European Community on Computational Methods in Applied Sciences

ECCOMAS
Thematic Conference

COMPDYN 2025

10th International Conference
on Computational Methods in Structural Dynamics
and Earthquake Engineering

PROCEEDINGS

Volume II

M. Papadrakakis, M. Fragiadakis (Eds.)

An IACM Special Interest Conference

Guerini M., Ermolli L., Stoura C.D., Ferrari R., Dertimanis V.K., Chatzi E.N., Rizzi E. (2025) *Modal dynamic identification of historic San Michele bridge (Italy, 1889)*. **COMPDYN 2025, 10th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering**, M. Papadrakakis, M. Fragiadakis (eds.), Rhodes Island, Greece, June 15-18, 2025, Eccomas Proceedia ID: 12784, Conference Proceeding ID: 26049, doi:10.7712/120125.12784.26049, ISSN: 2623-3347, ISBN: 978-618-5827-06-9, Category: C - TS 2 - Algorithms for Structural Health Monitoring, pp. 4923–4936. https://doi.org/10.7712/120125.12784.26049

Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2025) 492 -49 6

ECCOMAS
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COMPDYN 2025
10th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Rhodes Island, Greece, 15-18 June 2025

MODAL DYNAMIC IDENTIFICATION OF HISTORIC SAN MICHELE BRIDGE (ITALY, 1889)

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Abstract. *The San Michele Bridge, also known as Paderno d'Adda Bridge, stands as a striking example of 19th-century iron architecture and a prominent symbol of Italian industrial-archaeology heritage. Constructed between 1887 and 1889 by the Società Nazionale delle Officine di Savigliano (SNOS), this impressive infrastructure spans over the Adda River, linking the towns of Paderno d'Adda and Calusco d'Adda, near Milano.*

Since its inauguration in 1889, the bridge has continuously served as a vital connection between the provinces of Lecco and Bergamo in Lombardy, northern Italy. Following nearly 136 years of service, the bridge underwent extraordinary restoration works from 2018 to 2020, ensuring up to now its continued functionality for both railway and road traffic.

After that, from May 7 to 10, 2024, a dedicated experimental campaign was conducted on the bridge to investigate its current structural response under various dynamic excitations, including ambient vibrations with no traffic, dynamic response with vehicular transit and controlled train passages. During such a campaign, diverse acceleration data were collected and then analyzed with the aim of extracting the salient modal properties of the bridge.

A comparison of the processed data with available records prior to bridge restoration revealed a rather good correspondence with the identified modal properties, within a time span of about 14 years. This seems to suggest that the recent restoration works may have displayed a minimal impact on the global dynamic behavior of the structure, in terms of modal features.

The findings from this study shall provide valuable insights for future research developments and contribute to the ongoing deployment of a Structural Health Monitoring (SHM) platform for the San Michele Bridge, contributing to the long-term goal of monitoring and preserving this historic viaduct.

Keywords: Historic Bridge, Signal Processing, Frequency Domain Decomposition, Modal Identification, Structural Health Monitoring.

ISSN:2623-3347 © 2025 The Authors. Published by Eccomas Proceedia.
Peer-review under responsibility of the organizing committee of COMPDYN 2025.
doi: 10.7712/120125.12784.26049

1 INTRODUCTION

The San Michele Bridge, also known as Paderno d'Adda Bridge, is an iconic metallic structure completed in 1889 by the *Società Nazionale delle Officine di Savigliano* (SNOS, Cuneo). The bridge spans over the Adda River, connecting the provinces of Lecco and Bergamo, between the towns of Paderno d'Adda (LC) and Calusco d'Adda (BG), in Lombardy, northern Italy, near Milano [2, 3, 5**? ?**]. Following extraordinary maintenance works carried out by the owner (Rete Ferroviaria Italiana, RFI) between 2018 and 2020, after more than a century of continuous service, an opportunity was seized in 2024 to conduct an experimental campaign aimed at investigating its current dynamic characteristics.

Modal dynamic identification constitutes an essential aspect of Structural Health Monitoring (SHM), which is dedicated to evaluate the integrity and current condition of structures, such as bridges, over time. SHM involves the deployment of sensors, data acquisition systems, and analytical methods to detect potential damage or degradation, ensuring the continued safety, reliability, and longevity of structures through a periodic or continuous monitoring. Modal analysis aims specifically at assessing the underlying dynamic characteristics, including natural frequencies, mode shapes, and modal damping ratios.

In this study, the modal dynamic identification of San Michele Bridge has been performed through a Frequency Domain Decomposition (FDD) algorithm [7–10], based on data acquired during a dedicated experimental campaign conducted on the bridge from May 7th to May 10th, 2024. Among other devices, acceleration sensors were placed on the upper continuous box girder of the bridge, to capture mechanical vibrations induced by ambient environmental sources, train passages, and vehicle traffic.

The recorded data presented challenges for conventional Operational Modal Analysis (OMA) processes, due to non-stationary characteristics associated with transient excitation events. To address this issue, a dedicated preprocessing approach was developed, to isolate time consistent windows toward OMA applications. This enabled an effective implementation of the FDD method and a consequent identification of reliable modal parameters.

The present extracted modal properties were compared with results from previous identification campaigns reported by Gentile and Saisi [5], in 2010, conducted before the recent extraordinary restoration works. This comparison provided an opportunity to examine potential changes in the global dynamic behavior of the structure over time.

