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Modal testing of a reinforced concrete Gerber-type bridge

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Abstract

This study focuses on the modal identification of the “Ponte delle Grazie”, located in Faenza, northern Italy. The structure crosses the Lamone River and consists of a reinforced concrete deck with a Gerber-type configuration. The bridge, constructed in 1950, was found to be in a critical state of deterioration during inspections conducted in 2017, with significant damage observed in the rocker bearings, Gerber saddles, and lateral girders. These findings led to urgent repair interventions. A follow-up evaluation, carried out in line with Italian bridge guidelines, confirmed major structural issues. As a result, additional repair works were undertaken in 2024. Given these conditions, the bridge was deemed an ideal candidate for continuous monitoring via a permanent system, which was installed that same year as part of the DIGI-BRIDGE research project. This paper presents the results of dynamic tests carried out prior to the installation of the permanent monitoring system, aimed at assessing the dynamic behavior of the bridge. The tests were carried out using different acceleration measurement systems: one system consists of MEMS accelerometers, which was also used for the subsequent permanent monitoring of the bridge; a second system uses piezoelectric accelerometers and is intended to provide a more accurate characterization of the modal properties; the third is an innovative system based on fiber optic sensors. In the paper, results obtained from the different monitoring systems are discussed and compared.

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1. Introduction

Structural monitoring plays a central role in ensuring the safety, durability, and serviceability of civil infrastructure. In particular, the dynamic identification of bridges is a powerful tool for assessing structural behaviour under operational or ambient excitations, allowing engineers to extract key modal parameters such as natural frequencies, mode shapes and damping ratios (Magalhães et al. (2012); Romanazzi et al. (2023)). These parameters provide valuable insights into the health of a structure and enable the detection of anomalies or damage, often before they manifest visibly

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(Comanducci et al. (2016); Ponsi et al. (2023)). As such, dynamic testing and long-term vibration monitoring have become fundamental components of modern structural health monitoring (SHM) strategies (Maes and Lombaert (2021)). This has led to significant advancements in sensor technologies, expanding the possibilities for vibration-based assessment. Piezoelectric accelerometers are traditionally employed in high-accuracy dynamic testing applications due to their sensitivity, broad frequency bandwidth, and low noise performance. These sensors operate based on the piezoelectric effect, wherein mechanical stress induces an electrical charge in a piezoelectric crystal element. This property makes them particularly well-suited for detecting small-amplitude vibrations across a wide dynamic range (Vincenzi et al. (2019)). In the context of experimental modal analysis, piezoelectric accelerometers are considered the standard for capturing accurate estimates of modal parameters such as natural frequencies, mode shapes, and damping ratios. On the downside, this technology is expensive, commonly requires complex installation and can be very sensitive to external disturbances. In contrast, MEMS (Micro-Electro-Mechanical Systems) accelerometers represent a more recent but highly diffused generation of sensing technology. The MEMS-based monitoring system is characterized by two main features: the digital transmission of data and the capability to carry out preliminary signal processing and system analysis directly on-board the sensors. This enables the transmission of processed, high-level data—rather than raw measurements—to the main control unit, thereby reducing bandwidth usage and improving overall system efficiency. Additionally, the on-board intelligence allows for real-time diagnostics and faster decision-making in distributed sensing environments. Moreover, although they offer lower sensitivity and resolution than piezoelectric devices, their affordability, compactness, and ease of deployment make them well suited for long-term, in-situ monitoring. MEMS sensors are increasingly integrated into permanent systems for continuous observation of structural responses under environmental and operational loads (Guidorzi et al. (2014); Bassoli et al. (2015)). On the front of emerging sensing technologies, Fiber Bragg Grating (FBG) accelerometers offer a novel and innovative solution in structural monitoring. These optical sensors are immune to electromagnetic interference and lightweight, and capable of multiplexed measurements along a single fiber (Yassin et al. (2024)). While their use is still emerging in dynamic applications, FBG sensors hold significant promise for scenarios where traditional sensors face limitations. However, their performance and reliability for modal testing in civil engineering contexts require further investigation.

