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Automated Operational Modal Analysis of two nearby, short-span highway viaducts

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Abstract. In the context of assessing the structural condition of critical points along a portion of an urban highway in Italy, accelerometric recordings from two spans of nearby viaducts are currently being used for continuous, long-term structural health monitoring (SHM). The accelerometer layout enables vibration-based monitoring through output-only modal identification of the decks of the prestressed reinforced concrete viaducts under study, which are representative of a common short-to-medium span bridge typology in the national highway network. Dynamic identification was performed using a custom-made, recently introduced Automated Operational Modal Analysis (AOMA) algorithm. The procedure was performed using the SSI-DATA algorithm integrated with DBSCAN clustering analysis to automate the extraction of modal parameters (i.e., natural frequencies, damping ratios, and mode shapes). These results will serve as a reference for the ongoing continuous monitoring of this strategic infrastructure within a highly trafficked road network.

Keywords: automated operational modal analysis, highway bridge, structural health monitoring, dynamic identification, vibration-based monitoring

Introduction

The increasing use of Structural Health Monitoring (SHM) entails transitioning from qualitative periodic inspections to objective, data-driven frameworks, thereby requiring reliable procedures that operate under real operational conditions and automatically process large volumes of data with limited user supervision. In this context, SHM strategies that rely on the analysis of the structure's continuously measured response from a fixed sensor network have gained popularity and are now the standard procedure, indeed enabling the monitoring of global structural response. Vibration-based SHM represents probably the most popular and consolidated solution for civil structures. It enables the identification of modal parameters, i.e., natural frequencies, damping ratios, and mode shapes, from accelerometric signals, thus falling into the classification of output-only procedures. It is implemented through Operational Modal Analysis (OMA) algorithms [1], which have been vastly investigated in the last decades, since the identified modal parameters have proven to be effective as features for damage detection and condition assessment [2].
This contribution presents the results of an automated output-only dynamic identification approach applied to the decks of two short-span prestressed reinforced concrete (PRC) bridges under operational conditions. The accelerometric data acquired on some spans of the two case studies were processed using the proposed Automated Operational Modal Analysis (AOMA) algorithm, based on the Stochastic Subspace Identification (SSI) algorithm [3]. Modal parameters of the structures' decks were successfully identified, considering ambient vibration (AV) excitations.

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Although the focus of this work is the dynamic characterisation of the two target structures under study, this initial step is an essential prerequisite for ongoing long-term monitoring and subsequent diagnostic activities. This is because it establishes a robust benchmark against which any variation or structural anomalies can be quantitatively measured. Therefore, by tracking the modal parameters of a structure over time (i.e., modal tracking), damage in its incipient stages can be identified. Furthermore, the focus on case studies representative of the behaviour of one of the most common short- to medium-span bridge typologies is particularly strategic due to their prevalence across both national and international road networks, making the results of this study highly scalable, providing a valuable reference point for the health assessment and monitoring of a large number of similar structures. In conclusion, the present work also addresses the critical need for preventive monitoring and maintenance of bridges, which are potentially the most vulnerable elements in terms of the safety of the entire transportation infrastructure network. This is particularly important in the context of ageing infrastructures, which are now required to sustain modern traffic volumes that often exceed their original design specifications [4].
The remainder of this paper is organised as follows. Section 1 briefly describes the Automated Operational Modal Analysis procedure for dynamic identification under environmental excitation. In Section 2, a description of the two case studies is proposed. The dynamic monitoring systems setups are illustrated in Section 3, while the dynamic identification results are then reported in Section 4. The conclusions follow in Section 5.

