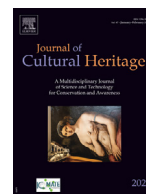




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## Case study

## Church of San Pietro Martire in Verona: A conservation-oriented approach between historical and structural interpretation

Emanuela Sorbo<sup>a,\*</sup>, Giosuè Boscato<sup>b</sup>, Gianluca Spironelli<sup>c</sup>, Tommaso Moretto<sup>d</sup>, Antonella Cecchi<sup>a</sup><sup>a</sup> Department of Architecture and Arts, Università Iuav di Venezia, Santa Croce 191, Tolentini, 30135, Venice, Italy<sup>b</sup> Department of Structural and Geotechnical Engineering, Sapienza University of Rome, via A. Gramsci 53, Rome, 00197, Italy<sup>c</sup> National PhD in Heritage Science, Dipartimento di Scienze dell'Antichità, Università degli Studi di Roma "La Sapienza", Piazzale Aldo Moro 5, 00185, Rome, Italy<sup>d</sup> PhD programme Architecture and Arts, School of Doctorate Studies, Università Iuav di Venezia, San Polo 2468, Badoer, 30135, Venice, Italy

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## ABSTRACT

The study presents an integrated structural assessment and damage interpretation of the former Gothic church of San Pietro Martire in Verona (13th century) within a multidisciplinary, conservation-oriented framework. While recent studies on historic masonry churches increasingly integrate non-destructive diagnostics and modelling, a persistent gap remains in validating crack interpretations through combined historical, geometric and mechanical evidence, capable of distinguishing between long-term historic mechanisms and more later-stage damage phenomena. This research addresses this field by proposing and applying an integrated methodological workflow that combines historical-critical analysis, high-resolution geometric survey, vibration-based dynamic identification, microseismic testing and material investigations. Beyond documenting the building condition, the study develops a comparative and multi-criteria interpretation of the experimental data, aimed at the mechanical interpretation of the governing failure mechanisms. The results allow the differentiation between two structurally and chronologically distinct crack patterns: (i) a historic and currently active out-of-plane bending mechanism affecting the south façade, and (ii) a recent and presently inactive damage pattern associated with stiffness reconfiguration of the adjacent building aggregate. This distinction is supported by geometric displacement fields, modal shapes, experimentally derived stiffness parameters and first-level kinematic assessment. The novelty of the research lies in the cross-validated integration of historical, geometric, dynamic and local mechanical evidence to distinguish active and inactive crack mechanisms in historic masonry churches. This enables the definition of a transferable methodology in the framework of applied research, tested on complex and stratified cultural heritage sites within the operational and decision-making processes of the Superintendence, aimed at developing a global interpretation of structural behaviour that integrates the historical perspective of the research process with the current state of conservation of the building. The research is carried out within the framework of a collaborative process between the Cluster-Lab MATESCA of Università Iuav di Venezia and the Superintendence ABAP for the Provinces of Verona, Rovigo, and Vicenza (local office of the Italian Ministry of Culture), and the proposed methodology has constituted the knowledge base for the Ministry's executive conservation design solutions.

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## 1. Introduction

Research on historic masonry churches has increasingly moved towards integrated diagnostic workflows in which geometric sur-

vey, vibration-based identification, local mechanical testing and historical analysis are combined to support the interpretation of damage mechanisms in historic masonry structures. While historical investigation and crack mapping remain essential, recent studies increasingly integrate non-destructive diagnostics, monitoring data, and numerical or limit analyses to reproduce observed damage and validate structural interpretations [1–3]. Within this framework, damage is interpreted as the outcome of interactions between original construction techniques, material properties, and

\* Corresponding author.

E-mail addresses: [esorbo@iuav.it](mailto:esorbo@iuav.it) (E. Sorbo), [giosue.boscato@uniroma1.it](mailto:giosue.boscato@uniroma1.it) (G. Boscato), [gianluca.spironelli@uniroma1.it](mailto:gianluca.spironelli@uniroma1.it) (G. Spironelli), [tmoretto1@iuav.it](mailto:tmoretto1@iuav.it) (T. Moretto), [cecchi@iuav.it](mailto:cecchi@iuav.it) (A. Cecchi).

multi-epoch transformations, rather than as an isolated pathology. Integrated workflows combining historical analysis, geometric documentation, experimental testing, modelling, and monitoring have thus become a reference approach, particularly for distinguishing long-term historic mechanisms from more recent transformation-induced phenomena.

Yet, despite this growing methodological sophistication, a persistent gap remains between engineering-driven diagnostic campaigns and the depth of historical interpretation required to validate structural readings. The integration of quantitative monitoring data with qualitative historical evidence is inherently challenging, as the two datasets differ in nature, scale and temporal distribution across the building's long life [4–8]. This difficulty is compounded by the fact that complex nonlinear analyses are becoming ever more widespread, yet historical buildings are characterised by limited initial knowledge concerning construction systems and inner heterogeneity due to overlapped construction phases – aspects that cannot be automatically accounted for in numerical analyses [9,10]. As a consequence, not considering detailed information on the architectural evolution of a monument over time has been shown to lead to incorrect model results at a local level, even within state-of-the-art integrated workflows [11,12]. The resulting knowledge gap is not confined to modelling practice alone: discrepancies and a lack of communication between the scientific, legislative and engineering communities further reduce the reliability of crack interpretations that depend on correlating historical transformations with experimentally derived mechanical evidence [13].

The church of San Pietro Martire represents an example of thirteenth-century Veronese religious architecture, which, despite its international recognition for the richness of its pictorial cycles, constitutes an unexplored object of study from an architectural perspective. Its conservation history is characterised by a sequence of targeted repair and structural consolidation interventions, which have ensured the preservation of a high degree of architectural, material, and constructive integrity. This condition underscores the church's relevance as a case study for interpreting long-term structural behaviour in historic masonry systems. The interior surfaces preserve one of the most significant cycles of medieval frescoes in Verona, recognised as among the highest expressions of Germanic heraldic culture between the 13th and 14th centuries [14]. These painted decorations depend entirely on the stability of the masonry substrate, making the conservation of structural equilibrium a prerequisite for their preservation. In addition to this medieval layer, the eastern wall hosts the allegorical fresco of the Annunciation attributed to Giovanni Maria Falconetto (1514), and a vertical settlement crack (*Crack EV*) affects it, highlighting the close relationship between structural vulnerability and preservation of cultural value. Another crack pattern affects the southern wall (South façade out-of-plane crack, *Crack SO*).

The identification of these high-significance architectural and artistic components, therefore, provides the necessary framework for the research aims, orienting the structural assessment toward a conservation-oriented interpretation in which failure mechanisms are evaluated in terms of structural performance and their potential impact on the monument's cultural heritage.

