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DYNAMIC IDENTIFICATION AND DIGITAL TWIN DEVELOPMENT FOR A ROMAN MASONRY BRIDGE: A METHODOLOGICAL APPROACH

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Abstract

Structural analysis of ancient masonry bridges is one of the most challenging issues related to the conservation of cultural heritage. To preserve their historical value, it is necessary to develop innovative non-destructive testing methodologies that can assess the structural health state of these structures. This paper proposes an integrated dynamic identification procedure of a Roman masonry bridge, which is located near Ascoli Satriano (Italy), addressing the state of the art toward the Digital Twin framework. The experimental campaign, in which both OMA and EMA techniques were combined, has made it possible to identify the dynamic behavior of the bridge under both environmental and forced excitation. Testing was performed using a network of 24 properly located accelerometers to capture the global dynamic response of the structure. In order to allow for an accurate characterization of the modal parameters of the structure, environmental vibration measurements are complemented by impact hammer testing.

A preliminary finite element model (FEM) has also been prepared for the interpretation of the experimental results and to serve as a foundation for subsequent updating procedures. In particular, the research methodology will follow a progression through phases that go from basic dynamic identification to the application of more sophisticated digital monitoring approaches. The proposed approach aims to bridge the gap between traditional dynamic testing methods and modern digital twin applications in the context of historical structures. This paper presents the initial phase of this comprehensive study, which focuses on the following aspects.

Keywords: Masonry bridges, Operational Modal Analysis, Experimental Modal Analysis, Structural Health Monitoring, digital twin, cultural heritage preservation

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1 INTRODUCTION

The preservation of historic masonry bridges poses a significant challenge in the field of structural engineering and cultural heritage conservation. These structures, many dating back centuries, are subject to environmental degradation, material deterioration, and increased loads due to contemporary transportation demands. The development of sophisticated numerical models and digital tools has been instrumental in evaluating the structural behaviour and ensuring their long-term preservation [1].

The Digital Twin (DT) paradigm has recently attracted significant interest in the fields of architecture and civil engineering, particularly in the context of heritage conservation. A Digital Twin is not merely a digital replica of a physical structure; rather, it is an adaptive, data-driven model capable of simulating real-time conditions and predicting structural responses under various scenarios. When applied to historical masonry bridges, Digital Twins enable engineers to evaluate damage progression, predict failure mechanisms, and optimise maintenance strategies through continuous updates based on experimental data and in-situ measurements [2]. Several studies have explored the integration of Heritage Building Information Modelling (HBIM) and Digital Twins for built heritage, emphasizing their potential in structural integrity assessment, damage detection, and conservation planning. Recent research demonstrates the effectiveness of Operational Modal Analysis (OMA) and Experimental Modal Analysis (EMA) in identifying the dynamic properties of masonry structures and refining numerical models for more accurate predictions [3]. The use of finite element modelling (FEM), coupled with modal updating techniques, is particularly relevant in historic structures where non-destructive testing is preferred over intrusive methods [4].

Additional studies have emphasized the role of 3D scanning and laser scanning technologies in accurately reconstructing and updating digital models of heritage structures, allowing for a more refined and realistic representation[5]. Furthermore, the automation of heritage conservation through machine learning and IoT-based monitoring systems has been proposed as a means to improve real-time structural assessment and damage detection, ensuring the predictive capability of Digital Twins [6]. Advances in Virtual and Augmented Reality (VR/AR) have also contributed to enhancing the accessibility and interpretability of Digital Twin models for heritage structures, providing innovative visualization and interaction tools [7,8].

This study proposes a methodological approach for the dynamic identification and Digital Twin development of the Roman masonry bridge in Ascoli Satriano, Italy. In this proposal, OMA and EMA techniques are combined with FE models to create and adapting model that accurately represents the bridge current condition and can predict its future behaviour. The proposed framework consists of the following elements:

1. Comprehensive dynamic characterization through a carefully designed experimental campaign that combines ambient vibration measurements (OMA) and targeted forced excitation tests to fully capture the bridge's modal parameters.
2. Development of a FE model based on geometric surveys and material characterisation, with initial parameters informed by engineering literature and historical documentation.
3. Implementation of an iterative model calibration and validation process where experimental data continuously refines the numerical model, gradually transforming it into a responsive Digital Twin capable of simulating the bridge behavior under various environmental and loading conditions.

