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Dynamic identification of the tabernacle of the church of Santa Maria Maggiore in Spello, Italy

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Abstract

The conservation of architectural heritage is a primary concern for the preservation of the cultural identity of a population and of the tangible proofs of historic architectural development. Architectural artifacts must be protected over time from all the threats that could derive by both the variation of inherent properties, as the aging of the constituent materials, and external actions, such as natural hazards and strong events, typically earthquakes. The preservation of architectural heritage against seismic events requires an in-depth knowledge of its dynamic properties, which can be affected also by local damages and material degradation.
In this work, the experimental tests carried out on the tabernacle of the church of Santa Maria Maggiore in Spello (Italy) for the estimation of its dynamic properties are presented. The tabernacle has been built at the beginning of the 16th Century by connecting stone elements through internal iron bars, resulting in a multi-block structure with a complex dynamic behavior.
An important role for the historical conservation of cultural heritage is entrusted to three-dimensional reconstruction of the built through the innovated techniques of Laser Scanner combined with UAV photogrammetry, that allowed to assess with a high degree of confidence the geometry of the built masterpiece.
Ambient Vibration Tests (AVTs) were carried out using 24 accelerometric channels divided in three different setups; the procedures have highlighted the complex behavior of such systems. In order to verify any effects of non-linearity and motion in free oscillation, the tabernacle has been further instrumented through 8 displacement transducers and subjected to an increasing applied lateral force, highlighting a rocking motion due to the presence of hinges located at the base of the columns.
The results, have highlighted the crucial role of diagnosis with a multidisciplinary approach in order to achieve proper decisions of interventions in the respect of the cultural heritage.

Keywords: Type your keywords here, separated by semicolons ;

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1. Introduction

Historic masonry buildings have a growing economic and social value in many countries. Preservation of the built heritage is considered an important goal in modern societies as, in addition to their historical interest, historical buildings significantly contribute to economy in a context where tourism has become a major industry. Preserving historic constructions is therefore not only a cultural requirement but also an economic and developmental demand (Bowitz et al. (2009), Galassi et al. (2022), Ruccolo et al. (2021), Zini et al. (2022)). In this context, in-depth analyses focused not only to the extreme load effects, but also to the aging and degradation of materials are fundamental for a comprehensive study of the monuments (Cavalagli et al. (2019), Biscarini et al. (2020), Hatir et al. (2021), Pepi et al. (2021)).

The dynamic behavior of monuments that are as fascinating as they are articulated cannot be easily interpreted by simple mechanical models due to the large uncertainties, affecting both the materials and structural behavior, that can come into play. In this work, a multidisciplinary approach is presented which has allowed to learn and model, with a high degree of confidence, the dynamic behavior of a monument, useful for the design of a subsequent seismic isolation intervention.

The Tabernacle of the main altar of the church of Santa Maria Maggiore in Spello, conceived by Rocco di Tommaso da Vicenza in the early 1500s, is one of the "masterpieces of Renaissance sculpture in Umbria". Made entirely of caciolfa stone (Focaoaru (1994)), the construction rests on four finely decorated pedestals, from which four Corinthian-style columns rise (Fig. 1.a), also rich in friezes and decorations, which support, through four circular arches, a hemispherical dome including a base of square shape in plan (Fig. 1.b). Each of the four arches presents at the impost a system of tie rods for the containment of the horizontal thrusts having a squared cross section of about 4 cm of side, presumably dating back to the construction phase of the artifact, and a temporary system of additional recently installed tie rods consisting of high strength steel cables (Fig. 1.c).