## 2. Research aim

The structural vulnerability mechanisms of the church of San Pietro Martire have been analysed using a holistic, multidisciplinary approach that integrates historical, humanistic, and scientific data with mechanical characterisation [15]. The applied methodology systematically analyses structural stratifications and deformations, enabling a comprehensive evaluation of the building's response [16]. This approach allowed an original analytical

framework by integrating heterogeneous datasets and information that would remain inaccessible [17]. By synthesising these insights, the study advances the epistemological foundation of architectural and structural analysis, enabling the identification of latent mechanisms governing the building's behaviour that conventional methodologies fail to detect.

The research aims to establish a systematic analysis of crack patterns in historic masonry structures related to the historical processes with a specific emphasis on differentiating between historical mechanisms associated with the original construction from cracks related to recent historical works or transformation of the church [18]. The cracking framework associated with the historical documentation has identified two different phenomena (*Crack SO* and *Crack EV*) that address the building's structural vulnerability and conservation status and are significant in exemplifying the research path.

The research aims to define a systematic procedure for the interpretation and classification of crack patterns in historic masonry structures through the correlation of diachronic documentary sources, geometric displacement fields, modal response and local mechanical properties. The proposed methodology is applied to the church of San Pietro Martire through the analysis of two distinct crack systems characterised by different chronological development, geometrical configuration and structural behaviour. The comparative interpretation of these phenomena constitutes the basis for evaluating the effectiveness of the integrated diagnostic workflow in distinguishing structurally active mechanisms from stable or non-evolving damage conditions within conservation-oriented assessment and decision-making processes.

## 3. Materials and methods

### 3.1. Historical-constructive framework and structural configuration of the church

The literature situates the construction of the church of San Pietro Martire between the late 13th and early 14th centuries [19,20]. Following the Napoleonic suppressions, in the early 19th century, the church was deconsecrated and subsequently acquired by the municipality of Verona [21].

The church is part of the former monastic complex of Santa Anastasia, presently used by the “E. F. Dall'Abaco” Conservatory of Verona and the “Scipione Maffei” State High School [22]. It is built in direct continuity with the *Arche Scaligere* [23], which were illustrated by John Ruskin during his stays in Verona in the 1860s. Although included within the group of the so-called *Chiese Minori* (minor historic churches) of Verona [24,25], the church stands as a significant testament to the historical, artistic, urban, and spiritual evolution of the city [26,27].

From a construction point of view, the church is described by a rectangular shape defined by a single hall measuring 10.10 m in width and 16.90 m long. The load-bearing system consists of a composite multi-leaf masonry arrangement, comprising an external brickwork facing laid in a regular Gothic bond and an inner core composed of fluvial pebbles and irregular lithic elements, bonded with lime-based mortar. This construction typology is consistently employed along the entire perimeter of the church's masonry envelope. The perimeter walls, with an average thickness of approximately 0.63 m, serve as the primary vertical load-bearing elements and springing supports for the masonry vaults, which span approximately  $8.10 \times 10.00$  m and have a thickness of about 0.30 m. Within the nave, three metal tie rods are installed at the level of the vault springing, aligned with the external pilasters. These pilasters, characterised by a Gothic brickwork texture, exhibit an average wall thickness of approximately 0.72 m and an

overall width of about 0.40 m; at the corner quoins, their dimensions increase substantially, reaching approximately 0.95 m.

From a structural mechanics standpoint, the combined geometric and constructive configuration—marked by relatively slender perimeter walls, large vault spans, and a non-ashlar masonry typology—plays a critical role in defining the equivalent mechanical properties of the masonry. Although the metal tie rods provide partial transverse restraint, the global structural system remains inherently vulnerable to horizontal actions. In particular, thrusts induced by the vaults and seismic excitations may activate unfavourable stress states, further aggravated by limited structural redundancy and a reduced capacity for the redistribution of horizontal forces. Moreover, the impossibility of experimentally verifying the presence, effectiveness, and continuity of transverse bonding elements (diatones)—owing to frescoed interior surfaces that preclude invasive or semi-invasive investigations—introduces a significant source of epistemic uncertainty. This uncertainty directly affects both the mechanical characterisation of the masonry and the robustness of numerical and analytical structural models of the perimeter walls.

Subsequent structural alterations, notably the installation of metal tie rods between the late nineteenth and early twentieth centuries and the replacement of the original timber roof with steel Polonceau trusses in 1965, have further modified the original static scheme. While these interventions locally enhanced tensile resistance and load-bearing efficiency, they also introduced stiffness discontinuities and altered load-transfer paths, potentially exacerbating incompatibilities between the historic masonry fabric and the later structural elements. As a result, the current structural behaviour reflects a stratified system in which the original construction logic coexists with successive restoration and consolidation measures, with significant implications for both global stability and the activation of local vulnerability mechanisms.

The church, currently closed to the public, is undergoing a conservation project promoted by the Ministry of Culture through the local Superintendency. The collaboration with the Cluster-Lab MATESCA of the Università Iuav di Venezia has enabled an in-depth and previously unpublished analysis, which revealed two significant structural pathologies, *Crack SO* and *Crack EV*.

*Crack SO* (Fig. 1a) is characterised by a diagonal fissure located in the upper portion of the south façade, oriented towards Piazza Santa Anastasia (Fig. 2). The phenomenon is associated with a broader process of surface spalling, leading to the localised detachment of lithoid material from the external masonry. Internally, this deterioration corresponds to a network of micro-cracks observed at the junction between the wall and the masonry vault. From a structural standpoint, this crack pattern is compatible with an out-of-plane bending mechanism of the south wall, induced by the horizontal thrust of the adjacent vault and favoured by the geometric slenderness of the wall–vault system.

*Crack EV* (Fig. 1b) is observed in the eastern masonry and presents as a vertical fissure. This structural discontinuity is centrally located on the façade, originating at the springing point of the attic oculus and extending downward to the arch of Leonardo da Quinto (one of the Scaliger tombs located in the external front), which is connected to the base of the wall [28]. On the interior side, the crack intersects with the allegorical fresco of the Annunciation attributed to Giovanni Maria Falconetto (1514) [29], descending towards the base of the masonry and adversely affecting a portion of the adjacent vaulted structure. This phenomenon indicates potential weaknesses in the structural integrity of both the masonry and the fresco, warranting further investigation. Unlike *Crack SO*, the geometry and orientation of this discontinuity do not indicate a thrust-related or overturning kinematic, but are instead consistent with a localised stress redistribution mechanism, likely associated with stiffness discontinuities induced by later construction phases. This interpretation points to a damage pattern gov-

erned by differential structural response rather than by an active global mechanism.