The methodology presented in this paper aims to provide a robust strategy for the assessment and monitoring of historic masonry bridges, ensuring their preservation while leveraging modern digital tools for structural analysis and predictive maintenance. The results of this study contribute to the ongoing discussion on Digital Twin applications in heritage conservation and their potential to enhance the sustainability and resilience of historic infrastructures [9].

2 DYNAMIC IDENTIFICATION OF MASONRY BRIDGES

2.1 Operational Modal Analysis

Operational Modal Analysis (OMA) represents an effective non-destructive technique for the dynamic characterization of civil engineering structures, particularly valuable for cultural heritage applications where preserving structural integrity is mandatory [10]. This methodology extracts modal parameters, i.e. natural frequencies, damping ratios, and mode shapes, from vibration measurements obtained while the structure operates under ambient environmental conditions such as wind, traffic, or pedestrian loading [11]. In OMA technique ambient excitations can be characterized as stochastic white noise processes, providing broadband excitation that activates multiple vibration modes simultaneously [12,13].

Several advanced signal processing techniques have been developed for OMA implementation, with the most applied methods falling into two main categories: frequency-domain approaches such as Frequency Domain Decomposition (FDD) and Enhanced Frequency Domain Decomposition (EFDD) [14], and time-domain methods including Stochastic Subspace Identification (SSI-UPC and SSI-CVA) [15].

The application of OMA to masonry bridges presents specific challenges due to their inherent characteristics: high stiffness, complex geometrical configurations, and non-linear material behavior [16–18]. These properties often result in closely spaced modes, limited ambient excitation of higher modes, and significant damping effects. To overcome these limitations in the context of Digital Twin development, OMA can be effectively complemented with targeted forced excitation tests that activate specific modes of interest while maintaining minimal impact on the structure [19].

For data acquisition in OMA applications, accelerometers are typically deployed at strategic locations to capture the global dynamic response of the structure [20]. The design of an optimal sensor layout represents a critical aspect of the methodology, requiring careful consideration of the expected mode shapes, structural features, and practical installation constraints [21–23].

The integration of OMA within a Digital Twin development process provides several advantages: it establishes a baseline for the structure's dynamic behavior, supplies essential calibration data for numerical models, and enables long-term tracking of structural changes through periodic or continuous monitoring campaigns [3,24].

The preliminary phase of this study consists of conducting an initial experimental analysis by measuring the oscillations of the structure under ambient conditions (Operational Modal Analysis) using accelerometers mounted on the bridge surface.

The data obtained are then processed with modern techniques for frequency and mode identification, such as SSI-UPCX or CFDD, implemented in the Artemis software. However, given the particularly stubby structure of the bridge, striking the center of the bridge with an instrumented hammer to excite the structure in case ambient vibrations did not allow for an experimental identification of its natural frequencies and modes.

3 CASE STUDY: ASCOLI SATRIANO ROMAN BRIDGE

3.1 The Roman Bridge

The case study focuses on the Roman bridge of Ascoli Satriano, a three-span masonry structure that crosses the Carapelle stream (Figure 1). The bridge, which dates back to the Trajan era (98–117 AD), was part of the ancient road network that connected Ausculum to Apulum. Its total length is estimated to be approximately 41.00 meters, with a width of 5.20 meters.
The bridge features a three-span masonry structure characterized by robust semicircular arches supported by massive piers. The construction technique employs precisely cut stone blocks arranged in regular courses. Despite numerous modifications and restoration interventions throughout its two millennia of existence, the bridge retains significant portions of its original fabric, making it an invaluable subject for historic preservation studies.

Figure 1: Bridge view

3.2 Experimental campaign

The dynamic testing campaign was developed following a sequential approach designed to support iterative Digital Twin development. The work was conducted in two distinct chronological phases. In the first phase, Operational Modal Analysis (OMA) was performed under ambient conditions to establish the bridge baseline dynamic properties. These measurements enabled the initial characterization of natural frequencies and mode shapes. Based on these results, a FE model was developed and calibrated, adjusting material properties and boundary conditions until achieving satisfactory correspondence between experimental and numerical modal parameters. The second phase was conducted after model calibration and focused on validation. A specific excitation scenario was first simulated on the numerical model, then replicated on the physical bridge using an instrumented impact hammer. The comparison between predicted and measured responses revealed discrepancies that are currently being used to refine the mechanical characteristics of the Digital Twin, accounting for structural changes that might have occurred between experimental phases.
The monitoring program focused on key structural locations, including the vaults keystone and skewbacks, where accelerometers were strategically positioned to capture structural vibrations (see Figure 2).