Within this context, the present research aims to evaluate the effectiveness and complementarity of the presented sensing technologies—piezoelectric, MEMS, and FBG accelerometers—in capturing the dynamic behaviour of a real-world case study: the "Ponte delle Grazie", a reinforced concrete Gerber-type bridge located in Faenza, northern Italy.

The paper is organized as follows: Section 2 describes the case study in detail. Section 3 presents the modal testing campaign, outlining the sensor technologies employed, with a particular focus on the novel FBG-based sensors. Section 4 discusses the results of the dynamic identification and, finally, Section 5 provides conclusions and future perspectives.

2. Case study

The analyzed case study is the "Ponte delle Grazie", located in Faenza (northern Italy) and shown in Figure 1. The structure crosses the Lamone River and consists of a reinforced concrete deck with a Gerber-type configuration. It has a total length of 72 meters and a width of 13 meters. It is composed by three spans: the two end spans measure 21 meters each, while the central span is 30 meters long and includes a beam supported by Gerber saddles with a length of 17.5 meters. The foundations of both the abutments and the piles are constituted by concrete posts. In more detail, the bridge deck is composed of 5 concrete girders with a height ranging from 2.40 m in correspondence of piles to 1.40 m at midspan. The girder spacing is 2.40 m. The bridge deck is completed by 16 transverse beams and by a 23 cm thick slab.

The bridge, constructed in 1950, was found to be in a critical state of deterioration during inspections conducted in 2017, with significant damage observed in the rocker bearings, Gerber saddles, and lateral girders. These findings led to urgent repair interventions, which included the positioning of safety devices beside the existing bearings, the installation of steel tie-rods as security devices for the Gerber saddles and the reconstruction and the reinforcement of the concrete bearings and of the lateral girder sections. Following evaluations, carried out in line with Italian bridge guidelines, confirmed major structural issues, regarding the deterioration state of several deck elements, especially for the central supported beam, the Gerber saddles and the slab. Moreover, flooding event further impacted the bridge.

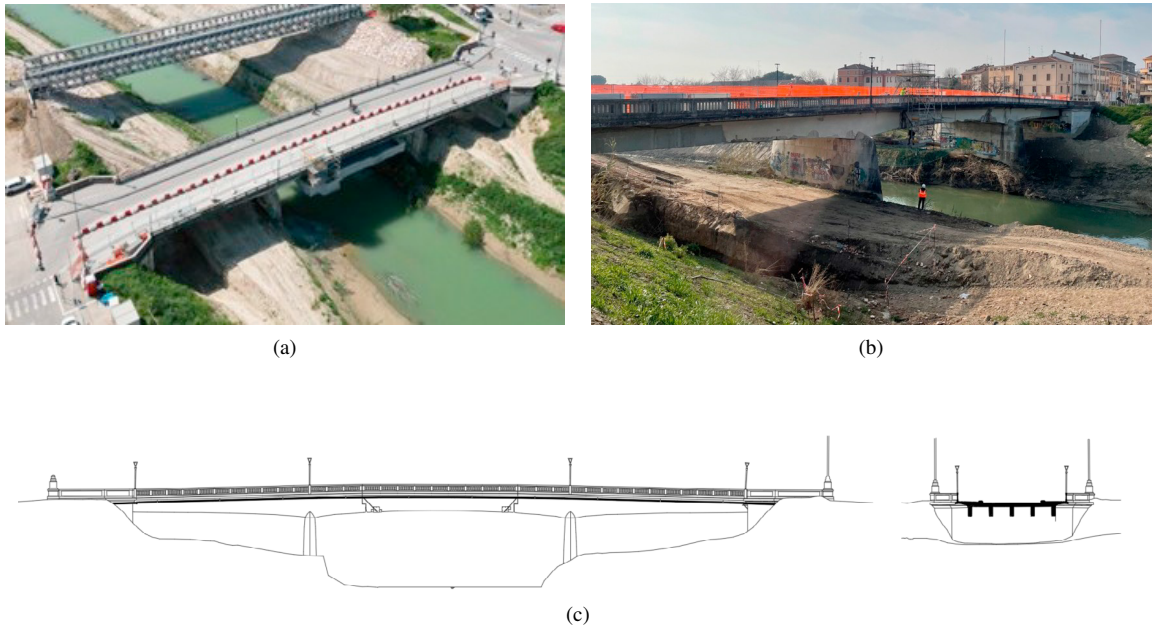


Fig. 1: "Ponte delle Grazie" - (a) aerial view; (b) side view; (c) longitudinal elevation and section.

