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Non-destructive tests for structural diagnosis of the so-called Temple of Minerva Medica, Rome

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***Abstract* – The structural diagnosis of historic buildings should integrate on-site and in-the-laboratory experimental testing techniques, with no harmful effects on the structural and aesthetic health of the monument. In the present paper several non-destructive tests (NDTs) were conducted to study an archeological ruined building located in Rome, the so-called Temple of Minerva Medica. In particular, the experimental program comprised 3D geometric surveys by laser scanning and stereo-photogrammetry, thermal imaging, microclimatic parameters acquisition, sonic testing and ambient vibration monitoring. The above NDTs were executed from summer of 2016 until summer of 2017, in order to investigate the seasonal effects and/or the eventual changes in the structural response of the building, after the 2016-2017 Central Italy seismic sequence. The acquired data were stored in a repository that is available to the end-users for future studies and analyses.**

I. INTRODUCTION

The restoration and conservation of the archeological heritage is a very crucial task in Italy, where the concentration of historical and monumental buildings in urban areas is the greatest worldwide, as documented by UNESCO. In particular, in big cities rich in archaeological assets, such as Rome, historic buildings are subjected to potential degradation phenomena caused by urban pollution, traffic vibrations and excavation works that might threaten their structural stability. Moreover, natural hazards, such as earthquakes can add further concerns in seismic areas, like central Italy. Consequently, a vital step to their preservation is a deep knowledge of the mechanical behavior of such structures through the study of their geometry, material properties and state of conservation.

The relevance of obtaining data on the mechanical behavior of historic buildings can guide in the choice of appropriate mathematical models for structural analysis and in the proposal of repair and strengthening techniques. Such diagnosis of the state of the structure should result from both on-site and in-the-laboratory experimental investigation with no impact on structural health and aesthetic of the monument. In this context, non-destructive tests (NDTs) for structural diagnosis have changed the way engineers approach structural assessment studies, as a wide range of NDTs and in situ diagnostics are available and becoming a common component of structural evaluation projects.

In the present paper a variety of NDTs able to provide valuable information on the mechanical behavior and state of conservation of the structure were applied to the so-called Temple of Minerva Medica. The experimental program was conducted within the CO.B.RA. project, which focuses on the development of advanced technologies and methods for the conservation of cultural heritage assets.

A particular focus was put on the dynamic characterization of the main hall, as it is subjected to relevant vibration intensity induced by the surrounding tramways and railways traffic [1]. Firstly, a 3D geometric reconstruction of the monument was obtained by integrating information from laser scanner surveys and stereo-photogrammetry. Subsequently, thermographic images by infrared camera were collected, as well as microclimatic parameters, such as air temperature and humidity, in order to evaluate the thermal behavior of the masonry, which is known to influence also the dynamic behavior of the structure. Moreover, sonic testing was performed to investigate the interior consistency of the pillars masonry. Finally, ambient vibration acquisitions were carried out to characterize the dynamic response of the structure and its dependency on the microclimatic conditions.

All the above parameters were stored into an integrated information system (repository) that preserves the collected data able to characterize the monument in terms of dynamic response and mechanical properties.

II. THE MONUMENT

The studied monument is an ancient ruined building located in the city-center of Rome, on the Esquiline Hill, between the via Labicana and Aurelian Walls.

Fig. 1. View from North of the so-called Temple of Minerva Medica.

In 16th century, it was erroneously interpreted as a temple dedicated to Minerva Medica (“Minerva the Doctor”), as mentioned by Cicero and other ancient sources. Recent studies hypothesized the structure might be an ancient nymphaeum of Imperial Rome (early 4th century A.D.), probably part of the *Horti Liciniani*, but attribution is still discussed [2].

After initial misinterpretation it was widely known, and still today, as the Temple of Minerva Medica. The structure is a majestic building with decagonal polylobate plan, a diameter of 25 m and a overall height originally of 32 m, currently reduced to only 24 m after the dome partial collapses during the centuries (Fig. 1).

Initially, the structure was entirely built using the typical roman technique called *opus latericium*. Soon after the construction the building presented structural problems. Consequently, it was restored and reinforced through works in *opus mixtum* of tuff bricks and Roman bricks. Also, the lateral niches were closed and some walls with the function of buttresses were built in the southeast side of the monument. The need for such additional buttresses testify the presence of structural weakness in this part of the structure. As a confirmation, the major historically documented damages were concentrated at the south side, where recent investigations indicated the presence of weaker foundations [2]. After several collapses during centuries of abandon, a major restoration intervention was carried out in 1846 for the reconstruction of first floor arcade of the southeast side. More recently, another relevant restoration intervention reconstructed also the upper floor arcade of the southeast side in 2012-2013. As a consequence of such a long history of collapses and reconstructions the current masonry results quite heterogeneous in materials and shapes.