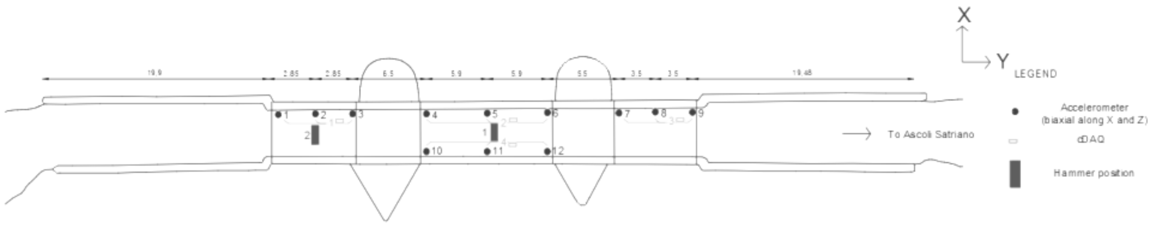

Figure 2: Set-up of the bridge sensor placement

A total of 23 accelerometers were installed across 12 locations on the bridge. One of these points was equipped with a uniaxial accelerometer (measuring only in the z-direction), while the remaining 11 locations used biaxial accelerometers (measuring in both the z and y directions). The acquisition system for both phases consisted of:

- PCB 393831 accelerometers
- RG58 coaxial cables (50 Ω impedance)
- NI-9230 data acquisition unit
- Four cDAQ-9178 data acquisition modules
- PCB-086D50 impact hammer with integrated ICP® power sensor (only for the second phase)

The measurements were sampled at 1024 Hz, ensuring high-resolution data for subsequent analysis.

The acquired data were analyzed using advanced signal processing techniques, including Time History analysis to quantify vibration amplitudes and Stochastic Subspace Identification (SSI-UPCX) to accurately determine mode shapes. The resulting dataset serves as a crucial reference for calibrating the FEM and validating the Digital Twin framework.

The analysis of experimental data identified primary modal frequencies within the range of 4.15–7.11 Hz, with dominant translational and vertical mode shapes influencing the overall structural response. These findings will be used in the next phase to iteratively refine the numerical model and improve its predictive accuracy.

This methodological approach not only offers valuable insights into the assessment and conservation of historic masonry bridges but also facilitates the continuous enhancement of the Digital Twin, enabling increasingly realistic and precise structural identification, so an accurate representation of the structure dynamic behavior.

4 EXPERIMENTAL RESULTS

The Artemis model used for experimental data processing is shown in Figure 3, where are also explicitly indicated, with arrows, the positions and directions of the monoaxial accelerometers used. The data processing was carried out using very narrow digital filters to identify a significant number of frequencies. Figure 4 shows an example of the identification diagram obtained for the first test under ambient conditions, while Table 1 provides a summary of the frequencies obtained from all tests, including those conducted under ambient conditions (tests 1 to 6) and those in which the bridge was subjected to a series of hammer impacts (tests 7 and 8).

