

The Roman Bridge on the Savuto River: understanding its dynamical structural behavior through the adaptive DFEM method

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Abstract – The valorization of heritage structures requires a multidisciplinary approach based on effective models, seen as epistemic tools that empower both scientists and heritage managers in understanding, contextualizing and interpreting the value of the historical structure as a characteristic element of local identity (*genius loci*). This vision goes well beyond classic structural behavior and health assessment, since it implies a different approach and the application of metrological knowledge in models’ development. This is the case of our innovative hybrid approach, the Dynamic Finite Element Modeling (DFEM) metrological procedure, consisting in the evolutive optimization of a classic Finite Element Model tailored on the measurements of a high-quality monitoring system. The application of this procedure to the Roman bridge on the Savuto River (Altilia-Scigliano municipalities, Calabria Region, Italy) shows its remarkable power not only in simulating the dynamic behavior of the bridge, but also in providing useful hints on the construction techniques.

I. INTRODUCTION

The valorisation of heritage structures requires the implementation of procedures that go beyond classic structural behavior and health assessment, allowing them to provide solutions to understand and to preserve structures of historical relevance.

With this respect, digital technologies have significantly helped the scientific progress, especially in the preservation and management of cultural heritage assets [1,2]. Heritage curation platforms enhance accessibility and sustainability, while digitization aids in protecting both tangible and intangible assets. However, the general finalization in the use of these platforms is their end-use as database for managers to reduce their potential risks. On the other hand, a sort of fascination for digital model and AI-based solutions risk reducing the investments in preserving and implementing the systems for collecting experimental data, which are necessary to validate digital

models to avoid the application of unrealistic results to the preservation of heritage structures.

An obvious solution, coherent with the evolution of the understanding of cultural heritage, that now integrates different tangible and intangible elements into a synergic multi-disciplinary and multi-perspective view, is to change the mindset for the management and valorization of heritage assets. This implies a different approach and application of metrological knowledge. In fact, models should become epistemic tools, that empower both scientists and heritage managers in understanding, contextualizing and interpreting the value of the studied structure of historical relevance in relation to the communities who built it, to its evolution over time and to the place where the structure is located, becoming a characteristic element of local identity (*genius loci*) within a landscape.

The development and validation of metrological physics models aiming at synergically assessing both structural health and functional implications of historical structures, may be an interesting solution along with the modern approach to tangible and intangible heritage, overcoming the present static and technically limited approaches adopted by professionals and managers for heritage assets preservation.

The most critical part of this methodology is the need to develop adaptive numerical models of a heritage asset, generally FEM (Finite Element Models), capable of adapting to its structural dynamics through a continuous process of minimization of the differences between numerical predictions and experimental data, to become a faithful model also capable of following its dynamic evolution over time.

This process requires two other important components, too often considered separately and inadequately [3]. The first one is a suitable data “provider”, a modular distributed data acquisition system capable to adapt its sensors number, typology, position, sensitivity and band to the heritage asset. The second one is the introduction of a suitable optimization procedure, that, step-by-step,

provides all the information to adapt both the numerical model and the monitoring system in a synergic way.

To overcome this problem, we introduced the Dynamic Finite Element Model (DFEM), a mutual optimization procedure to develop and validate models of structural dynamics of ancient heritage structures, integration of advanced computational models and high-sensitivity broadband distributed monitoring systems, which can evolve by dynamically adaptation to the ancient heritage structures [4].

This procedure is based on a mutual optimization process, that minimizes the point differences between the theoretical predictions of the FEM models (virtual sensors) and the experimental measurements obtained with advanced measurement systems (real sensors), allowing in a direct way also the identification of the number of degrees of freedom necessary for the description of the system, that are minimum number of independent sensors (degrees of freedom) necessary for predictions and measurements of its structural dynamics.

This new approach has been applied to the ancient Roman bridge over the Savuto River, also known as the Hannibal or Sant'Angelo bridge, built in the 2nd century BC along the Roman via Popilia. For the first time measurements of linear and angular displacements have been obtained, including day-night cyclic deformations, allowing not only the determination of the number of degrees of freedom, necessary for the development of the simulation model, but also for highlighting the need for conservative actions of the bridge, as well as further archaeological excavations for better understanding the real structure of the bridge, including the not visible part.

