Evaluation of the masonry and timber structures of San Francisco Church in Santiago de Cuba through nondestructive diagnostic methods

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Summary

Recently, due to a renewed interest in the religious architectural heritage of the Caribbean island of Cuba, some important interventions for the restoration and reinforcement of the colonial churches of the island were carried out. The authors, collaborating with the Archdiocese of Santiago de Cuba in a project concerning the protection of Cuban churches, applied some nondestructive and noninvasive destructive tests for an in-depth study of the main characteristics of those structures. The diagnostic method, developed mainly for the historical buildings or monuments of Europe and North America, was used to study some peculiarities of the building construction traditions of this area. The proposed techniques revealed the existence of several original solutions, for example, defenses for seismic mitigation, developed to resist the earthquakes that frequently affect the area.

KEYWORDS

colonial churches, Santiago de Cuba, sonic tests

1 INTRODUCTION

The article presents the results of a diagnostic campaign carried out on some structures of the church of San Francisco in Santiago de Cuba. The church, an 18th century neoclassic building, was constructed in a seismic area of the island and, according to the historical research, should present unusual structural solutions to face the actions induced by earthquakes.

The convent of San Francisco in Santiago de Cuba was founded in 1750 and consists by a church, the second most important in the city, and the convent to house the friars and their charity activities.

This paper focuses on the church and its structures, aiming to complete the knowledge of the constructive techniques and the changes occurred during centuries after many earthquakes and interventions of restoration. In a plan dated 1796, the sections of the pillars are represented with a small brown square inside. By comparison with building techniques used in colonial churches of Santiago, the placing wooden columns inside brick masonry pillars is assumed to a way of improving seismic performance.

Some specific diagnostic tests were planned and performed to analyze this building technique typical of Oriente (the eastern region of Cuba) during Spanish colonization.

In this paper, the diagnostic procedure and their results are documented, in order to create a preliminary scientific study of the traditional building techniques in colonial Cuba.

The proposed methods were mainly based on nondestructive (ND) and minor-destructive (MD) techniques. The diagnostic plan was organized first for an overview of the morphology of the masonry structures through direct sonic tests. Large and massive pillars were further investigated by applying a simplified sonic method, based on crossing sonic wave paths. A few MD investigations, such as core drilling and boroscopy, were limited to a few areas previously identified through the interpretation of the sonic velocity distribution in the masonry structures.

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Other tests were carried out for the study of the moisture content in the load-bearing walls.

2 SHORT DESCRIPTION OF THE BUILDING CHARACTERISTICS DEFINED THROUGH THE HISTORICAL ANALYSIS

The presence of the Franciscan friars is documented since the foundation of the city of Santiago de Cuba, in 1515.[1] Their convent was previously built in the center of the ancient city, but in the 18th century, the religious order moved to the current location. As written in a document now archived in the Archivo de Indias in Seville (Spain), the construction of the new church began several years before 1793, probably around 1750.[2]

After only a few years, on July 11, 1766, at 11:50 am, a major earthquake destroyed several buildings in Santiago, including the church of San Francisco.[3]

In 1786, friar J. Saco rebuilt the roof of the church, and in 1790, the reconstruction of the building began. During colonial times, the design of every monument built in the new cities of Central and Latin America by Spanish settlers was developed in Spain: double copy of the document was prepared, one was sent to the colony, and the other was stored by the Spanish government. Local craftsmen received the plan and built the monument using local materials and techniques. A fusion between the European design of sacred architecture and civil government buildings and the local traditional techniques of construction gave rise to the most important buildings in the Spanish colonies. Currently, many of these documents are archived in the Archivo de Indias in Seville: several projects are still available for study and comparison with colonial buildings realized by local craftsmen. The influence between the planning procedures in Spain, the traditional Spanish building techniques, and the real constructive knowledge in the colonies have still to be investigated.

In plan MP-SANTODOMINGO 588 (Figure 1), dated 1796, the progress of reconstruction of the church of San Francisco is indicated by red or yellow lines technique[4,5]: complete church (in red) is built, but the Chapel of the Holy Sacrament and the Sacristy are still missing (in yellow), but planned. In the document attached to the plan, materials and costs of the reconstruction are indicated.[6] The most interesting element in the plan is the drawing, inside every pillar, of a small brown square with an uncertain significance (Figure 2). Comparing the structure of the churches built during the colonial era in Santiago, some common features are clear. Every church has an external wall built with stone masonry, but the internal structure and the roof are sustained by wooden pillars. This technique is extremely important in

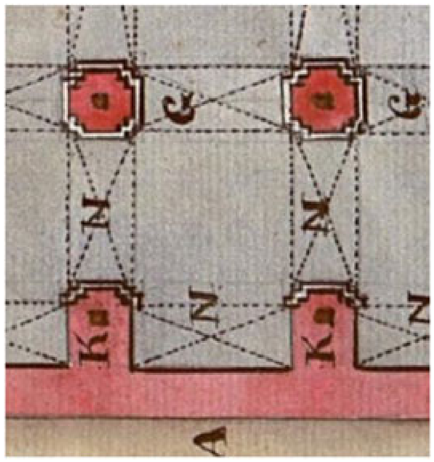

FIGURE 2 A detail of the pillars with the dark rectangular shape inside the structures

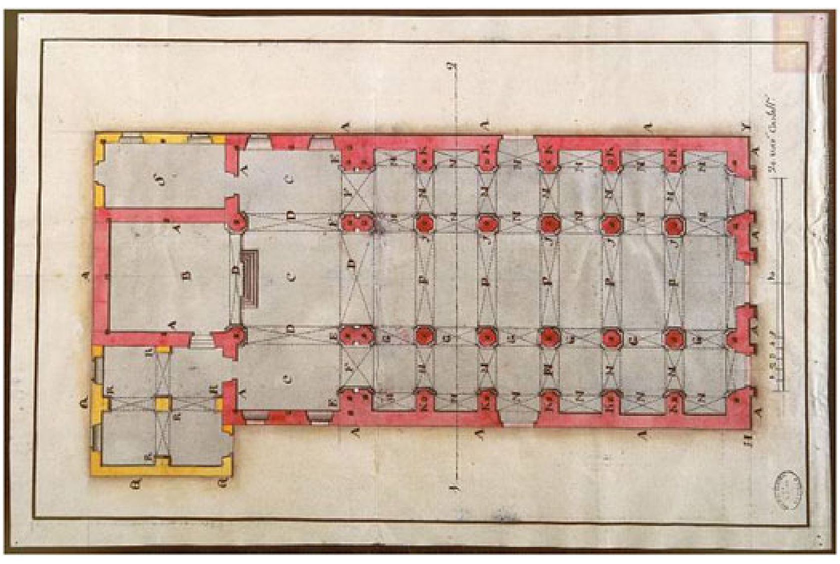

FIGURE 1 Plan MP-SANTODOMINGO 588 (1796) showing the state of the reconstruction by the red or yellow (here dark or clear) technique

this area, permitting the monuments to resist both the strong winds (hurricanes and tropical storms are frequent) and the earthquakes. The pillars of San Francisco are now built externally with very regular and well-constructed brick masonry, but specific investigations were necessary to verify if it was possible to find a wooden structure inside the pillars.

The complex was seriously damaged again in 1842 and 1843 by some major earthquakes, which occurred in the area.

In 1850, the bell tower, no longer standing, was built. The conservation conditions of the building were extremely poor in that moment; this is demonstrated by some documents in the Archive of the Archbishopric of Santiago, where several materials are listed to be bought to reconstruct the pillars of the church in 1853–1856.[7] Using exclusively archival documentation, it is not possible to determine the effectiveness of this intervention and the changes operated in the church: diagnostic investigation was necessary.

At the beginning of the 20th century, Santiago architect Carlos Segrera Fernández designed and built the new façade of the church, a structure including a new bell tower. The new façade is attached to the historical structure of the church, which was modified to sustain the concrete structure of the tower. The drawings reported in Figure 3 show the actual geometrical characteristics of the church, according to the ongoing survey of the complex.

Presently, the church of San Francisco remains seriously damaged by Hurricane Sandy, which struck the city in October 2012. The structure lost part of the roof, which was temporarily restored in 2013–2014. A complete restoration is necessary to stop the decay of materials and structures. This investigation is the first step towards bringing the second most important church of Santiago back to its religious, cultural, and social role for the city and its community.