### 3.2. Historical and archival research

Bibliographical and archival research has defined a pivotal phase of the proposed methodology. Historical investigation and diachronic analysis aimed to examine in depth the transformations that took place between the 19th and 20th centuries concerning the restoration and reconstruction interventions carried out on the roof structure of the church and the spaces of the former convent [30–33].

To achieve this purpose, materials were gathered from various sources, including the State Archives (ASVr), the General Archives of the Municipality (AgVr), the archives of the Civic Library of Verona (BcVr), the photographic and monumental archives of SABAP-Vr, and the catalogued photos at the Alinari Photographic Archives (Afa).

Through an analysis of the minutes of the *Commissione Consultiva Conservatrice di Belle Arti e Antichità* conserved at the State Archives of Verona [AS.1] [AS.2] [AS.3], it was possible to identify between 1880 and 1910 a period characterised by conspicuous restoration work on the former convent complex and the Scaliger Tombs (Arche Scaligere). The examination of contracts from this period, preserved in the historical archives of the Municipality of Verona, has facilitated a reconstruction of the work conducted on the church in 1895, which included the replacement of the roof, the reinforcement of the masonry vaults, and restoration interventions on the façades [AC.1] [AC.2] [AC.3] [AC.4] [AC.6] [AC.7].

About Fig. 2, archived within the Alinari collection, an examination reveals the conservation status of the façade facing St. Anastasia Square as documented in 1900, immediately following the reconstruction of the church roof. Newly implemented masonry restoration interventions remained confined to the localised area affected by *Crack SO*. These interventions exhibit noticeable variations in the colour of the added bricks and differences in the size of the mortar joints. In the earlier photograph (Fig. 2a), the traces of the chain lugs associated with the pilasters are absent. In contrast, the picture taken a decade later (Fig. 2c), dated between 1915 and 1920, clearly shows these features. By comparing these photographs with the current state, it was possible to deduce that the bulging wall mechanism was already operational at that time. The reconstruction of the roof structure using steel trusses, installed in 1965, as documented in the executive project in the AgVr archives [AC.8], represents a subsequent intervention following the emergence of structural issues. This modification can be interpreted as reinforcing the structure in response to identified damage in the affected section.

Concerning *Crack EV* on the east front, no documented evidence of cracking occurs before 1979. Therefore, it has been possible to link the origin of this phenomenon to the renovation of the adjacent rooms of the Conservatory, which happened between 1984 and 1992, as documented in the archives of SABAP-Vr [SABAP.1] [SABAP.2] [SABAP.3].

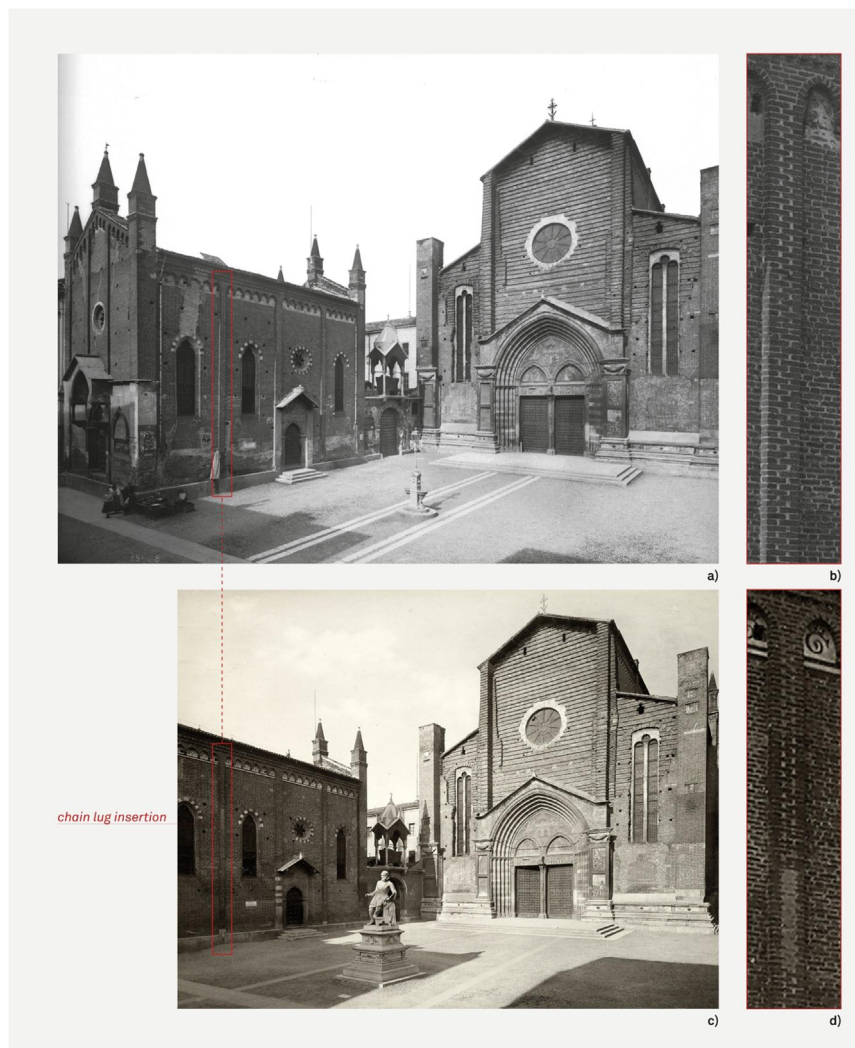
Non-destructive diagnostic activities are carried out in collaboration with the laboratories of the Università Iuav di Venezia: the CIRCE Geomatics lab (for the execution of the geometric survey), the LabSCo Construction Science lab (for mechanical characterisation and structural assessments) and the LAMA ancient materials lab (for the material characterisation of the surfaces).

### 3.3. Geometric survey and TLS processing

Data acquisition methodologies integrated topographic surveys, terrestrial laser scanning (TLS), and both aerial and terrestrial photogrammetry [34]. A comprehensive topographic network estab-



**Fig. 1.** Università Iuav di Venezia, 2024. *Integrated Geometric Survey and Characterisation of the Crack Pattern.* (a) South elevation showing the Crack SO and previous scuci-cuci repair areas; (b) East elevation showing the Crack EV; (c) Longitudinal section of the church; (d) Transversal section; (e) Ground-floor plan with the location of the diagnostic investigations, including ambient vibration testing, microseismic measurements and thermographic surveys.