Given these conditions, the bridge represents an ideal candidate for continuous monitoring via a permanent system, which was installed that same year as part of the DIGI-BRIDGE research project.

3. Modal testing

This section describes the dynamics tests carried out prior to the installation of the permanent monitoring system, aimed at assessing the dynamic behaviour of the bridge. The tests are carried out using different acceleration measurement systems: one consisting of a few MEMS accelerometers (shown in Figure 2a), the same used in the permanent monitoring system; another including a larger number of PCB accelerometers (Figure 2b), aimed at a more accurate characterization of the modal properties, and lastly an innovative system based on fiber optic sensors (Figure 2c). The MEMS accelerometers are Beckhoff EP3751-0160 with a tri-axial MEMS sensor ADXL355. They have a 20-bit resolution, a dynamic range of ± 2 g and a declared noise level of $22.5 \mu\text{g}/\sqrt{\text{Hz}}$. The uni-axial piezoelectric accelerometers are of the type PCB/393B12 and PCB/393B31. They have a dynamic range of ± 0.5 g, a bandwidth ranging from 0.15 to 1000 Hz and a resolution of $8 \mu\text{g}$ (PCB/393B12) and $1 \mu\text{g}$ (PCB/393B31). The last monitoring system employs Fiber Bragg Grating based sensors. They represent one of the most innovative technologies in the field of structural monitoring, where a wavelength shift provides a reliable and accurate measurement mechanism for detecting physical changes in structures. In detail, due to their dielectric composition, FBG sensors are inherently immune to electromagnetic interference, making them suitable for deployment in electrically noisy or high-voltage environments. Their lightweight, passive nature and capability to multiplex multiple sensing points along a single optical fiber allow for efficient implementation of distributed sensing systems with high spatial resolution. These characteristics enable comprehensive monitoring over large structural areas with minimal cabling and system complexity. FBG technology is widely regarded as a robust and reliable optical sensing approach, owing to its relatively straightforward fabrication process and the stability of the reflected optical signal. FBGs are created by inducing a periodic modulation of the refractive index within the core of an optical fiber along its longitudinal axis. These gratings act as narrowband optical reflectors, operating based on the diffraction grating principle. As light propagates through the grating, partial reflections occur at each modulation interface. Constructive interference of these reflections results in a pronounced

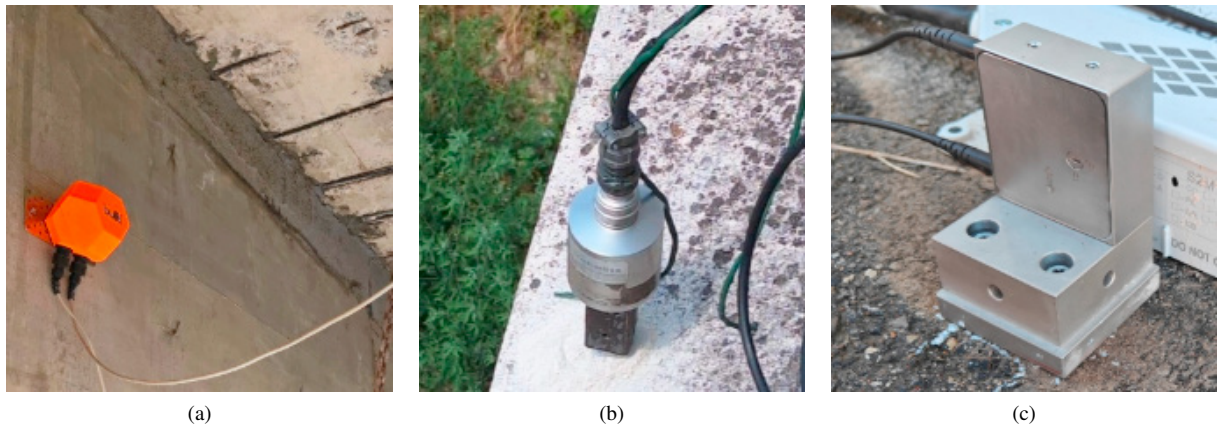


Fig. 2: Sensors used for the dynamical tests: (a) MEMS, (b) piezoelectric and (c) FBG.

