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Operational modal analysis of two similar multi-span bridges

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ABSTRACT

This paper presents the dynamic characterization of two similar multi-span viaducts, supporting the two carriageways of A4 highway between Padova and Trieste. The bridges are characterized by 7 spans of different lengths, steel-concrete composite girders and slightly curvilinear planimetric shapes. The main differences between the East and West carriageways are primarily related to the length of the second span; nevertheless, the resulting dynamic behaviour is quite different. With the aim of Structural Health Monitoring (SHM), each viaduct was equipped with a continuous dynamic monitoring system consisting of 42 accelerometers, enabling real-time vibration measurements. During the first days of monitoring, many key vibration modes were identified within the 0–8 Hz frequency range. The comparison of the identified modal parameters highlights the impact of span arrangement on mode shapes, revealing significant variations despite the structural similarities. These findings contribute to a better understanding of the dynamic behaviour of multi-span continuous viaducts and provide the reference parameters for the SHM of the two structures.

Keywords: Structural Health Monitoring, Vibration testing, Steel-concrete composite bridges, Multi-Span Viaducts, Condition assessment, Twin bridges

1. INTRODUCTION

Operational modal analysis (OMA) aims to identify the modal parameters of an existing structure, which include natural frequencies, mode shapes, and damping ratios. These parameters play an important role in various engineering applications, such as vibration control, Finite Element (FE) model validation, damage detection, and Structural Health Monitoring (SHM). Unlike traditional experimental modal analysis, which requires artificial excitation, OMA relies on ambient vibrations from environmental and operational loads, making it well-suited for large civil structures like bridges.

While OMA has been widely applied to different bridge types [1–4], studies on multi-span continuous viaducts remain relatively limited [5,6]. The present study focuses on two similar seven-span viaducts with a steel-concrete composite girder (Figure 1 and Figure 2) and analyses their modal characteristics based on the first recordings from the continuous monitoring system. The comparison of identified modal parameters highlights how relatively small differences in the geometric arrangement of the spans determine important variations in the mode shapes.

2. THE SPINEA VIADUCTS

The investigated structures (Figure 1) are the two carriageways (the East and West carriageways) – each one with two one-way lanes – of a multi-span viaduct sustaining the A4 highway between Padova and Trieste (Italy). The East carriageway is referred as *Spinea East Viaduct* (SEV) while the West carriageways as *Spinea West Viaduct* (SWV).

The viaducts, completed in 2008, are characterized by a steel-concrete composite deck with a slightly curvilinear planimetric shape (Figure 2). The typical cross-section has an overall width of about 18 m for the SWV and 20 m for the SEV. Each deck is composed of steel beams and a concrete slab, in detail: the main girders are two I-shape longitudinal steel beams with a height of about 2 m, than the concrete slab is sustained by numerous I-shape transverse beams (height 1.1 m), and two secondary longitudinal beams (height 0.5 m). The span lengths are equal to (a) 50.80 m + 26.70 m + 5×38.80 m for the East track and (b) 38.24 m + 38.25 m + 38.24 m + 38.21 m + 38.23 m + 34.66 m + 50.05 m for the West track. Overall, the total lengths of the SEV and SWV are 271.5 m and 269.9 m, respectively. Therefore, the two bridges have a very similar structural arrangement, with the main differences related to the length of the second span.



Figure 1. The *Spinea* viaducts.

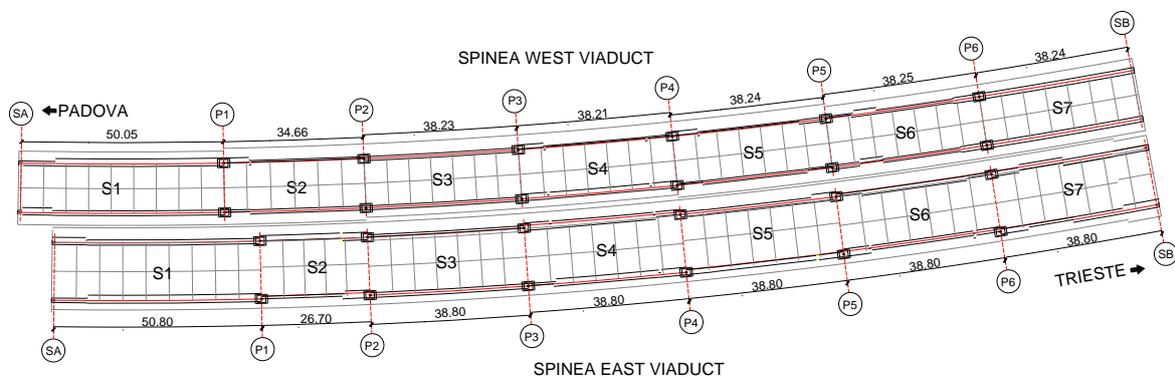


Figure 2. Plans of the *Spinea West Viaduct* and the *Spinea East Viaduct*.

