Italian Middle Byzantine Churches: A Comparison Through Masonry Quality Analysis

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The work focuses on the structural properties of two Byzantine churches built during the 11[th] century in Torcello (Venice Laguna) and Stilo (east coast of Calabria). Despite the large distance between the two religious buildings and deep differences in the building typology, some common features are detectable, recalling the construction solutions of the Byzantine structures. Both churches, well known from an historical and artistic point of view, represent two important examples of the Byzantine period. The authors, involved in a vulnerability analysis of these buildings, had the opportunity to investigate some structural characteristics of the masonry walls through non-destructive tests (NDT). The results of the experimental campaign are pre-sented here in order to contribute to the knowledge of Byzantine constructive systems.

KEYWORDS
Byzantine churches; direct sonic tests; La Cattolica; masonry quality; NDT; Santa Fosca

1. Introduction

Byzantine architecture still needs an in-depth analysis, for a proper level of knowledge to be reached inside the scientific community of medieval studies. In fact, the current studies on this tradition mostly concern art, history, and liturgy, and therefore this culture is seldom acknowledged as an essential part of the exclusive European architectural development (Cameron 2009, 2011; Ousterhout 1996). The limited interest in Byzantine buildings is also due to the lack of documentation related to them: most information available nowadays comes from works of the 1800s, when scholars elaborated drawings, surveys and notes, took pictures of monuments and their conditions. In such a lack of documentation, it became in fact natural to examine these architectures on site, searching for hints about their history. Although the analyses carried out in the Nineteenth century are by now considered obsolete, they provided the current background, fundamental in order to reconstruct at least the most recent history about these monuments, whose life has been lasting for a millennium and even more (Mango 1974).

In view of the above, this work intends to offer a contribution to the still much-debated issue related to Byzantine architecture and, in particular, to its influence in the West. To this aim, the material consistency of two churches erected in the Italian Peninsula during the Byzantine domain of the 11th–12th century is taken into account through the analysis of their masonry quality. The two architectures under consideration are the church of Santa Fosca (Figure 1 left) on Torcello Island (belonging to the Venetian Lagoon) and the Cattolica di Stilo (Figure 1 right), founded in the Southern Italian region of Calabria. A comparison between these two buildings is deemed advisable, since, notwithstanding their location at the exact opposites of Italy and their rather different architectural configuration, they show many common features likely due to their mutual connection with the Eastern tradition. As a matter of fact, in the well-known masterpiece of Krautheimer (1965), both churches are included in the chapter dedicated to the Middle-Byzantine tradition in the West.

The recent studies related to the analysis of the masonry quality of the Byzantine architecture in the East are here taken into account. In fact, the investigation of the construction techniques and materials characterising some important monuments of the Byzantine Greece has been recently carried out, while computing structural analyses for seismic damage (e.g. Miltiadou-Fezans 2008; Miltiadou-Fezans, Vintzileou, and Delinikolas 2010; Psycharis et al. 2010).

In this specific study, instead, the analysis has been carried out taking advantage of two different experiences, during which the authors were involved in the study of the masonry walls of the two churches. The aim of the research was addressed to a qualitative characterization of the masonry cross-sections. The diagnostic campaign, based on sonic tests, a non-destructive

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Figure 1. View of the Church of Santa Fosca (left) and of the Cattolica di Stilo (right).

technique, was proposed for assessing the state of conservation of the walls and their internal organization.

Before focusing on the masonry quality analysis of the two buildings, an outline is given on the methodological approach used throughout this study as well as on the two churches here under discussion.