3 APPLICATION OF A MULTILEVEL STUDY APPROACH TO THE CASE STUDY

As mention before, the Archbishop of Santiago de Cuba has initiated a progressive restoration of the main religious buildings. The definition of the interventions is mainly based on

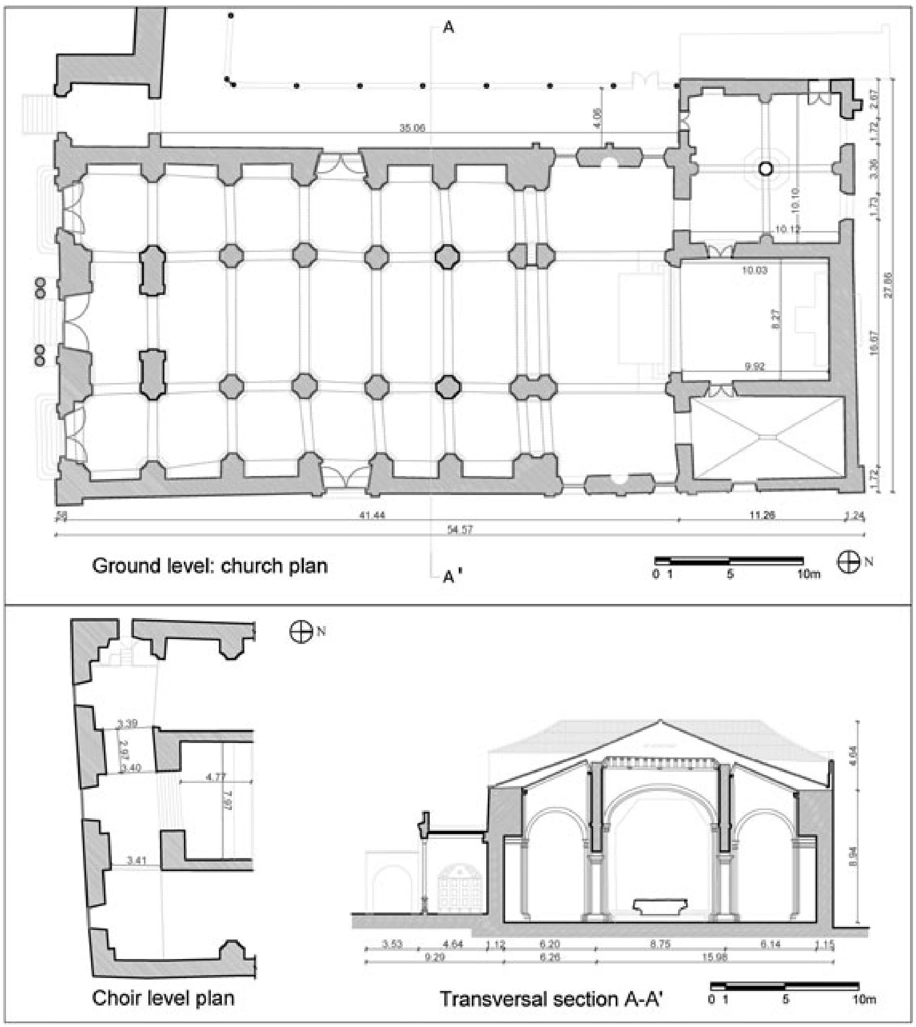

FIGURE 3 Geometrical survey of San Francisco Church in Santiago de Cuba

surveys of the most common pathologies recognized by visual inspections. For the evaluation of the structural conditions of the building, a diagnostic plan based on ND and slightly destructive investigations was arranged.

The authors proposed a series of ND and MD tests in order to provide a significant overview of the building techniques used by the local builders and an evaluation of the general state of conservation of the structures.

Direct pulse sonic tests were proposed for a first investigation of the masonry sections of the pillars and the load-bearing walls.

The setting of the so-called diagnostic plan benefitted from important historical analysis of the building. Some documents examined in the Archive of Indias indicated the presence of timber vertical trunks inside the masonry pillars. The diagnostic plan was consequently organized with a special configuration of sonic tests in order to verify this information.

3.1 The multilevel approach for the in-depth study of a historical building

The research on a reliable study methodology on the characteristics of historical structures was applied to a historical church presenting several decay problems and the common assessment limits imposed by historical buildings. The study in depth of the building properties was organized by a multi-level approach, including the historical analysis and some ND and MD testing techniques for evaluating the condition of structural elements.

The in-depth study of historical buildings is a topic that was treated by several authors involved in the preservation of the architectural heritage.[8–10] According to the experiences compiled by different authors, some remarks for the study procedure can be drawn out:

1. Historical research is fundamental for the comprehension of the building evolution: it allows for interpreting the general construction logic and recognizing the main changes and transformations.
2. The complete survey of the building, composed by plans, main fronts, and sections is useful for identifying the geometrical characteristics, and the accuracy of the drawings can support further studies of the materials, their pathologies, and the presence of mechanical problems (revealed by deformations or important crack patterns).
3. ND tests, such as thermovision, radar, or sonic tests, applied to historical masonry, commonly composed by irregular and fairly homogeneous structures, provide qualitative results, usually presenting some uncertainty for their final interpretation. It depends on the low invasiveness presented by these techniques when used for studying inhomogeneous elements: thanks to this characteristic, ND tests can be applied to large surfaces or to many areas of the building, respecting the integrity of the historical structures. The interpretation of the qualitative results is not always clear and requires specific expertise for its comprehension.
4. MD methods can better address the characterization of the historical structures, according to their direct contact with the material components forming the building elements. Tests such as video boroscopy or the partial dismantling of masonry sections are based on the visual inspection of the building components, but these procedures must be limited to precise areas and cannot be carried out in an extensive way in order to avoid evident damages to the historical buildings.
5. Being not invasive procedures, ND tests such as thermovision, radar, and sonic tests can also be carried out in a complementary way in order to combine the results for improving the final interpretation of the state of conservation of the structures.

These general indications where obtained during the experimentation and sometimes the calibration of diagnostic tests on large and complex historical buildings. The use of a large amount of complementary testing techniques, providing qualitative and quantitative results, requires important economic investments or strategic cost containment. These conditions are typically present for important public conservation works on monuments or in the academic field. For the proposed research, the in-depth study of a colonial church in Cuba was carried out with a limited budget and consequently, the diagnostic plan was based on the use of limited testing techniques:

1. Direct sonic tests on the main masonry structures, in order to qualify the morphology of the wall sections;
2. Video boroscopy limited to a few significant points of the previously examined structures (according to sonic tests results);
3. Material sampling, for characterizing the properties of the mortar used in the joints.

In the next paragraphs, a detailed description of the historical information related to the case study is reported. The organization of the diagnostic plan was derived from important observations deduced by the historical analysis.

3.2 Short overview of the direct sonic test

Sonic tests are based on the propagation of elastic waves into a solid body. In theory, if the material is homogeneous, isotropic and elastic, the velocity of the sonic waves is directly associable to its mechanical characteristics: elastic modulus above all.[11–14]

The sonic velocity varies for different materials. According to experimental studies, the sonic velocity into compact rocks is around 3,480 m/s, while it decreases to 342 m/s into atmospheric air.[15]

Historical buildings, characterized by heterogeneous structures, can be also studied by applying sonic tests, but the results are only qualitative. If the heterogeneous structures respect the common building roles in its composition, such as a certain care in the connections of the different materials components (such as in multiple leaf walls), the propagation of the sonic waves is not affected by local discontinuities in the masonry section and the sonic velocity can be associated to this condition. Due to the low velocity characterizing the propagation of the sonic waves into air, the test can reveal the presence of discontinuities (caused by cavities, cracks, or not optimally assembled elements) in the historical structures.

The test is carried out through specific probes: an instrumented hammer is used on the emission point to generate the pack of waves travelling inside the material, and an accelerator is placed on the receiving point. Both instruments contain a piezoelectric device allowing the conversion of a mechanical quantity into an electrical tension. The instruments are connected to a personal computer, through a dedicated signal acquisition board, where the data are stored and visualized using specific software: commercial software sold with the test instrumentation is diffused. Although some differences between the commercial software are present, the common representation of the acquired data is given by an amplitude–time graph where the signals provided by the instrumented hammer and the accelerometer are displayed.

The sonic test is carried out by reporting a grid of points on the surfaces of the object that has to be investigated. According to the main standards,[11–14] three main test configurations (Figure 4) are identified:

1. Direct sonic test: when the emission and the acquisition points are reported on the opposite sides of the structure and the hypothetic connecting straight line is perpendicular to the vertical surfaces.
2. Semidirect sonic test if emitter and receiver are displayed on adjacent walls.
3. Indirect sonic test, if emitter and receiver are displayed on the same side of the wall.

The elaboration of the test consists in the evaluation of the travel time of the pack of waves from the origin to the arrival point. Knowing the distance between emission and receiver point, the ratio between the distance and the travel time provides the sonic velocity. The calculation of the travel time can be obtained manually, through the interpretation of the acquired signals, or automatically, using specific algorithms implemented in the last years for this purpose.[16]

The common representation of the results is given by bar charts, showing the distribution of the velocity for each point. If the distance between the points used for the grid is short, the different punctual velocities can be extended to the areas contained between the points through specific software. The final output is a map of the velocity of the tests area in gray or color scale. This representation supports the qualitative interpretation of the sonic tests.