This study is part of a broader research initiative aimed at developing an integrated SHM platform and an efficient maintenance strategy for the San Michele Bridge. The envisioned platform is intended not only to ensure the bridge's continuing safety and functionality but also to safeguard and promote its historical and architectural value. The results here presented shall represent a foundational step in this ongoing effort and lay down the groundwork for future analysis and long-term monitoring of the historic infrastructure.

Following presentation is structured in three main parts. Section 2 starts with a brief description of the carried out experimental campaign, which provides insights into data acquisition and sensor positioning. Section 3 introduces the procedure for analyzing the acquired data, highlighting the importance of a coherent preprocessing approach for successfully performing OMA. Section 4 presents the results of modal dynamic identification, with comparisons to earlier outcomes. Finally, Conclusions summarize main findings and perspectives of the study.

2 EXPERIMENTAL CAMPAIGN

2.1 San Michele Bridge (1889)

San Michele Bridge [1–5], depicted schematically in Figure 1, is a riveted iron structure that spans over the Adda River, connecting the towns of Paderno d'Adda (province of Lecco) and Calusco d'Adda (province of Bergamo) at an elevated height of approximately 85 m above water level and represents one of the masterpieces of 19th-century iron architecture and a true symbol of Italian industrial-archaeology heritage.

It still serves as an important local link between the provinces of Lecco and Bergamo, in the area North-East from Milan, Lombardy, northern Italy. Nowadays, the San Michele Bridge keeps serving as a combined road and railway bridge, with the top deck of the truss-box girder carrying one lane of alternate road traffic and the bottom deck housing inside the tracks of a single-line railway (see Figure 2a).

The bridge has undergone limited restoration works throughout its history. Decades after completion, the Paderno d'Adda Bridge was bombed during World War II; however, the resulting damage was minimal and was promptly repaired. In 1972, the original road deck was replaced with a steel orthotropic plate, and a subsequent intervention in 1992 focused primarily on stiffening the truss-frame of the road and railway decks. The Paderno d'Adda Bridge has currently been the subject of several studies aimed at assessing its present state of conservation. In September 2018, after 129 years of continuous service, the viaduct was closed to both rail and road traffic to allow for extraordinary maintenance works, by RFI.

Protected by the *Soprintendenza per i Beni Ambientali ed Architettonici della Lombardia* since 1980, recognized as an element of industrial archaeology by the *Consorzio Parco Naturale Adda Nord* since 2000, and currently under consideration with few other similar bridges in Europe for inclusion in the UNESCO heritage list, the bridge was reopened to road traffic in November 2019 and to rail traffic in September 2020, and is presently in service, with regulated train and vehicle traffic.

2.2 Brief description of the experimental campaign (May 2024)

The experimental campaign aimed at registering overnight dynamic vibrations induced by ambient excitation, vehicular transit, and controlled train passages on the San Michele Bridge, acquired by various sensors, including structure-mounted accelerometers. Specifically, 12 seismic accelerometers *Model 731A*, *Wilcoxon* were deployed during the experimental campaign. Sensors measured vertical and transverse horizontal accelerations of the bridge and were positioned along the upper continuous beam, from inside, at the level of the inner railway deck, as depicted in Figures 1 and 2.

Sensors were installed at the level of the railway deck, primarily at the interfaces between beams and piers, as well as at the beam-arch contact points. An exception was constituted by the pair of sensors positioned at the key of the arch (midlength of the fourth span from Paderno, Sensors C4V and C4T in Figure 1). Data acquisition was carried out exclusively during night hours, corresponding to the daily train stop period, allowing access to the railway level to sensor setup and cabling. The recordings captured both vehicle and train traffic-induced vibrations and were collected in time windows with durations ranging from 140 to 180 seconds. The signals were originally sampled at 2500 Hz, corresponding to a time step of 0.004 s.

In this study, five response signal datasets from vehicular traffic acquisitions were selected for subsequent OMA analysis. Each acceleration dataset includes recordings from five transverse horizontal and seven vertical acquisition channels (see Figure 1). For the purposes of the present

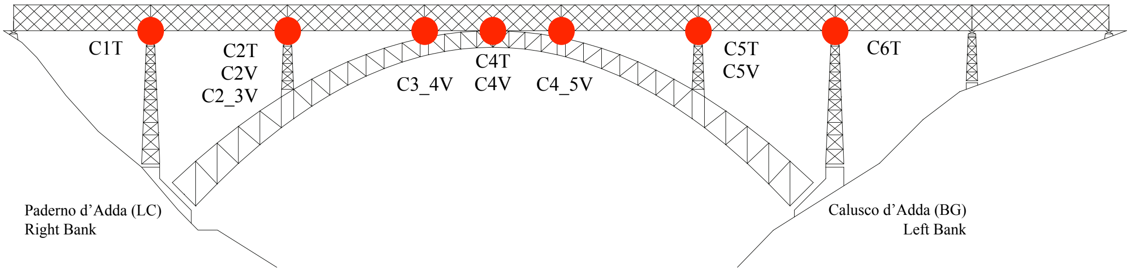


Figure 1: Downstream view of the scheme of accelerometer placement on San Michele Bridge, 1889 (red markers). Typically, in label C2T, "2" indicates a clamp-mounted sensor between second and third spans (red circle in Fig. 2b), while in C2_3V, "2_3" refers to a niche-mounted sensor at the same location (green circle in Fig. 2b); "T" and "V" denote transverse horizontal and vertical acceleration measurements, respectively.