2. The investigation approach

2.1. A brief historical overview

Since the late tenth to the twelfth century, Byzantine ecclesiastical architecture was mature and culturally inde-pendent in the Eastern regions of Europe. The International Gothic style did not predominate in Byzantine lands, despite its conscious introduction by the Crusaders in the shape of few large buildings. Something similar occurred in Italy, where there was a strong and independent local tradition accompanied by an opposition to foreign trends and styles (Bouras 2001). Most noticeably, it is worth noting that the Italian Peninsula has always played an important role in the relations with Byzantium, with which it never broke its ties, although they became weaker after the flourishing 6th century, when Justinian gave order to build the well-known church of Saint Vitale in Ravenna (Mango 1986). It is in Italy, indeed, that the two outposts of the Middle-Byzantine architecture developed in the West. The cul-tural hegemony held by the Roman Empire in the Peninsula was progressively eroded by the new administrative organization of the territory, divided into different areas of influence: the Byzantine cities along the Adriatic coast, the State of the Church in Central Italy and in the areas under the increasing control of the Lombards. The contemporary permanence of different populations in Italy drove to a flourishing building activity, characterised by the realization of important architectures, according to local traditions and new influences. The churches consid-ered for this study, one in north Italy (Venice) and the second in the south (Stilo) are representative of these two Middle-Byzantine Italian outposts (Krautheimer 1965). More specifically, Santa Fosca, on Torcello Island, belonged to the Venetian lagoon, at the time under the Serenissima's power, which maintained close diplomatic relations with the Eastern Byzantine Empire. The com-mercial links with the Byzantine ports of Central Greece and Peloponnesus easily clarify the reasons of the Oriental influences in the 10th–12th architecture of Venice (the Basilica of Saint Mark is the most striking example of this phenomenon). On the other side, the Cattolica di Stilo was erected during the Byzantine domain of Southern Italy and as the other churches built within this period in the area, it is small and modest.

2.2. From the typological approach to the masonry quality analysis

The two churches considered within this study represent two different typologies of Byzantine buildings (Pevser 2002).

Due to the huge number of Byzantine constructions, built during the very long period of 1000 years in a very wide area, academics tried to establish some methods of classification, in order to give them their own place in history (Mango 1986). Among the others, the typological approach has been adopted since the studies of the 1800s, and even nowadays every time a resemblance is found, a connection between churches far away in space and time is assumed (Johnson, Ousterhout, and Papalexandrou 2012).

The cataloguing by typologies might help to provide an order in the wide scenario of Byzantine architecture. However, the study of these constructions through a mere typology comparison is a rather stationary criterion, since it does not take into account the variety of the details as well as the materials that every single building shows (Johnson, Ousterhout, and Papalexandrou 2012; Mango 1974).

From a methodological point of view, an interesting effort for the study of Byzantine churches was carried out by considering the differences in the building techniques in different periods. Some authors observed that the ratio between the vertical proportion of bricks and joints changed from 1:1 in the 4th century masonry apparatus to 1:2 or even 1:3 in the 6th century apparatus (Mango 1974; Zanini 1994).

More recently, Lombardini (2001) tried to evaluate the main Byzantine masonry apparatus comparing these differences by numerical analysis, providing indications for their mechanical behaviour. In such cases, the thick Byzantine joint plays a significant role for the general response of the vertical structures. Different authors remarked that the increase of height of the joint depends on the diffusion of hydraulic mortars, based on Pozzolanic mixtures and small aggregates (Baronio, Binda, and Lombardini 1996; Binda, Lombardini, and Guzzetti 1996a; Karaveziroglou, Papayianni, and Penelis 1989; Stravrakakis et al. 1995). The physical and chemical characteristics were put into relation with the mechanical properties of bricks and mortars after sampling campaigns that allowed a further investigation phase by laboratory tests (Binda and Baronio 1996b).

A detailed structural analysis of the San Vitale Basilica in Ravenna is described in Taliercio and Binda (2006). The authors assessed some mechanical property of this 6th century masonry building characterised by the so-called 'recessed brick' technique, by performing a double flat jack test .

Considering the various approaches, the two churches show different typologies: the Cattolica can be classified with the quincunx church type, whereas Santa Fosca has been compared since the late 1800s to a specific group of Greek churches belonging to the so-called Middle-Byzantine octagonal type, which is a variation of the single-domed cross-in-square church, where, instead of four, eight pilasters support the central dome (De Angelis D'Ossat 1942; Krautheimer 1965; Manzo 2016; Millet 1899). It is worth recalling the later Church of the Parigoritissa at Arta (14th cent.), which is a quincunx basilica belonging to the octagonal domed-type, hence it summarises the typological characteristics of both Santa Fosca and the Cattolica. Notwithstanding the typological and stylistic differences, the masonry apparatus is visible, and, except for some decorated and plastered areas, it is possible to notice that in both churches brickworks compose the load bearing walls.