3. MONITORING SYSTEM AND DATA PROCESSING

The monitoring system of the *Spinea* viaducts was designed to identify the key vibration modes of the two structures in operational conditions and to evaluate the regularity in their structural response over time. Consequently, a dynamic monitoring system (Figure 3) was installed on each viaduct including 42 tri-axial MEMS accelerometers – 3 for each side of each span – and temperature sensors. The acceleration data are recorded at a sampling rate of 200 Hz and time windows of 3600 s are adopted in the modal parameter estimation.

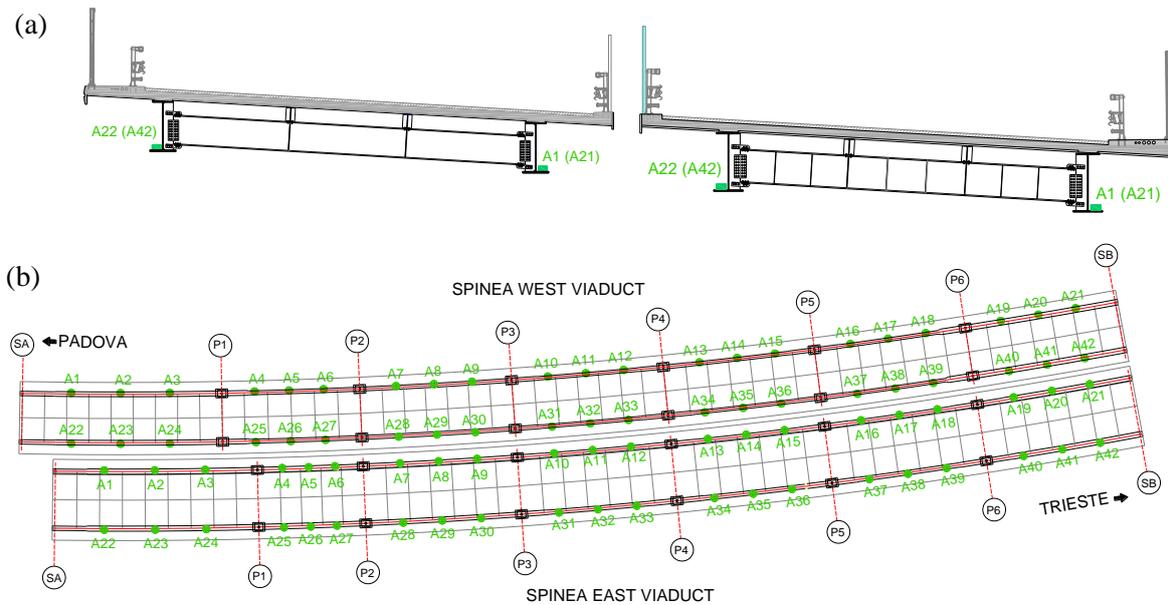


Figure 3. The dynamic monitoring system of the *Spinea* viaducts: (a) transversal sections and (b) plans.

The raw acceleration data are stored in a dedicated web platform managed by the road operator in which the entire procedure – from modal parameter estimation to anomaly detection – is performed. In the present paper, selected datasets from the first month of monitoring are analysed to characterise the dynamic behaviour of the two viaducts and to ensure that the system is properly working.

Firstly, low-pass filtering and decimation are applied to the raw data. Subsequently, the modal parameters of each viaduct are evaluated by fully automated procedures [7] based on the well-known Covariance-driven Stochastic Subspace Identification (SSI Cov) technique [8]. It is worth highlighting that the modal parameter estimation for the two bridges is performed separately since – with the only exception of the abutments – the two bridges are structurally independent.