OMA analysis, only transverse horizontal acceleration signals were considered. Furthermore, the sampling rate was downsampled to 250 Hz (retaining one out of every ten original samples), toward data decimation.

(a) (b)

Figure 2: Global inside view of railway deck (a) of San Michele Bridge (1889); typical sensor placements (b).

3 RESPONSE-SIGNAL ANALYSIS

Operational Modal Analysis (OMA), performed using a Frequency Domain Decomposition (FDD) self-implementation [8–10], relies on several key assumptions: (i) output signal to be ergodic and stationary, (ii) mechanical system under analysis to be linear and time-invariant, and (iii) input excitation to approximate a pink-noise distribution, that is, white noise limited to a narrow frequency band [6, 7]. In addition, based on the Central Limit Theorem, the instantaneous values of the excitation signal may be assumed to follow a Gaussian distribution; consequently, under the aforementioned assumptions, the output (structural) vibration signals are also expected to exhibit Gaussian characteristics [6].

To ensure a consistent application of the FDD algorithm to transverse acceleration data, specific time intervals were selected to attempt meeting the previously outlined conditions. This process involved identifying segments of the original signals that approximately exhibited a Gaussian probability density function, zero mean, constant variance, and stable root mean square values. An automated procedure was then developed to extract time windows from each dataset that met these criteria, with a minimum duration of 50 s. The process began by identifying windows with kurtosis values between 2.5 and 3.5, as this range shall indicate a good approximation of the signal distribution to a Gaussian distribution. This analysis was performed independently for each dataset and across all channels. For each dataset, a unique time window was identified. A FDD algorithm was then applied within this window, and the corresponding modal properties were extracted. This confirmed that the automated selection process successfully isolated stationary signal segments, while transient segments (typically caused by vehicle crossings) that may introduce non-stationary effects were disregarded.

As an illustrative example, Figure 3 shows the raw recorded signals from a specific dataset (DataSet 2) across all available channels corresponding to transverse horizontal acceleration acquisitions. The automated procedure selected the signal portion within the time range defined by the red dashed lines, which corresponds to a time window with kurtosis values in the range of 2.5–3.5. Figure 4 illustrates the evolution of kurtosis, calculated over successive 50 s windows, with the x-axis representing the start time of each window. For such dataset, the selected time window ranges from 66 s to 116 s, as highlighted in both figures.

4 MODAL DYNAMIC IDENTIFICATION

The Frequency Domain Decomposition (FDD) technique is a modal identification procedure employed within Operational Modal Analysis (OMA). It is an output-only method that relies on evaluating the Power Spectral Density (PSD) functions derived from the recorded response of the structural system [7–10].

As previously mentioned, a FDD algorithm was applied to all considered datasets, in order to evaluate natural frequencies and mode shapes of the bridge. For the purposes of this preliminary study, only signal frequency contents within a 0–10 Hz range was analyzed.

Figure 5 illustrates the evolution of the first three singular values of the PSD matrix, for the selected signal portions from each dataset. The depicted red circles mark the peaks picking on the first singular value functions, which shall point out to the frequencies associated with the system's modes of vibration.

Using the signal-selection process described above, eight modal frequencies and the corresponding mode shapes were identified. Specifically, in Figures 6 and 7, Modes 1–4 and Mode 6 were identified across all datasets, while Modes 5, 7 and 8 were identified from four datasets. Modes 5 and 7 were detected from DataSets 1–3, and 5, and Mode 8 was identified from DataSets 1, 2, 4, and 5.

Main results are summarized in Table 1, which lists the modal frequencies extracted from each of the analyzed datasets. Empty cells indicate either that the modal frequency was not detected or that the mode was discarded due to inconsistencies with respect to the other modes. Additionally, the table provides the mean and standard deviation values for each acquired modal frequency. In particular, the minimal differences in the identified frequency values, as reflected