Due to the attention imposed by the preservation of such important evidences of the Byzantine architecture, invasive and slightly destructive tests cannot be repeated and carried out on large areas. Other non-destructive tests are preferred for investigating the masonry walls of this kind of buildings, like the direct sonic tests, which are the methodology followed to study both Santa Fosca and La Cattolica.

3. Comparison between the two churches

3.1. Santa Fosca on Torcello Island (Venice)

3.1.1. The architectural configuration

Santa Fosca is characterized by a Greek cross plan with very short Western, Northern and Southern arms. The central space is square and crowned by a wooden roof that stands on a circular masonry drum about 1.75 m high and with a diameter of about 10 m. At the intersection of the arms, eight marble columns surround the square central space. These columns, together with four masonry pillars located at the corners of the square, support couples of overlapping niches, which allow the transition from the square to the circle (at the level of the drum) through the octagonal arrangement of the supports. (Figure 2).

Furthermore, a barrel vault roofs each nave, whereas a cross vault covers each aisle.

On the eastern side, deeper than the others, a longer barrel vault covers the main apse, and two groin vaults cover the two aisles. All the three apses end with semicircular walls and hemispherical niches. Outside, the lateral Eastern naves remain circular, while the main apse becomes polygonal (Figure 3-left). Very peculiar external ornaments characterise this part of the church: tooth-dogs, triangular motives, little columns and blind arches embellish the masonry brickwork. This decoration easily recalls the triangular ornaments present on the apse of the closer church of Santi Maria and Donato on Murano Island (Figure 3-right) as well as those characterising, for instance, some churches on Chios Island (Spagnesi 2008) (Figure 4).

3.1.2. Dating problems

The foundation period of Santa Fosca is still a debated subject, since no certain data exist that can testify its erection. Cornaro (1749) reported a document of year 1011, which provides the only reference, on which the subsequent literature based the several assumptions about the foundation date of Santa Fosca and its early history. In fact, scholars consider it the first reliable information source about the existence of Santa Fosca, and date the church back to the 11th century (among the others see Bettini 1940; Polacco 1984, Zuliani 2008).
The excavations recently conducted under Santa Fosca have further confirmed such an assumption: they revealed that the current building must be dated back to the end of the 10th century. In fact, beyond any reasonable

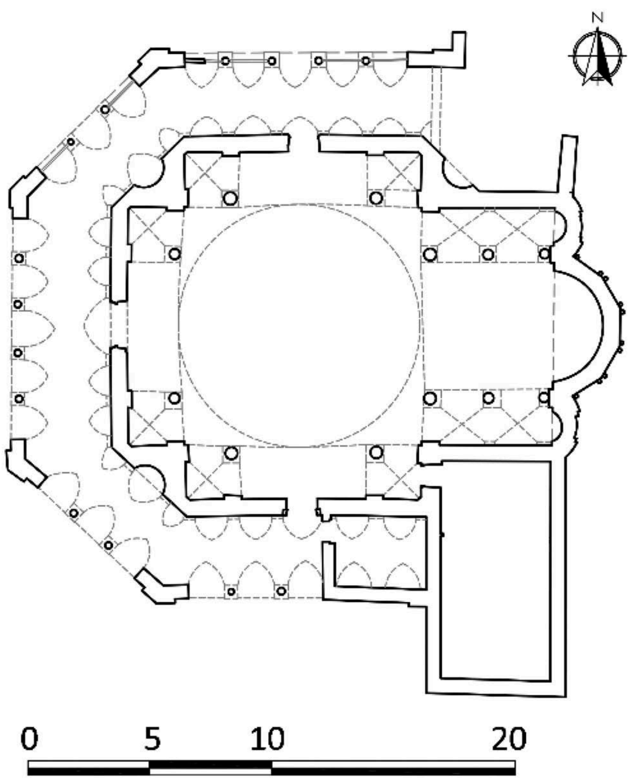

Figure 2. Plan view of the church of Santa Fosca.

doubt, its foundations belong to the most ancient phase of the laying of the graveyard, located in front of the church and dated between the end of the 10th and the end of the 12th century (Leciejewicz 2000).