As it is common for SSI-based techniques, the adopted algorithm needs some input parameters to perform the analysis in an automated way. In detail, the SSI parameters herein adopted are the following: (a) the time lag needed to fill the block Toeplitz matrix was set equal to 30; (b) the minimum and maximum model order have been set equal to 42, and 140, respectively; (c) the maximum allowable damping ratio and Modal Phase Collinearity (MPC) – adopted in the noise modes elimination step – were set equal to 5% and 0.80, respectively.

4. DYNAMIC CHARACTERISTICS OF THE SPINEA VIADUCTS

The modal parameter estimation was firstly performed on a reference dataset of 3600 s, recorded on 01/05/2024 at 16:00. For both viaducts, a large number of key vibration modes are identified in the frequency interval of 0-8 Hz (Figures 4-7).

Figure 4 and Figure 6 report the stabilization diagram obtained from the application of the SSI-Cov technique on the reference datasets for the *Spinea East Viaduct* and *Spinea West Viaduct*, respectively.

The alignments of stable poles indicates the resonant frequencies. Overall, 16 vibration modes – 10 bending modes and 6 torsion modes – are identified for the SEV and 20 vibration modes – 13 bending modes and 7 torsion modes – are identified for the SWV.

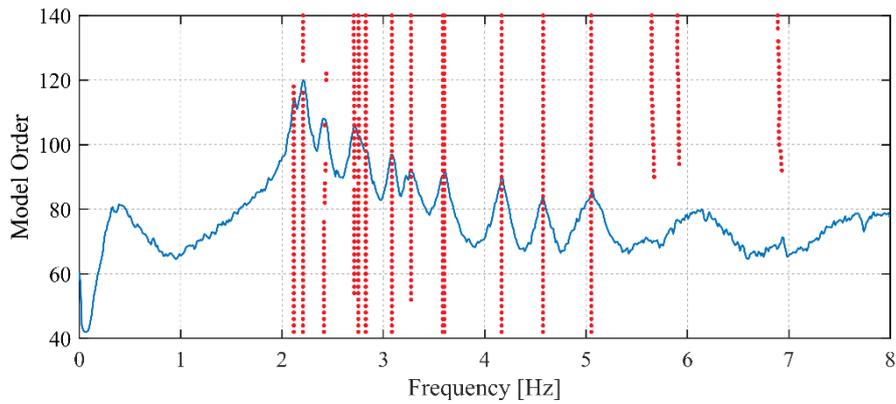


Figure 4. Stabilization diagram of the *Spinea East Viaduct* in the reference dataset.