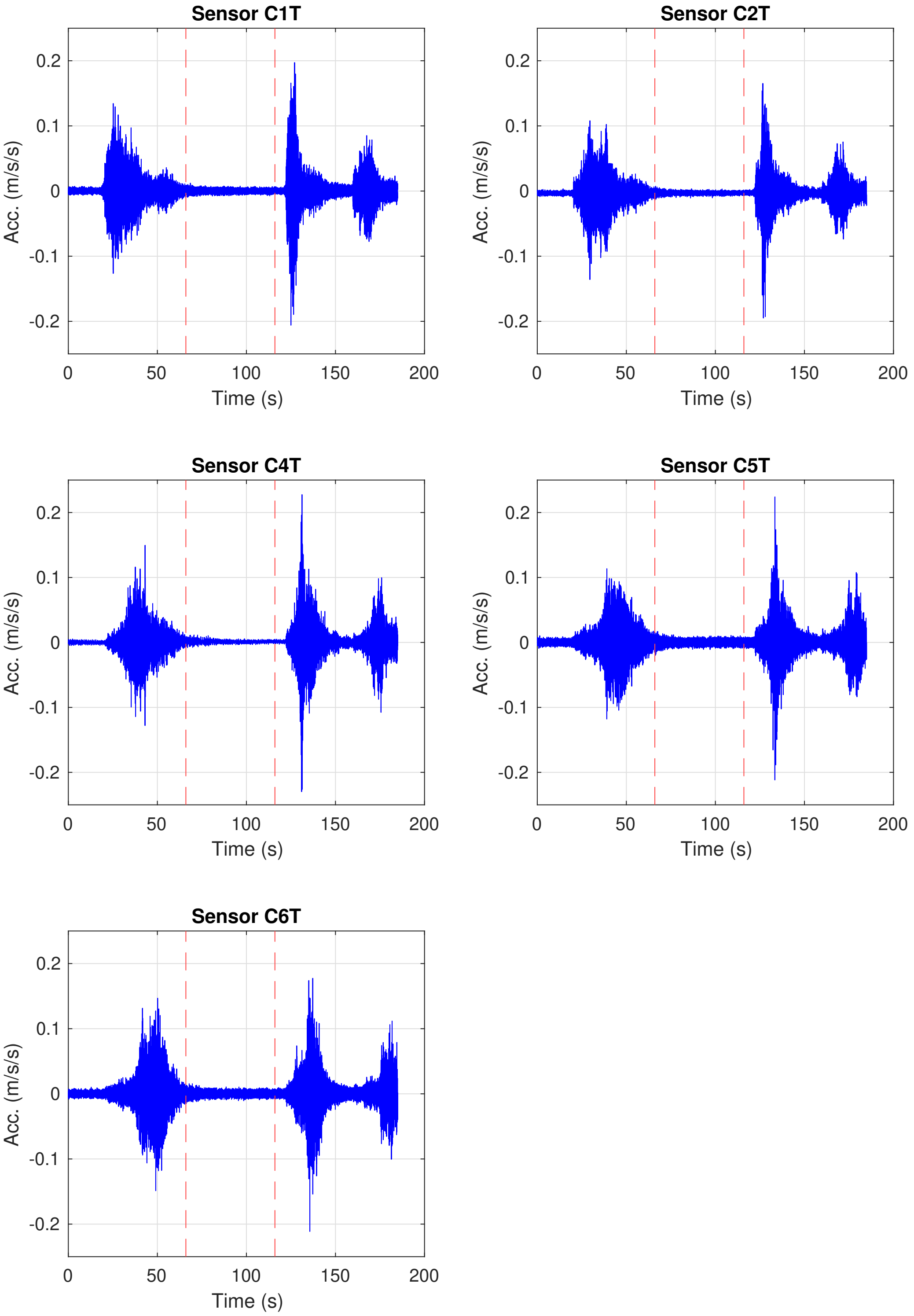


Figure 3: Plots of transverse horizontal acceleration signals from DataSet 2. Red dashed lines highlight portions of signal identified to be suitable for subsequent FDD application (66–116 s).