3.3 The crossing path sonic test proposed for the depth study of the pillars of the church

After the controls on the state of conservation of the church carried out through the geometrical survey, the large number of structural elements (eight cross-shaped pillars, four composite pillars, fourteen in-built pillars, and several load-bearing walls) had to be investigated. The direct sonic test was proposed in order to study the different masonry elements with a technique that could ensure an extensive application without compromising the respect for the historical surfaces.

As described in Section 4.1, the direct sonic tests were carried out by reporting a geometrical grid of points on the opposite sides of the masonry walls. This configuration was used also for the pillars of the central nave: the points grids were reported through removable adhesive on the north side (emission points) and on the south side (receiver points). This organization of the test was repeated also for the east

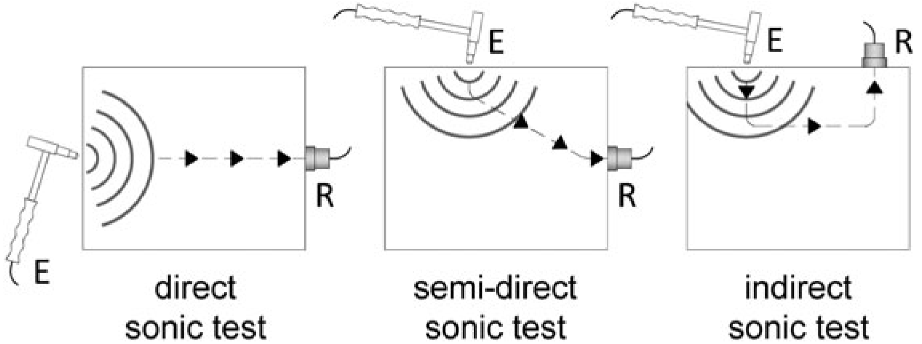

FIGURE 4 Sonic tests layouts according to the position of emitter (E) and receiver (R)

(emission) and west (receiver) sides of the pillars (Figure 5). After the elaboration of the acquired data obtained to the two separate tests, a sonic velocity was associated to each point of the north–south grids and to the east–west grids. After collecting these data, a further elaboration was proposed in order to achieve more reliable qualitative results. The purpose was to refine the results for the pillars in which the presence of timbers was expected.

The pillars were also studied through sonic tests based on perpendicular crossing trajectories. This method is founded on the common acquisition of the sonic travel time of two separate tests. These tests are organized along the trajectories set by reporting a grid of points on the opposite sides of the pillar: north–south and east–west direction. The grids for the tests are arranged in order to have an ideal straight line connecting two points placed on the opposite sides of the structure, perpendicular to the wall surface. As a result, reporting the points on the four sides of the pillar, for each level of the tests, the crossing between north–south and east–west paths forms a horizontal grid where the intersection between the trajectories leads to a series of ideal points (Figure 6). Instead of elaborating the results

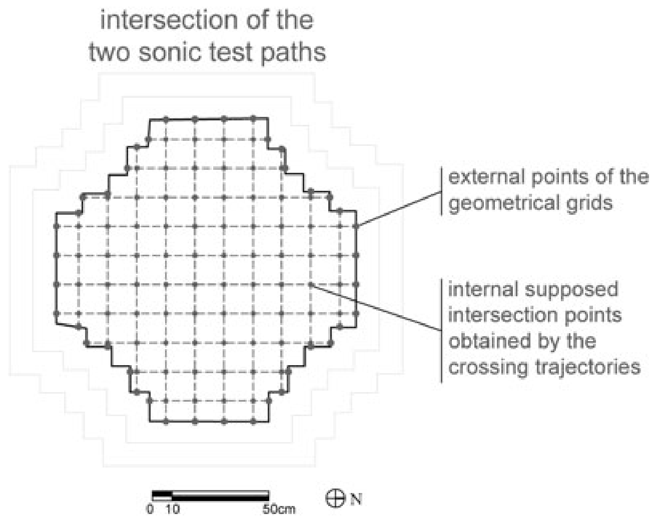

FIGURE 6 Sonic tests layout obtained by the intersection of the north–south and east–west testing paths

as separate tests, the influence of the discontinuities in the masonry section can be studied by evaluating the intersection points obtained by the crossing horizontal trajectories.

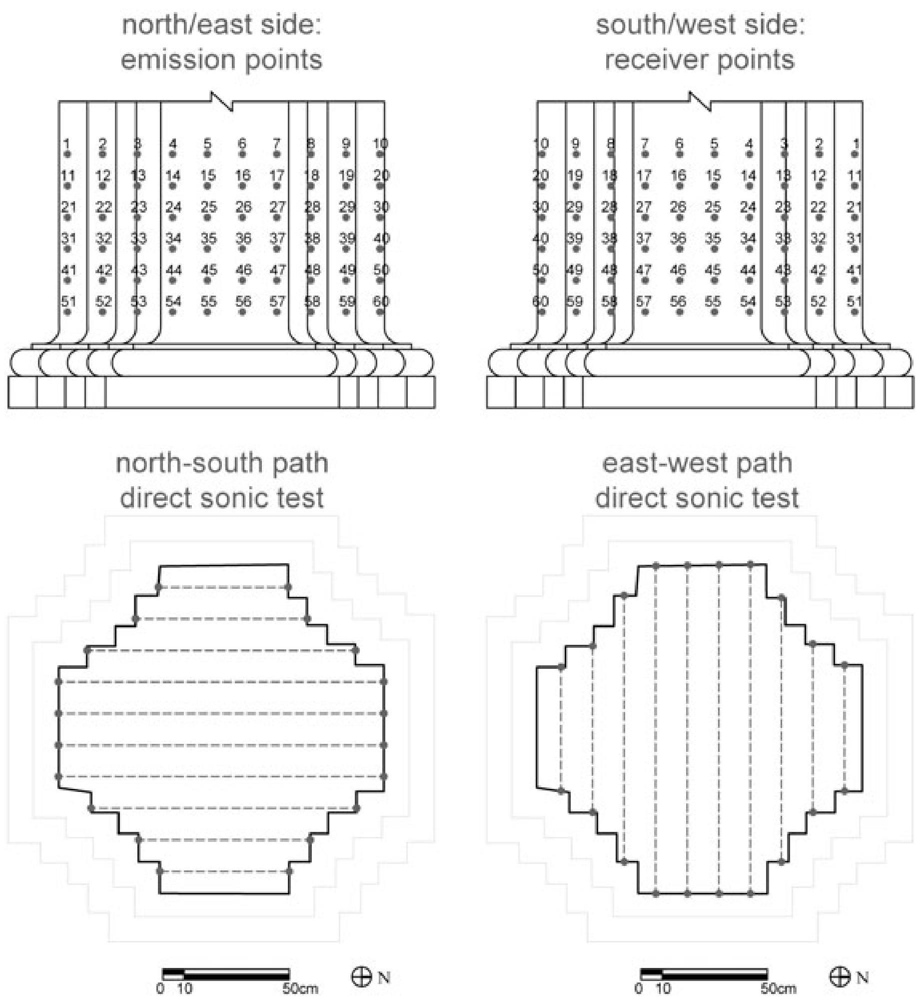

FIGURE 5 Sonic tests layouts used on the cross-shaped pillars of the church

Computing the average value of the sonic velocity obtained from north–south and east–west paths, a velocity speed can be attributed to each intersection point. This test configuration can reveal with more precision the presence of discontinuities in the organization of the masonry section, due to the presence of the designed timber piles.

This method, indicated as crossing path sonic test, is an alternative to other ND tests, such as radar tests, or tests that are more destructive based on the direct inspection of the masonry section, such as video boroscopy. Radar, based on the different dielectric constant of each material, can identify the discontinuities between the materials inside a masonry section by measuring the electromagnetic waves emitted and received through an antenna. Video boroscopy requires the previous coring of the wall: the technique is not able to respect the integrity of the historical structures. Moreover, direct inspections are referred to limited areas of the structure, and a significant result can be obtained only through several inspection points, compromising respect for the integrity of the masonry.

The aforementioned sonic test configuration allows a more precise interpretation of the results through the association of the sonic velocities to the virtual points obtained by the intersection of the perpendicular test trajectories. The configuration of the test is the basic condition for carrying out the final elaboration of the data, consisting in three phases:

1. The computation of the sonic wave travel time in the common direct sonic test configuration;
2. The evaluation of the sonic velocity according to the distance between emission and arrival point; and
3. The calculation of the mean value for each point obtained by the crossing trajectories used for the test.