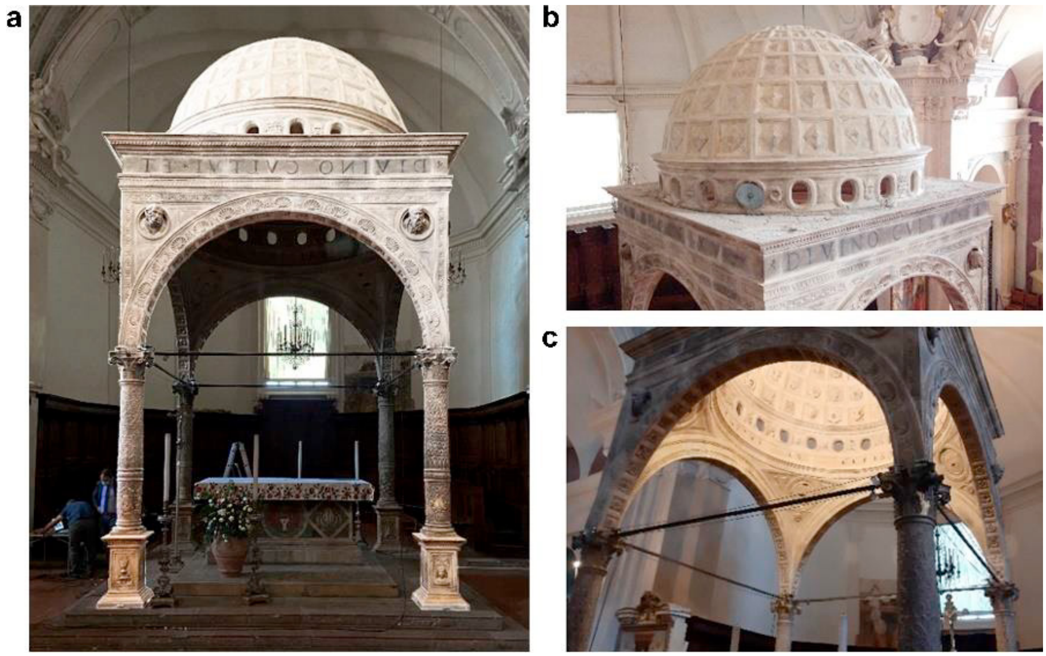


Fig. 1. (a) Tabernacle from aisle side; (b) Detail of the dome; (c) System of tie rods.

The structure is regular in plan, square in shape with a side of about 4.00 m. The columns develop to a height of 3.00 m, from the base to the top of the capitals, from which the circular arches stand on with a radius of curvature at the intrados of about 1.75 m. The structure above the four arches reaches 5.65 m in height, from which the hemispherical dome rises, which gives to the architectural complex a maximum height of almost 8.00 m. Internally, the hemispherical vault is connected to the arches through plume vaults, also made of stone.

In the first years of '90s, material investigation campaigns have been carried out through non-destructive tests after the seismic events that hit the Umbrian territory in the previous years. Material degradation was found at the base of the columns and in the walls of the plume, in which its basicity was lost due to carbonation processes. Investigations also revealed a significant degradation of the internal metal skeleton, a closed frame of a square shape that follows the plane of the arches, and the oxidation due to the material degradation of the plume walls.

In particular, the mortar of the sections on which the several blocks of the Tabernacle are connected are still today affected by a significant degradation (Fig. 2) due to the movements of the structure during seismic events.

(a) (b)

Fig. 2. Images of the state of degradation of the joints observed at the base of the columns.