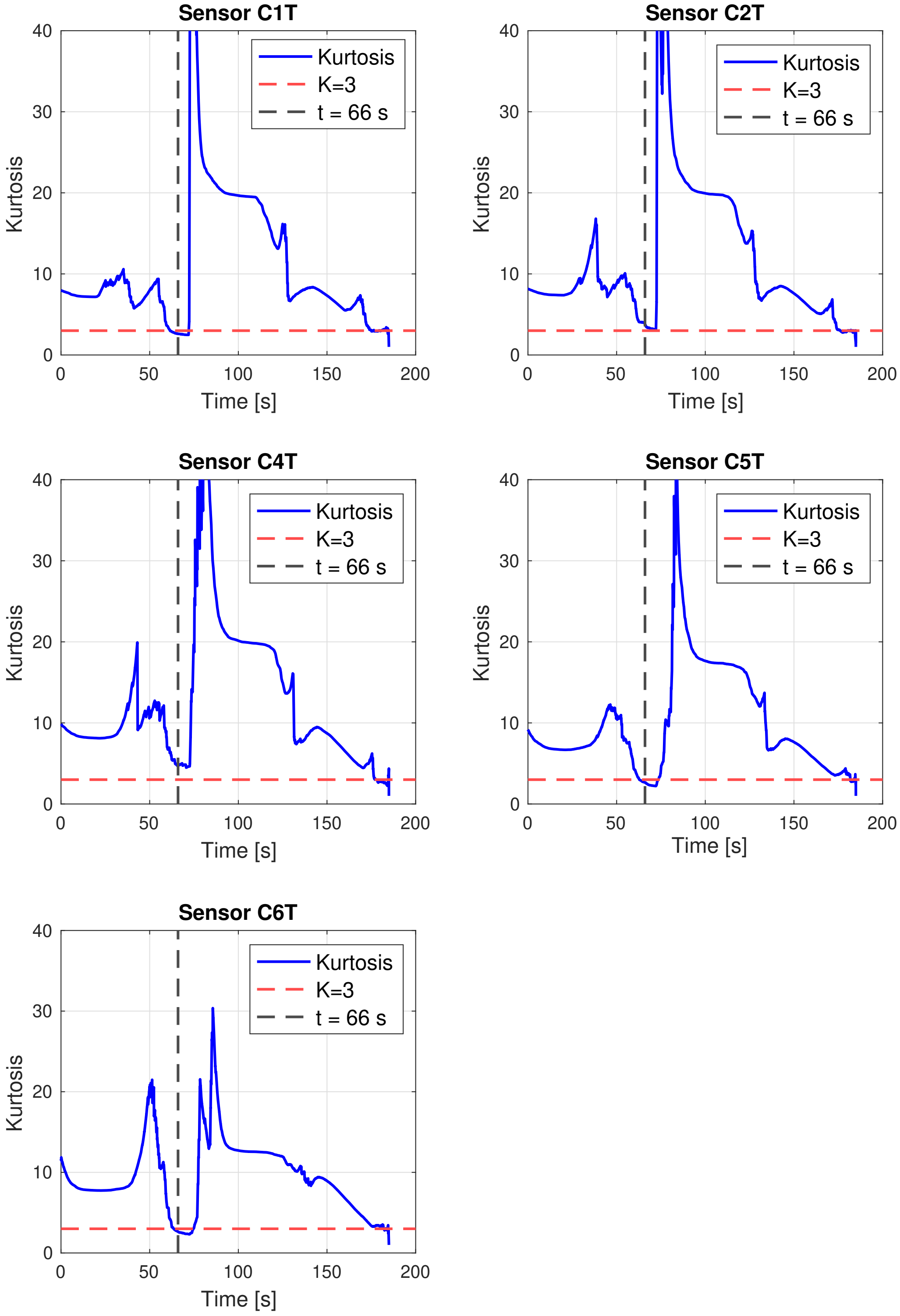


Figure 4: Kurtosis evolution plots of the transverse horizontal acceleration signals from DataSet 2 (Fig. 3), computed over moving 50-second windows. Each kurtosis value is plotted at the start time of the corresponding window, shown on the x-axis.

in the small standard deviations, suggest a rather high level of consistency across the various considered datasets.

Mode	DS 1	DS 2	DS 3	DS 4	DS 5	**Mean**	*Std*
1	0.976	0.976	0.976	0.977	0.977	**0.976**	*0.001*
2	1.343	1.343	1.343	1.343	1.343	**1.343**	*0.000*
3	1.648	1.648	1.648	1.648	1.648	**1.648**	*0.000*
4	2.197	2.197	2.197	2.223	2.197	**2.202**	*0.012*
5	2.502	2.502	2.502	-	2.502	**2.502**	*0.000*
6	2.899	2.899	2.899	2.808	2.899	**2.881**	*0.041*
7	3.174	3.143	3.143	-	3.143	**3.151**	*0.016*
8	3.662	3.662	-	3.601	3.662	**3.647**	*0.031*

Table 1: Comparison of identified modal transverse horizontal vibration frequencies, mean values, and standard deviations [Hz] across five considered DataSets (DS) analyzed from vehicular traffic acquisitions.

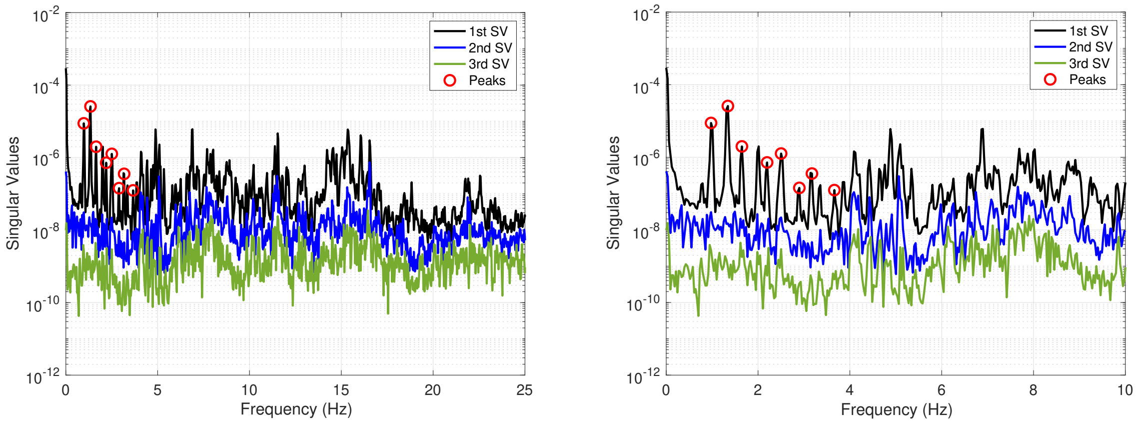
4.1 Comparison of the identification results with previous studies

The modal properties of San Michele Bridge have been investigated over years. The most extensive and recent experimental campaign prior to this study, to the authors' knowledge, was conducted in 2010 by Gentile and Saisi [5], who installed sensors on both the railway and vehicular decks. For confrontation purposes, results specifically related to the mode shapes associated with the transverse horizontal vibration of the railway deck may be considered. A useful comparison is provided in Figures 6 and 7, where the modes identified in the present analysis (on the right) are compared with those from Gentile and Saisi [5] (on the left). In these figures, the identified mode shapes corresponding to the datasets considered in this analysis are shown, providing an additional level of comparison with the previously reported analyses.

