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Procedia Structural Integrity 78 (2026) 671–677

Structural Integrity
Procedia

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XX ANIDIS Conference

Preliminary dynamic identification of a masonry cross vault

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Abstract

Cross vaults are fundamental structural elements of historical heritage. Their seismic vulnerability has been often proven by past earthquakes, often resulting in significant cultural, social and economic losses. The complex three-dimensional response of these structures, strongly influenced by boundary conditions, geometric configuration, masonry quality as well as mortar joint properties, poses significant challenges for the development of realistic and representative numerical models. As part of the REVHEAL project (Structural Rehabilitation of Vaults in Heritage Asset Learning: collapse identification and design of compatible strengthening systems supported by adaptive 3D models), a full-scale clay bricks masonry cross vault, measuring 3.5x3.5m in plan and 0.9m in height, was subjected to dynamic identification processing ambient vibrations records through Operational Modal Analysis (OMA) techniques. This enabled the identification of the vault's natural frequencies and mode shapes. These results provide a valuable benchmark for further investigations into the vault's dynamic behaviour under varying conditions and lay the groundwork for the development of increasingly refined numerical models and compatible intervention strategies.

Keywords: Masonry cross vaults; dynamic identification

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10.1016/j.prostr.2025.12.086

1. Introduction

Masonry cross vaults are one of the most common and iconic structural elements in historic buildings in Europe, such as churches, monasteries and monumental complexes. They have been used as primary load-bearing structures for centuries and are valued for their structural efficiency and distinctive geometry. However, their seismic vulnerability has become a major concern, especially after recent earthquakes that have caused significant damage or even complete collapse, threatening not only structural stability but also the preservation of irreplaceable cultural heritage. The seismic behaviour of cross vaults is extremely complex, as their response depends on numerous factors, including boundary conditions, geometry, masonry quality and mortar joint properties. In addition, the interaction with other adjacent elements such as walls or arches further complicates the prediction of the overall structural performance. Therefore, understanding the behaviour of cross vaults during earthquakes and finding effective, compatible reinforcement solutions remains a major challenge.

Several studies have investigated the dynamic properties of vaults through experimental and Operational Modal Analysis (OMA) techniques (Bendezu, Pellegrini and Chácara, 2025; Brincker and Andersen, 2000; Pellegrini, 2023). In recent years, the importance of structural identification and health monitoring has increased. Notable contributions include the work of Gattulli, Lepidi and Potenza (2016), Degli Abbati et al. (2024), Bartoli, Betti and Giordano (2013) and Cimellaro, Piantà and De Stefano (2012), who have demonstrated the importance of such techniques for understanding their actual behaviour and detecting possible damages. The REVHEAL project (Structural Rehabilitation of Vaults in Heritage Asset Learning: collapse identification and design of compatible reinforcing systems supported by adaptive 3D models) addresses this challenge directly (Gandelli et al., 2025; Monaco et al., 2025). The project integrates experimental testing, numerical modelling and innovative digital tools to investigate the collapse mechanisms of masonry cross vaults and develop sustainable strengthening strategies, such as the application of Textile Reinforced Mortar (TRM). As part of this research, a full-scale masonry cross vault was constructed and subjected to lateral cyclic displacements. The full-scale cross-vault specimen, with a span of 3.5 m and a rise of 0.9 m, was inspired to the historical vaults of the "Palazzata" in the pilgrimage church Regina Montis Regalis in Vicoforte, Italy (see Figure 1). The vault was confined by three boundary arches and a RC back wall. The back wall and the two adjacent abutments were clamped to the strong floor by means of post-tensioned bars, while the two abutments on the front side were supported by roller bearings (moveable side) and connected to each other by a RC beam and to the fixed supports by steel rods. Prior to the mechanical tests, a dynamic identification under ambient vibrations was carried out to determine the natural frequencies and mode shapes of the structural configuration. These preliminary tests provide valuable insights into the original condition of the vault and provide a reference point for future damage detection and monitoring strategies.