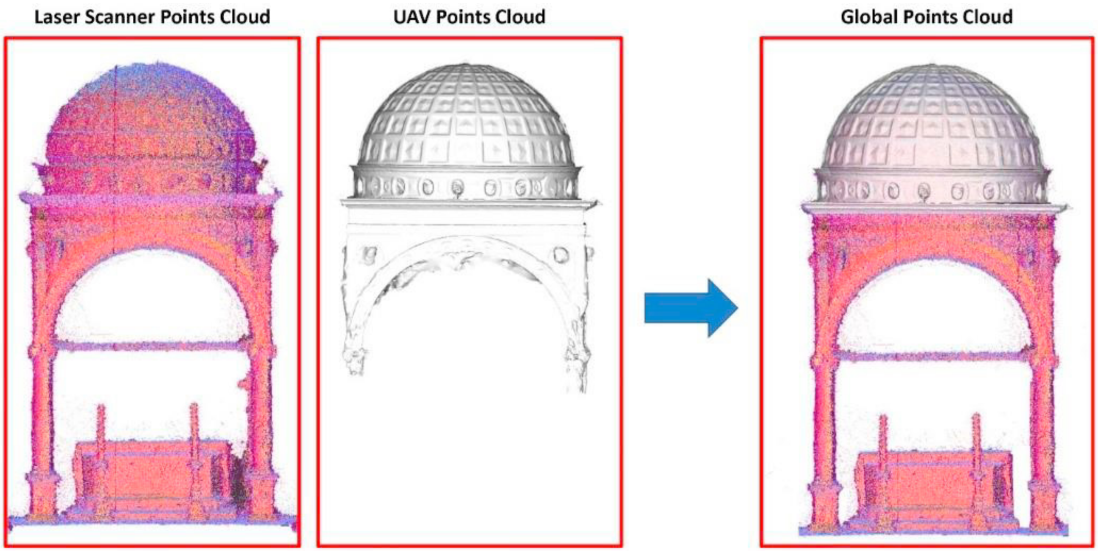


Fig. 3. Superimposition process of the two different points clouds.

2. Geometric survey of the Tabernacle: Laser Scanner e UAV Photogrammetry

An important role for the historical conservation of cultural heritage is entrusted to three-dimensional as-built reconstruction of the structure through the innovative techniques of Laser Scanner combined with UAV photogrammetry in extremely confined settings. The benefits of this approach allows to work in a conservative manner towards the cultural heritage, obtaining a very high degree of precision in a relatively limited time, in both the on site measurements and post-processing stage.

The relief of the tabernacle was approached with the use of two different technologies: a portable laser scanner model Zeb GO was used for the substructure and the intrados of the dome; the point cloud of the superstructure was obtained through UAV photogrammetry. With an acquisition time of about 6 minutes and 50 seconds, a dense cloud of points of the substructure was created, on which the dense cloud obtained with UAV photogrammetry made using 71 photos taken in manual flight was superimposed (Tab. 1). Figure 3 shows the outcome of the combined survey.

The synergy between these two different methods allowed to assess with a high degree of confidence the geometry of the built, essential in the reconstruction process of a digital model useful for the following analysis.

Table 1. Specification of the point cloud obtained by Laser Scanner and UAV Photogrammetry.

Technology	Time Acquisition (*s*)	Points
Laser Scanner	6m 50s	20.170.965
UAV Photogrammetry	12m 35s	49.557