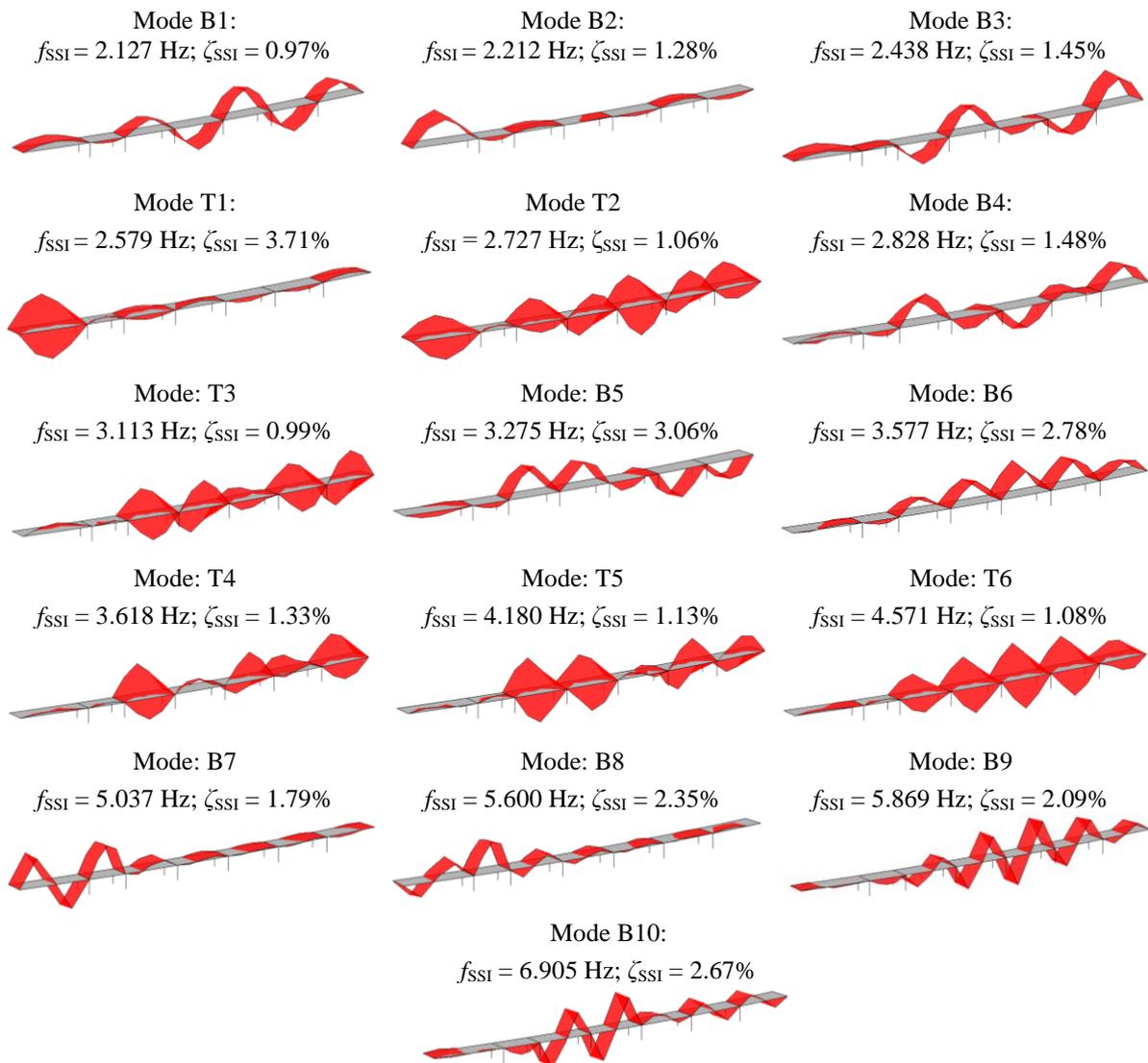


Figure 5. Identified vibration modes of the *Spinea East Viaduct* in the reference dataset.

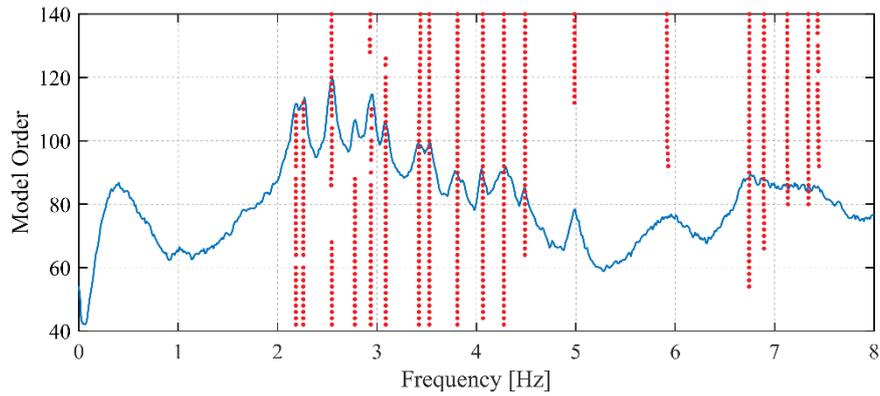


Figure 6. Stabilization diagram of the *Spinea West Viaduct* in the reference dataset.