**Fig. 2.** View of Piazza S. Anastasia. Historical comparison over a twenty-year period from 1900 to 1920: (a) *The churches of S. Anastasia and S. Pietro Martire in Verona (c. 1900)*, Alinari Archives, Florence, Alinari Archive, ACA-F-012680-0000; An area rebuilt using the scuci-cuci technique is visible above the first window; (b) a detail of the same photo showing the external wall without traces; (c) *View of the churches of S. Anastasia and S. Pietro Martire in Verona. The monument to Paolo Veronese is visible at the centre of the square. 13th – 15th centuries. Brogi, c. 1915–1920*, Alinari Archives, Florence, Alinari Archive, BGA-F-013164-0000; (d) a detail of the same photo showing the external wall with the traces of chain lug insertion.

lished a local reference system, enabling the georeferencing of point clouds from TLS scans and the orientation of the photogrammetric model. The TLS-derived point clouds were processed within the open-source software *CloudCompare* [35] to obtain deviation maps with respect to reference planes defined at the masonry base. The façade coordinates were mapped onto a scalar field represented by an RGB gradient, where colour variations indicate deviations from the vertical axis of the façade. The resulting scalar fields were used as quantitative indicators for identifying out-of-plane displacement trends (Fig. 3) and comparing them with crack location, modal deformation and local stiffness variations.

A comparable methodology assessed the geometric deformations of the interior vaults. The findings indicate that the vault associated with *Crack SO* demonstrates downward displacement at its interface with the adjacent masonry, thus corroborating its function as a thrusting component within the structural framework (Fig. 3e).

### 3.4. Ambient vibration testing

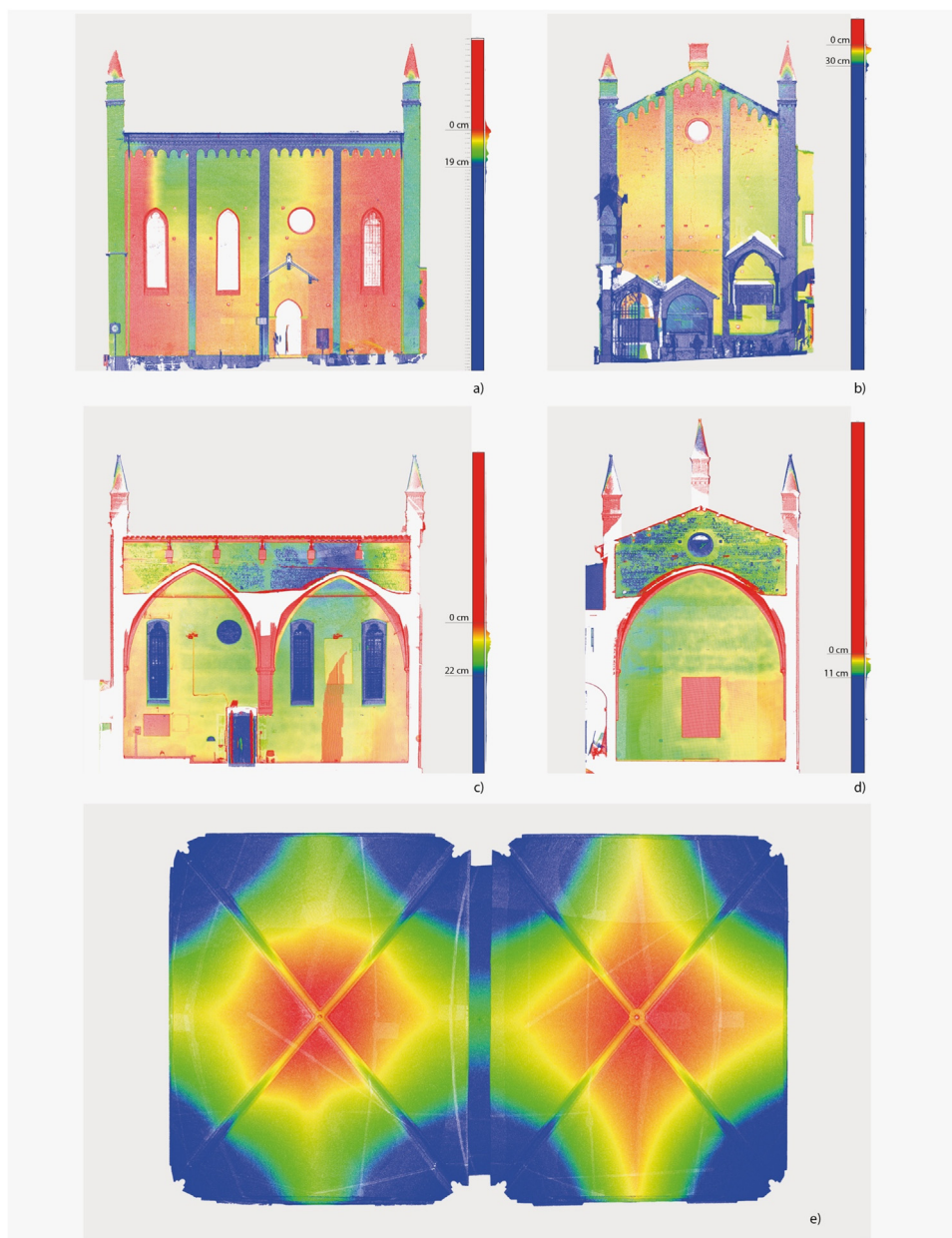
Global dynamic identification was carried out through ambient vibration testing [36,37] using twelve mono-axial piezoelectric ac-

celerometers (PCB Piezotronics 393C series; sensitivity 10 V/g; frequency range 0.1–800 Hz), connected to two HBM MX840A acquisition units (24-bit resolution). Signals were recorded simultaneously for approximately 37 min with a sampling frequency of 2048 Hz.

The tests were performed under ambient vibration conditions, without artificial input force. Sensors were positioned near the vault springing level, at an average height of approximately 12.5 m above the internal church floor level, in order to capture the global dynamic response of the structural system. The acquisition lasted approximately 37 min, with simultaneous recording at 2048 Hz. The recorded signals were processed in the frequency domain to identify the main natural frequencies and associated modal shapes.

### 3.5. Local microseismic testing

Local microseismic investigations were performed using a PCB 353B33 accelerometer coupled with an instrumented impact hammer (PCB 086C20). Measurements were organised on predefined grids in order to analyse wave propagation and relative stiffness variations within the masonry [38–40]. Thermographic surveys were conducted using an infrared thermal camera (7.5–14 μm



**Fig. 3.** Università Iuav di Venezia, 2024. TLS-derived deviation maps of the masonry façades and vaulted system. (a) South elevation; (b) East elevation; (c) Longitudinal section; (d) Transversal section; (e) Vault intrados deviation map. Colour gradients represent the measured deviations from the reference geometric planes derived from point-cloud processing.

spectral range), enabling the detection of subsurface discontinuities beneath plastered and frescoed surfaces.