III. NON-DESTRUCTIVE TESTING PROGRAM

The NDTs were executed in a period of time that went from summer of 2016 until summer of 2017, in order to investigate the seasonal effects and/or the eventual changes in the structural response of the building, in consideration also of the possible effects of the seismic sequence that hit Central Italy from August 2016 to February 2017.

The experimental program can be summarized as follows:

- Geometric survey;
- Thermal images and microclimatic parameters;
- Sonic testing;
- Ambient vibration acquisitions.

A. Geometric survey

Laser scanner acquisitions and photogrammetric mapping for 3D reconstruction and geometry survey of the structure were performed. The laser scanner measurements were acquired in summer of 2016 (August 5th) and in winter of 2016 (December 20th), when air temperatures were supposed to be the highest and the lowest of the year, respectively.

Both acquisitions were carried out in late morning at similar daytime in order to analyze the seasonal effects neglecting the day/night cycle effect in terms of thermal expansion phenomena. In particular, they were performed using a Riegl Z360 equipped with a Nikon D100 digital camera (see Fig. 2a). The instrument nominal angular resolution is 0.0025° horizontal and 0.002° vertical, while range accuracy can achieve +/- 6 mm. Retro-reflecting targets fixed at each pillar at the height 2.5 m from ground level were used as reference positions in order to compare the two surveys.

Such a detailed 3D geometrical survey was the base both for measurements of distances between walls at unreachable points and for the mathematical modelling for successive structural analyses (see Fig. 2b). For instance, several internal walls distances from summer and winter surveys were compared in order to assess the effects of masonry thermal expansion.

In addition, also a stereo-photogrammetric survey was executed with the use of a Nikon D60 camera and comprised about 500 digital images (10 Mpx each). The above images were post-processed with Structure from Motion (SfM) methodology [3].

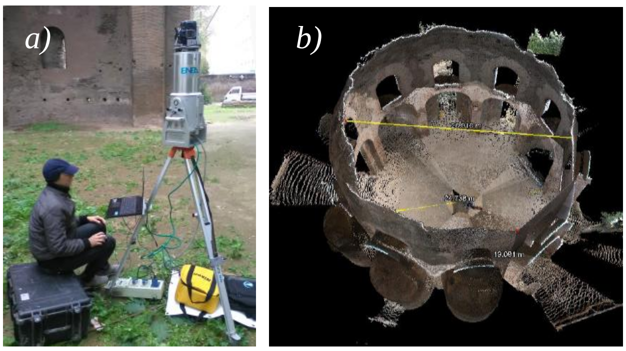

Fig. 2. Laser scanner setup (a). 3D reconstruction of the monument by acquisitions in summer 2016 (b).

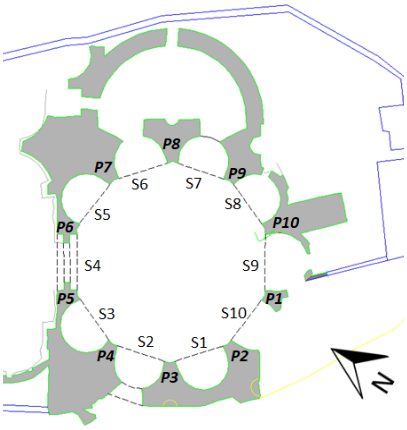

Fig. 3. Decagonal plan of the main hall.

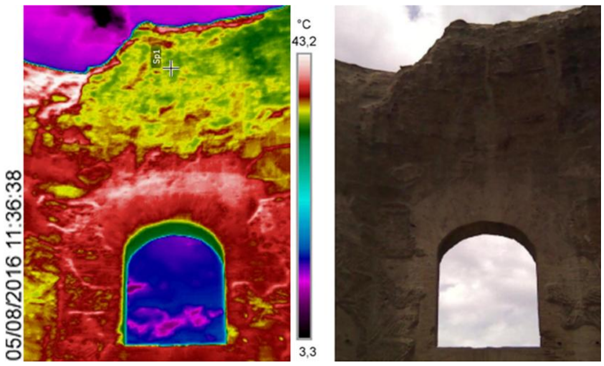

Fig. 4. Thermal image of upper floor arcade on the northwest side (S3) of the monument.

Data processing for SfM was performed by Agisoft PhotoScan software via ENEAGRID, available on CRESCO (Computational Research Center for Complex Systems) HPC infrastructure [4].

A dense cloud of 30 million points was obtained and mesh returned more than 200,000 tria element.