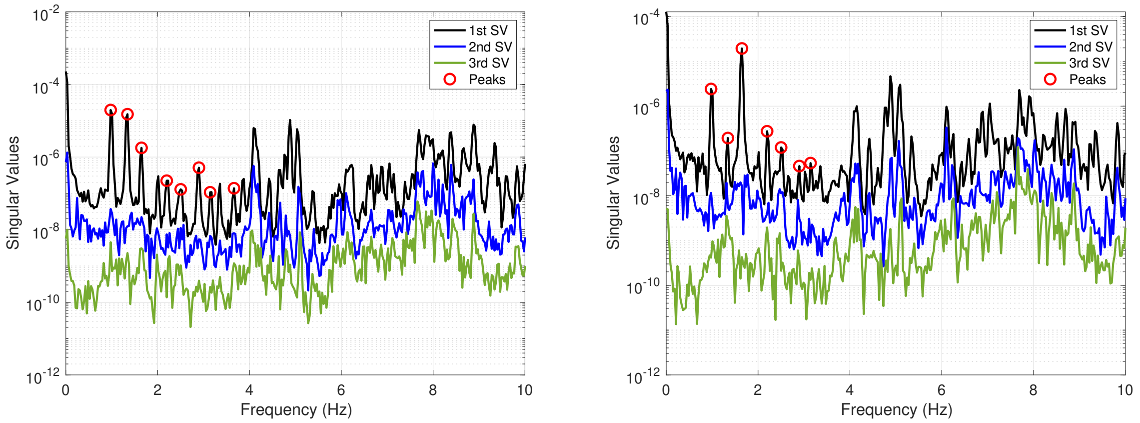
Mode Shapes 1–4, extracted from all datasets, look highly consistent, with a minimum MAC value exceeding 0.85. Mode Shape 6 shows slight differences in the first support, where the mode shape extracted from DataSet 4 appears to be slightly underestimated. Despite this, the four mode shapes closely align with those earlier obtained by Gentile and Saisi [5]. Mode Shapes 5 and 7 exhibit strong similarities. Specifically, for Mode Shape 5, the mode shape from DataSet 1 closely matches that from DataSet 5, while the mode shape from DataSet 2 is similar to that from DataSet 3. In general, mode shapes well align with those identified in 2010 in [5]. Finally, Mode Shape 8 appears consistent across DataSets 1, 2, 4, and 5. The comparison with the mode shapes from the 2010 study is herein based solely at the railway deck level, as Gentile and Saisi [5] observed a torsional component that differed between the rail and vehicular decks.

The achieved results shall demonstrate a good agreement between the modal properties identified by the two considered experimental campaigns, in 2010 and 2024, indicating that there have been no substantial variations in the modal properties of the bridge over the last 14 years of service.

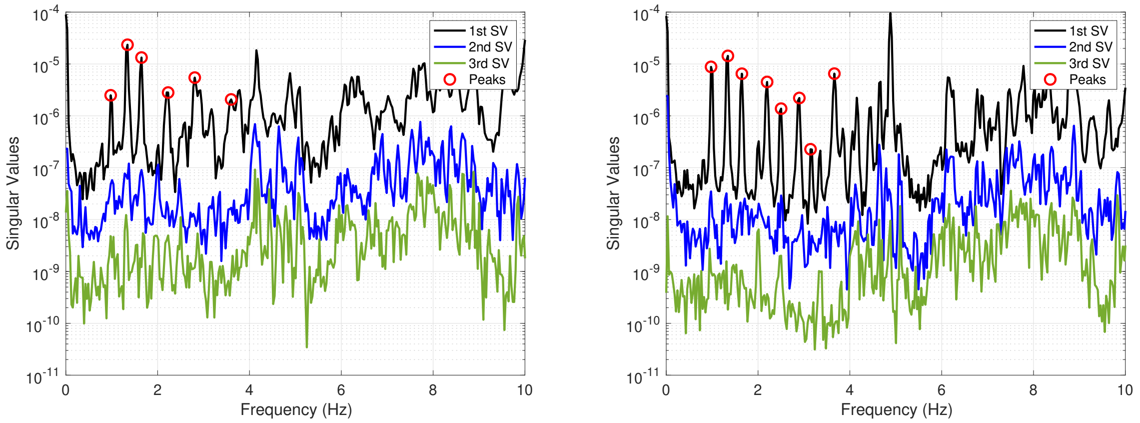
This consistency may be interpreted as a positive indicator of the current structural health condition of the infrastructure, as it seems to display a minimal variation of the global stiffness in the examined time span. Based on the obtained results, the aging and restoration interventions do not appear to have considerably altered the global dynamic behavior of the viaduct, in terms of deciphered modal properties.



(a) DataSet 1 (0–25 Hz)   (b) DataSet 1 (0–10 Hz)

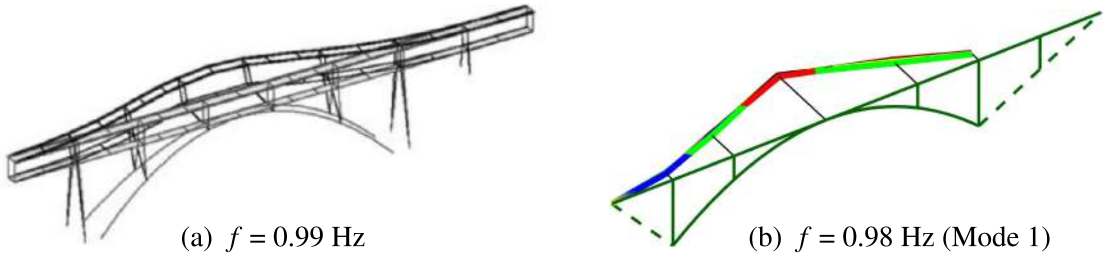


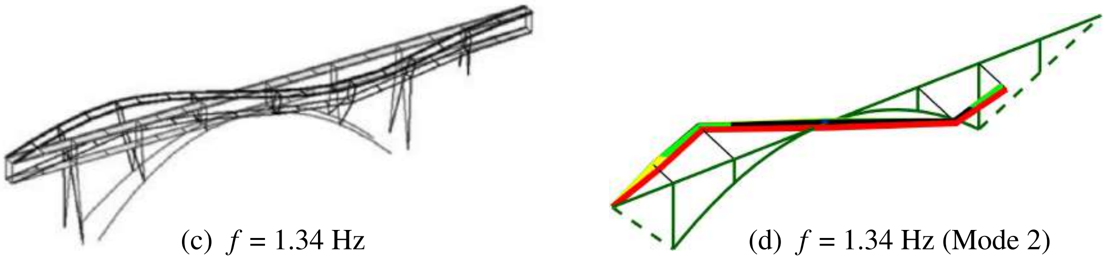
(c) DataSet 2 (0–10 Hz)   (d) DataSet 3 (0–10 Hz)