According to those passages, a previous geometric survey is necessary for the correct estimation of the distances between the test points and for the geometrical reconstruction of the virtual crossing points position.

The resulting velocity map is realized by the distribution of the velocity calculated in each intersection point between the crossing trajectories. This representation increases the number of points considered in the tested area and can reveal new indications on the section of the wall if compare to the one obtained by the common direct sonic tests. A usual way to validate the results coming from sonic tests is the use of direct inspections. This checking can be carried out only in limited areas of the structure, where the interpretation of the sonic tests indicates the presence of relevant discontinuities in the composition of the masonry.

Furthermore, the problem of the decay observed on the covering materials (painted and decorative plasters above all) was studied using specific contact probes for the moisture content determination. This technique is not exhaustive at all, but it allows interpreting the extension and the depth of the moisture in masonry structures.

4 THE ON-SITE SONIC TEST CAMPAIGN

4.1 Application of the pulse sonic tests to masonry walls

Although the ND method known as sonic pulse test has been well documented since its first applications on building structures, standards and codes indicate that this technique is suitable for very homogenous materials, limiting its field of use to concrete structures or monolithic stone elements. Even recent studies on the reliability of sonic test results focus on the difficult interpretation of the data due to the certain conditions that may be present during the acquisition phase.[10,11]

A very complete study published by G. Pascale[15] points out that the accuracy of the qualitative information obtained by this technique is strictly connected to the sonic waves frequency range: elastic waves with high frequency are characterized by short wavelength, but long wavelength characterizes low frequency elastic waves. In this sense, the ultrasonic tests, using high frequency range, can be considered suitable for the investigation of the defects contained in building elements composed by single stones or compact artificial materials. If the sonic pulses have a short wavelength, having a dimension close to the one of the defects contained in the investigated material, the test can reveal with more precision the presence of the discontinuities. This consideration follows the previous indications contained in the available standards,[14–17] set for ultrasonic wave sonic tests. These standards are designed for the characterization of natural stones and concrete structures, where the used high frequency allows detecting very contained defects. Experts used to focus on the relationship between frequency and wavelength that drives to the so-called resolution of the test.[18,19]

As reported by several authors, materials characterized by inhomogeneity or different layers such as masonry structures are not indicated for the propagation of short wavelengths, and for this reason, sonic tests are carried out by low frequency in order to adopt long wavelengths. This means that ultrasonic waves are very affected by the presence of very contained defects (around few centimeters), and the simple coupling between different materials is able to slow down the waves propagation. Large massive structures, composed of different layers such as the historical masonry walls and pillars, require the use of sonic tests characterized by long wavelength. As a result, the resolution of the sonic tests is less precise if compared to the ultrasonic investigation.

Anyway, sonic tests offer the chance to apply an ND testing method to massive structures presenting inhomogeneous composition and large dimensions.[20]

4.2 Calibration of the sonic tests on multiple leaf masonry structures

Sonic tests require a preparatory identification of the main characteristics of the structural elements. The different masonry types (i.e., stone-blocks type or earthen-based type) present different mean density, and the sonic test acquisition setup can be calibrated by few preliminary tests for setting the following parameters: sampling rate, signal amplification, and amplitude resolution.

Collecting the main information on the masonry structures of the church, some indications were obtained. The referenced structures can be divided into two types, according to the materials and to their structural role: single cross-shaped or double cross-shaped pillars and internal or external walls. According to the historical research, the pillars are made with an outer coating of regular bricks and an inner core composed of loose material (fragments of bricks, mortar) cavity and logs of wood. The walls are made of rough-hewn stone, wedges, and earth-based mortar. Historical research indicates the use of a rammed earth masonry with irregular stones named "mampostería." The maximum thickness of the pillars varies from 1.5 m to 3.2 m.

Considering the peculiar constructive technique used for the pillars, characterized by empty space or loose material and wood, some beating practice with the sonic device was performed in order to identify the best settings for the acquisition of the generated sonic signals.

The program supplied with the instruments allows the setup of the acquisition parameters. In detail, the expert user can act on the following parameters:

1. the modulating power of the transmitting transducer (hammer);
2. the setting of the submitted analogical signal amplification level, before being converted into digital;
3. the manual selection of the most appropriate sampling frequency in relation to the desired acquisition time; and
4. the selection of the duration of signal acquisition.

The amplification of the receiving probe was maintained at 20 dB (preamplification of the receiver), and the sampling frequency was varied in order to record the resulting signal transposed in the time window. This calibration was carried out for each analyzed structure. For walls made of "*mampuestos*," with a thickness of 1 m, the 500-kHz sampling frequency was selected and the maximum acquisition time window was identified by software setting, that is, 2,000 µs (Figure 7).

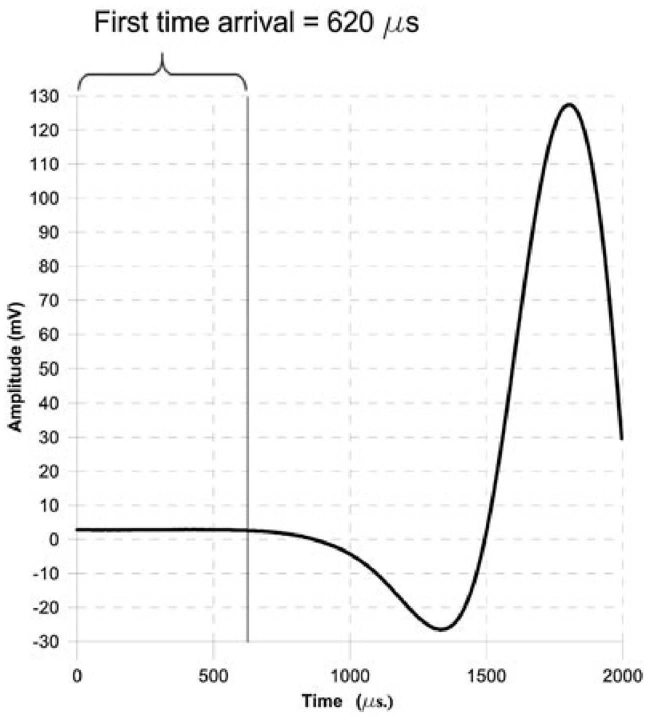

FIGURE 7 Calibration of the sonic wave time of flight on the "*mampuestos*" wall

For the brick masonry pillars, the same test layout used for the investigations on the *mampuestos* walls was repeated, but some difficulty in grasping the initial part of the transposed signal was experienced. This condition is probably due to the thickness of the walls, greater than 1.5 m. In this case, in order to have a correct interpretation of the arrival time signal from the receiving probe, the signal sampling was reduced to 250 kHz and the maximum permitted temporal window was decreased to 4,000 µs (Figure 8). The settings used on the "mampostería" walls did not allow the correct acquisition of the time of flight on the pillars. In these cases, the signal was not detected by the accelerometer, since the arrival time of the sonic pulse took more than 2,000 µs (maximum time after which the signal was cut from the acquisition software) to reach the receiver. A comparison between the main settings used for the signal visualization are reported in Figure 9.

4.3 Sonic test execution and remarks on the data elaboration

The crossing-path sonic method, applied to the pillars, requires the execution of the common sonic direct tests performed placing the grid of points on the opposite sides the structure, as described in Section 4.1. The acquisition and the elaboration of the data of the direct sonic tests are carried out by using the commercial software provided with the equipment. After the geometrical representation of the crossing paths layout, the mean sonic value obtained from the