For each investigated masonry portion, repeated impacts were performed and the recorded accelerometric responses were used to estimate wave propagation times. The resulting velocities were compared among different wall portions to identify relative stiffness variations, rather than to define absolute homogeneous material properties.

### 3.6. Thermographic and chemical-physical material analyses

A chemical-physical campaign assessed material consistency as an integral part of the mechanical characterisation process. This dual approach significantly enhances the model's accuracy and reliability in predictive analysis. The evaluation focused on determining the conservation status of the lithoid elements and binders. It encompassed several methodologies, including thermographic sur-

veys of the interior masonry facilitated through an infrared thermal imaging apparatus, complemented by targeted micro-sampling of mortars, bricks, and their associated deterioration products; mineralogical-petrographic analysis employing thin sections analysed via transmitted light polarizing optical microscopy (TPLM); X-ray powder diffraction (XRD) techniques to elucidate the mineralogical composition of lithoid materials; ion chromatography (IC) for the quantification of soluble salts present in the mortars; and the application of a mercury porosimeter to evaluate the porosity of the sampled masonry elements.

## 4. Results

### 4.1. Geometric deformation results

The point clouds obtained from the terrestrial laser-scanning survey and photogrammetry reveal substantial geometric irregu-

larities in the masonry affected by the *Crack SO* system and the adjacent vault's webbing. Fig. 1 provides the geometric framework for the experimental results, correlating crack patterns, building morphology and the spatial distribution of investigations. The south façade macro-element affected by the crack system is clearly identifiable in elevation and section, allowing the localisation of the out-of-plane deformation field subsequently quantified through point-cloud processing. Likewise, the east façade macro-element associated with the East façade vertical settlement crack is explicitly framed within the building geometry, enabling the verification of its current vertical alignment and the absence of measurable out-of-plane displacements.

The sections allowed the metric quantification of the out-of-plane bending affecting the south façade. The scalar-field analysis associated with the RGB gradient recorded a maximum overhang of 19 cm. The processing also verified that the phenomenon affects a wider portion of the masonry, with an average overhang value of approximately 10 cm (green colour scale) over an area of 77 m<sup>2</sup> out of 545 m<sup>2</sup>.

The orthophoto of the south façade also highlighted masonry portions rebuilt through *scuci-cuci* interventions (Fig. 2a), associated with the insertion of tie-rods and otherwise difficult to identify through direct visual inspection. The analysis enabled the identification and quantification of different repair campaigns implemented over the last two centuries in the affected pilasters, also documented in the historical photographs, as attempts to restore the continuity of the wall structure. The temporal stratification of these interventions, combined with the use of different materials, has resulted in a heterogeneous conservation condition of the masonry joints and repaired areas. The discretisation of the structure into macro-volumes [32] therefore supports the interpretation of a confined out-of-plane bending mechanism, aggravated by the poor cohesion of the wall face and by the horizontal thrust exerted by the deformed vault.

#### 4.2. Dynamic identification results

Global dynamic identification further supports the interpretation of the observed deformation mechanisms. The first vibration mode ( $f_1 = 4.26$  Hz) is dominated by an out-of-plane deformation of the south wall, coherently involving the portion affected by the *Crack SO*. Higher modes ( $f_3 = 12.42$  Hz;  $f_4 = 15.29$  Hz) activate both the south and east macro-elements. These modal shapes indicate that the cracked sectors correspond to structurally active portions of the system, susceptible to kinematic responses rather than to purely localised material deterioration [41].

Fig. 1e synthesises the investigation layout, highlighting the correspondence between the dynamic monitoring system, the microseismic test points (DIR.MXX) and the mechanical parameters reported in Table 1.

#### 4.3. Microseismic results

Microseismic tests performed on the south façade indicate locally reduced wave propagation velocities in correspondence with the *Crack SO* and adjacent stitched areas, consistent with a heterogeneous masonry fabric characterised by zones of lower stiffness. The spatial distribution of these velocity variations correlates with the mapped bulging profile, confirming the mechanical discontinuity of the involved macro-element.

Table 1 summarises the results of the experimental vibrational tests carried out on selected masonry portions, including wall panels, attic masonry and isolated piers. For each investigated element, elastic wave velocities were derived from controlled hammer impacts and in-situ accelerometric recordings. The experimentally

obtained longitudinal and transverse wave velocities were subsequently used to compute the dynamic Young's modulus by adopting representative density values according to elastic wave propagation theory. The results highlight a marked variability in stiffness values, confirming the heterogeneous nature of the load-bearing fabric. Lower dynamic moduli systematically correspond to areas affected by cracking and previous stitched repairs, whereas higher values are associated with more compact masonry zones.

#### 4.4. Thermographic and material results

Thermographic surveys carried out on the interior surfaces reveal subsurface thermal discontinuities beneath the frescoed layers, spatially consistent with the irregular composite masonry texture observed in the attic spaces. These results corroborate the persistence of internal heterogeneities behind the decorated surfaces.

The chemical-physical analyses confirmed the heterogeneous nature of the masonry fabric, with differences in mortar composition, porosity and conservation state between original portions and repaired areas. These results do not directly explain crack formation as an isolated material decay process, but they support the interpretation of a mechanically non-uniform wall system, in which stiffness discontinuities may favour the localisation of deformation and cracking.