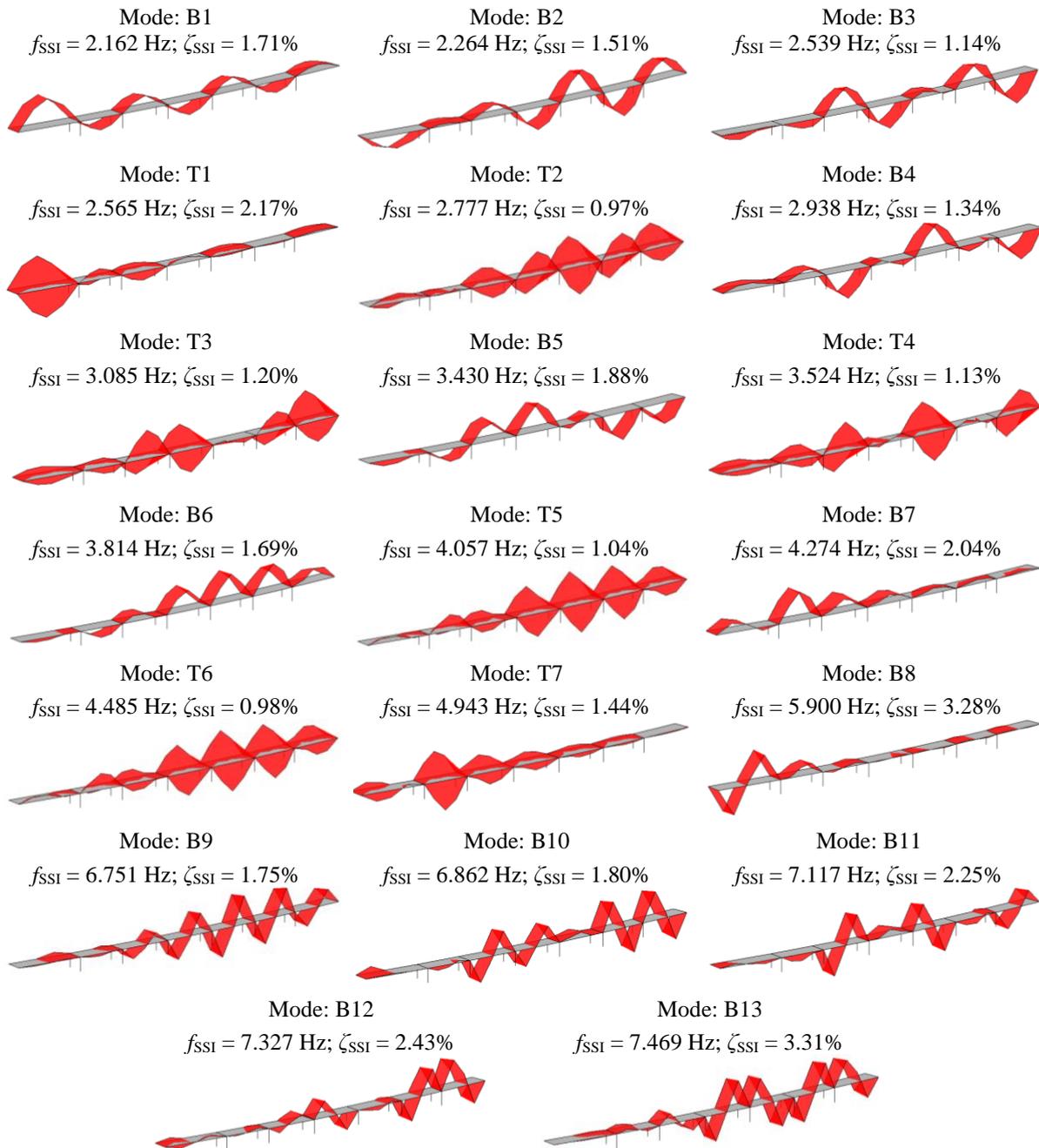


Figure 7. Identified vibration modes of the *Spinea West Viaduct* in the reference dataset.

Table 1. *Spinea East Viaduct*: statistics of the natural frequencies identified in selected datasets from 01/05/2024 to 03/06/2024.

	Modes 1 to 8							
	B1	B2	B3	B4	B5	B6	T1	T2
f_{mean} (Hz)	2.125	2.195	2.424	2.838	3.287	3.601	2.681	2.741
f_{min} (Hz)	2.115	2.184	2.409	2.826	3.273	3.577	2.579	2.723
f_{max} (Hz)	2.134	2.212	2.438	2.851	3.300	3.617	2.747	2.755
σ_f (Hz)	0.006	0.010	0.009	0.008	0.009	0.015	0.045	0.012
	Modes 9 to 16							
	T3	T4	T5	T6	B7	B8	B9	B10
f_{mean} (Hz)	3.093	3.616	4.182	4.586	5.075	5.667	5.932	6.878
f_{min} (Hz)	3.079	3.601	4.165	4.571	5.037	5.600	5.869	6.852
f_{max} (Hz)	3.112	3.632	4.198	4.607	5.119	5.734	6.009	6.904
σ_f (Hz)	0.011	0.010	0.011	0.012	0.025	0.043	0.055	0.037

Table 2. *Spinea West Viaduct*: statistics of the natural frequencies identified in selected datasets from 01/05/2024 to 03/06/2024.