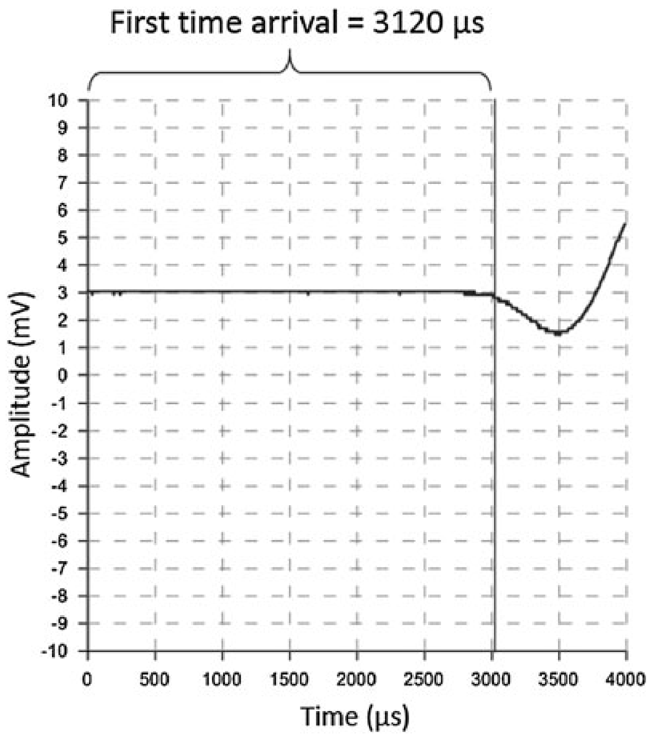

FIGURE 8 Calibration of the sonic wave time of flight on the "*mampuestos*" wall

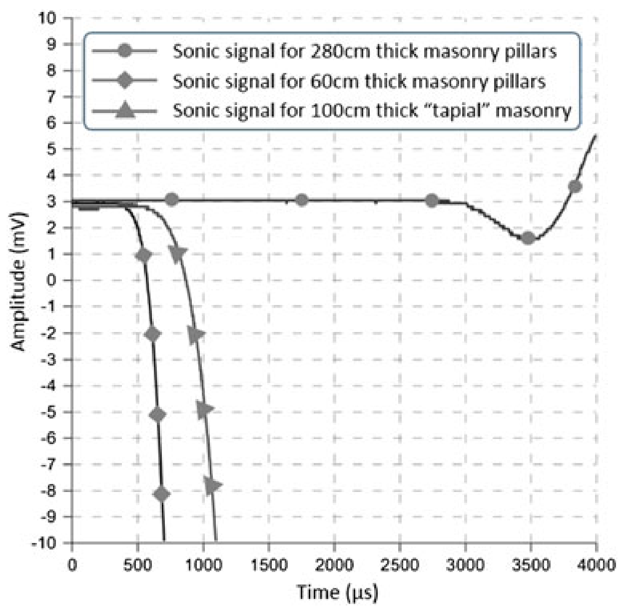

FIGURE 9 Comparison among the three main sonic signals acquired on three different masonry types

crossing trajectories can be associated to each intersection point of the scheme. This calculation can be easily obtained through the correct organization of an electronic sheet.

This method is not based on the application of specific algorithms for the inversion computation used by tomographic software but constitutes a solution for increasing the precision of the results. The reliability of this method is based on three main factors:

1. The accuracy of the acquisition phase;
2. The good quality of the external masonry components (bricks or stones and bedding mortar); and
3. The correct coupling between the devices (emitter and receiver) and the surfaces.

The commercial devices for sonic tests allow the visualization of the acquired signals on digital screens, and this is particularly important for a correct control of the parameters used for the elaboration of the tests. The signals can be subjected to several variables (from atmospheric conditions to cables or wireless connections) influencing the correct signals acquisition.

Considering the most diffused masonry types, historical buildings can present covering layers made by plaster or stone slabs. In these cases, the regular propagation of the sonic impulse can be altered by lack of adhesion between coating and masonry structure or due to the decay conditions of the covering material. To avoid this kind of problems, the plaster observed in the church of San Francisco, already damaged and partially detached, was removed before carrying out the tests.

The correct execution of the test requires a careful coupling between the devices used for emitting and receiving the sonic waves on the masonry surfaces: the contact between the receiver and the building surfaces in particularly important for the right recording of the arrival time of the pack of waves.

If the above-mentioned premises are respected, the data of the common direct sonic tests are suitable for the elaboration through the computation of the average velocity of the crossing paths. As a result, the adopted configuration provides a representation of the sonic velocity distribution inside the section: the graphical output merges the geometrical proportions of the masonry horizontal section with the sonic velocity results.

5 COMPLEMENTARY TESTS CAMPAIGN

As shown in previous studies, the limits commonly observed in ND methods can be overcome by complementary use of different testing techniques.[21–23] The aim of the sonic tests was to determine the morphology of the masonry sections (for walls and pillars) in order to establish some main properties of the structures: compactness and presence of discontinuities. Other tests were introduced in the diagnostic plan for supporting the interpretation of the results obtained from the sonic tests campaign. Visual inspection were used for checking the areas with low velocity characterized by sonic tests: the aim was to associate the range of velocity with the presence of specific discontinuities, such as the timber elements inserted in the pillars.

5.1 Visual inspections

The control of the results obtained through sonic tests was allowed through video-endoscope inspections carried out in the masonry sections of the structures previously tested.

This kind of observations were planned for a more refined calibration of the sonic tests results. The inspections were carried out aiming to verify the presence of cavities and timbers in the investigated elements.

The inspections were planned after examining the crossing-path sonic results on the pillars. The acquired information was useful for reconstructing the internal stratigraphy of the structures and were represented by graphic layouts.

5.2 Moisture content analysis

Moisture and salts presence are the most diffused causes of decay afflicting the structures of the church. The moisture detection was carried out with contact probes able to evaluate the water content in the first centimeters of the masonry surface and in deeper layers. The presence of humidity in the masonry structures of the church was analyzed using two different sensors.

The first moisture sensor (Figure 10) utilizes the dielectric constant of water (Er = 80) for measuring the moisture content in mineral construction materials, in a matter of seconds.[24] A high frequency field penetrates the investigated material and, by a capacity test (open capacitor), generates a voltage signal, which is proportional to the moisture content in the material.

The depth of the penetration into the material is approximately 25 mm, and this allows measuring the moisture content in deeper layers. The device provides special coefficient for each material category (such as brick–clay category) in order to calibrate the probes response.

A microwave probe was used for second range of measurements (Figure 11). The diffusion of electromagnetic waves in masonry walls produces a flow of water molecules captured by the electromagnetic field generated by increasing frequencies (gigahertz order). The friction between the water particles and the masonry materials produces a waste of heat due to dielectric loss. The portable microwave hygrometer works with a frequency range between 2 and 10 GHz in order to avoid dielectric dispersion affected by salt presence.[25] The measurement works by reflections: the device emits electromagnetic waves running over a material volume similar to a cylinder (h = 20–30 cm and d = 10–15 cm) and records the reflected waves providing an index referred to the water content.

The test points are arranged in geometrical grids with a distance of about 23 cm.

These kinds of devices are not able to provide a quantitative result such as the moisture quantity obtained through powder drilling tests, but they allow mapping the different moisture concentration in the investigated areas, indicating a qualitative distribution of the water content along the walls.

5.3 Mortar samples microscope analysis

In the church of San Francisco, two samples of mortars were analyzed: a render (SF_r) and a fragment of bedding mortar (SF_b). They both were collected in the area of the church indicated as already built in the document of 1796 (see circle in Figure 12).

FIGURE 10 Calibration of probe sensor with test block for construction materials

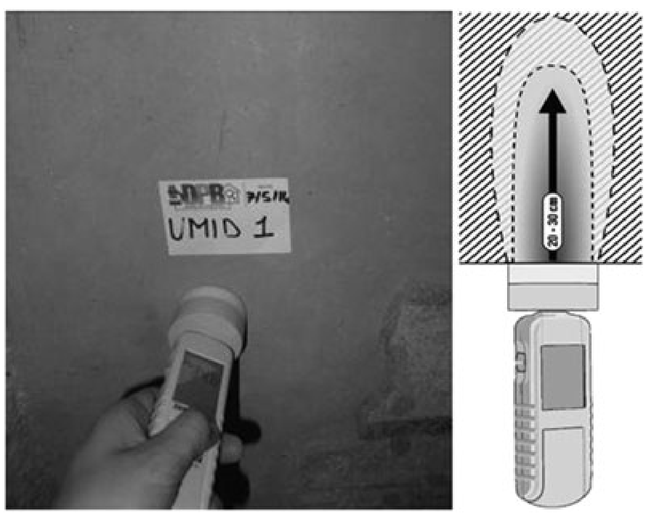

FIGURE 11 Electromagnetic microwaves probe

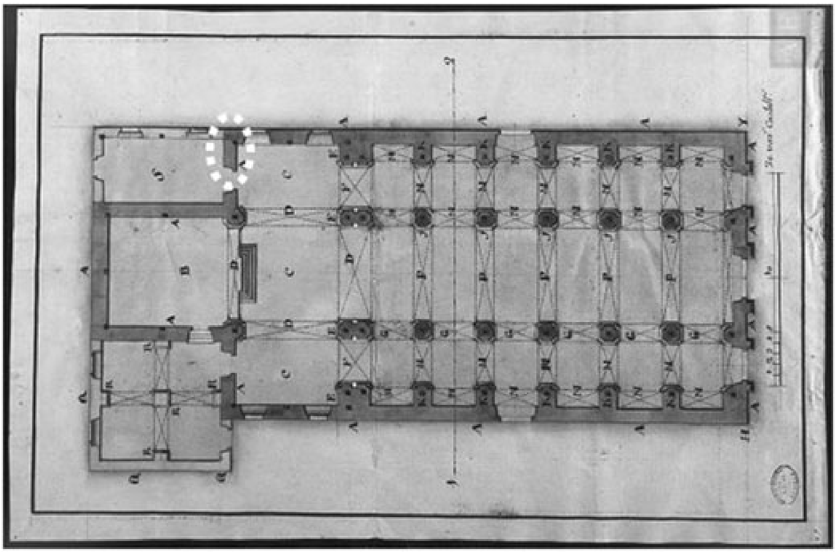

FIGURE 12 Mortar samples microscope analysis: localization of sampling area

Both the samples were analyzed with a stereomicroscope (set for reflected light observation) and in PFM (for transmitted light observation), in order to identify the main characters of the binder (porosity, inclusions, fibers, etc.) and the mineralogical and petrographic composition of the aggregate.