reflected signal only when the Bragg condition is met. In the context of dynamic testing, FBG-based accelerometers can accurately capture structural vibrations, providing valuable insights into the modal behaviour of the bridge. The adopted FBG interrogation system allows high-frequency acquisition (with a sampling frequency equal to 1000 Hz), enabling accurate dynamic measurements suitable for modal analysis.

The configuration of the monitoring campaign setup is detailed below. A total of 14 uniaxial piezoelectric accelerometers with a nominal sensitivity of 1 mV/g, denoted as P01 to P14 in Figure 3, are installed across the structure. Specifically, two sensors are positioned at the midspan sections of the edge girders of the central span, four at the quarter-span locations. The remaining accelerometers are placed on both sides of the bridge symmetrically, in order to accurately capture the largest possible number of modes, avoiding nodal points (Figure 3).

Additionally, five triaxial MEMS accelerometers, labeled M01 to M05, are installed near some of the piezoelectric accelerometers for comparison of the results (see Figure 3). The MEMS units are oriented such that the local Z-axis aligns with the vertical axis of the girder, the X-axis lies within the bridge plane, and the Y-axis follows the longitudinal axis of the edge girder. Only the acceleration data acquired along the vertical (Z) axis are considered since the external excitation predominantly acts along that direction.

As for the fiber optic monitoring system, due to the limited number of available FBG sensors, two distinct configurations are implemented. Each of the two configurations consists of four uniaxial FBG accelerometers oriented along the vertical axis (Figure 3). In the configuration named Setup01, two reference accelerometers (F01,ref and F03,ref) are positioned at the midspan sections of the edge girders of the central span, while two additional sensors (F02,setup1 and F04,setup1) are installed at the quarter-span locations, aligned with the positions of piezoelectric sensors P02 and P09, respectively. In the second setup (Setup02), the two reference sensors (F01,ref and F03,ref) remain at the midspan locations, while the other two sensors (F02,setup2 and F04,setup1) are relocated to the third-span sections of the edge girder, in correspondence with piezoelectric sensors P05 and P12. To extract the global modal characteristics of the structure from the FBG-based measurements, the dynamic identification results from the two independent configurations are post-processed and merged, using sensors F01,ref and F03,ref as common reference points.

4. Results of the dynamic identification

This section presents the results of the dynamic identification conducted on the data registered by the monitoring systems introduced in Section 3. Data acquisition is performed over windows of variable duration, each one lasting no less than 1500 seconds (approximately 25 minutes). The sampling frequencies are set at 200 Hz for piezoelectric and MEMS sensors, and 1000 Hz for FBG sensors. Table 1 lists the Root Mean Square (RMS) values for the signals acquired by the different monitoring systems. These values refer to a common time window and represent the

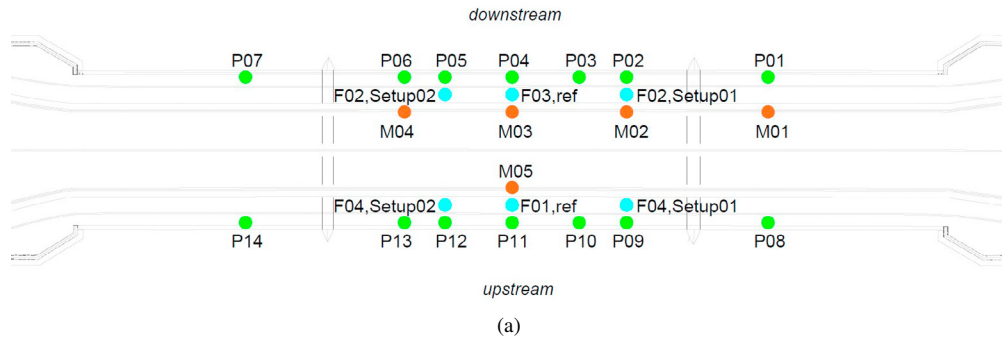


Fig. 3: Monitoring set-up - Piezoelectric (P01 to P14), MEMS (M01 to M05) and FBG (F01 to F04) sensors.