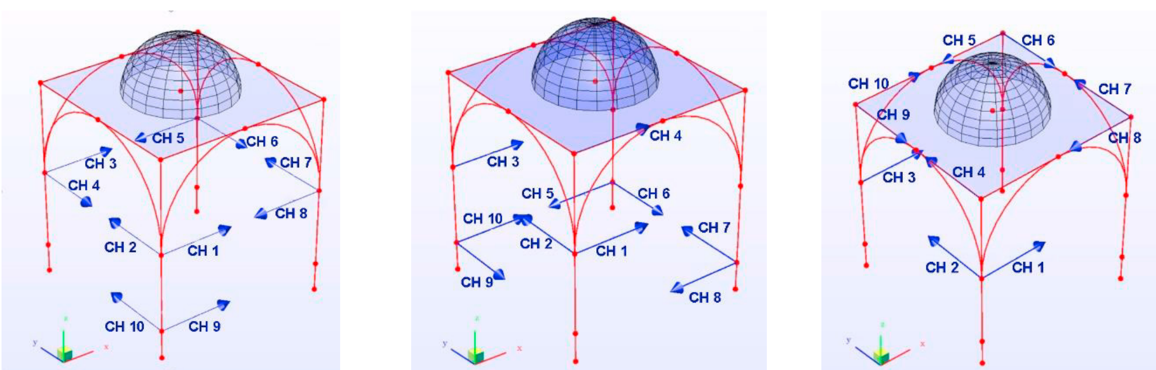
3. Dynamic identification

3.1. Description of the investigations and experimental setup

Dynamic identification in ambient noise conditions was performed through the use of high sensitivity PCB 393B12 piezoelectric accelerometers (10 V / g), mounted by threaded screws on steel angles to allow bi-axial measurement configurations (2 accelerometers). Each accelerometer was connected via a coaxial cable to the analog / digital acquisition and conversion system composed of NI 9234 type modules connected to a synchronization chassis model NI cDAQ 9188 both produced by National Instruments.

The structural response, in terms of acceleration, was recorded with a time step Δt = 0.000605 s for a total duration of about an hour. Recordings of 1800 seconds were used for each modal identification. In order to obtain an adequate spatial reconstruction of the modal displacements of the structure, three different measurement setups were used, in which the sensor arrangements illustrated in Figure 3 were adopted.

The three setups (Fig. 4) consisted of 10 acceleration sensors each, 3 of which were used as "Reference Transducers" (Ch 1, 2 and 3), kept in a fixed position in the various setups. In this way it was possible to carry out a dynamic identification of the 24-channel structure. The three instrumented levels are the base below the grafting section of the columns, the tax base of the arches, or the section above the capitals of the columns and the top floor, at the base of the dome.



(a) (b) (c)

Fig. 4. Layout of the sensors installed in the three configurations: Setup 1 (a), Setup 2 (b) and Setup 3 (c).

3.2. Analysis of the results

The MOVA software, implemented by the research group of the Department of Civil and Environmental Engineering of the University of Perugia (Garcia-Macias et al. (2020)), was used for dynamic identification.

The signals were pre-processed using a Butterworth band-pass filter with a frequency interval of 0.2-50 Hz of second order and resampling at a frequency of 100 Hz. The dynamic identification was performed in the time domain by means of the "Stochastic Subspace Identification" (SSI-COV) technique.

It was possible to identify 5 modes of vibration, whose properties are summarized in Table 2 and in Fig. 5.

Table 2. Description of the identified dynamic properties.

Mode No.	Decription	Frequency (Hz)	Damping (%)
1	Global Bending Mode – 1° Order – F(x1)	2.13	0.63
2	Global Bending Mode – 1° Order – F(y1)	2.44	0.73
3	Global Torsional Mode – 1° Order – F(x1)	3.52	0.76
4	Disjointed Mode – Dome, Drum and Arches Plane	17.46	0.7
5	Disjointed Mode - Pillars	25.04	1.00

In addition to the first 3 structural global modes, consisting of the first order bending modes in x (Fx1) and y (Fy1) directions and in torsion (T1), two higher order distortional modes (M1 and M2) have clearly been identified, which are associated to the multi-connected nature of the artifact. In particular, mode M1 involves the stone blocks of the upper part of the Tabernacle consisting of arches, the overlying structure and the dome, while the M2 mode is located on the supporting pillars of the structure.