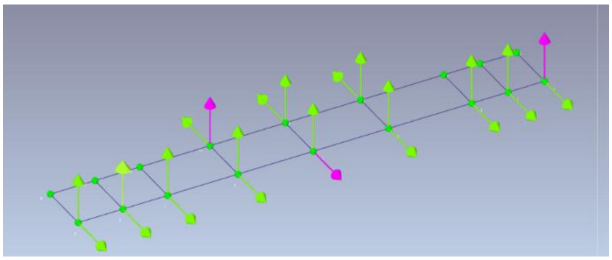

Figure 3: Artemis model used for all experimental data processing

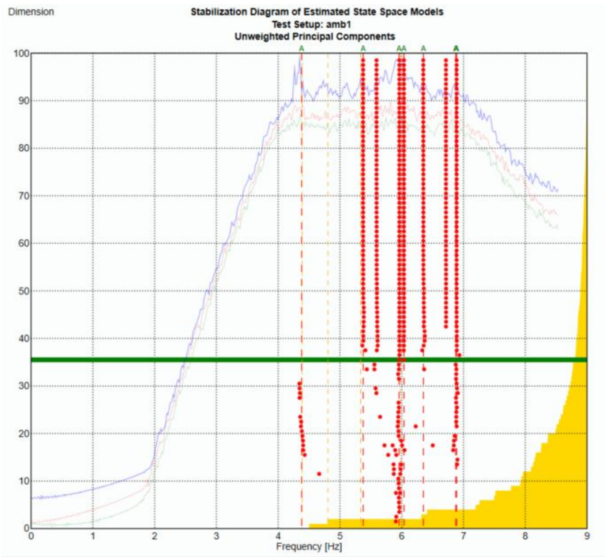

Figure 4: Identification results (in Hz) for Test n.1 by using SSI-UPC method

Test number	1st fr.	2nd fr.	3rd fr.	4th fr.	5th fr.	6th fr.
1	4.38	5.37	5.96	6.04	6.35	6.89
2	4.36	-	5.93	6.02	6.37	6.87
3	4.39	-	5.93	-	-	6.85
4	4.55	-	-	-	6.22	6.73
5	4.69	5.28	5.95	-	6.29	6.83
6	-	-	-	5.97	-	-
7	4.15	5.41	5.59	-	6.19	7.11
8	4.23	-	5.93	-	6.29	6.92
Avg.	4.39	5.35	5.88	6.01	6.28	6.88

Table 1: Identification results for experimental data

5 NUMERICAL MODELLING AND DIGITAL TWIN DEVELOPMENT

The Digital Twin framework developed for this research comprises four interconnected components:

- Physical Asset Layer: The actual Roman bridge and its embedded sensor network for continuous monitoring.
- Data Acquisition Layer: Hardware and software systems for collecting, transmitting, and storing monitoring data.

- Numerical Representation Layer: Finite element model that simulates the structural behavior.
- Integration Layer: Algorithms for data processing, model updating, and simulation control.

This integrated approach establishes bidirectional information flow between the physical structure and its digital counterpart, allowing for continuous model updating based on real-time or periodic measurements.

5.1 Preliminary Finite Element Model

The numerical simulation of the Ascoli Satriano Roman bridge was developed with the Abaqus software for the purpose of realizing an experimentally calibrated Digital Twin. The geometry of the model was defined on the basis of direct surveys and pre-existing documentation, faithfully replicating the current structure.

The bridge has a multi-span structure of arches and main span, the cross-section being defined by an upper slab. Modelling was undertaken using masonry material with elastic-linear behavior, as a basis for future upgrading using non-linear effects. The mechanical properties used are shown in Table 2 and are within the average values of the standards and scientific literature for each material as given in the same table. The reproduction of vault and abutment members was advanced, featuring a realistic representation of stiffnesses distribution.

Materials	Density [kN/m^3]	Elastic Modulus [MPa]	Poisson Coefficient [-]
Masonry [25]	21	1500	0.20
Earth filling [26,27]	22	2000	0.30
Asphalt slab [28]	21	3500	0.25

Table 2: Mechanical Properties of Numerical Model.

The boundary conditions were specified with respect to in-situ support conditions. In order to model the actual static response of the bridge, fixed restraints were applied at the bottom of the abutment to model the effect of foundations, as shown in Figure 5. Lower degrees of freedom along the span supports were also applied to model the eventual contact with the ground and surrounding materials.

Figure 5: Numerical model and boundary condition.

In order to achieve a high degree of accuracy in the simulation of the dynamic responses, a structured mesh discretization was carried out.

The 8-node solid elements (C3D8) provide a good representation of internal stresses, with local refinement in the areas of greatest dynamic interest, such as the interfaces between arches and piers. The mesh density was optimized to balance solution accuracy with computational efficiency, resulting in approximately 42,304 elements and 54,455 nodes. The modal analysis conducted enabled the identification of the main vibration modes of the bridge.

The numerical model will serve as the basis for the subsequent calibration and validation phases, with the ultimate goal of developing a Digital Twin capable of adapting to external actions and supporting long-term structural monitoring.

5.2 Calibration Process

The calibration of the numerical model bridged the gap between the preliminary model and the experimentally identified dynamic properties through systematic refinement of key parameters. The elastic modulus of masonry and the stiffness of boundary conditions were identified as the primary variables affecting the dynamic response of the structure. These parameters were iteratively adjusted to minimize discrepancies between numerical and experimental modal parameters, focusing particularly on matching the natural frequencies identified during the OMA tests. Frequency deviation analysis served as the primary calibration metric, with particular emphasis on the first three modes identified experimentally. This iterative calibration process resulted in refined material properties and boundary conditions that significantly improved the correlation between the model and measured data.
Figures 6.a, 6.b, and 6.c illustrate the first three modal shapes obtained from the calibrated model.