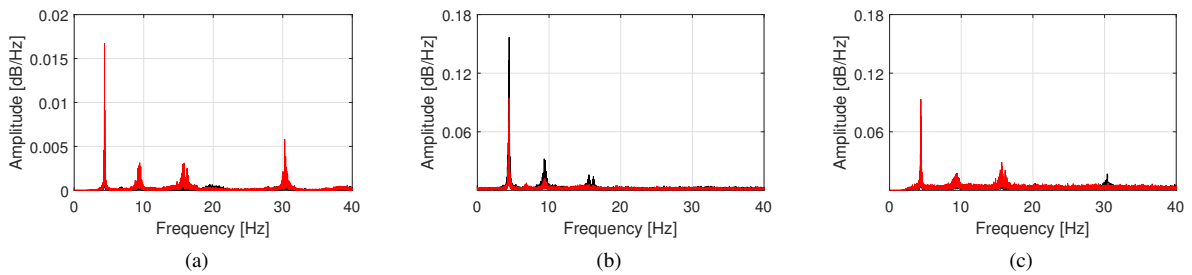


Fig. 4: Power Spectral Densities (PSDs) related to the midspan (black) and the quarter point (red) of the central span, close to the second pier: (a) Piezoelectric, (b) MEMS and (c) FBG sensors.

contribution of noise and environmental excitation. MEMS and FBG sensors present similar values, while the one of piezoelectric accelerometers is of a lower order of magnitude. Pre-processing steps of raw accelerations involved signal demeaning, followed by the application of a sixth-order Butterworth band-pass filter with cutoff frequencies between 0.5 Hz and 40 Hz. The Power Spectral Densities (PSDs) presented in Figure 4 focus on two locations where all sensor types are co-located: the midspan (black line) and the quarter point (red line) of the central span. The PSDs demonstrate a consistent identification of peak frequencies across the different sensor technologies. Nonetheless, the FBG accelerometer data exhibit a pronounced background noise level, which is likely attributable to ambient vibration power content or potential contamination in the sensor cabling connections.

Table 1: RMS acceleration values for different sensor technology.

Sensor Type	Piezoelectric	MEMS	FBG
RMS [mg]	0.08	0.44	0.37

The dynamic identification capability of the sensors is assessed using both frequency-domain and time-domain identification methods applied to the pre-processed data. The Enhanced Frequency Domain Decomposition (EFDD) method (Brincker et al. (2001)) and the Covariance driven Stochastic Subspace Identification (SSI-CoV) method (Peeters and De Roeck (2001)) are employed. The recently proposed Iterative Hierarchical Clustering algorithm (Romanazzi et al. (2023)) is exploited in order to provide a fully automated procedure capable of identifying and extracting modal properties from SSI-CoV analyses. For the sake of clarity, only the modes that are identified from all

the three monitoring systems are discussed here. Table 2 provides a comparison of the natural frequencies obtained from different monitoring systems, based on both the EFDD and SSI-CoV/IHCA methods. The modal frequencies of the identified modes are in the range 0-30 Hz, with four modes identified based on the accelerations acquired by the piezoelectric sensors and only three modes identified for MEMS and FBG sensors. Consistency among the identified modal frequencies for different sensor types and for different identification techniques is observed from Table 2. However, the second bending mode is not identified using MEMS and FBG sensors, probably due to the limited number of sensors installed and the higher noise level compared to that of the piezoelectric accelerometers. Considering the piezoelectric system as the reference, Table 3 highlights the relative difference among the the identified modal frequencies. The largest difference is obtained for the third mode (local bending) using the EFDD method with MEMS sensors, but it is fairly limited, namely lower than 3%.