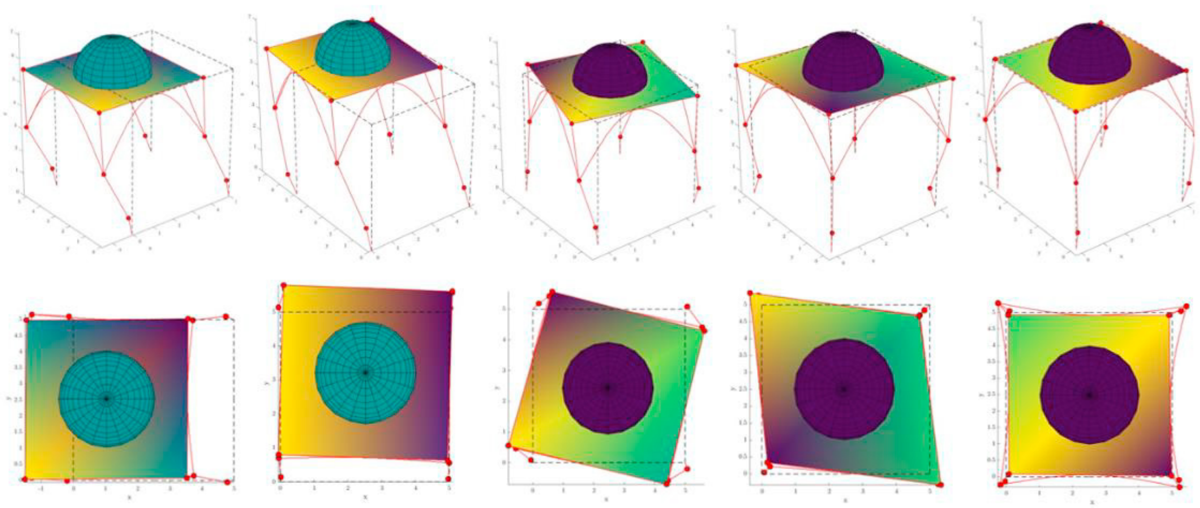


Fig. 5. Graphic representation of the modal shapes both in axonometric view and in xy plane (modes 1 to 5 from left to right).

The results highlight the multi-connected nature of the artefact, even in the regime of small displacements and deformations. In fact, by focusing attention on the pillars, all the modal shapes exhibit broken lines at the joints of the columns, which is more evident in the high-frequency modes.

4. Free oscillations tests

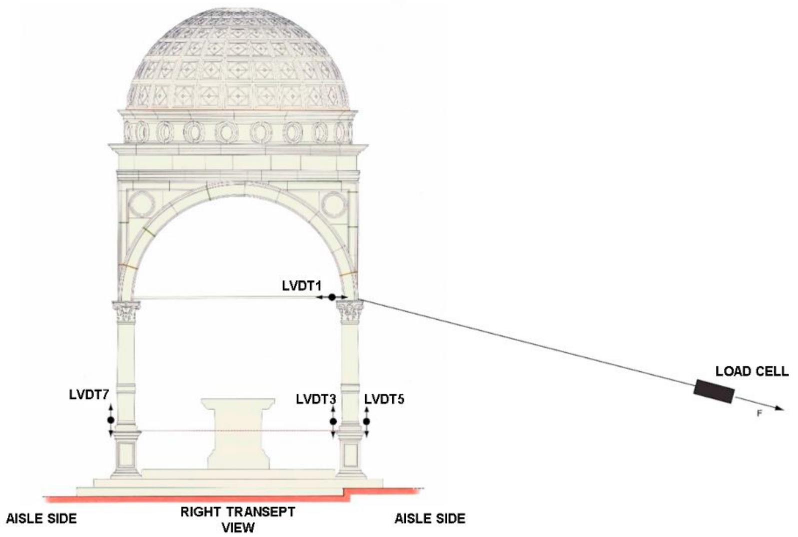
4.1. Description of the investigations and experimental setup

In addition to the modal tests, a quasi-static free oscillation test was carried out in which the Tabernacle was subjected to an increasing lateral force applied to the height of the shutters of the arches, or at the top of the columns, by means of a rope (Fig. 6). The purpose of the test was to verify any non-linearity effects and analyze the free response, in terms of oscillation frequencies and amplitude of displacements.