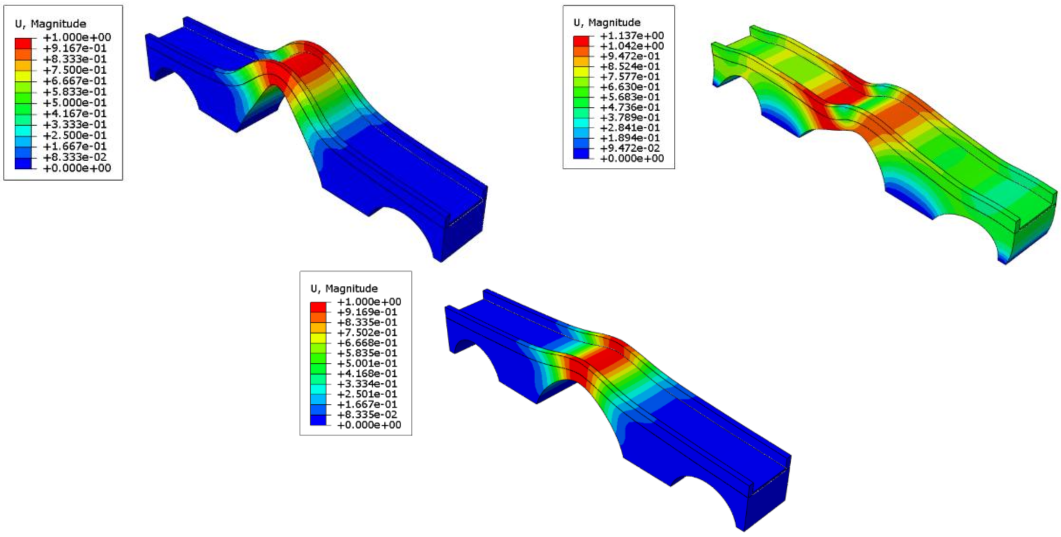

Figure 6: a, b and c, the first three Modal Shapes obtained.

The first mode, occurring at 4.65 Hz, exhibits a global vertical oscillation of the structure. Higher modes demonstrate more complex deformation patterns involving individual spans and local torsional effects, with frequencies ranging between 5 and 15 Hz. The calibrated model achieved a maximum frequency deviation of less than 5% for the primary modes when compared with OMA results, demonstrating good agreement with the experimental dynamic identification, as shown in Table 3.

Numerical Frequencies [Hz]	Average OMA Frequencies [Hz]
4.65	4.39
5.97	5.88
6.38	6.28

Table 3: Comparison between numerical and average experimental frequencies.

5.3 Digital Twin Development

The transition from a calibrated finite element model to a functional Digital Twin required implementation of a validation process that evaluated the model's predictive capability under controlled conditions. Following the model calibration based on OMA data, a specific excitation scenario was simulated by applying an impulse to a predefined location on the numerical model, as shown in Figure 7. This simulated impact was designed to approximate the force characteristics of the instrumented hammer with integrated ICP® power sensor, enabling direct comparison with subsequent physical testing.

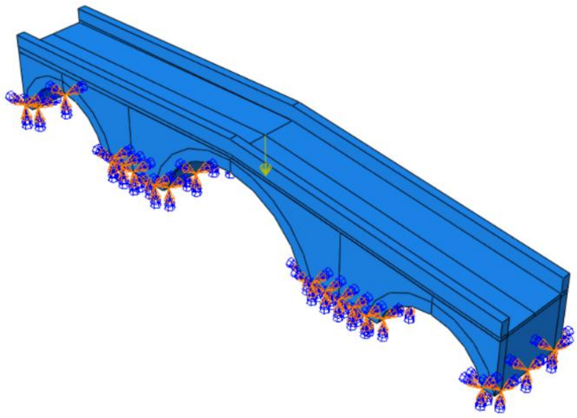

Figure 7: Position of the simulated impulse for the calibrated numerical model.

The structural response to this simulated excitation was analyzed in both time and frequency domains, extracting the modal parameters activated by the impulse. The numerical results revealed distinctive resonant frequencies of 6.25 Hz, 7.42 Hz, and 8.98 Hz for the first three primary modes under this specific excitation scenario.