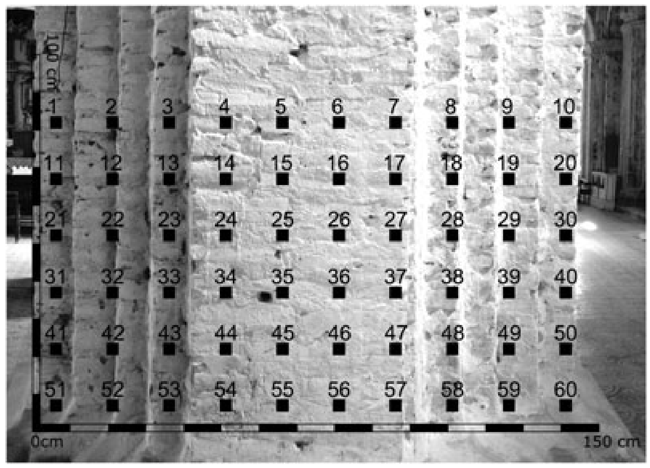

FIGURE 13 Displacement of the grid of points used for the direct sonic test on one cross-shaped pillar

6 EVALUATION OF THE RESULTS OBTAINED BY THE APPLIED ASSESSMENT TECHNIQUES

The results obtained from the testing campaign provided several indications for the interpretation of the masonry section morphology. The strategy followed by the organization of the tests was based on a diffused application of sonic direct tests in order to characterize large structural elements through ND tests. Further MD methods were applied for a better calibration of the sonic tests response providing a cross-relation between the adopted investigation techniques that are described in the following paragraphs.

6.1 Common direct sonic tests evaluation

Organized on regular geometric grids of points (Figure 13), direct sonic tests provide a map of the velocity distribution that can be represented by bar charts or gray scale surface graphs. Through the interpretation of the velocity distribution, some qualitative indications concerning the masonry consistency, the good or bad connections between the materials can be drown out.

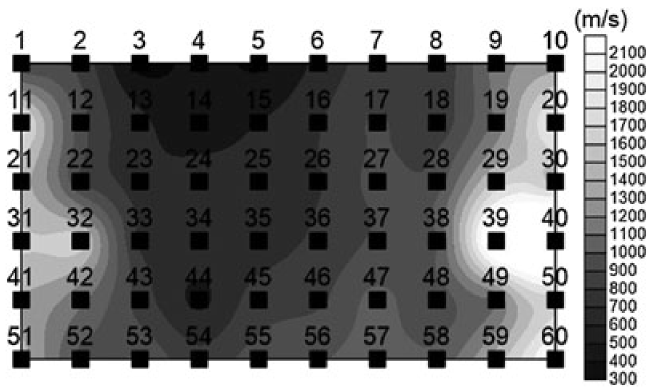

FIGURE 14 Velocity map indicating the distribution of the velocities obtained on pillar P3b. Path direction: north–south

As shown in Figure 14 and Figure 15, higher velocities (around 2,000 m/s) are concentrated along the edges of the

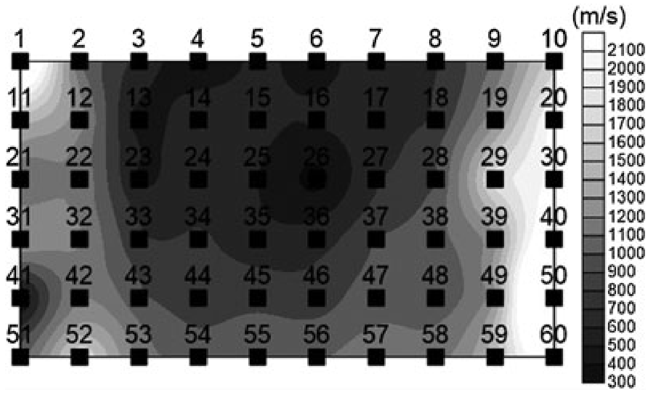

FIGURE 15 Velocity map indicating the distribution of the velocities obtained on pillar P3b. Path direction: east–west

pillar, composed by a sequence of compact materials, and the central columns of the grid of points present lower values (between 400 and 900 m/s). These quality results offer limited information: in this case, the low velocities can be associated with the supposed organization of the masonry section, presenting a brickwork with several mortar joints that can mitigate the sonic waves velocity.

Examining the values obtained by the direct sonic tests, the central areas of the grid of points, with an average value around 800–900 m/s, indicate the presence of some anomaly that requires further in-depth study.

The common direct sonic tests carried out on the cross-shaped pillar were used for computing the average velocity in each intersection point between the propagation trajectory layouts (Figure 16) for the fourth row of the grid (at 110 cm from the floor). The same elaboration was carried out also for a higher level of the point grid (at 154 cm from the floor). As a result, the distribution of the average velocities on the horizontal section was obtained. The results were transposed in gray scale maps, reported in Figures 17 and 18. This computation of the sonic tests provide a more detailed indication of the position of the areas characterized by a low velocity range. This indication was later used for localizing the drilling core used for the inspection through the video endoscope.

Further elaboration referring to other levels of the pillar showed that the positioning of the lower velocity range is always recurring in similar position. Considering the distance between the points of the grid, the presence of a recurrent discontinuity can be identified.

6.2 The information acquired by endoscope inspections

The results obtained by the proposed sonic computation provided very detailed indications for localizing the inspection of the areas characterized by low velocity (here associated

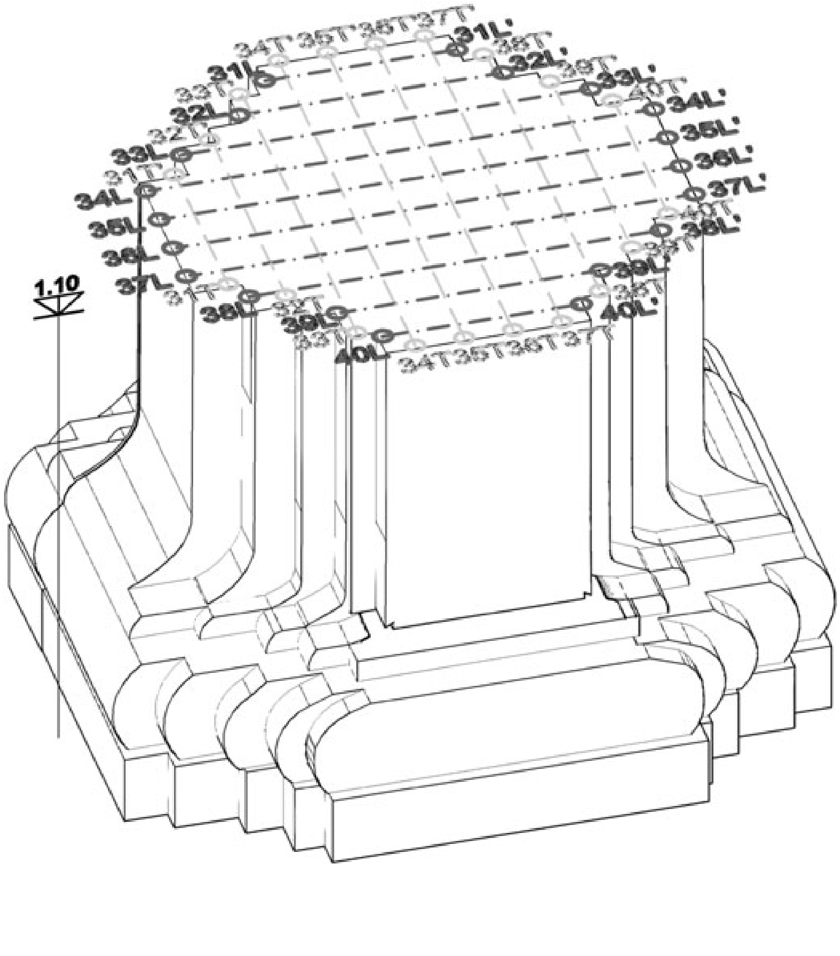

FIGURE 16 The cross path used for the elaboration of the average velocity in each point formed by the intersection between the trajectories of the two sonic direct tests