3.1.3. Recent-past interventions and current structural problems

Little information exists about the interventions on the church before the 1800s, while well documented are especially the interventions undertaken to the church in the 20th century. More specifically, during the second decade of the century Domenico Rupolo demolished a major part of the masonry walls, since he found several cracks and out-of-plumbs, which denounced serious structural problems. He reconstructed the walls with new bricks joined by hydraulic lime mortar. By removing the plaster from the inside walls he also discovered traces of three single-lancet windows, which, according to him, were the Byzantine "original" openings of the building. Hence, aiming at returning to the previous appearance of the building, he substituted the existing semi-circular windows with those he discovered. He also restored the porch by substituting the ancient covering with a concrete cross vault.

Ferdinando Forlati carried out other important interventions in the 1930s: he reopened the window of the apse and renovated part of the external masonry walls of the sacristy, which probably suffered problems due to rising humidity and salt infiltration. The most invasive intervention he carried out during his office dealt with the realisation of a concrete ring above the pre-existent masonry drum. He also reinstalled the wooden ties at the springs of the arches inside the church and removed the plaster from the inside walls obtaining the image of the church still visible nowadays.

Other restoration works have been recently carried out, since fissures developed above the walls and the vaults of the porch partly due to the water percolation from the roofs, partly due to the environmental conditions characterised by high humidity levels. Manzo and Chesi (2016, 2018) studied the crack pattern inside the church and its deformed configuration and supposed that ground settlements are probably further damaging the structure of the church. Nonetheless, no severe crack is present on the South elevation. Furthermore, due to the presence of repointed mortar all over the inside masonry walls, as well as plaster outside, it is not possible to carry out a stratigraphic analysis; however, from the archival documentation, it can be pointed out that this elevation was largely demolished and reconstructed during the Twentieth century as Figure 5 shows.

Figure 3. Santa Fosca apse (on the left); Santi Maria e Donato apse (on the right).

Figure 4. The Church of Agioi Apostoloi at Pyrgi on Chios Island with the detail of the drum characterised by arches decorated with triangular motives and toothdogs).

3.2. The church La Cattolica di Stilo (Reggio Calabria)

3.2.1. The architectural configuration

The Cattolica di Stilo shows a very different architectural configuration (Figure 6). The plan of the building, a Greek cross inscribed into a square, has a proportion of about 7.50 × 7.40 meters. Examining the elevations, the compact walls are covered by 5 domes presenting tall drums. The east wall is formed by three apses, used for specific purposes as in other byzantine churches: the central one hosting the altar, the north one for oblation (proskomide) and the south one for keeping the liturgics objects.

Inside, the space is structured in a complex way. Four columns subdivide the room in nine equal square areas. The order of the volumes is organized by using barrel vaults for the spans adjacent to the central one. Furthermore, domes with a rather short proportion with respect to the central one characterize the corner spans.

Important evidences of the Byzantine tradition are documented in Calabria since the 10th century (Venditti 1969). The origins of La Cattolica di Stilo are dated between the 10th and 11th century (Orsi 1929; Teodoru 1930), but the role of this small church, built on the slope of Mount Consolino over the village of Stilo, is still under discussion. Some researchers assumed the presence in the area of a series of tombs, excavated in the rock for seclu-sion monks, as the proof connecting the Cattolica with an ancient monastery.

The space distribution of the quincunx plan characterizes several examples of five-domed byzantine churches built in Laconia and Arcadia between the Tenth and Eleventh century. In addition, the external features of the domes present a decorative motif (Figure 7) that is well documented in this period in the Balkan Peninsula (Megaw 1964).

Some portions of the frescoes characterizing the interior walls and vaults are still preserved: experts'