1. Automated Operational Modal Analysis for SHM

Automated Operational Modal Analysis (AOMA) procedures were developed to provide a framework that mitigates the influence of subjective user-based decisions and saves time in dynamic identification procedures, given that the amount of data collected from continuous monitoring can be vast. By automating the extraction of modal parameters from raw recorded data, these procedures ensure more objective and robust results for reliable SHM applications. In this study, the dynamic identification of the bridge decks was performed using a workflow based on the Data-driven Stochastic Subspace Identification (SSI-DATA) algorithm [5] integrated with clustering analysis to facilitate the automatic identification of actual vibration modes, as schematised in Fig. **1**. The same algorithm was also very recently tested and verified on railway bridges, as reported in [6,7].
The procedure follows the established state-of-the-art workflow proposed by many authors [8–11], starting with data pre-processing and the selection of optimal algorithm parameters, followed by System Identification (SI) conducted over increasing model orders, which is the core of the procedure. Without requiring manual interpretation, the successive steps include a series of automated pole filtering passes that sift the identified poles. Finally, the estimation and validation of cluster-level modal parameters are performed automatically.
In more detail, the outcomes of the SI phase consist on the extraction of a set of system poles, obtained by running the algorithm multiple times on the same signals across increasing model order n within a user-defined range [n_{min}, n_{max}]. The results are visualised in a stabilisation diagram, which presents natural frequencies, damping ratios, and mode shapes relative to the corresponding system order. However, the raw output includes both stable (physical) and spurious (numerical) poles, making a pole sifting process essential. This is done by working on the automatic interpretation of the stabilisation diagram and the subsequent extraction of the physical vibration modes, based on the definition of a set of physically-principled and data-driven criteria, defined as “hard” and “soft” validation criteria, respectively, to distinguish possibly physical poles from certainly spurious ones based on some modal indicators [12]. The steps used here to enable this procedure, as adopted in the presented methodology, are briefly outlined.
The first step concerns the application of Hard Validation Criteria (HVC), which consists of eliminating poles with non-physical damping ratios – i.e., negative or excessively high (> 20%) – and those whose eigenvectors are not complex-conjugate pairs. Subsequently, the remaining poles are passed to the Soft Validation Criteria (SVC), which compares the modal parameters of the poles remaining from the previous step, classifying those that exceed some selected data-driven thresholds

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as unstable, following the work by Mugnaini et al. [13]. The calculation of these dimensionless distances in the stabilisation diagram is achieved through the estimation of the absolute differences between the estimated eigenvalues dλ, natural frequencies df, damping ratios dζ, and the Modal Assurance Criterion (MAC), ν = 1-MAC [14]. Finally, the DBSCAN algorithm (Density-Based Spatial Clustering of Applications with Noise) [15] is implemented to group the poles with similar modal features and discard any remaining outliers, following the work of Civera et al. [16].
Each resulting cluster then individuates a set of probable physical modes. Modal parameters representative of each cluster, namely, the natural frequency f_n, the damping ratio ζ_n, and the mode shape φ_n are estimated as the average values of the poles within the cluster [10]. Importantly, the physical significance of each mode is verified by analysing the associated mode shapes to confirm that they represent actual expected structural behaviour. In particular, the specific algorithm applied here was also recently reported in [7].
The procedure detailed above is applied separately to each recorded signal; hence, a final ensemble average is performed across all acquisitions to obtain reliable modal parameters (f_m, ζ_m, and φ_m) for each one of the two case studies. These identified modal parameters will then serve as a reference for the ongoing monitoring.

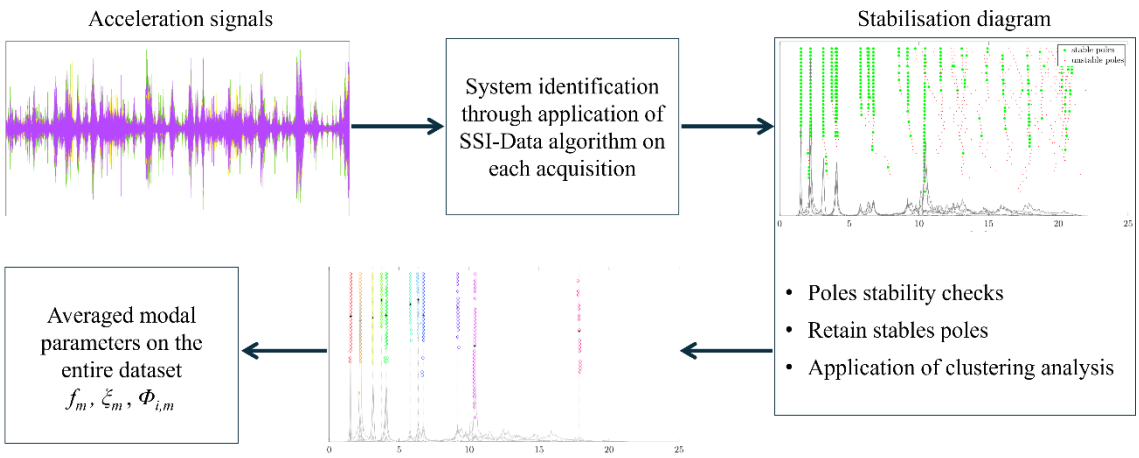

Fig. 1: Schematic workflow for the adopted AOMA procedure.