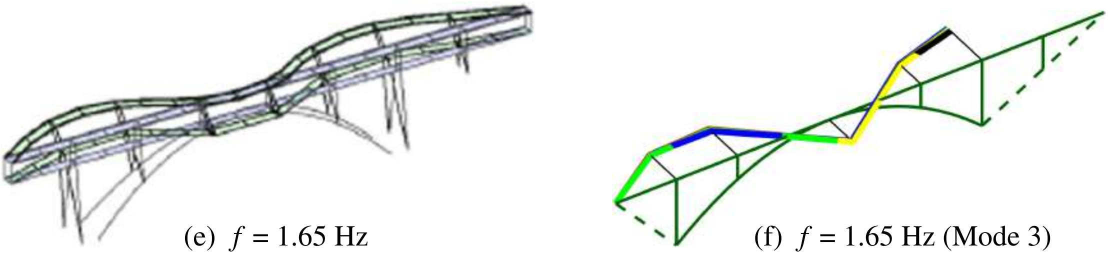


(e) DataSet 4 (0–10 Hz)   (f) DataSet 5 (0–10 Hz)

Figure 5: Singular Values representation of PSD functions calculated from DataSets 1–5.


(a) $f = 0.99$ Hz (b) $f = 0.98$ Hz (Mode 1)


(c) $f = 1.34$ Hz (d) $f = 1.34$ Hz (Mode 2)


(e) $f = 1.65$ Hz (f) $f = 1.65$ Hz (Mode 3)

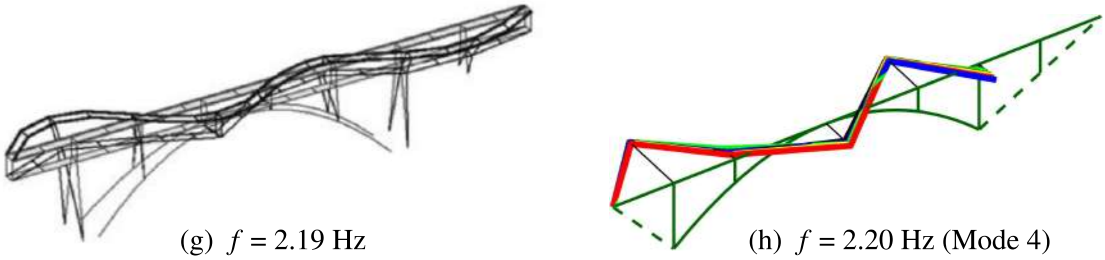
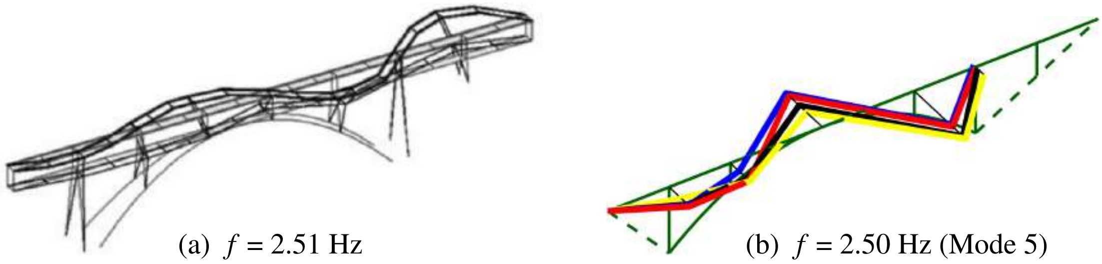
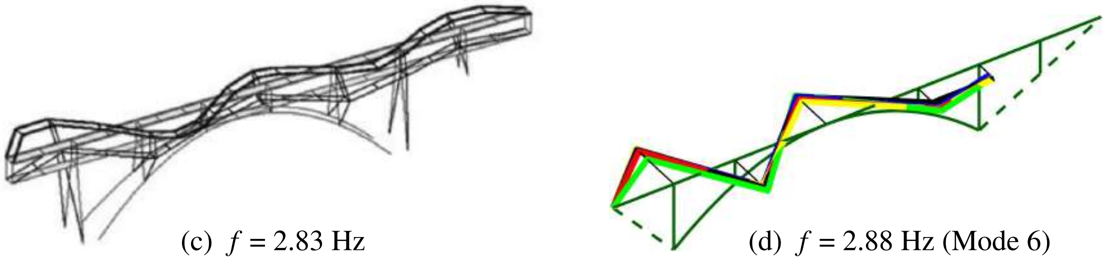

(g) $f = 2.19$ Hz (h) $f = 2.20$ Hz (Mode 4)