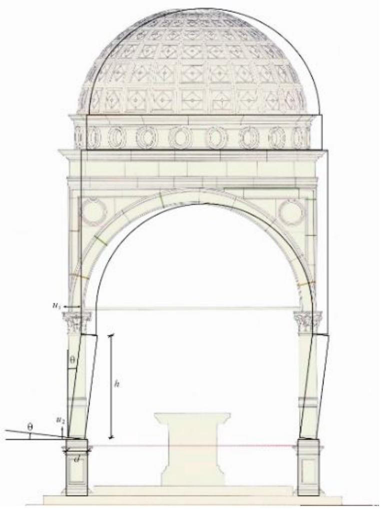
The adopted instrumentation consisted of a strain gauge load cell (model TC4 by AEP Transducers, max load 75 kN), used for measuring the pull in the rope, and 8 displacement transducers (LVDT), of which 4 (LVDT1-LVDT4) characterized by a measurement range of 0÷50 mm and 4 (LVDT5-LVDT8) of 0÷10 mm, for measuring displacement in specific points considered of particular interest. In particular, LVDT1 and LVDT2 were used for the measurement of the horizontal displacement at the top of two columns and LVDT3÷LVDT8 for the measurement of the opening/closing of the joints at the base of the columns.

In particular, the pull was applied at a distance of about 6 m and a height from the ground of about 1.50 m, so that the effective part of the applied force was calculated as the horizontal component of a vector inclined of about 15 ° on the horizontal. The displacement transducers have been positioned both at the top of the columns, that is near the point of application of the load, and at the base of the 4 columns, in correspondence with the joints with their respective bases, possible sites of rocking motion due to the formation of localized hinges. In fact, it is known from previous investigations that the monumental artifact consists of stone blocks connected by internal iron pins, in particular at the base and at the top of the columns, with further use of layers of mortar, which at present locally show poor states of preservation.

It can be deduced that the dynamics of the monument is conceivably characterized by the presence of further localizations of deformation, in addition those found and the deformation of the constituent material.



(a)



(b)

Fig. 6. (a) Side views of the test pattern and positioning of the displacement transducers. Fig. 6 (b) Hypothesis of the kinematic mechanism characterizing the dynamic motion of the monumental Tabernacle.

4.2. Analysis of the results

The application of the pull at the top of the columns made it possible to carry out an analysis of the motion of the Tabernacle in free oscillations, starting from an imposed displacement of about 1 mm. The plots in Fig. 7 show the time histories of the measured displacements, which show an evident oscillatory motion of the columns both at the top of the columns (Fig. 7.a) and at the base with opening/closing of the joints (Fig. 7.b and 7.c).

The power spectral densities of the recorded free response time histories are shown in Fig. 8. The results consistently indicate a main frequency of 1.84 Hz. Comparing this value with the first frequency identified in ambient vibrations - which corresponds to a flexural modal form in oscillation consistent with the motion imposed in free oscillations - a decrease of more than 20% is noted.

On the basis of the measurements performed, it can be deduced that this difference is linked to the presence of a rocking motion between the constituent elements of the monumental Tabernacle, which, moreover, is manifested by very limited displacements compared to what could be observed under horizontal actions of high intensity.