II. THE ROMAN BRIDGE ON THE SAVUTO RIVER

The Roman bridge over the Savuto River in Calabria (Fig. 1), built in the 2nd century BC, is the oldest Roman bridge in the world (Fig. 1). It lies on the ancient via Popilia, which connected Capua (Campania Region) to Reggio Calabria (Calabria Region), covering a route of 517 km along the Tyrrhenian coast [5]. The road passed through the municipality of Vibo Valentia (ancient Hipponion), the Savuto valley, and other significant locations before joining the Appian Way, which led to Rome. Nearby, on the Scigliano municipality side, stands a ruined farmhouse with Roman foundations and a small church, Sant'Angelo.

The bridge consists of two concentric round arches of dry tuff blocks. The inner arch serves as the primary support, while the outer acts as a counterweight. The arch spans 21.5 meters, with a width of 3.55 meters and a height of 11 meters above the river. The 48-meter-long walking surface includes a Roman ramp on the Scigliano side and a longer slope leading to Altilia. The exact structure of the Altilia ramp remains unclear: it may contain an arch that was closed off over time, supported by buttresses for stability.

Previous archaeological reports hypothesized the existence of internal space within this ramp for troop shelter, though this fact remains unconfirmed [6]. The results of 1961 archaeological survey suggested also that the bridge foundation lies about 1.5 meters below the riverbed, built on a platform of squared, overlapping blocks approximately 5 meters wide and 1.5 meters high.



Fig. 1 Picture of the Roman bridge on the Savuto river along the Roman road known as via Popilia taken from a drone.

The primary construction material of the bridge is red limestone, sourced from a quarry near Altilia municipality, with the arch made of dry calcarenite using precisely squared stones. This choice has provided the structure enduring stability and resistance to weathering. It is believed that these stones were transported down the valley for construction or lime production in a nearby kiln.

III. THE MONITORING SYSEM

As discussed above, the implementation of the procedure for the development of a digital model (DFEM) capable of describing the dynamics of the bridge does not involve primarily the FEM numerical model, since many effective software exists capable of providing such an efficient description. The critical point remains the monitoring system, that must be distributed and provided with sensors characterized by enough sensitivity and band to provide useful data and by the optimization procedure chosen for the implementation of the iterative process leading to the final configuration of the DFEM numerical model [3,7].

A. The Distributed Modular Monitoring System

The monitoring system constitutes the evolution of a previous monitoring solution, which was applied, for the first time, for the monitoring of Trajan arch in Benevento (Italy) [8]. The same type of system was successfully installed and still operates as a permanent monitoring solution on the Neptune (Hera II) temple in Paestum

(Salerno, Italy) [9]. However, non-permanent systems of the same type were also installed to characterize vibroacoustic behavior of chamber music room [10], as well as of historic worship spaces, like the Basilica of Santa Maria di Monserrato (Vallelonga municipality, Italy). Finally, portable versions of the same system, as variants of the standalone solution described in a previous literature work [11] were used to monitor the late medieval cave church of San Michele di Mezzo (Fisciano, Italy) the Longobard bell tower of San Pietro a Corte (Salerno, Italy) and the bell tower of the Salerno Cathedral.

For this specific application, the distributed monitoring system was implemented in a very simplified way since only vibration sensors are necessary for providing the data for this DFEM procedure. In fact, based on the operational and administrative constraints, the monitoring solution assembled for the Roman bridge was limited to a maximum of 16 structural degrees of freedom (pairs of dominant poles, 8 linear and 8 angular). The general simplified architecture of the distributed monitoring system is instead shown in Fig. 2.

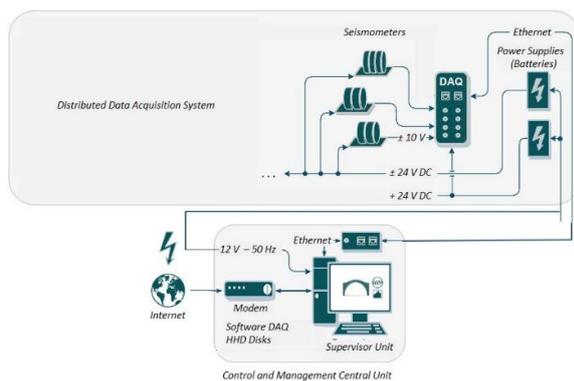


Fig.2 Schematic structure of the configuration of the distributed monitoring system used for monitoring the Roman bridge over the Savuto river.