2. Description of the two case studies

The two case studies are located along a highly trafficked urban highway in Italy. A satellite view of the sites of interest is reported in Fig. **2**. As mentioned, the two viaducts under study are characterised by a PRC deck with very similar structural configurations, both featuring four simply supported spans with a girder deck system.

Fig. 2. Satellite view of the portion of highway with highlighted the two case studies: **Viaduct A**, in red, and **Viaduct B**, in orange.

In particular, Viaduct A comprises two adjacent decks, one for each carriageway direction, each 13.25 m wide, allowing three traffic lanes per direction. The two decks have slightly different spans lengths because of the landscape morphology, indeed, the deck in the East-to-West traffic direction has a total length of about 73.16 m with four spans of length 18.20 m, 1 8.38 m, 18.38 m, and 18.20 m; while the deck for the opposite direction (West-to-East) has a total length of 75 m, divided in 18.50 m, 19.00 m, 19.00 m, and 18.50 m long spans. Each of the two decks consists of eight I-shaped prestressed concrete girders spaced 1.65 m apart, connected by a 20 cm RC slab and four transverse girders. The viaduct is supported by two abutments and three circular RC piers for each deck. The piers have a 2.20 m diameter and variable heights, ranging from 1.75 m to 6.90 m, each one topped by a supporting beam. The main girders rest on these beams via neoprene bearings, with a total of 16 bearings provided per span, directly seated on the supporting beams.
Viaduct B has the peculiarity of occupying only the southernmost half-carriageway (West-to-East direction), as highlighted in orange in Fig. **2**. For this reason, it is also referred to as a 'Semiviadotto' (semi-viaduct) by the asset managing company. It is 12.95 m wide for a total length of 73 m, with four spans of length 16.32 m, 17.10 m, 17.00 m, and 16.20 m. Each deck comprises nine prestressed concrete I girders (specifically, model TAS 120/46), spaced 1.40 m apart, connected by a 20 cm-thick top slab and five cast-in-place transversal girders. The three intermediate piers are composed of three circular columns, each 1.20 m in diameter and 3.00 m high. The columns are connected at the top by a connection beam, on which nine reinforced neoprene bearings (200×400 mm, with heights varying between 25 and 30 mm) are placed, totalling 18 bearings per span.
In recent years, Viaduct B underwent a retrofitting intervention, which also included the replacement of the supporting bearings and expansion joints. Therefore, the results presented in this contribution for case study B refer to the current post-intervention state. Conversely, Viaduct A did not undergo any significant structural intervention.
Finally, the location in a densely populated area and the high traffic volumes make these viaducts a key component of the urban transportation network, thus requiring a long-term monitoring strategy to ensure public safety; furthermore, these two case studies provide some insights into how maintenance and retrofitting interventions influence the behaviour of similar, common bridge typologies.

3. SHM system setup

As anticipated, the aim of this study was to establish the reference dynamic characteristics of the bridge. To this end, the results presented here aimed to identify the modal parameters of the two viaducts by acquiring ambient vibration signals under operational conditions, considering ongoing traffic, wind, and random microtremors as the main sources of excitation.
Due to their modular structural schemes, only one representative span has been instrumented for each bridge. In particular, for Viaduct A, eight biaxial wired MEMS accelerometers were installed on the deck of the second span in the East-to-West traffic direction (Fig. **3** (i) and (ii)). The sensor acquisition channels located on the external longitudinal girders acquire data in the vertical and longitudinal directions, while the one sensor in the midspan of the first transverse beam acquires data in the x-y plane. While for Viaduct B, eight high-performance triaxial wireless MEMS accelerometers, whose specifications can be found in [17], were installed on the outermost and central main girders of the third span, as illustrated in Fig. **3** (iii) and (iv). These sensor layouts allowed the identification of vertical flexural and torsional modes, as well as in-plane modes.
All accelerometric signals are acquired with a sampling rate of 100 Hz, ensuring that the Nyquist frequency limit $f_s/2$ = 50 Hz remains well above the highest frequencies of interest (approximately 13-14 Hz for both case studies, as will be shown in the following Sections). The acceleration data are continuously recorded but are saved on an hourly basis to facilitate storage and processing. In particular for this study, six hourly night-time acquisitions were used for Viaduct A and 12 for Viaduct B, recorded over two consecutive nights.