#### 4.5. Integrated comparison

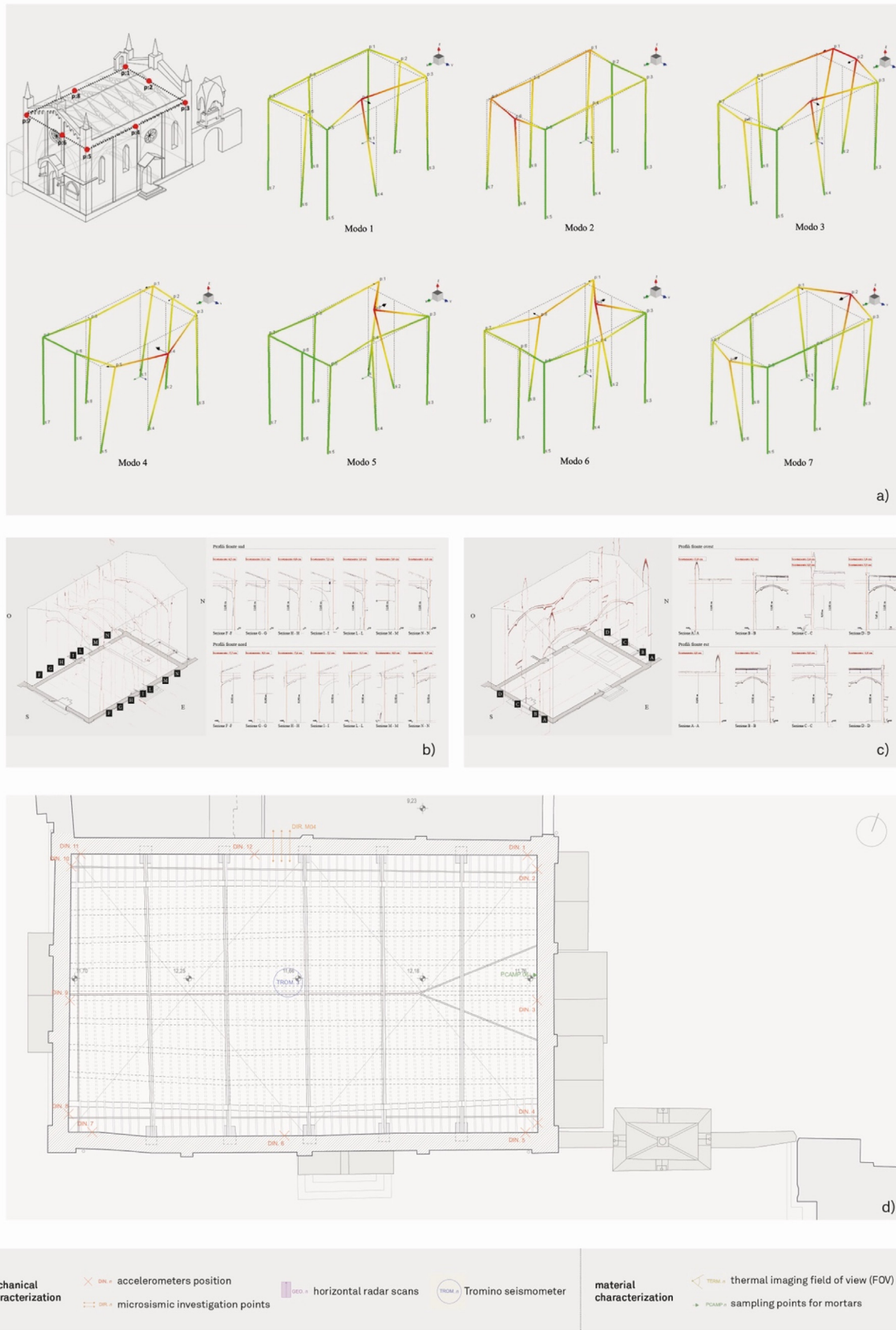
The comparison between geometric, dynamic, thermographic and microseismic results provides converging evidence supporting the interpretation of the identified damage mechanisms. The correspondence between out-of-plane deformation fields, modal participation and local stiffness reduction confirms the active mechanical behaviour of the south façade macro-element. At the same time, the absence of measurable geometric deformation in the east façade, despite the presence of cracking, supports the interpretation of a structurally stable damage condition associated with local stiffness reconfiguration rather than with an active overturning mechanism.

The integration of heterogeneous diagnostic datasets therefore enables a cross-validated interpretation of the structural behaviour of the church, linking geometric evidence, experimentally derived mechanical parameters and historical transformation processes within a unified conservation-oriented assessment framework.

### 5. Discussion

The diagnostic investigations and material characterisation analyses highlight a markedly heterogeneous masonry fabric, resulting from the coexistence of multi-leaf masonry, localised stitched repair interventions (*scuci-cuci*), and multiple mortar joint repointing campaigns executed with materials exhibiting different mechanical properties. Infrared thermographic surveys performed on the interior surfaces revealed subsurface discontinuities beneath the frescoed layers [42], which closely correspond to the irregular masonry texture directly observable in the attic spaces, where plaster is absent. These findings confirm the persistence and continuity of the mixed masonry assemblage behind the decorated surfaces, despite the apparent visual homogeneity of the interior finishes.

This intrinsic heterogeneity leads to pronounced local variability in physical and mechanical parameters—particularly stiffness, cohesion, and deformability—which governs the initiation, localisation, and progression of deformation and damage mechanisms under both static and dynamic loading conditions. Consequently, the structural response is dominated by differential behaviour among

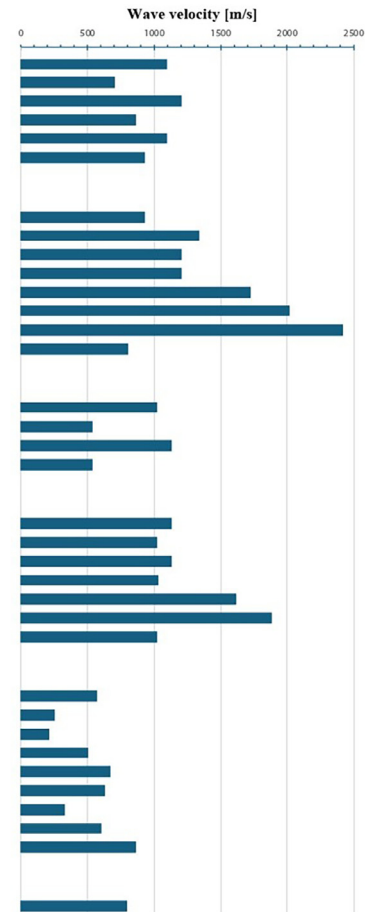


**Fig. 4.** Università Iuav di Venezia, 2024. Correlation between modal shapes and geometric deformation profiles. (a) Principal vibration modes and sensor layout derived from ambient vibration testing; (b) South façade deviation profile obtained from TLS processing; (c) East façade deviation profile; (d) Plan-view distribution of the investigation points and measurement locations.

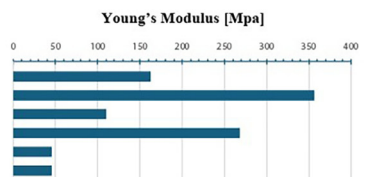
**Table 1**

Università Iuav di Venezia. Results of the microseismic and vibrational tests performed on selected masonry portions. The upper part of the table reports the experimental measurements obtained for each test point, including wall thickness, accelerometric response time, hammer–contact duration and elastic-wave propagation velocity. The lower part summarises the mean transverse and longitudinal wave velocities, the assumed material densities and the corresponding dynamic Young's moduli derived for the investigated masonry portions.