Stereo-photogrammetry by SfM is complementary to laser scanning, since it is less accurate in 3D geometry reconstruction, but is able to provide more detailed documentation of the crack pattern [5].

B. Thermal images and microclimatic parameters

Thermographic data of the inner walls of the monument were acquired using a Flir T440 thermal infrared camera from the center of the main hall at around midday. The building images were subdivided in 10 ground floor and 10 upper floor views, corresponding to the sides of the decagonal plan (Fig. 3). The thermal images were captured on the same two dates as the laser scanner surveys and in August 2017.

The thermographic measurements were calibrated by correlation with the temperatures resulting from two microclimatic monitoring stations, which provided also the air humidity and pressure data. In particular, air temperature and humidity were monitored by two MSR145 mini data loggers positioned on the west side (pillar P4) and on the east side (pillar P8), respectively.

A difference of about 30° C was recorded between the maximum temperature values of the masonry in August and in December surveys.

A temperature diagram was obtained as a function of the walls solar exposure (ground and upper floor sides) for all three acquired seasons, putting into evidence the thermal differences between walls. The temperature of the walls was higher in the upper arcade and particularly in sides S1, S2 and S3 (northwestern sides of the monument), where temperatures reached 40° C in August (Fig. 4), as a result of the direct solar beam exposure of their upper inner wall-faces due to the big hole left by the collapsed dome. Walls on the eastern and southern sides (S7, S8, S9 and S10) revealed maximum values of only 34-35° C. In December the walls temperature resulted more uniform, increasing only slightly, from 8° C at the bottom to 12° C at the upper arcade.

C. Sonic testing

The base of each pillar was investigated through sonic tests in order to verify the state of compacity of the masonry and to estimate its compression strength. The sonic tests were executed in February 2017 using the sonic transmission procedure, i.e. through the thickness of the wall [6]. This technique is especially useful for investigating heterogeneities in construction materials, such as historic masonry, allowing the identification of layering of the sections, the presence of voids, cavities and anomalies in material density. Equipment comprised an instrumented hammer with a PCB ICP accelerometer, as well as the probe, both cabled to the acquisition unit. Data were acquired with a sampling frequency of 500 kHz. the sonic measurements was made reference to the UNI 10627-1997 [7].

In (Fig. 5) a diagram showing the sonic test velocity recorded at each pillar, labeled as in Fig 3, in function of the distance d from internal pillar face (see measurement configurations in Fig. 6), is depicted. Initial values (d = 0) tend to decrease at higher values of d, indicating poorer material properties of the core (*opus caementicium*) with respect to the wall-face brickwork layers (*opus latericium* or *mixtum*). The low initial value of pillar P4 is due to a crack in the wall-face layer. The lowest values were measured in pillars P9 and P10 at d in the range 80-120 cm. For d > 120 cm the lowest values were obtained for pillars P1 and P2, which were rebuilt in mid-19th century.

D. Ambient vibration acquisitions

Ambient vibrations were acquired by digital recorders equipped with triaxial velocimeters provided with a GPS antenna for time synchronization.

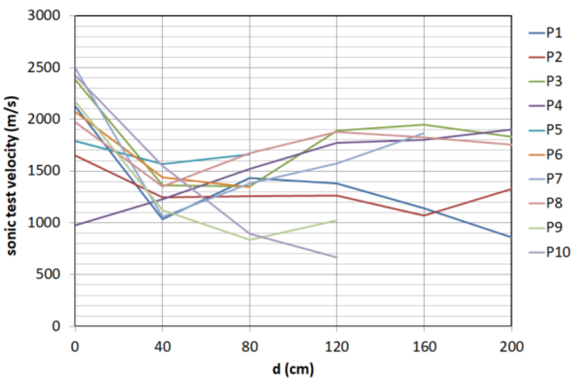

Fig. 5. Sonic test velocity recorded at each pillar in function of the distance from internal face (d).

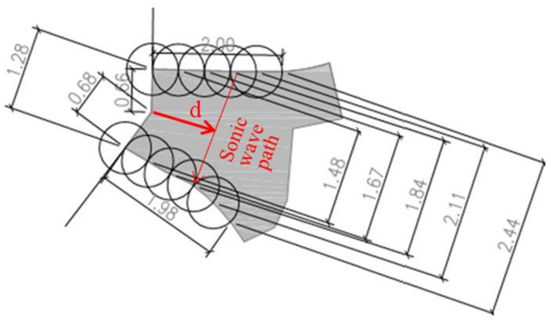

Fig. 6. Sonic test configurations at pillar P1.

