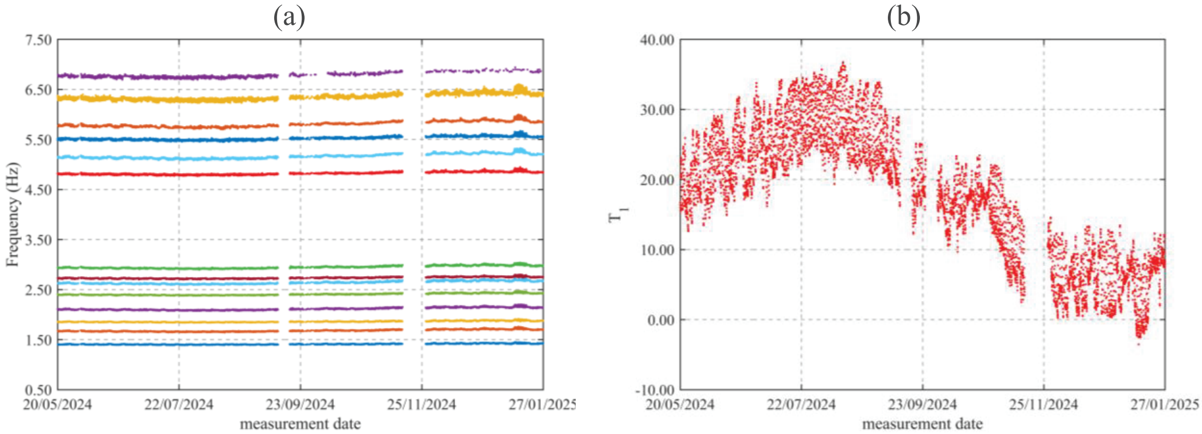


Figure 4. Time evolution of (a) identified natural frequencies and (b) measured temperature during the first 8 months of monitoring.

Table 1. Statistics of the identified modal parameters during the first 8 months of monitoring.

Mode	f_{avg} (Hz)	σ_f (Hz)	f_{min} (Hz)	f_{max} (Hz)	R^2_{f-T}	MAC_{avg}	σ_{MAC}	MAC_{min}
B_1	1.405	0.007	1.390	1.430	0.710	0.9999	0.0002	0.9935
T_1	1.670	0.013	1.642	1.713	0.922	0.9917	0.0120	0.9015
B_2	1.854	0.008	1.837	1.883	0.804	0.9997	0.0004	0.9900
T_2	2.102	0.016	2.073	2.154	0.917	0.9936	0.0080	0.9068
B_3	2.397	0.011	2.376	2.433	0.891	0.9996	0.0005	0.9861
T_3	2.625	0.018	2.593	2.689	0.910	0.9845	0.0155	0.9021
B_4	2.727	0.012	2.701	2.763	0.841	0.9992	0.0010	0.9832
T_4	2.935	0.017	2.896	2.993	0.906	0.9957	0.0071	0.9018
B_5	4.810	0.018	4.767	4.876	0.894	0.9991	0.0007	0.9797

T_5	5.143	0.030	5.082	5.228	0.901	0.9829	0.0148	0.9035
B_6	5.508	0.023	5.451	5.592	0.886	0.9961	0.0028	0.9434
T_6	5.784	0.036	5.701	5.884	0.893	0.9752	0.0180	0.9002
B_7	6.319	0.040	6.230	6.477	0.871	0.9944	0.0050	0.9305
T_7	6.761	0.032	6.694	6.877	0.852	0.9565	0.0244	0.9001

It is further noticed that the available observation period (about 6 months) does not contain enough information on the normal effects of low temperatures on natural frequencies and, therefore, does not yet represent an adequate training period for the identification of structural anomalies based on natural frequencies.

The statistics of the natural frequencies and mode shapes identified during the first months of monitoring are summarized in Table 1, in terms of average value (f_{avg}), standard deviation (σ_f), extreme values (f_{min}, f_{max}) of each frequency and the coefficient of determination frequency-temperature ($R^2_{f\text{-}T}$); furthermore, Table 1 also collects the average, the standard deviation and the minimum value of MAC.

The inspection of Table 1 allows to verify that natural frequencies are characterized by relatively small standard deviations (generally smaller than 0.04 Hz) and undergo oscillations of the order of a few percentage points of the mean value. In addition, it should be noticed that both the overall evolution of the natural frequencies (Fig. 4a) and the frequency-temperature correlations exemplified in Fig. 5 suggest that the frequency variations are mostly determined by the temperature variations. In more details, Table 1 and Fig. 5 indicate different sensitivity of natural frequencies to thermal effects, with the frequency-temperature correlation being higher for torsion modes ($0.852 \le R^2 \le 0.922$) than for bending modes ($0.710 \le R^2 \le 0.894$).