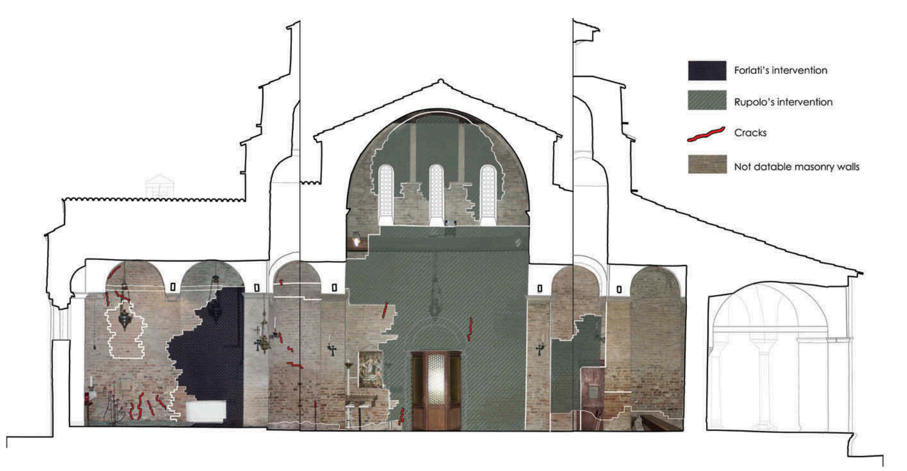

Figure 5. Southern cross section of Santa Fosca with crack pattern (red colour). Hypothesis of Rupolo's intervention (1910–1912) is reported in green and of Forlati's intervention (1930) in blue. The other portions of the masonry walls are not datable.

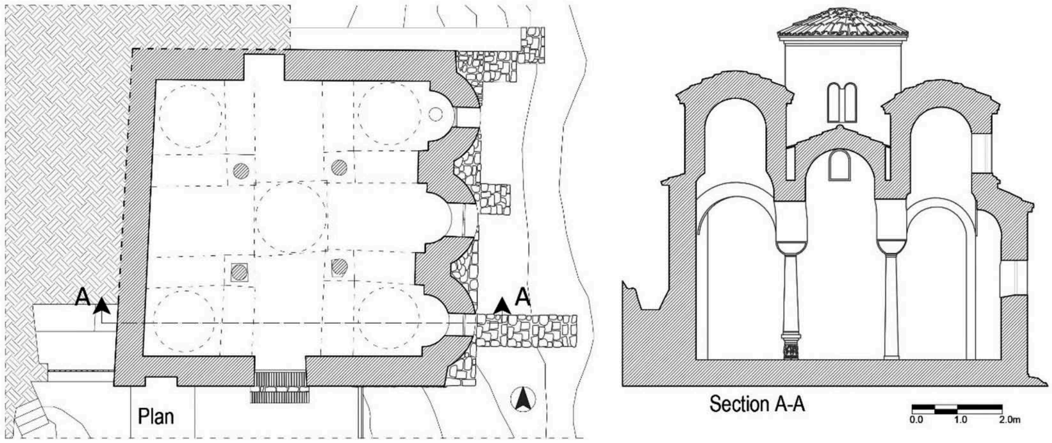

Figure 6. Plan and section of the Cattolica di Stilo.

analyses of the remaining parts allow dating the origin of the church. Considering the subjects of the frescoes displaced on the internal walls, Zago (2009) indicated the origin of the decorations between the 10th and the 11th century. According to the Byzantine liturgy, considering the symbols of the cult and the knowledge of the psalms interpretation coming from the 10th century imperial court, the frescoes in the Cattolica di Stilo can be assumed as a new model of an iconographic system that had a large diffusion between 10th and 11th century through the monastic itinerancy.

3.2.2. Recent-past interventions and current structural problems

The main information on the transformations occurred to the building are limited to the first half of the 20th century, when Paolo Orsi promoted the restoration of the church together with a complete study of the Byzantine religious buildings in Calabria (Orsi 1929). The interventions started by Orsi and further concluded during the 20th century by other Superintendence officers were focused on the elimination of minor decorative features, like the Baroque tympanum added during the 17th century (Arena, Colistra, and Mediati 2015). The modifications of the walls are clearly recognizable by analyzing two discontinuities of the masonry texture on the south and the north side: the presence of two closed doors, probably realized when the church was turned into a stable for animals, modified the walls original continuity.

Observing the crack pattern on the south wall (further described in section 5.2), the diagonal displacement of the crack seems to be more in relation with soil settlements than mechanical effects of the complex arch and vault system of the church. Taking into account the high slope of the mountain, the massive buttresses supporting the east side of the building appear as a preventive measure for avoiding settlement problems.