Data were acquired both at ground level, to obtain indications on the points where the base excitation due to the nearby traffic (road, trains and trams) is stronger, and on the façade, to assess the amplification to the structure and the dynamic behavior of the building. Each position was acquired for at least 20 minutes at a sampling frequency of 200 Hz.

Vibrations were acquired in four sessions carried out on separate dates over a one-year span in order to evaluate the seasonal effects, listed in chronological order as follows:

- Session 1: summer 2016 (4 July 2016);
- Session 2: winter 2017 (1 February 2017);
- Session 3: spring 2017 (19 April 2017);
- Session 4: summer 2017 (13 July 2017).

Several time/frequency domain calculations and modal analysis techniques were applied for mutual validation of results. In particular, the Frequency Response Function (FRF) was calculated using the Transmissibility Function H [8], the Frequency Domain Decomposition (FDD), the Enhanced Frequency Domain Decomposition (EFDD), the Cristal Clear Subspace Stochastic Identification (CCI-SSI) [9] and the Horizontal Vertical Spectral Ratios (HVSR) [10] were calculated at windows and on top of the façade.

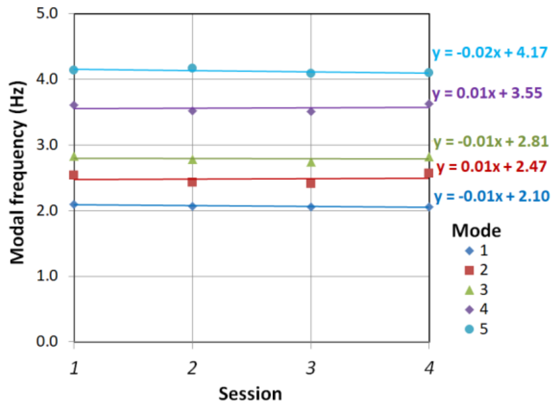

Fig. 7. Modal frequencies of the monument from July 2016 (session 1) to July 2017 (Session 4).

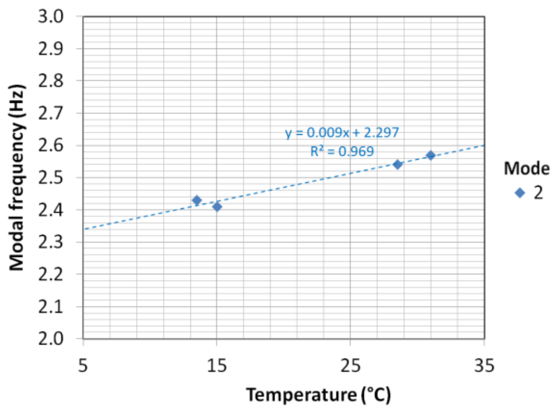

Fig. 8. Influence of air temperature on the second modal frequency of the monument.

In Fig. 7 the average values of the calculated modal frequencies are depicted for each acquisition session, demonstrating the substantial seasonal stability of the dynamic response of the structure. In fact, the modal frequencies slightly increase with the temperature (Fig. 8), but recorded variations are limited in the range of 2-6 %. A remarkable correlation was found between modal frequencies and air temperature, as showed in Fig. 8.

E. Repository

The architecture of COBRA repository is designed so that acquired data are transferred to a storage area by synchronization with the dedicated OwnCloud partition specifically created for the project. This mechanism runs automatically allowing researchers to acquire their data in the usual modes and formats. In this way the great amount of data produced during the surveys is stored in full safety and integrity.

Stored data can be permanently retrieved by the authorized users. A staging area is provided, where raw data can be enriched with metadata and then be stored in the repository as structured data to be possibly submitted to dedicated analysis software. Further, a software system that allows real-time remote monitoring of monument's parameters and image flows was developed.

The CO.B.RA. repository is accessible upon registration from the CO.B.RA. project site (http://cobra.enea.it/). The end-user is provided with credentials to freely download data of the monitoring campaigns and other useful information on the monument.

IV. CONCLUSIONS

In the present paper the results of a variety of NDT techniques applied to the study of the so-called Temple of Minerva Medica are shown. The several investigated physical properties of the monument were integrated in an effective database for a comprehensive understanding of the overall structural behavior. On the one hand, the influence of the geometry and of the environmental conditions (especially, in terms of solar exposure) on the thermal behavior of the structure was highlighted. On the other hand, the thermal properties resulted the main factor affecting the dynamic behavior of the structure, as proved by slight variations of modal parameters highly correlated with the air temperature. Consequently, no evidence was found of any relevant impact of the Central Italy seismic sequence on the dynamic behavior of the monument.

The mechanical properties of the masonry, investigated by sonic tests and the surveyed crack pattern will be fundamental for the production of representative numerical models, e.g. finite element models (FEMs), to be used for future structural analysis.

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