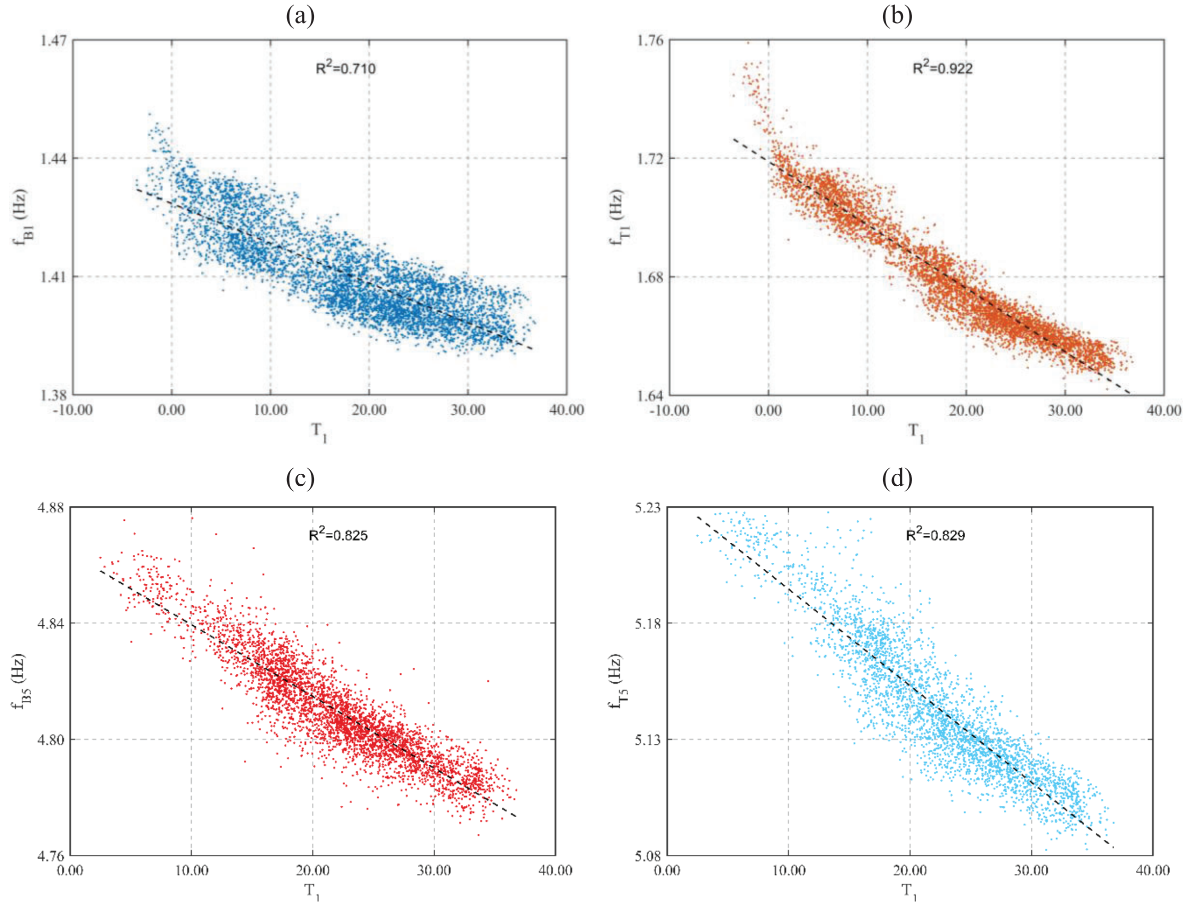


Figure 5. Temperature-frequency correlation for (a) mode B_1, (b) mode T_1, (c) mode B_5 and (d) mode T_5.

While waiting to reach an adequate training period for removing the environmental and operational effects from frequency records, the health assessment of the bridge is performed by verifying the consistency and time invariance of modal deformations. Although the mode shapes are usually not sensitive to environmental and operational effects, novelty detection is rarely based on mode shapes because a quite dense and well-distibuted network of sensors is needed across the structure and mode shapes might be not enough sensitive to the onset of local structural changes.

In the case of Olona West bridge, mode shape invariance was evaluated using the MAC [6], which should ideally remain close to unity and, most important, should not exhibit any abrupt or irreversible drop. As shown in Table 1 and in Fig. 6, bending modes exhibit average MAC values very close to unity during the observation period, whereas the average MAC is slightly larger for torsion modes (that are also charcterised by higher dispersion than the one observed for bending modes).