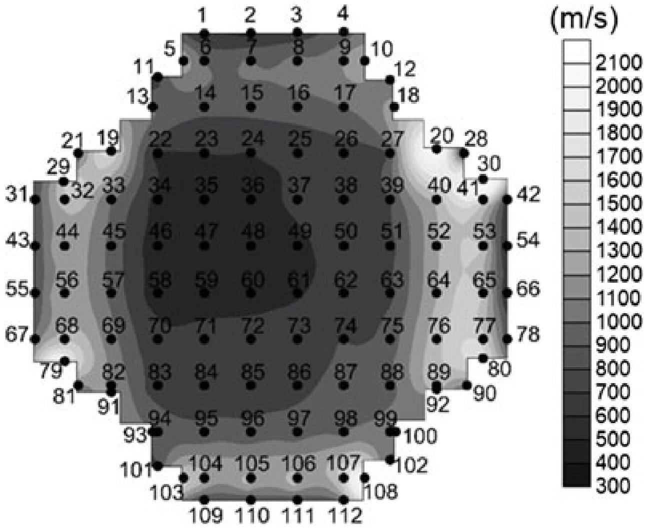

FIGURE 17 Distribution of the velocities obtained by the cross-path computation on the horizontal section of the pillar at 110 cm from the floor

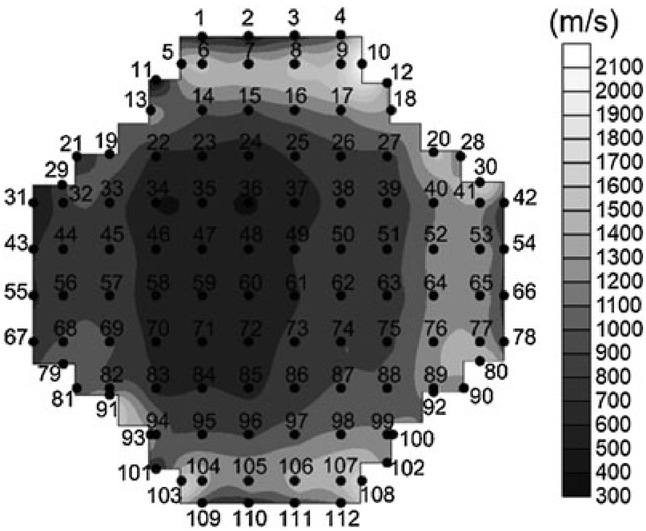

FIGURE 18 Distribution of the velocities obtained by the cross path computation on the horizontal section of the pillar at 154 cm from the floor

to low density of the structure). After carrying out a 70 cm drill in the area corresponding to low sonic velocity range, the video endoscope allows observing the masonry section stratigraphy (Figures 19). The pillars are formed by a brickwork structure containing a cavity (Figures 20) hosting a timber element (Figures 21). According to the historical analysis, the pillars contain timber columns.

6.3 Mortar analysis

Sample SF_b is a single layer fragment of lime-based bedding mortar, homogeneous in binder and aggregate (Figure 22). At the stereomicroscope analysis, a very good adhesion between aggregate and binder is detected. In the binder, a few lime lumps are visible, max diameter: 1 mm. Aggregate has a fluvial origin; fragments are rounded and homogeneous in characters and shape, average diameter: 1 mm, max diameter: 4 mm. Pores are mainly present in the binder, not numerous and with a max diameter of 1.5 mm. No fibers or inclusions were detected.

PFM analysis shows Sample SF_b to be air-lime based, with a high binder-aggregate ratio (about 1:2.5). Binder is coarse grained and not homogeneous in distribution. Aggregates are mainly quartz, volcanic, and meta-

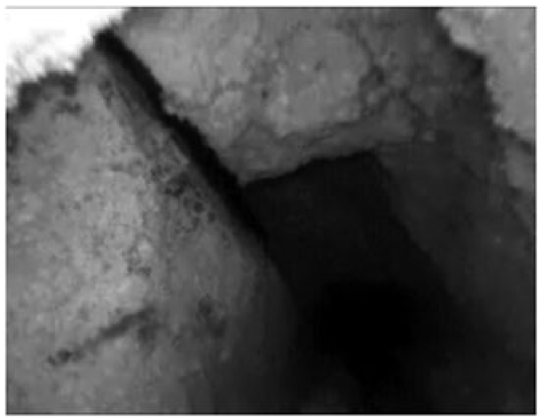

FIGURE 20 The cavity observed inside the pillar

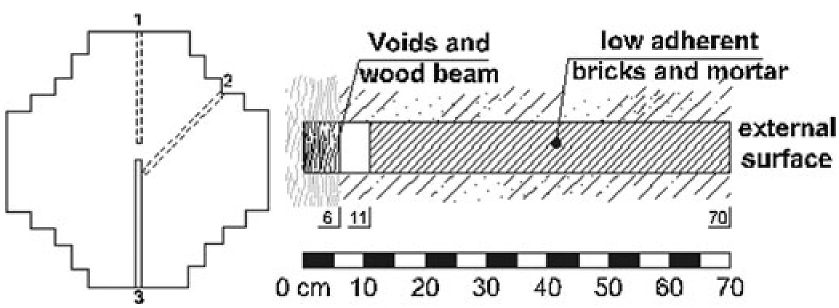

FIGURE 19 Stratigraphic analysis of the pillar section

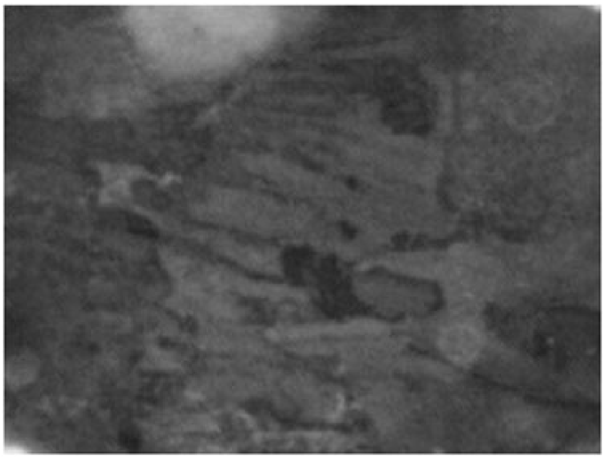

FIGURE 21 The wooden surface observed inside the pillar

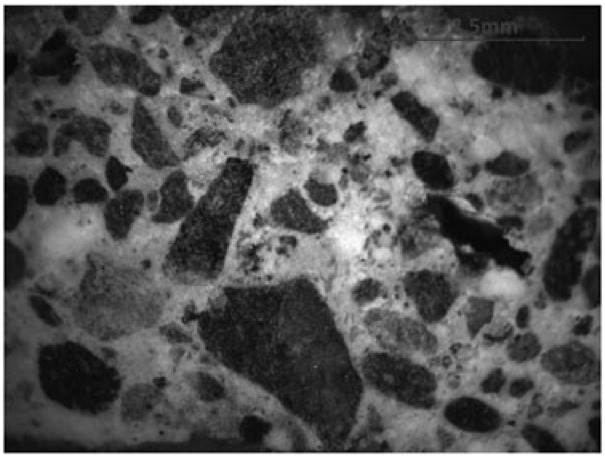

FIGURE 22 Stereomicroscope analysis of sample SF_b (bedding mortar)

morphic rocks. Several lime lumps, even of millimeter dimension, are detectable.

Sample SF_r is a 5-layer fragment (Figure 23), constituted by a 20-mm thick fragment of render (layer 1), a 3- to 5-mm-thick lime wash (layer 2), and three layers of color (layers 3–5). Layers 1 and 2 seem to have a good adhesion. Aggregates of layer 1 are similar to sample SF_b (but a bit more angular), average diameter: 2 mm, max diameter: 7 mm. Compared to SF_b, sample SF_r has a lower binder-aggregate ratio (about 1:3).

PFM analysis shows a partial disconnection between layers 1 and 2, separated by a thin and continuous crack. They are also different in binder: layer 1 has an air-lime based binder, very dense and coarse grained. Layer 2 is characterized by a fine-grained air-lime binder, with several pores and no aggregate. Layers 3, 4, and 5 are modern, synthetic materials. Aggregates are, in layer 1, homogeneous in shape and nature: metamorphic and volcanic rocks and a few quartz are present. In the binders, no hydraulic reaction was observed.