The monitoring system modularity is mainly due to the standard Ethernet network architecture to connect the 24-bit data acquisition (DAQ) local stations, configured according to standard or hybrid daisy-chain and star links. Each local station, model FD-11603 of the National Instruments™ FieldDAQ class, allows the acquisition of a maximum of eight 24-bit channels, with a sampling frequency of the order of 100 kHz. The data acquisition system is managed through a dedicated graphical interface (Supervisor), developed by Adv3S™, running on a workstation with a Windows 11 operating system. The Supervisor manages the DAQ remote configuration, synchronization, data acquisition operations, as well as real-time data presentation and control. The whole monitoring system is battery powered to minimize electromagnetic noise. The characteristics of this DAQ station are shown in Table 1.

Table 1. Main Characteristics of the DAQ unit, Model FD-11603 from National Instruments™

Channel Number	8 channels – analogic input
ADC type	24 bits – Delta Sigma
Input Voltage Range	± 10.5 V
Maximum Sampling Rate	102.4 kSamples/s
Sampling Typology	Simultaneous
Accuracy	± 30 ppm max

For this application, we chose the model SE-10HL Monolithic Mechanical Seismometers (Fig. 3). This instrument is a real horizontal seismometer (no force feedback control), manufactured by Advanced Scientific Sensors and Systems (Adv3S™). The main technical characteristics of the SE-10HL seismometer are reported in Table 2.



Fig. 3. Model SE-10HL mechanical seismometer produced by Advanced Scientific Sensors and Systems (Adv3S™).

Table 2. Main features of the SE-10HL model seismometer, produced by Adv3S™

Architecture	Model SE-10HL – class EB-100 Monolithic Folded Pendulum (Pat.)
Configuration	Seismometer (without feedback)
Natural Frequency	3.80 Hz ± 10%
Readout	LVDT
Band	DC – 100 Hz
Sensitivity	72 V/mm ± 10%
Spectral Sensitivity	< 10 ⁻⁸ m/√Hz (3.5 Hz < f < 100 Hz)
Output Signal (dual)	± 10 V (range)

IV. EXPERIMENTAL RESULTS

The sensors were positioned on the bridge roadway. To guarantee their stability, they were placed on stone elements to couple firmly the sensors to the bridge. This technique, previously applied for the permanent distributed monitoring system of the Neptune (Hera II)

temple in the National Archaeological Park of Paestum and Velia (Capaccio Municipality, Salerno, Italy), guarantees an effective measurements and full respect of the historic asset, since no invasive anchoring means were used. Fig. 4 and Fig. 5 show the positions of some of the sensors in one of the measurement tests performed during the DFEM optimization process.

The mutual optimization procedure was repeated until the FEM modal analysis data and the spectral analysis of the seismometers led to the best possible match, considering the administrative and technical constraints and restrictions related to the protection of the heritage asset.



Fig. 4. Couple of mechanical seismometers positioned on the roadway of the Roman bridge.



Fig. 5. Detail of installed seismometers. The stone elements on which the sensors were positioned, acting as support base, guarantee a perfect sensors' stability and the quality of the measurements.

Despite the limited number of optimization steps, the obtained results already prove the effectiveness of a metrological procedure in providing results that can go beyond a technical assessment of the structural health of

the asset under study. In fact, the measures revealed very low stable peak frequencies, that, being dependent on the mass of the bridge, suggest the presence of mass beyond the visible structure. In fact, the structure might include a basement under the river, in the form of a platform that connects the two main pillars of the bridge. This sort of basement provides also a possible relevant justification for the fact that, after more than two millennia, the bridge is still perfectly intact and utilizable.

The DFEM metrological procedure, in this case, is used as an epistemic tool to formulate a new hypothesis on the ancient construction techniques and practical solutions adopted by Romans on the basis of their experience and knowledge of natural phenomena, as well as of the specific site where the bridge is found. Consequently, the metrological procedure can be used as an epistemic tool to derive some knowledge on the intangible dimension of this heritage asset (i.e.: the know-how and techniques used to build a bridge). Obviously, this hypothesis must always be validated or simply re-formulated, based on archaeological and historical evidence, to provide a solid foundation for future research.

Nonetheless, the diagnostic potential of this metrological procedure is not lost. In fact, another piece of information obtained during the application of DFEM to the Roman bridge on the Savuto river is that the South pillar of the bridge exhibits an anomalous rotational motion, always in counterphase with respect to all the other parts of the bridge.