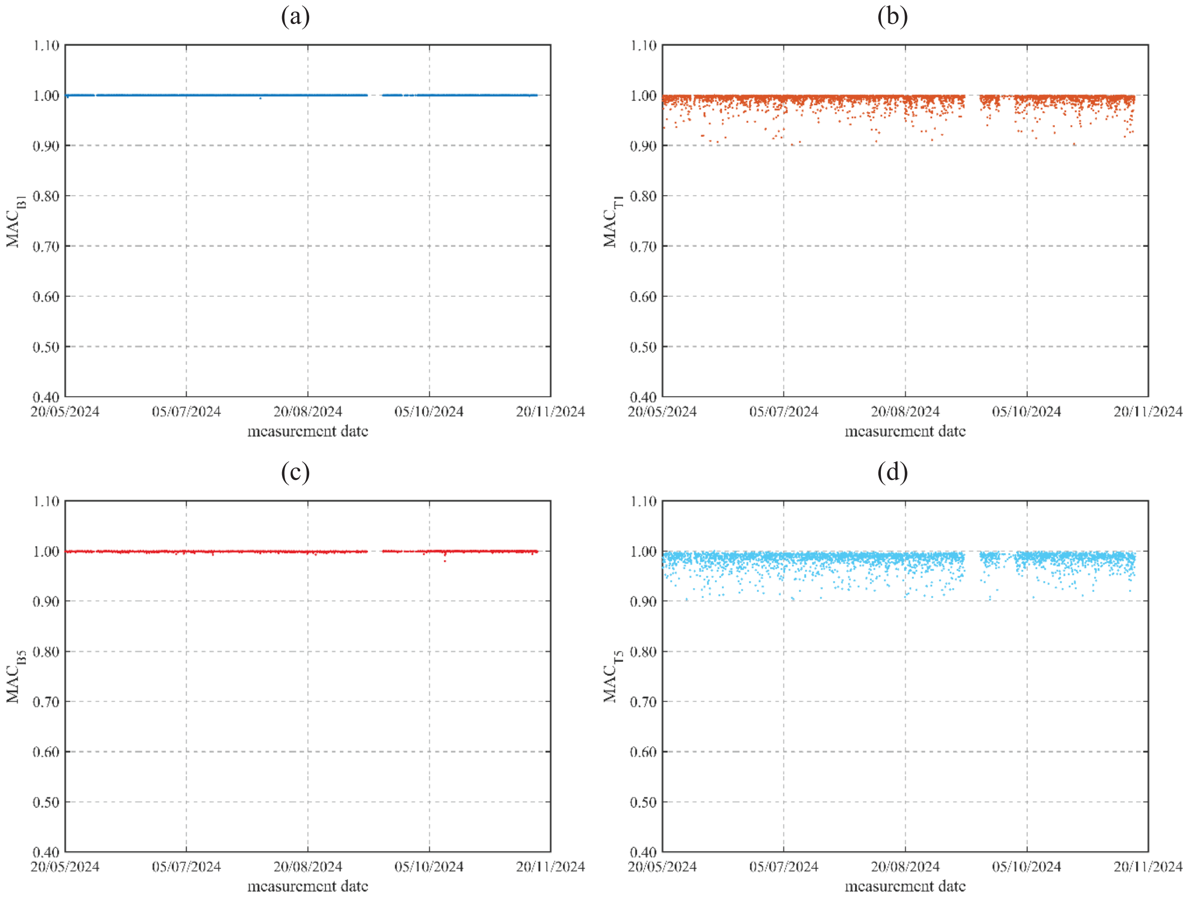


Figure 6. MAC evolution for (a) mode B_1, (b) mode T_1, (c) mode B_5 and (d) mode T_5.

5. CONCLUSIONS

Selected results collected during the first months of continuous dynamic monitoring of the Olona West bridge are presented in the paper. In particular, the following main conclusions can be drawn:

1. Compared to the 9 mode shapes identified during the AVTs, the continuous monitoring allowed to successfully identifying a total number of 14 mode shapes.
2. Air temperature emerged as the primary factor influencing the daily and seasonal fluctuations of all identified natural frequencies.
3. The frequency-temperature correlation appears higher for torsion modes ($0.852 \leq R^2 \leq 0.922$) than for bending modes ($0.710 \leq R^2 \leq 0.894$).
4. Since an appropriate training period is not yet available to fully assess and eliminate the impact of temperature variations on the bridge's frequencies, health assessment was performed by checking the mode shapes consistency through the MAC parameter, which

remains very close to unity for all modes and does not exhibit any abrupt or non-reversible drop.

It is further noticed that, for future analyses, the linear cointegration approach will be applied to investigate the effects of environmental and operational variability on natural frequencies and to attain a reliable control chart.

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