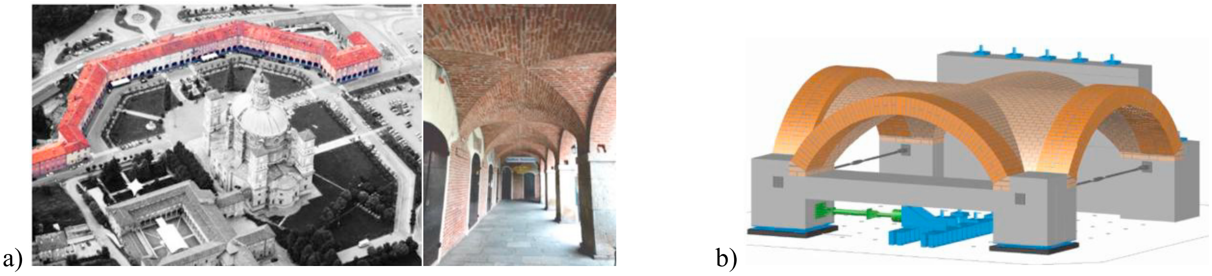
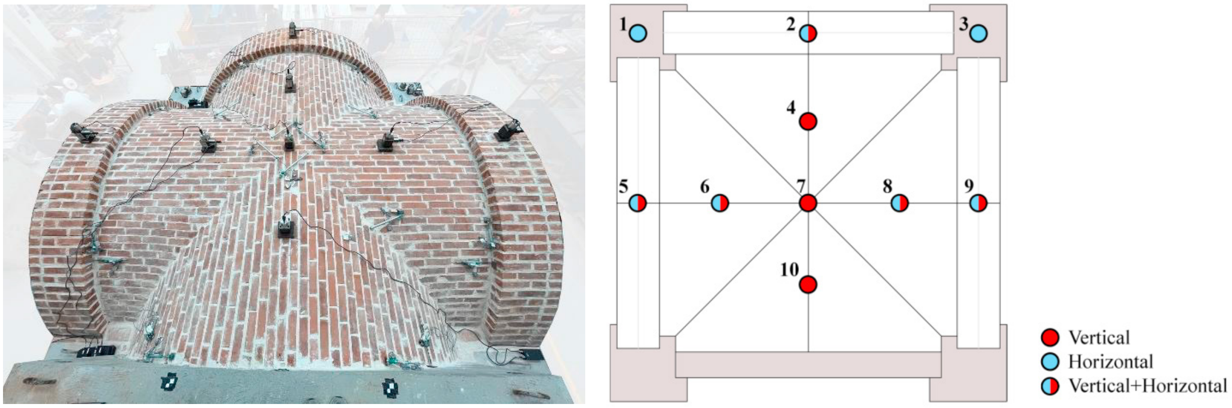


Fig. 1. (a) the "Palazzata" cross-vaults of the Sanctuary Regina Montis Regalis of Vicoforte, Italy (from Alforno et al. 2024); (b) testing rig for the seismic assessment of twin masonry cross-vault specimens from the cloister.

2. Sensors setup

Sixteen piezoelectric Wilcoxon 731A-P31 accelerometers with a sensitivity of 10 V/g and a spectral noise density of 0.01 µg/ √ Hz (10Hz) were used for structure identification. Each sensor was equipped with a battery and an anti-aliasing filter. They were all connected to an HBM Quantum Gateway, which synchronised the sensors and transmitted the data to the computer. Prior to the dynamic identification procedure, preliminary impact tests were carried out with an instrumented hammer as well as measurements of the ambient vibrations. A total of eight accelerometers were installed in the vertical direction, five in the horizontal direction and three on the supports of the vault, two in the transverse direction and one in the orthogonal direction. This arrangement was intended to maximise the probability that the mode shapes would be recorded along both axes. The sensors were mounted on metal cubes that were firmly anchored in the masonry with expansion bolts. Each cube was placed on a steel plate to ensure accurate positioning and correct alignment. This configuration provided a rigid and stable connection between the sensors and the structure, effectively minimising the influence of local vibration or relative movement at the mounting points. The arrangement of the sensors is shown in Figure 2. The same test setup was maintained during all measurement sessions and will be maintained for future recordings after damage. The ambient vibration data was collected in 50-minute sessions at a sampling rate of 600 Hz.



a) b)

Fig. 2. (a) photographic representation of the vault with sensors; (b) position in plan of the sensors.