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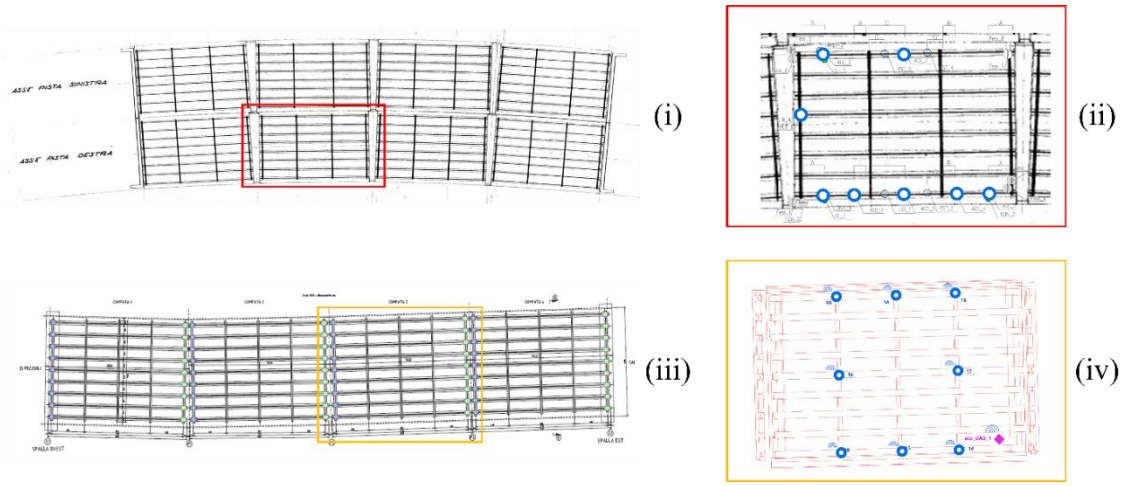

Fig. 3. Plan schemes of Viaduct A with highlighted in red the monitored span (i) and its sensor placement (ii), and of Viaduct B (iii) with sensors layout of the monitored span in orange (iv). In (iii), green points indicate the fixed supports, while light blue marks longitudinally free supports.

4. Results

The acceleration signals acquired for each instrumented span were analysed after pre-processing. In particular, for all signals in both case studies, the pre-processing included mean removal and decimation of factor $n_{dec} = 2$. Only for the signals from Viaduct A, it was also necessary to implement a fourth-order low-pass Butterworth filter to mitigate unphysical low-frequency drifts (<0.5 Hz). After these preliminary steps, the dynamic identification process successfully captured the fundamental vibration modes of the monitored decks under ambient excitation.
The stabilisation diagrams were obtained by considering system model orders ranging from 10 to 140, in steps of 2, and using the single-pole comparison parameters for the SVC step adapted to each case study. For the same structure, these parameters were set once for all analyses to ensure consistency in the outcomes.
The results of the AOMA algorithm are illustrated in the stabilisation diagrams, reporting the identified stable clusters, taken by one example signal per dataset (Fig. **4**). For both structures, the frequency range of interest goes from 8 to 20 Hz, where clear peaks can be observed in the singular values, and where a total of 8 and 7 stable probably physical modes were identified for Viaduct A and B, respectively. Real physical modes were identified as the ones corresponding to mode shapes with physical significance, resulting in 4 fundamental modes for Viaduct A and 3 for Viaduct B. The resulting natural frequencies and damping ratios are presented in Table 1, and the associated mode shapes are illustrated in Fig. **5** and Fig. **6**.
In more detail, two vertical bending modes (1V and 2V) and a torsional mode (1T) were identified for both structures. Such first bending and torsional modes are in line with the theoretical expectations for a rigid simply supported deck. Regarding mode 2V, the placement of accelerometers also on the central main girder of Viaduct B enables a clearer and more precise definition of the related mode shape, hence it is possible to appreciate the nature of such mode as a local or plate-like mode of the deck (Fig. **6** (vii)). Conversely, in Viaduct A, the corresponding mode shape is difficult to distinguish from the first flexural one (Fig. **5** (iv)) due to the more limited number and positioning of sensors, which lack the resolution to capture these local differences. These results demonstrate that while the AOMA procedure is reliable in extracting natural frequencies, the sensor layout is always a critical choice for accurately capturing mode shapes, especially for higher modes. Moreover, it is worth noting that damping ratio estimates show larger variability, reflecting known uncertainties related to the evaluation of this parameter [18].
Comparing the experimental results highlights the expected consistency between the two structures, given their similar geometries and structural schemes. Despite the different sensing devices employed, the fundamental flexural and torsional modes have been reliably identified in both cases.