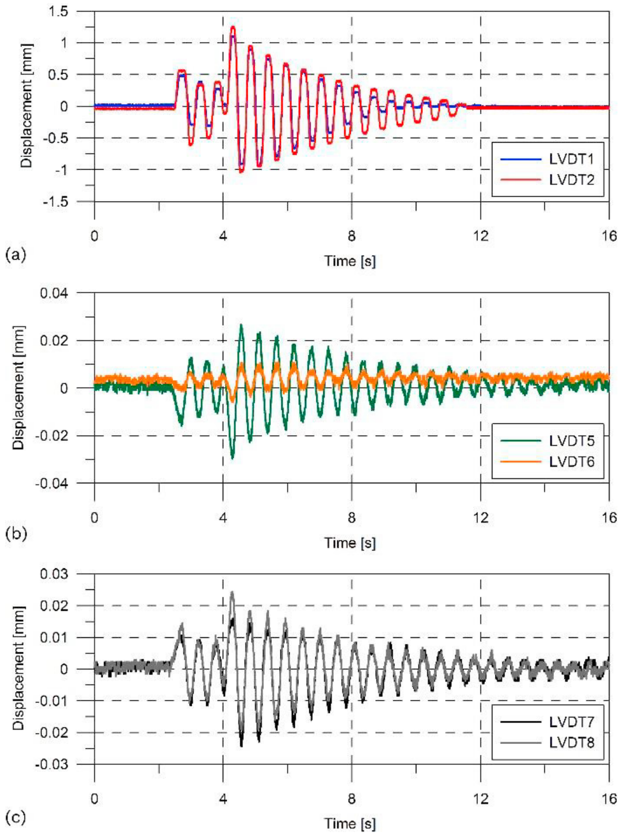


Fig. 7. Time histories of the displacements of the Tabernacle in free oscillations in the horizontal direction at the top of the columns (a) and vertically at the base, at the joints of the bases (b-c).

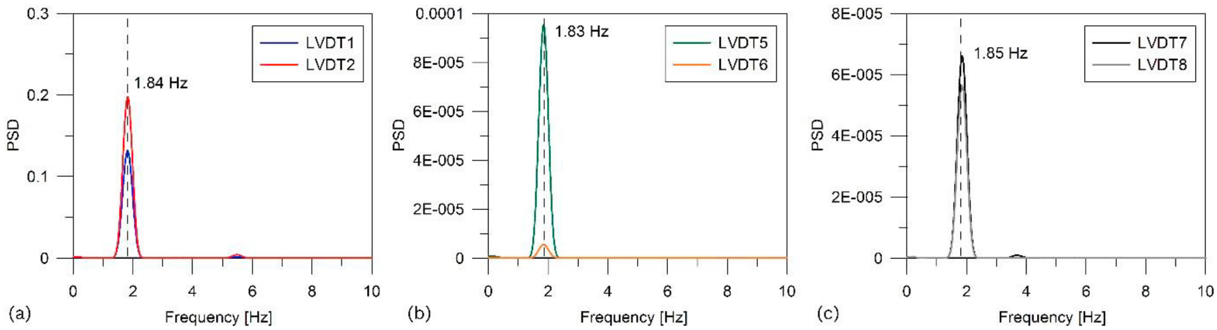


Fig. 8. Frequency spectrum of free oscillation displacement signals measured horizontally at the top of the columns (a) and vertically at the base, at the joints of the bases (b-c).

5. Concluding remarks

The paper has presented an investigation on the dynamic behavior of an architectural masterpiece, the tabernacle of the church of Santa Maria Maggiore in Spello, Italy, which is preparatory to designing a seismic retrofit intervention. The results, also strengthened by the outcomes derived by different nondestructive tests carried out about 20 years ago on the constituent materials, which emphasized the degradation state of the stone material corresponding to the most stressed areas of the joints, have highlighted the crucial role of diagnosis with a multidisciplinary approach in order to achieve proper decisions of interventions in the respect of the cultural heritage.

Three modes of vibration of the tabernacle have been clearly identified, the first two of the flexural type, along the direction parallel and orthogonal to the aisle, respectively, and the third torsional. The modal forms exhibit a disjointed motion of the blocks that make up the structure, even in the regime of small displacements and deformations. In fact, by focusing attention on the pillars, all the modal shapes show a broken line at the joints of the columns, which is more evident in the high-frequency modes.

By using displacement sensors applied at the top of the columns and at the base of the same, at the connection joints with the respective bases, it was possible to measure the opening / closing of the joints. The free oscillation test showed the presence of a localized rotation motion of the columns around the connection joints. It was also found that this motion is characterized by an oscillation frequency lower than that identified by identification tests in ambient vibrations of over 20%.

It can therefore be deduced that the structure under investigation is characterized by a non-linear dynamic behavior, the characteristics of which are manifested even in the presence of small displacements. Such a non-linear behavior is already attained at small displacement levels and should be carefully considered in designing a seismic retrofit intervention on the tabernacle.

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