Finally, Figure 5 illustrates the mode shapes for the piezoelectric and FBG sensors, identified for both sensors by means of the EFDD method. Modes identified by means of the SSI-CoV/IHCA method are not represented for the high similarity with those of Figure 5. With reference to piezoelectric sensors, the four identified modes are represented in Figures 5a-5d. The first mode at 4.37 Hz corresponds to the first global bending mode of the structure (Figure 5a); the second mode at 9.27 Hz is the first torsional mode (Figure 5b); the third one in Figure 5c involves local bending of the central span, while the fourth mode is a global second bending mode (Figure 5d). With regard to FBG sensors, some of the modes extracted from the combined datasets of SetUp01 and SetUp02 are presented. If a comparison with the previously illustrated modes is performed, there is consistency in terms of frequencies and mode shapes for the first (Figure 5e), the second (Figure 5f) and the third (not represented in the figure) identified modes. The correlation between the modes extracted using piezoelectric sensors and the modes extracted with MEMS and FBG sensors is quantified in Table 4. The largest MAC value is obtained for the first bending mode, as expected. Slightly lower MAC values are found for the other two modes, which are still greater than 0.80, confirming the consistency between the modes identified with different sensors.

Table 2: Comparative analysis of the identified modal frequencies obtained through different monitoring systems and dynamic identification methods.

Mode	Piezoelectric sensors		MEMS		FBG sensors	
	EFDD (Hz)	SSI-CoV/IHCA (Hz)	EFDD (Hz)	SSI-CoV/IHCA (Hz)	EFDD (Hz)	SSI-CoV/IHCA (Hz)
Bending (1st)	4.37	4.38	4.37	4.38	4.38	4.38
Torsional	9.27	9.29	9.35	9.33	9.31	9.32
Local bending	15.70	15.79	16.15	15.99	16.06	15.83
Bending (2nd)	30.27	30.27	–	–	–	–

Table 3: Relative difference of identified modal frequencies for MEMS and FBG sensors compared to piezoelectric accelerometers.

Mode	MEMS		FBG sensors	
	EFDD (%)	SSI-CoV/IHCA (%)	EFDD (%)	SSI-CoV/IHCA (%)
Bending (1st)	0.00	0.00	0.23	0.00
Torsional	0.86	0.43	0.43	0.32
Local bending	2.87	1.26	2.29	0.25

5. Conclusions

The paper presents the results of the dynamic identification of the "Ponte delle Grazie", a reinforced concrete Gerber-type bridge located in Northern Italy. The results refer to preliminary tests carried out with the aim of char-