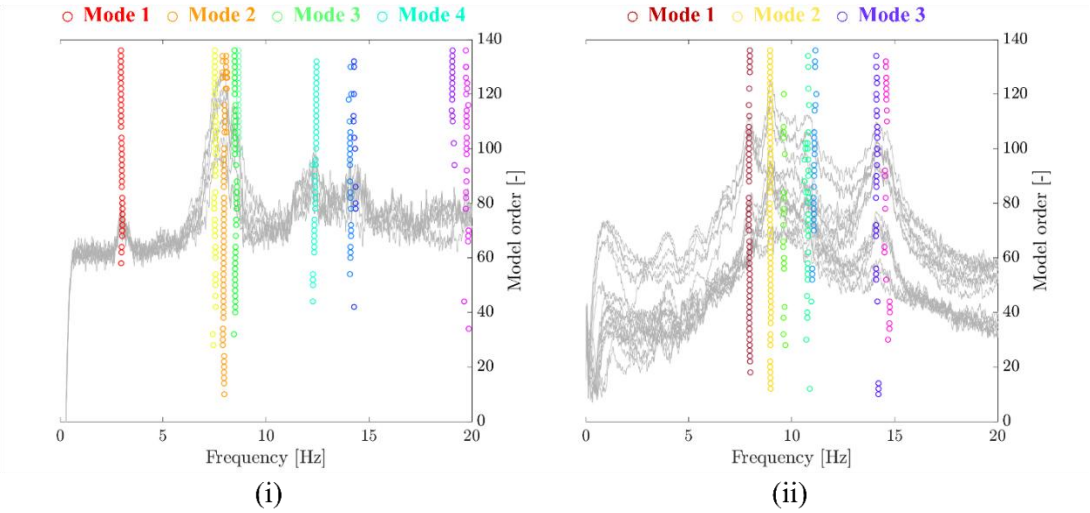

Fig. 4. Stabilisation diagrams with identified clusters of stable poles and singular values superimposed for Viaduct A (i) and Viaduct B (ii).

Table 1. Natural frequencies f and damping ratios ξ identified from AOMA for the two structures A and B. V-Vertical Bending; T-Torsional; P-in plane

Mode n°	Mode type	Viaduct A		Viaduct B	
		f [Hz]	ξ [%]	f [Hz]	ξ [%]
1	1 P	2.92	5.61	-	-
2	1 V	7.99	3.65	7.94	2.51
3	1 T	8.56	1.91	8.92	2.11
4	2 V	12.29	1.68	13.89	2.10

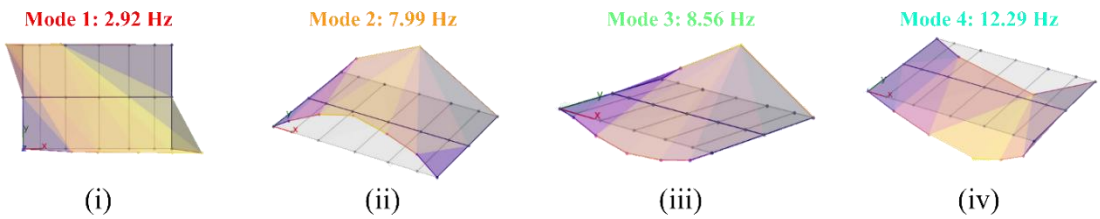

Fig. 5. Identified experimental mode shapes for Viaduct A.