3. Operational Modal Analysis

To obtain a reliable estimate of the modal properties of the vault, two algorithms were used for system identification: Frequency Domain Decomposition (FDD) and Stochastic Subspace Identification – Covariance Driven (SSI-Cov). The first method, FDD, works in the frequency domain and allows the identification of natural frequencies and mode shapes by calculating the power spectral matrix through the auto- and cross-correlation of the measured signals, followed by a Singular Value Decomposition (SVD) of this matrix. The second method, SSI-Cov, works in the time domain and estimates the modal parameters by fitting a stochastic state space model to the measured output data. Both methods are widely used in Operational Modal Analysis (OMA) and have proven successful in assessing the dynamic properties of structures (Brincker et al., 2001; Brincker and Ventura, 2015; Rainieri and Fabbrocino, 2014; Belleri et al., 2013; Castelli et al. 2024; Gandelli et al., 2024).

The two methods were applied with MACEC (Reynders et al., 2021), a MATLAB-based toolbox developed by the KU Leuven for the modal analysis of structures. This software enables the extraction of natural frequencies, damping ratios, mode shapes and modal scaling factors from both measured input-output and pure output vibration data. Before applying the identification algorithms, the recorded signals were processed with the MACEC Pre-Processing Toolbox.

The signals were resampled at 100 Hz, filtered with a 4th order Butterworth bandpass filter (0.5-50 Hz) and detrended to remove low frequency drifts. A 45-minute time window was selected for the analysis. After pre-processing, the two algorithms were applied. Figure 3a shows the singular value spectrum from the FDD analysis where the PSD (Power Spectral Density) matrix was calculated with a rectangular window and 50% overlap, while Figure 3b shows the stabilisation diagram derived from the SSI applied with model order 50. The identified peaks corresponding to the real modes are highlighted in the plots. Before this final solution was selected, several other peaks were analysed and then discarded based on the evaluation of modal indicators such as Modal Phase Collinearity (MPC), Mean Phase Deviation (MPD) and the imaginary part of the mode shapes. These indicators have proven to be useful in distinguishing true structural modes from noise-related modes.