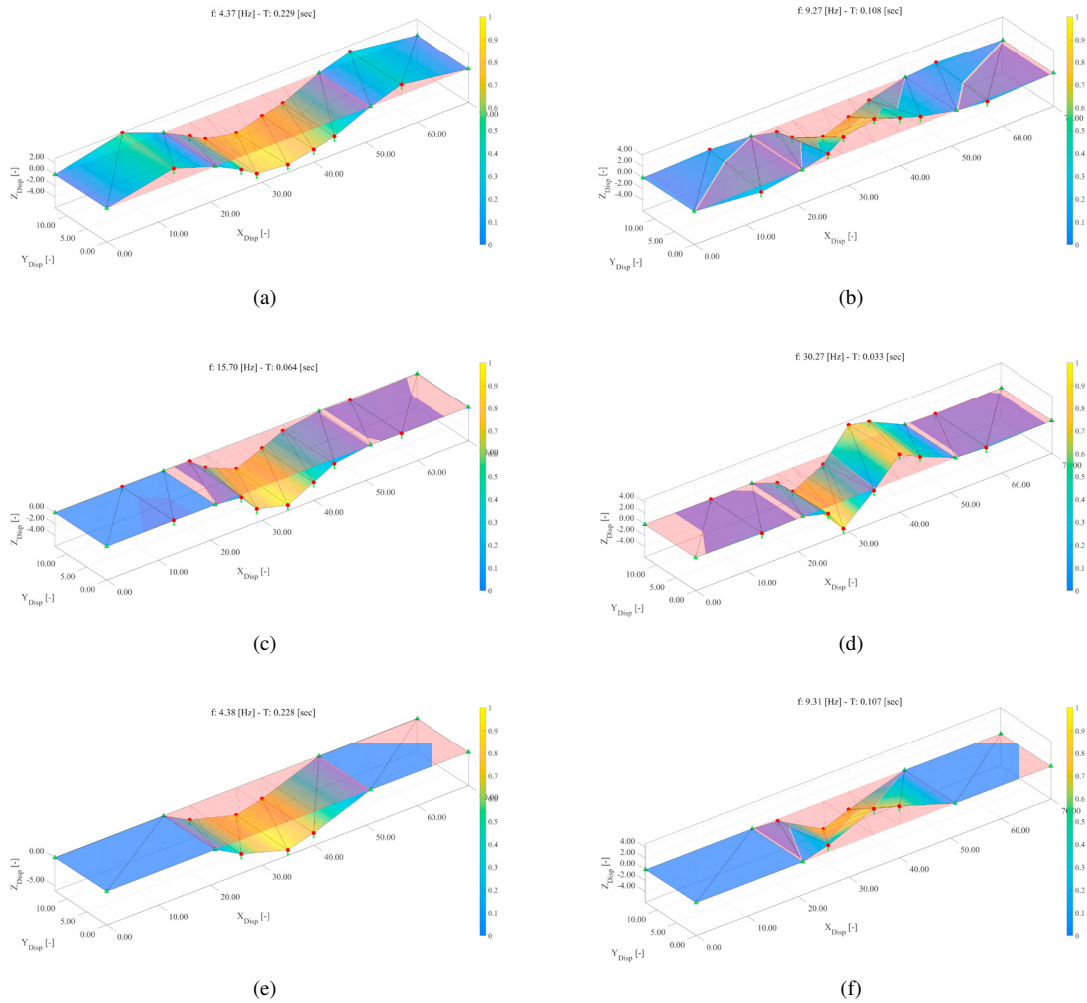


Fig. 5: EFDD mode shapes from pre-processed data: piezoelectric sensors (a-d) and FBG sensors (e-f).

Table 4: MAC values between the reference modes identified with the piezoelectric sensors and the modes identified with MEMS and FBG sensors.

Mode	MEMS		FBG sensors	
	EFDD (-)	SSI-CoV/IHCA (-)	EFDD (-)	SSI-CoV/IHCA (-)
Bending (1st)	0.96	0.95	0.97	0.97
Torsional	0.83	0.88	0.83	0.93
Local bending	0.84	0.91	0.82	0.87

acterizing the dynamic behavior of the bridge, which will be subjected to permanent monitoring. At the same time, the potentiality of a innovative sensing technology, Fiber Bragg Grating sensors, in the context of dynamic structural monitoring is assessed with the comparison with well-established technologies like piezoelectric and MEMS accelerometers. The tests were carried out under ambient vibration conditions and piezoelectric accelerometers ex-

hibited superior accuracy, as evidenced by the lower noise levels observed in the Power Spectral Density analysis. High sensitivity and low noise make them particularly suitable for accurate vibration measurements, although their higher cost and the need for careful installation may represent practical constraints. The MEMS system showed a good balance between cost, size, and sensitivity, delivering reliable performance with slightly higher noise levels compared to piezoelectric sensors. Additionally, MEMS can be integrated into continuous, permanent monitoring systems and allow for real-time processing of raw data, enhancing their suitability for long-term structural health monitoring applications. The PSD analysis also revealed a marked background noise in the recordings from the FBG accelerometers compared to the MEMS and piezoelectric sensors. This increased noise is likely attributable to operational challenges related to maintaining connector cleanliness in the FBG system, as even small dust particles can degrade signal quality and increase noise in dynamic recordings. Despite this, FBG sensors offer advantages such as immunity to electromagnetic interference and the capability for multiplexed distributed sensing, which are valuable in complex structural monitoring applications. Despite these differences, a coherent identification of natural frequencies and mode shapes was achieved across the different sensor types and characterization methods, demonstrating the overall reliability of all the technologies tested.

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