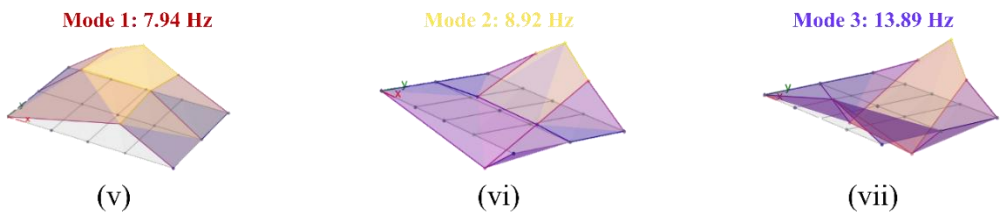

Fig. 6: Identified experimental mode shapes for Viaduct B.

An observation is needed regarding the first identified mode of Viaduct A (1P at 2.92 Hz), characterised by longitudinal in-plane motion. This mode, which is not identified in Viaduct B, could be either a rigid-body motion of the piers or an effect of span interaction through the joints. These phenomena may have been modified in Viaduct B due to the aforementioned structural interventions, which increased global stiffness and altered the constraints on the interaction between the bearings

and expansion joints. Alternatively, this weakly excited mode could have remained unidentified due to higher measurement noise in the wireless MEMS system, all other things being equal (same identification algorithm, range of model orders, and parameters).
Finally, the mode shapes identified for the two viaducts decks are compared based on the Modal Assurance Criterion (MAC), as showed in the correlation matrix in Fig. **7**. Due to the different sensors' configurations, the MAC was computed using a restricted subset of channels, that is to say, only the ones laying in geometrically comparable points in both monitoring setups (see Fig. **3** (ii) and (iv)). The results indicate a high correlation between the two sets of mode shapes, except for the mode indicated as 1P identified just for Viaduct A, which corresponds to the first row in the matrix. As already mentioned, this lateral mode went unidentified in Viaduct B. Furthermore, it is to observe the relatively high MAC values between modes 1V and 2V, as expected due to the flexural nature of both mode shapes, very similar at the few comparable channels. Excluding this low-spatial-resolution issue, this comparison experimentally determines that the mode shapes corresponding to 1V, 1T, and 2V are quantitatively very similar between Viaduct A and B.

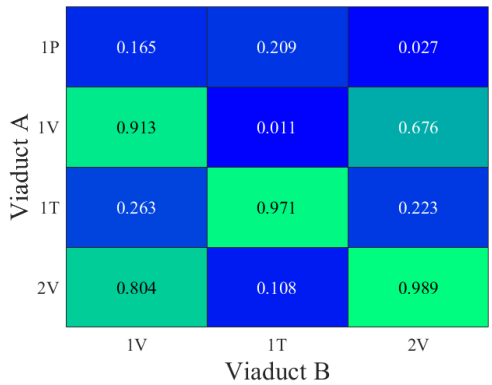

Fig. 7: MAC matrix of mode shapes identified for the two case studies (**green**: higher similarity; **blue**: lower).

5. Conclusions

Dynamic monitoring, i.e., the analysis of the vibrational behaviour of civil structures and infrastructure, is a key component of Structural Health Monitoring (SHM). In particular, output-only identification, also known as Ambient Vibration Testing (AVT), is extremely useful for asset management and life-cycle assessment in road and rail transportation networks.
In this context, this study investigated the application of a recently proposed Automated Operational Modal Analysis (AOMA) algorithm, developed in MATLAB environment, to the monitoring of road bridge decks. The AOMA procedure, based on the Data-driven Stochastic Subspace Identification (SSI-DATA) algorithm integrated with DBSCAN clustering, was applied to two prestressed reinforced concrete (PRC) viaducts representative of typical short- to medium-span road infrastructures. Employing high-sensitivity accelerometers installed on two selected spans, AVT data were recorded under operational conditions, without interrupting traffic flow. The proposed AOMA approach successfully extracted modal parameters, i.e., natural frequencies, damping ratios, and mode shapes, which can serve as reliable damage-sensitive features. In particular, the first three vertical vibration modes were identified for both viaducts, establishing a robust benchmark.
Ongoing work will focus on analysing data from the continuous, permanent monitoring system of the two viaducts, within the framework of long-term SHM and the assessment of strategic infrastructures. Consequently, these results serve as a reliable benchmark for future modal tracking. These will enable the early detection of structural anomalies through continuous monitoring of modal parameters, providing a non-invasive tool for structural performance evaluation in dense urban infrastructure.

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