Fig.6. Directions of the angular displacement at sunrise and at the sunset as measured by the transverse sensors positioned in three critical points of the bridge roadway; a) sunrise (left); b) sunset (right).

This motion anomaly is probably due to the restoration, done in 1960, that, blocking the North side of the bridge with two buttresses, does not allow it to adapt its periodic deformations in relation to the internal variations of temperature dependent on the solar radiation direction, due to the different positions assumed by the Sun during the day (Fig. 6).

Table 3 reports the result of the modal analysis, obtained through the FEM after the mutual optimization process. The seven frequency peaks identified through the computation process were compared, then, with the frequency spectrum obtained by analyzing the data collected through the sensors installed on the bridge. The

relative frequency deviation, in terms of percentage, was also reported in the table.

Table 3. Theoretical (FEM) and experimental (spectral analysis for all sensors) modal frequencies after the mutual optimization process. The relative (percentage) deviations in frequency between theoretical and experimental values is reported in the right-side column.

Computed Frequency [Hz]	Experimental Frequency [Hz]	Relative Frequency Deviation [%]
2.54	2.56	0.79
4.57	4.45	-2.63
9.87	9.85	-0.20
13.39	13.93	4.03
17.24	16.59	-3.77
21.74	23.96	10,21
38.46	38.07	1.01

Finally, just as matter of study, it is relevant to note that, thanks to the high sensitivity of the seismometers, it is possible to determine the number of degrees of freedom necessary to build a reliable model of the structure, that can be evaluated on the basis of the number of peaks present in the spectral density graph of the signal measured by the sensor.

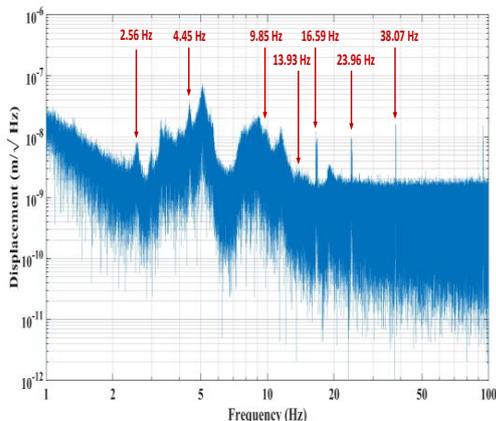


Fig.7. Structural modal frequencies (red arrows) identified from the comparison of FEM theoretical frequencies and the experimental measures on the bridge after the mutual optimization along the DFEM procedure. The comparison allows to disentangle the expected structural dynamics from the dynamics depending on the environmental excitation, as well as from any structural variable perturbation derived from the potential presence of structural damages.

Fig. 7 indicates the measured structural modal frequencies, identified from the comparison of FEM theoretical frequencies and the experimental measures on the bridge after the mutual optimization step of the DFEM

procedure. The higher number of peaks obtained during the measurements with respect to the number (degrees of freedom) of sensors used for this preliminary set of measurements indicates that the bridge structure is more complex than the visible part. Consequently, more sensors are necessary for a complete adaptation of the FEM representing the Roman bridge to the experimental reality observed through the monitoring system.

V. CONCLUSIONS

We have introduced the Dynamic Finite Element Model (DFEM) mutual optimization procedure, a very effective innovative procedure, not only to develop and validate models of structural dynamics for ancient heritage structures, based on the integration of advanced computational models and high-sensitivity broadband distributed monitoring systems, but also as a metrological basis to implement new archaeological and historical hypotheses, related to the intangible dimensions of the studied heritage asset, such as the characterization of undocumented building techniques and solutions.

This new methodology has been applied to the ancient Roman bridge over the Savuto River, also known as the Hannibal or Sant'Angelo bridge, built in the 2nd century BC along the Roman via Popilia, allowing for the first time both measurements of linear and angular displacements, including day-night cyclic deformations, and the determination of the number of degrees of freedom useful for the definition of the simulation model. The results highlight the capability of identifying structural dynamic anomalies, that can evidence the need for conservative actions on the bridge. They also highlight the possibility of using this type of metrological approach as an epistemic tool through which new research hypotheses can be expressed, as in the case of the bridge basement, whose existence could be investigated in the future through new archaeological excavations, aiming at better understanding its real structure.

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