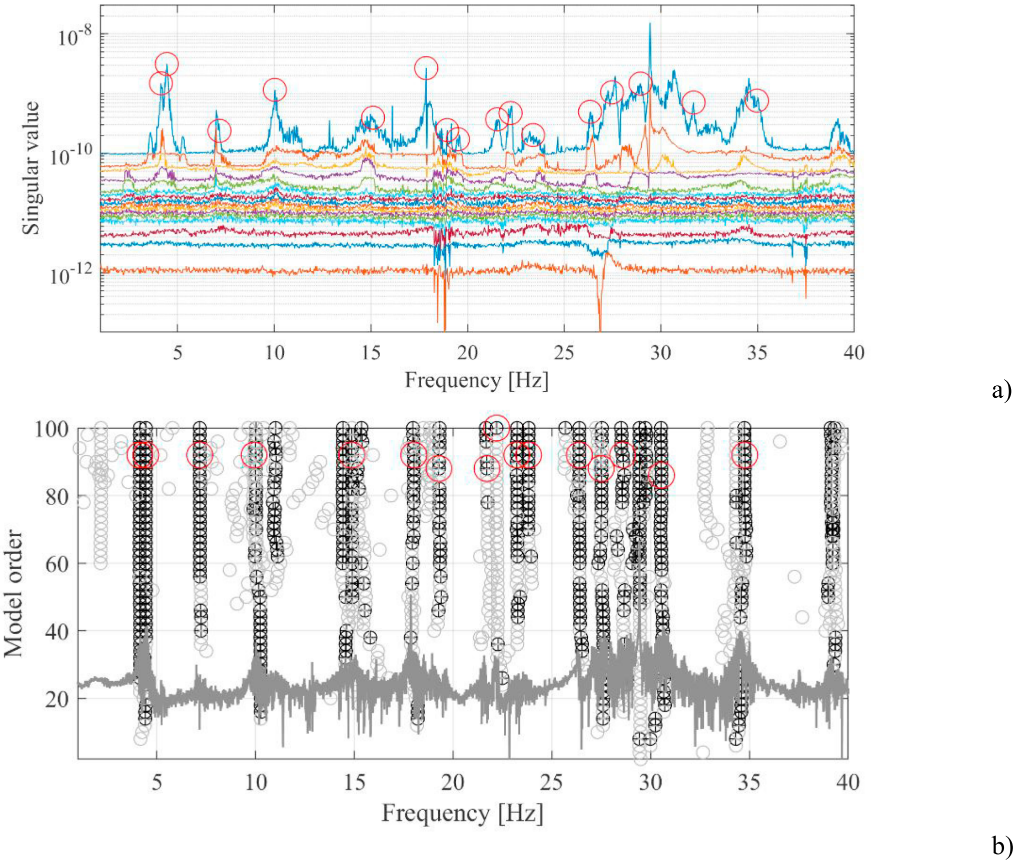


Fig. 3. (a) singular values from FDD; (b) stabilization curve from SSI-Cov.

Several peaks are clearly visible in the first singular value plot (Figure 3a), together with consistent alignments in the stabilisation diagram (Figure 3b), allowing the identification of sixteen mode shapes, shown in Figure 4 and Figure 5 of FDD and SSI respectively. Table 1 reports the summary of the identified modal parameters. These include transverse modes, vertical modes and hybrid modes that combine components in both directions. As expected, the behaviour observed at the supports indicates a roll-like response, with certain modes exhibiting noticeable motion in these regions. The transverse modes in particular are more clearly recognisable. In the frequency range between 28 and 32 Hz, distortion occurs in both the singular value and stabilisation plots, which is likely due to electrical interference or ambient noise and slightly affects the clarity of the response. Nevertheless, the modes in this area could be identified with sufficient certainty. Both the FDD and SSI-Cov algorithms successfully detected most of the modes and generally provided consistent results. However, some discrepancies were observed: some modes appeared at slightly different frequencies and others did not match between the two algorithms. Adjustments to the SSI model order and changes to the PSD parameters in FDD did not lead to significant changes in the results. These discrepancies may be attributed to measurement noise or the complex dynamic behaviour of the vault itself, highlighting the need for further investigation. A continuation of the study, possibly including a finite element model, could lead to a deeper understanding of these anomalies and support the interpretation of the unexpected dynamic responses.

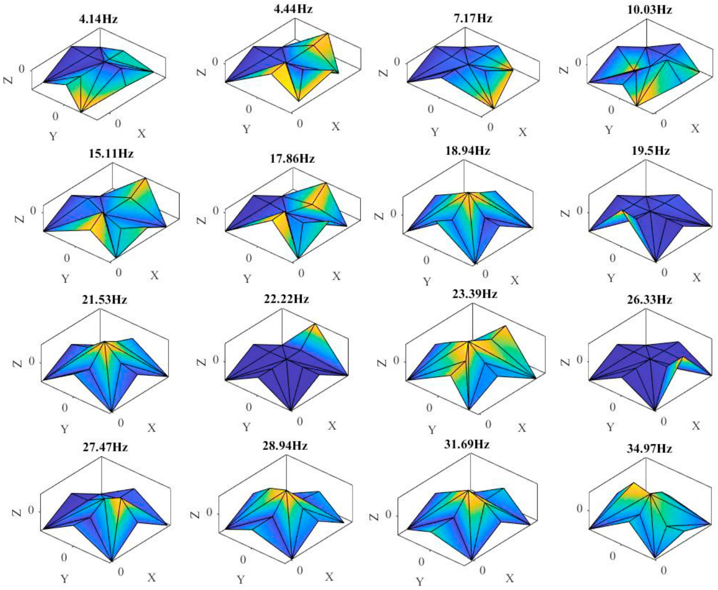


Fig. 4. Frequency Domain Decomposition identified modes shapes.