To validate these predictions, the same excitation pattern was physically reproduced on the actual bridge using an instrumented impact hammer at the corresponding location. Figure 8 shows the measured accelerogram and FFT spectrum obtained during this experimental validation. The Experimental Modal Analysis (EMA) conducted on the physical bridge yielded frequency values of approximately 4.75 Hz, 5.24 Hz, and 6.24 Hz for the first three modes – results that aligned closely with the original OMA measurements but revealed a significant discrepancy when compared with the numerical predictions.

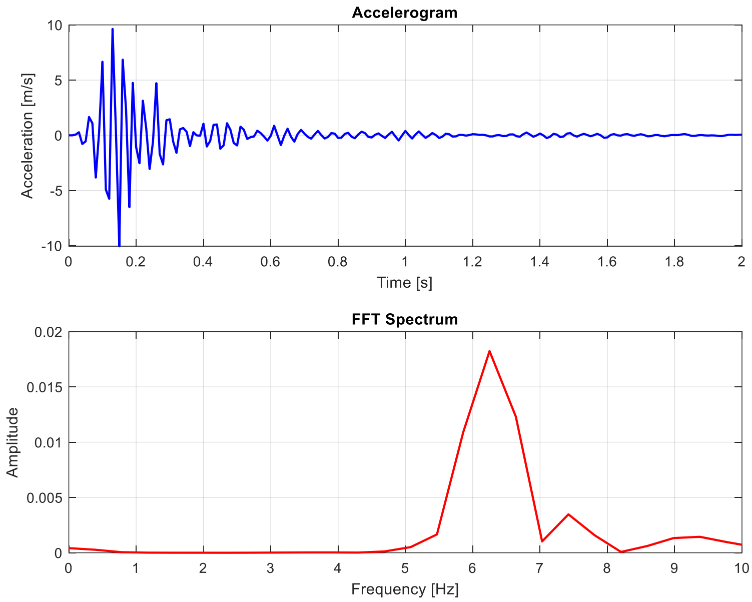

Figure 8: a. Accelerogram and FFT Spectrum of forced numerical test with the hammer.

This frequency shift of approximately 2 Hz observed between the experimental measurements and numerical simulations represents a critical finding for the Digital Twin development process. While the model had been successfully calibrated to match the ambient vibration characteristics, its response to impulsive loading exhibited notable differences from the physical structure behavior. This discrepancy suggests the presence of non-linear dynamic properties or boundary condition effects that were not fully captured in the initial model formulation.

These findings are currently informing further refinements of the Digital Twin, with particular attention to implementing more sophisticated material models that can account for the strain-dependent behavior of historical masonry and the complex soil-structure interaction at the foundations. The observed frequency shift provides valuable insights into the bridge actual dynamic response characteristics under different loading conditions, enhancing understanding of its structural behavior beyond what could be determined from ambient measurements alone.

Through this iterative process of simulation, physical testing, and model refinement, the Digital Twin continues to evolve toward a more accurate representation of the bridge complex dynamic behavior. This progressive enhancement of the model fidelity represents the essence of the Digital Twin concept, a living digital counterpart that continuously learns from measurement data to improve its predictive capabilities.

6 CONCLUSIONS

This paper has presented a methodological approach for the dynamic identification and Digital Twin development of a Roman masonry bridge. The integration of experimental modal analysis with advanced numerical modeling has provided valuable insights into the structural behavior of this significant cultural heritage asset. The main findings of this study can be summarized as follows:

- The combination of Operational Modal Analysis (OMA) and targeted forced excitation testing proved effective for characterizing the dynamic properties of the masonry bridge, identifying primary modal frequencies in the range of 4.15-7.11 Hz.

- The calibrated Finite Element Model successfully reproduced the dynamic behavior observed under ambient conditions, achieving close correlation with experimentally identified modal frequencies and shapes.
- A significant frequency shift of approximately 2 Hz was observed between the experimental measurements (4.75 Hz, 5.24 Hz, 6.24 Hz) and numerical simulations under impulse loading (6.25 Hz, 7.42 Hz, 8.98 Hz), revealing complex dynamic behavior not fully captured in the initial model formulation.

The ongoing development of this Digital Twin will focus on implementing more sophisticated material models to account for the non-linear behavior of historical masonry and refining the representation of soil-structure interaction effects. Future research will also explore the integration of continuous monitoring systems for real-time model updating and the development of damage detection algorithms based on modal parameter evolution.

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