Test Code	Examined Section	Hammer Impact Point	Accelerometer Time [s]	Hammer Time [s]	$\Delta$	Wall Thickness [cm]	Wave Velocity [m/s]
M.01	Est wall	M.01a	10,84427	10,843854	0,000573	0,63	1099,48
		M.01b	5,197917	5,197031	0,000886		711,06
		M.01c	5,602239	5,601719	0,00052		1211,54
		M.01d	4,977344	4,976614	0,00073		863,01
		M.01e	7,016614	7,016041	0,000573		1099,48
		M.01f	5,960937	5,96026	0,000677		930,58
M.02	North wall	M.02a	5,794375	5,793698	0,000677	0,63	930,58
		M.02b	3,721927	3,721458	0,000469		1343,28
		M.02c	3,380469	3,379948	0,000521		1209,21
		M.02d	5,758489	5,757969	0,00052		1211,54
		M.02e	5,512812	5,512448	0,000364		1730,77
		M.02f	6,395312	6,395	0,000312		2019,23
		M.02g	3,1875	3,18724	0,00026		2423,08
		M.02h	3,926979	3,926198	0,000781		806,66
		M.03	West wall	M.03a	4,726302		4,725729
M.03b	2,177344			2,17625	0,001094	539,55	
M.03c	1,569375			1,568854	0,000521	1132,44	
M.03d	2,675573			2,674479	0,001094	539,31	
M.04	West wall, roof space	M.04a	10,345729	10,345208	0,000521	0,59	1135,55
		M.04b	11,888906	11,888333	0,000573		1029,67
		M.04c	25,863281	25,86276	0,000521		1132,44
		M.04d	5,754531	5,753958	0,000573		1031,69
		M.04e	4,191042	4,190677	0,000365		1616,45
		M.04f	4,950625	4,950312	0,000313		1884,98
		M.04g	2,157604	2,157031	0,000573		1025,71
M.05	North wall	M.05a	7,858177	7,857083	0,001094	0,63	575,87
		M.05b	4,463073	4,460625	0,002448		257,35
		M.05c	4,790677	4,787708	0,002969		212,19
		M.05d	4,104687	4,103437	0,00125		504,00
		M.05e	5,163281	5,162344	0,000937		672,36
		M.05f	3,268073	3,267083	0,00099		636,36
		M.05g	2,682292	2,680417	0,001875		336,00
		M.05h	6,954062	6,953021	0,001041		605,19
		M.05i	6,337448	6,336719	0,000729		864,20
		M.06	East wall pillar	M.06a	4,4425		4,441562



Test Code	Examined Section	Average Shear Wave Velocity [m/s]	X	Average Longitudinal Wave Velocity [m/s]	Density [kg/m <sup>3</sup> ]	Young's Modulus	
						[N/m <sup>2</sup> ]	[Mpa]
M.01	Est wall	985,86	0,58	571,80	2000	1630231012	163,02
M.02	North wall	1459,29	0,58	846,39	2000	3571951651	357,20
M.03	West wall	810,24	0,58	469,94	2000	1101159338	110,12
M.04	West wall, roof space	1265,21	0,58	733,82	2000	2685018733	268,50
M.05	North wall	518,17	0,58	300,54	2000	450363095	45,04
M.06	East wall pillar	799,57	0,58	300,54	1800	460995630	46,10



adjacent masonry portions, with stress concentrations preferentially developing at material interfaces, repaired zones, and areas characterised by reduced mechanical compatibility.

The critical analysis of the acquired data, contextualised within the scope of historical-constructive investigation, reveals significant insights regarding the bulging phenomenon observed on the southern façade (*Crack SO*). The interventions implemented during the examined timeframe indicate several attempts to address the underlying kinematic mechanisms. The restoration of the roof and the execution of *scuci-cuci* to the exterior, finalised in 1895, demonstrated inadequate performance, as indicated by the later installation of tie rods in the early 20th century (Fig. 2). These structural reinforcements mitigate the lateral thrust exerted by the vault, as further shown in a comparison with Fig. 1. Additionally, the roof replacement conducted in 1965 did not rectify the existing structural issues, reinforcing the conclusion that the observed bulging is not solely attributable to the thrust generated by the po-

tential deformation of the masonry connected to the metal truss. Instead, this phenomenon indicates a static equilibrium that has evolved and stabilised over time. The findings of the modal analysis further support this hypothesis by revealing the nature of the structural behaviour involved [43].

In order to further validate the experimentally derived interpretation, a simplified kinematic assessment was developed by schematising the south façade as a macro-element susceptible to out-of-plane bending. The geometry extracted from the laser-scanning survey, together with the detected crack pattern and the position of historical tie-rods, allowed the definition of a potential overturning/bending mechanism consistent with kinematic limit analysis approaches for masonry walls. The assumed mechanism involves the upper portion of the south façade rotating outward around a lower hinge line, with the vault acting as a thrust-transferring element. This kinematic configuration is coherent with: (i) the measured out-of-plane displacement field, con-

**Table 2**

Università Iuav di Venezia. Cross-validation framework for interpreting the investigated crack systems. The table summarises the correlation between historical documentation, TLS-derived deformation analysis, dynamic response, microseismic investigations and crack monitoring results for the two investigated crack systems. The comparison integrates geometric, mechanical and chronological evidence in order to support the classification of the identified damage mechanisms and their current structural condition.

Evidence	Crack SO (South façade out-of-plane crack system)	Crack EV (East façade vertical settlement crack)
Historical documentation	Present since late 19th century	Not documented before 1979
TLS deformation	Out-of-plane displacement up to 19 cm	No relevant out-of-plane deformation
Dynamic response	Involved in first mode	Involved only in higher modes
Microseismic data	Local stiffness reduction	Limited/local discontinuity
Crack monitoring	Compatible with active mechanism	No recent opening detected
Interpretation	Historic and active	Recent and currently inactive

centrated in the upper third of the wall; (ii) the first vibration mode, dominated by an out-of-plane response of the same macro-element; and (iii) the local reduction in stiffness detected through microseismic testing. The convergence of geometric, dynamic and kinematic evidence supports the interpretation of *Crack SO* as the manifestation of a long-term active bending mechanism, rather than as a localised surface pathology. Although a full nonlinear or limit equilibrium numerical implementation lies beyond the scope of the present study, this first-level kinematic verification provides an independent mechanical validation of the NDT-based interpretation, confirming the reliability of the adopted diagnostic framework for the identification of governing failure mechanisms in historic masonry churches.

### 5.1. Cross-validation of the crack interpretation

The interpretation of the two crack systems is supported by the convergence of independent evidence (Table 2), including historical documentation, geometric deformation analysis, dynamic behaviour, local stiffness variations and direct monitoring data.

The formation of *Crack EV* corresponds to a more recent timeframe. The iconographic analysis narrows its origination to the two decades between 1979 and 1995 [Mic.1]. Between 1984 and 1992, most of the complex underwent demolition and reconstruction using reinforced brick-concrete floor slabs. This reconstruction of aggregate sections with a distinct construction technique likely altered the overall structural stiffness, leading to a new equilibrium condition. This shift manifested as deformations in the less rigid portion of the system, specifically the historic irregularly bonded masonry of the church, ultimately resulting in the formation of *Crack EV*. The analysis of the cross sections from the east façade, derived from point cloud processing, revealed no evidence of deformation in the masonry associated with *Crack EV*, either in the horizontal or vertical planes.