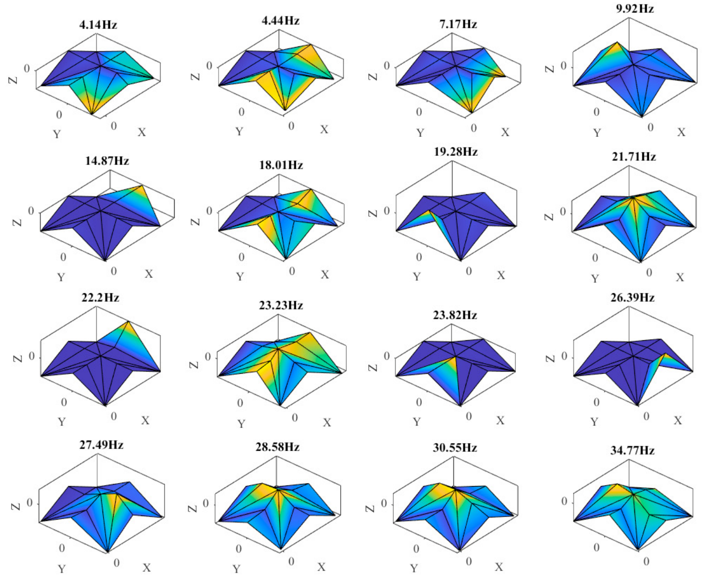


Fig. 5. Stochastic Subspace Identification identified modes shapes.

Frequency Domain Decomposition (FDD)		Stochastic Subspace Identification (SSI)	
Frequency	**Mode shape**	**Frequency**	**Mode shape**
[Hz]	**[-]**	**[Hz]**	**[-]**
4.14	Hybrid	4.14	Transverse
4.44	Hybrid	4.44	Hybrid
7.17	Hybrid	7.17	Hybrid
10.03	Hybrid	9.92	Hybrid
15.11	Hybrid	14.87	Transverse
17.86	Hybrid	18.01	Hybrid
18.94	Vertical	19.28	Vertical
19.50	Vertical	21.71	Vertical
21.53	Vertical	22.20	Vertical
22.22	Vertical	23.23	Hybrid
23.39	Hybrid	23.82	Transverse
26.33	Vertical	26.39	Vertical
27.47	Vertical	27.49	Vertical
28.94	Hybrid	28.58	Hybrid
31.69	Hybrid	30.55	Hybrid
34.97	Hybrid	34.77	Hybrid

Table 1. Summary of identified modal parameters.

Conclusions

A system identification study of a full-scale masonry vault was presented, resulting in the identification of sixteen mode shapes using Frequency Domain Decomposition (FDD) and Stochastic Subspace Identification (SSI-Cov). The identified modes included transverse, vertical and hybrid modes. Both algorithms provided largely consistent results, although some discrepancies were noted, such as modes occurring at slightly different frequencies or identified by only one method. These discrepancies may be due to measurement noise or to the complex dynamic behaviour of the vault. The acceleration data was collected before any damage occurred. Although the investigation is still ongoing, the results already show an extremely complex structural behaviour, which underlines the need for further research. The dynamic behaviour appears to be strongly influenced by several interacting factors, including boundary conditions, geometric configuration and material properties. This complexity underlines the importance of complementary tools such as finite element modelling to achieve an accurate and comprehensive dynamic characterisation. The identified modal parameters provide a valuable benchmark for future assessments and serve as a critical reference for evaluating the evolution of the vault in case of damage. The research will now continue with post-damage experimental investigations aimed at tracking the changes in modal properties. These upcoming analyses will play a key role in calibrating the increasingly refined numerical models and in developing compatible, sustainable strengthening strategies. Ultimately, deepening our understanding of the seismic response of masonry cross vaults is not only a complex engineering task, but also a fundamental step towards the preservation of architectural and cultural heritage.

Acknowledgements

This study was carried out within the “Structural Rehabilitation of Vaults in Heritage As-set Learning: collapse identification and design of compatible strengthening systems supported by adaptive 3D models - REVHEAL” project – funded by European Union – Next Generation EU within the PRIN 2022 PNRR program (D.D.1409 del 14/09/2022 Ministero dell’Università e della Ricerca). This manuscript reflects only the authors’ views and opinions and the Ministry cannot be considered responsible for them.

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