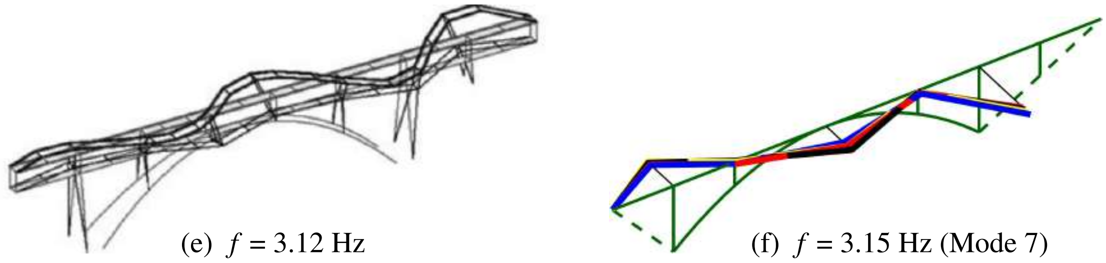
Figure 6: Comparison of modal properties (Modes 1–4) identified from present 2024 experimental campaign (right), at lower deck level, for transverse horizontal displacements, with those from a previous 2010 experimental campaign [5] (left). In the mode shape representations in the right column, black represents the mode shape identified from DataSet 1, blue from DataSet 2, red from DataSet 3, green from DataSet 4, and yellow from DataSet 5 (Table 1).



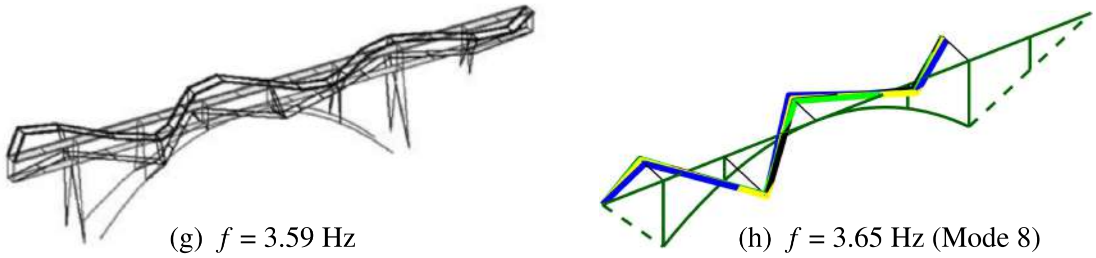
(a) $f = 2.51$ Hz (b) $f = 2.50$ Hz (Mode 5)



(c) $f = 2.83$ Hz (d) $f = 2.88$ Hz (Mode 6)



(e) $f = 3.12$ Hz (f) $f = 3.15$ Hz (Mode 7)



(g) $f = 3.59$ Hz (h) $f = 3.65$ Hz (Mode 8)

Figure 7: Comparison of modal properties (Modes 5–8) identified from present 2024 experimental campaign (right), at lower deck level, for transverse horizontal displacements, with those from a previous 2010 experimental campaign [5] (left). In the mode shape representations in the right column, black represents the mode shape identified from DataSet 1, blue from DataSet 2, red from DataSet 3, green from DataSet 4, and yellow from DataSet 5 (Table 1).

5 CONCLUSIONS

This study focused on the modal dynamic identification of San Michele Bridge (1889) through a Frequency Domain Decomposition (FDD) technique, applied to acceleration response signals collected during an experimental campaign conducted in May 2024. The acquired signals were carefully processed and initially analyzed in the time domain to identify suitable sub-parts toward modal identification purposes.

The resulting mode shapes and natural frequencies were compared with those of a previous experimental campaign conducted in 2010 [5]. The results showed a good correlation between the identified modal properties, indicating that globally they shall have largely remained unchanged in a time span of 14 years. This consistency sets a positive indicator of the current structural health condition of the bridge, as it points out to a relative invariance of the global behavior of the structure. Furthermore, recent prior restoration works, loyal to design-stage outline, carried out between 2018 and 2020, do not appear to have substantially affected the modal properties of the bridge.

This work is part of a larger project aiming at developing an innovative methodology for designing an efficient platform dedicated to permanent SHM for the Paderno d'Adda Bridge. The ultimate goal is the establishment of a dynamic, data-driven maintenance strategy to optimize the bridge's management over its remaining service life (see also parallel companion studies [11, 12]).

Future phases of this project will explore the integration of recent advancements in vehicle-bridge interaction (VBI) analysis [13–16] and mobile sensing techniques. These developments shall offer promising tools for extracting modal parameters through train-mounted sensors, while mitigating VBI effects, thereby enhancing the long-term, data-driven maintenance strategy. Future work will also focus on identifying modal damping ratios and achieving a full automation in signal processing analysis. This shall include enabling taxonomic characterization and identification of appropriate time windows aiming at isolating stationary parts of the signals toward robust systematic identification.

ACKNOWLEDGMENTS

The research conducted at the University of Bergamo was supported by the Italian Ministry of University and Research (MUR) under the PRIN 2022 program (funding following reallocation of resources from final ranking), Project Code 2022744YM9, CUP F53C24000930006, and by "Fondi di Ricerca d'Ateneo ex 60%" funds and a doctoral grant at the Dept. of Engineering and Applied Sciences. RFI, the bridge owner, is gratefully acknowledged for interaction and accessibility to the bridge. The third author would also like to acknowledge the Marie Skłodowska-Curie Actions (MSCA) program under the OMoRail project, Grant ID: 101104968.

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