	Modes 1 to 10									
	B1	B2	B3	B4	B5	B6	B7	T1	T2	T3
f_{mean} (Hz)	2.173	2.274	2.552	2.952	3.426	3.813	4.269	2.588	2.785	3.101
f_{min} (Hz)	2.155	2.259	2.539	2.938	3.410	3.792	4.251	2.565	2.770	3.085
f_{max} (Hz)	2.190	2.285	2.563	2.966	3.442	3.826	4.286	2.617	2.802	3.120
σ_f (Hz)	0.012	0.009	0.009	0.010	0.010	0.011	0.014	0.019	0.010	0.010
	Modes 11 to 20									
	T4	T5	T6	T7	B8	B9	B10	B11	B12	B13
f_{mean} (Hz)	3.534	4.072	4.491	4.968	5.901	6.718	6.871	7.109	7.352	7.476
f_{min} (Hz)	3.518	4.057	4.483	4.943	5.863	6.668	6.817	7.018	7.327	7.428
f_{max} (Hz)	3.545	4.085	4.502	4.988	5.934	6.751	6.901	7.138	7.375	7.539
σ_f (Hz)	0.010	0.009	0.006	0.017	0.024	0.028	0.025	0.037	0.017	0.043

Figure 5 and Figure 7 illustrate the vertical mode shapes associated with the identified vibration modes, reporting the identified natural frequencies (f_{SSI}) and damping ratios (ζ_{SSI}). The bending modes are referred to as B, while the torsion mode with the letter T. From the qualitative comparison of mode shapes identified from SEV and SWV, the following observations can be drawn.

- The first two bending modes, B1 and B2, are similar in terms of natural frequencies, with a percentage change for both modes of about 2%, but they exhibit substantial differences in mode shapes. Mode B1^(SEV) is characterised by half-sine waves between spans 3 and 7, while spans 1 and 2 are only partially involved. Conversely, mode B1^(SWV) exhibits mode shapes with half-sine waves on all the spans with the maximum modal displacement at span 1. The mode shape of B2^(SEV) mainly involves span 1, while mode B2^(SWV) involves the entire deck with a minor involvement of span 2.
- The third bending B3 exhibits a mode shape that is very similar on both bridges but with a frequency percentage change of about 4%.
- The torsion mode T1 is almost coincident in terms of natural frequencies and mode shapes; modes T2 and T3 have very similar frequency values but slight differences in mode shapes.

- Regarding the higher vibration modes, a lower number of vibration modes were identified on the SEV in the frequency range of 0-8 Hz.

Overall, the 8-meter difference in length of span 2 – equal to 26.7 m for SEV and 34.7 m for SWV – is most likely the main source that generates the discrepancies between the dynamic behaviour of the two infrastructures.

The modal parameters estimation is then repeated on selected datasets between 01/05/2024 and 03/06/2024 at different daytime hours to include temperature variations. Table 1 and Table 2 report the resulting statistics of identified natural frequencies in terms of mean, minimum, and maximum values and standard deviations. The results highlight the invariance of the structural behaviour over the selected period, with very modest variations in the natural frequencies.

5. CONCLUSIONS

The paper presents the dynamic characterisation of the Spinea East and West Viaducts, two similar multi-span steel-concrete composite bridges supporting the A4 highway in the municipality of Spinea, Italy. The bridges are characterised by seven spans with a continuous girder. Despite the similarity in the geometry, the relatively small differences in the length of the second span determine a significant discrepancy in dynamic behaviour, especially in terms of mode shapes.

From the analysis of selected datasets collected by the dynamic monitoring system in the first month of recording, numerous vibration modes were identified within the 0–8 Hz frequency range through the SSI-Cov technique. The results showed that while the two viaducts share similar values of natural frequencies associated with lower-order vibration modes, the mode shapes exhibit notable variations. In particular, the first two bending modes showed substantial differences in mode shapes. These findings confirm that even small geometric variations can result in significant differences in modal behaviour, highlighting the importance of detailed geometric surveys for existing structures.

Moreover, the analysis of modal parameters over different daytime hours demonstrated the low variability of the dynamic properties of the two viaducts, with only minor variations in natural frequencies due to temperature changes. The extracted reference modal parameters will serve as a baseline for the modal tracking of long-term monitoring.

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