However, the photogrammetric analysis identified minor cracks in the vault's web, particularly near the reconstructed adjacent building (Conservatory "E.F Dall'Abaco"), completed between 1984 and 1992.

Global monitoring using dynamic identification techniques detected the potential development of kinematic responses associated with *Crack SO* and *Crack EV*. Fig. 4 correlates the experimentally identified modal shapes with the geometric deformation profiles obtained from TLS processing. The figure therefore supports the comparison between dynamic vulnerability and measured displacement fields. Mode 1 deformation, activated with frequency 4.26 Hz, underlines potential out-of-plane tilting mechanisms of the south wall, characterised by *Crack SO*. Vibration modes 3 and 4, 12.42 Hz and 15.29 Hz, respectively, activate both the South macroelement (*Crack SO*) and East one (*Crack EV*).

The East macroelement exhibits behaviour influenced by a torsional mechanism induced by the adjacent structure. The same analyses suggest that the wall of the South elevation is subject to horizontal bending caused by the local overhang corresponding to

*Crack SO*. It describes the current geometric condition of the element and, therefore, identifies a kinematic mechanism already active. Modes 5, 6 and 7 highlight the vulnerabilities related to the east and west fronts, qualitatively returning the greater instability of the east front, characterised by *Crack EV*.

Microseismic testing, complemented by thermographic analysis and a thorough examination of mortar composition tests made during the research, indicates a heterogeneous state of conservation among the affected wall surfaces. The localised deterioration identified within the masonry does not substantially compromise the overall structural integrity of the system. The fracture pattern observed in *Crack EV* further substantiates these findings, as it affects the lithoid element without following the joint line, indicating an independent failure mode. Consequently, this analysis clarifies that the observed lesions are not attributable to insufficient cohesion among the masonry elements but point to other underlying factors influencing material performance.

## 6. Conclusion

Through the interpolation of different data and methods, the research has permitted the identification of a classification of cracks by dividing them into *Crack SO* - historic and active - and *Crack EV* - recent and inactive - which, for the conservation-oriented design solution and monitoring of the church allow for different modes of operation, precisely identifying the damage of the building due to external and internal disruptive causes (such as the physiological ageing of the structure and materials).

The *Crack SO* system is classified as historic and currently active on the basis of four converging and mutually independent lines of evidence. First, archival sources document the kinematic behaviour as far back as the late nineteenth century, with repeated intervention campaigns: vault reinforcement (1895), tie-rod installation (early twentieth century) and roof replacement (1965). Each of the mentioned interventions fails to resolve the underlying mechanism, thereby confirming its persistence over more than a century. Second, TLS-derived deviation maps quantify an out-of-plane displacement of up to 19 cm concentrated in the upper third of the south wall, spatially consistent with the crack geometry. Third, ambient vibration testing identifies the first natural mode ( $f_1 = 4.26$  Hz) as dominated by out-of-plane deformation of the same macro-element, confirming its structural involvement under dynamic excitation. Fourth, microseismic testing detects local stiffness reductions in the cracked and stitched masonry zones, consistent with the mechanical degradation expected in an actively deforming element. These four independent datasets converge on the same structural interpretation. This convergence is further corroborated by a first-level kinematic assessment, which demonstrates that the assumed out-of-plane bending mechanism (with the vault acting as thrust-transferring element and the hinge line located at the base of the affected portion) is geometrically and mechanically consistent with all experimentally observed quantities. The classi-

fication is therefore grounded in cross-validated experimental evidence rather than in interpretive assumption.

The *Crack EV* is classified as recent and currently inactive on the basis of five converging indicators. The absence of any documented cracking prior to 1979, combined with archival evidence of demolition and reconstruction works in the adjacent Conservatory between 1984 and 1992, establishes a well-constrained temporal window for crack formation and a plausible causal mechanism due to the differential stiffness reconfiguration induced by the introduction of reinforced brick-concrete floor slabs in the aggregate. TLS cross-section analysis reveals no measurable out-of-plane deformation of the east wall in either the horizontal or vertical plane, excluding any active overturning or bending kinematic. Dynamic identification associates the east macro-element only with higher vibration modes ( $f_3 = 12.42$  Hz;  $f_4 = 15.29$  Hz), consistent with a torsional influence from the adjacent structure rather than with an autonomous instability. Chemical-physical and microseismic analyses exclude cohesion loss or material degradation as primary causes, with the crack morphology (cutting through lithoid elements rather than following joint lines) confirming a stress-redistribution failure mode independent of material decay. Finally, the installed Tell-Tale crack meter records no recent opening, confirming the current stability of the crack system. The classification as inactive is thus supported by the absence of geometrical, mechanical and monitoring evidence of ongoing evolution, and is independently grounded in historical documentation of the causal event.

The key innovation of this approach lies in the methodology employed for processing data obtained through detection and analysis practices [44].

The diagnostic framework developed in this study was directly adopted by the Superintendence ABAP for the Provinces of Verona, Rovigo, and Vicenza (local office of the Italian Ministry of Culture) as the scientific basis for the ongoing conservation design. Specifically, the cross-validated classification of the two crack systems informed a differential intervention strategy: priority monitoring and local structural stabilisation of the south façade macro-element, given its active kinematic condition, and the avoidance of unnecessary invasive works on the east façade, where the damage pattern is currently stable. This institutional adoption constitutes an external validation of the proposed methodology: the research outcomes were evaluated by the competent heritage authority and judged sufficiently robust to govern operative conservation decisions on a nationally significant monument.

The research approach used for the church of San Pietro is potentially applicable across various contexts, providing enhanced insights into the underlying structures within their historical and constructional frameworks and identity. Thus, this perspective supports a more accurate classification of existing conditions, which is instrumental and critical for developing targeted conservation strategies and interventions combining cultural studies with heritage science.

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## Author contributions

Conceptualisation, E.S.; Methodology, E.S., G.S., T.M, Validation, E.S., A.C., G.B., G.S., T.M.; Formal Analysis, E.S., A.C., G. B., G.S., T.M.; Investigation, E.S., G.S., T.M.; Writing – Original Draft Preparation, E.S., G.S., T.M.; Writing – Review & Editing, E.S., G.S., T.M.; Visualization, T.M., G.S.; Supervision, E.S., A.C.; Project Administration, E.S.; Funding Acquisition, E.S. All authors have read and agreed to the published version of the manuscript.

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## Availability of data and materials

The datasets generated and/or analysed during the current study are not publicly available due to the data’s co-ownership with the Italian Ministry of Culture. Still, they are available from the corresponding author upon reasonable request.

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