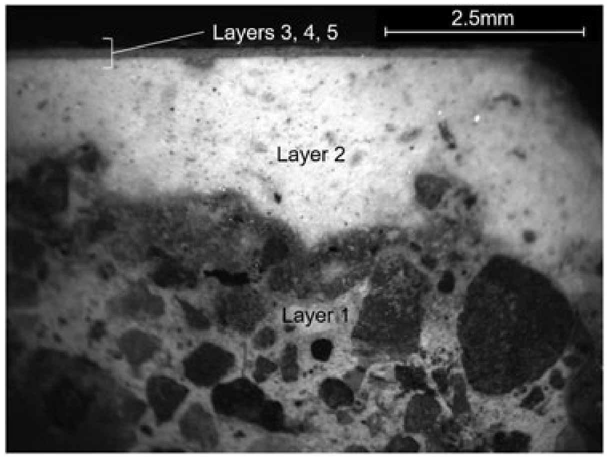

FIGURE 23 Stereomicroscope analysis of sample SF_r (render)

7 LIMITS AND POTENTIALITIES OF THE ON-SITE INVESTIGATION CAMPAIGN

The tests carried out in the examined case were able to identify the presence of timber elements (named "*horcones*" in Spanish), composed by not shaped trunk parts and inserted inside the masonry pillars. Through direct video inspections, localized in the area characterized by low sonic velocity range, the timber elements were observed. The frames acquired by the endoscope showed a decay condition of the wood, hosted in a not airy cavity subjected to moisture content.

The reduction of the sonic velocity was not only dependent on the coupling of different materials, such as brickwork and timber, but also on the separation between the cavity coating and the timber structures was observed by the endoscope: this space was designed for allowing the natural deformation of the wood and, in general, the movements of the timber column under the actions induced from seismic events. According to the archive documents, the timber structures appeared to be covered by melted mortar ("*pilares engargantados*").

The endoscope inspections were driven by the interpretation of the sonic tests, and the real dimension of the load-bearing element was identified through the cross-relation of the different data. The cavities hosting the timber columns are between 55 cm and 60 cm. Considering the section of 150 cm, a third of it is occupied by the cavities for the timber elements.

Sonic tests confirm that the brickwork masonry presents good connections between its components, represented by very high velocities (between 1600 and 2,000 m/s).

In some areas characterized by moisture content, presenting superficial decay and pulverization of the mortar joints, the sonic velocity range is lower than the one observed in not decayed structures.

The results of the sonic tests carried out on the rammed earth masonry with irregular stones (*mampostería*) showed the efficacy of this constructive technique, characterized by high density and a good state of conservation. The sonic velocity (around 2,000 m/s) distribution indicates an effective connection between the external layers and the internal section. Also in this case, where the moisture content was detected, the sonic tests provided low velocity values (close to 400 m/s).

This combination of data obtained by the complementary use of different technique was useful for interpreting the characteristics of the large massive pillars (double cross-shaped pillars) facing the internal side of the facade of the church. As shown in Figure 24, several acquisitions were planned reporting many points along the surfaces of the structure. Compared with the velocity distribution obtained from the common direct sonic tests, the cross-path-based sonic computation provided a result that allows

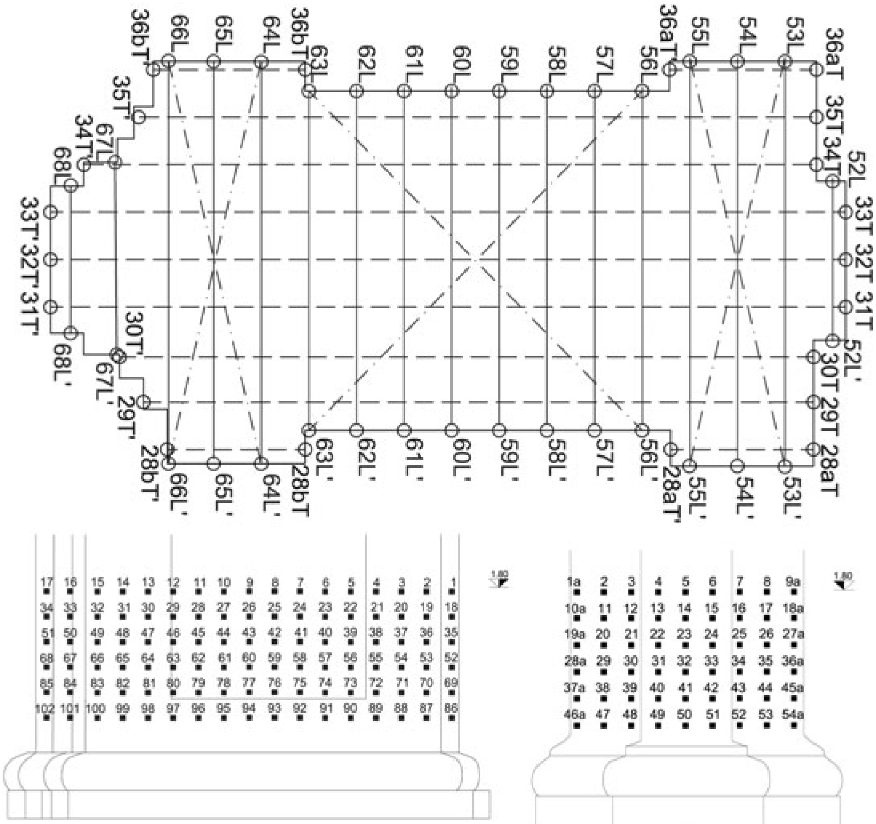

FIGURE 24 The geometric grid of points set for the direct sonic tests carried out on the large pillar

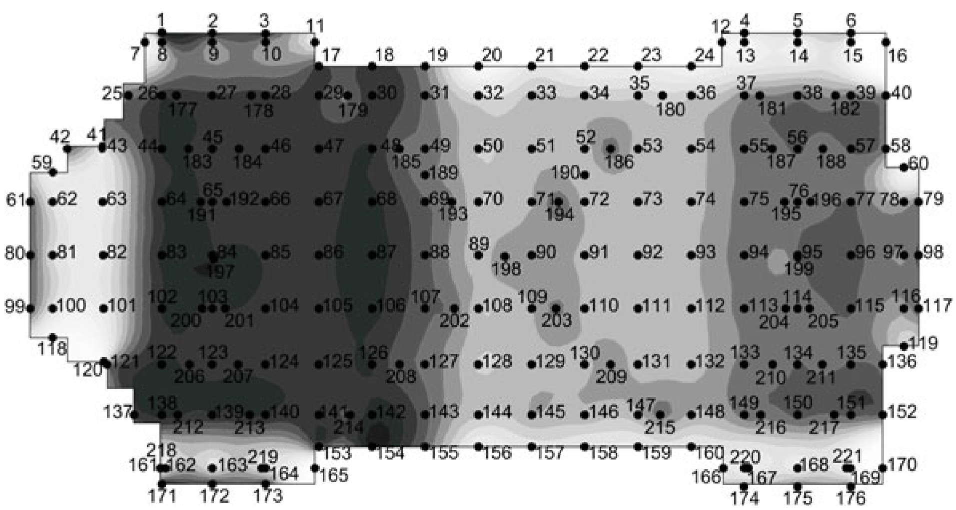

FIGURE 25 Velocity map on the horizontal section of the large pillar

a more refine interpretation of the presence of discontinuities in the masonry structure. The distribution velocity map (Figure 25) reveals the influence of the cavities hosting the timber columns in two separate areas of the horizontal section. The large area characterized by a sonic average velocity of about 700 m/s indicates a relevant part of the supposed load-bearing structure that is subjected to low density in the section morphology. Thanks to historical analysis, the low velocity range can be associated to the presence of the vertical timber elements and the result suggests the utility of an in-depth study of this area through MD tests.

8 CONCLUSIONS

Considering the difficulties offered by commercial software for tomographic tests carried out on historical structures, the methodology based on a combination of different ND and MD tests provided reliable results.

The choice of carrying out the sonic tests exclusively in direct mode was essential to guarantee the best reception of the signal generated by the instrumented hammer. This test mode is recommended in situations such as this, where the investigated walls are very thick and, as evidenced by preliminary historical research, characterized by material discontinuities not verified by previous surveys.

The use of the crossed trajectories in the sonic test has led to significant results thanks to a very tight grid of points, with a distance not exceeding 15 cm, and to a sample rate and acquisition time calibrated case by case.

The quality of building materials and the good state of conservation of the surfaces have reduced the occurrence of noisy signals due to an improper coupling of instrumentation and test surface.

The sonic tests setup provided qualitative velocity distribution maps allowing the interpretation of the horizontal section organization of the main structures. In addition, the further characterization of the masonry elements through ND tests such as moisture content analysis, and MD methods such as endoscope, supported a complete evaluation of the state of conservation of the load-bearing structures. The achieved information, together with the observations obtained by stereomicroscope, led to a reliable interpretation of the building techniques used for the masonry walls and the internal pillars.

The multilevel approach, from the historical analysis to the on-site diagnostic investigations, showed that the mechanical properties of the historical structures can be examined by collecting results from different tests. The cross-relation among these results provides a valid solution for confirming and interpreting the building techniques adopted for the different structures.

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