4. The sonic tests methodology

4.1. Sonic tests calibration for the evaluation of the masonry quality

In the last decades, diagnostic campaigns have been progressively carried out to detect the morphology of

Figure 7. The lozenge decoration motive on the domes of the Cattolica di Stilo (left) and the dome of the 10th century church of Panagia Koumbelidiki in Kastorià (right).

masonry walls. In relation to Byzantine architectures, attempts have been made to investigate cross-sections of churches damaged by earthquakes in Greece (Palieraki et al. 2008; Vintzileou et al. 2009). These studies, however, detected masonry walls composed of stones and bricks, whilst within this contribution the architectures under discussion are exclusively made of brick rows.

As already noted, these architectures show an impor-tant value and must not be destroyed by invasive and slightly destructive tests, which cannot be repeated and carried out on large areas. For this reason, non-destructive tests are preferred. Among them, direct sonic tests, based on the measure of the travel time of a pack of elastic waves, produced by an impact on a face of the wall and received on the opposite one, provide a distribution of sonic velocities that can be correlated with the mechan-ical properties of the tested material (ASTM-C597–02 2002; ASTM-D 2845–00 2000; Onsiteformasonry). The principle of the test is that sonic waves can travel with different velocities in a solid material: the travel time depends on the physical characteristics of the mean. In dense materials, like stones or bricks, the sonic velocity is much higher than in fluids. For example, in clay-rocks the sonic speed is about 3480 m/s, whereas in atmospheric air the value decreases to 342 m/s. Thus, the direct sonic tests are commonly used for damage detection connected to the presence of discontinuities into the masonry sections (Binda et al. 2007; Cantini 2016), when large cavities are hidden in the internal layers of the structures.

In Santa Fosca and La Cattolica, regular grids of points were reported on some selected areas of the wall surfaces. For each area, a graphic layout was rea-lized associating colours to the various velocity ranges. The interpretation of the masonry morphology was then based on the evaluation of these parameters:

- the sonic speed homogeneity: the building techni-que, if realized properly, should be characterized by regular connections between the component materials, working as a continuous mean for the sonic waves' propagation. Thus, the obtained sonic velocities should present a uniform distribu-tion over the grid, with values corresponding to those observed for stones or brickworks;
- the sonic speed range: thanks to specific literature concerning the reliability of direct sonic tests, the propagation speed values of the sonic wave can be associated to a qualitative interpretation of the consistency grade of the transversal section.

Considering the distribution of the measured velo-cities and according to the test geometry, a final interpretation of the state of conservation of the struc-ture and some reliable hypotheses about the arrange-ment of the transversal section were carried out.

The above-mentioned parameters require a precise calibration of the instrumentation and of the test con-figuration, in order to be correctly acquired. The sonic tests here presented were carried out by using the following devices:

a. an instrumented hammer with a head mass of 150 grams and an aluminium handle tip able to generate a frequency of about 2–3 kHz (depend-ing on the contact time with the surface);
b. an accelerometer with a range 0.1–4800 Hz coupled with a thin layer of a commercial clay for modelling, used for toning down the effects of the brick surface roughness;
c. a dedicated acquisition digital board connected to a laptop for acquisition control and data-storage.

For this study, the authors calibrated the sonic tests results on empirical criteria derived from experimenta-tion. As outlined in Figure 8, the quality of common masonry elements can be based on comparative mean velocity values characterizing well-known structural components. The different ranges of velocities obtained from direct sonic tests carried out on a plinth, a dado, an upper plinth, a ionic base and a column shaft, reveal the use of different materials. Thanks to further calibrations, on natural stones and artificial stones like bricks, the response given by the sonic tests can also lead to a reliable interpretation of the masonry components. For the ionic column and its base presented in Figure 8, velocities higher than 5000 m/s indicate the use of com-pact natural stones, whereas values near 2000 m/s testify the presence of bricks with mortar joints.

4.2. Direct sonic tests applied to multiple leaf masonry walls

In the case of multiple leaf walls with poorly connected layers, the presence of discontinuities shows low velo-city results (Miranda et al. 2015; Valluzzi et al. 2018). On the contrary, good connections between the layers forming the masonry section correspond to high velo-cities. As a composite material, the byzantine walls are not homogeneous and not isotropic. For this reason, the result of sonic tests can provide only qualitative interpretations.

Using a sonic tests campaign carried out on the San Vitale Basilica in Ravenna as a reference for a first qualitative assessment of the masonry characteristics for a Byzantine building, a layout of the tests position and

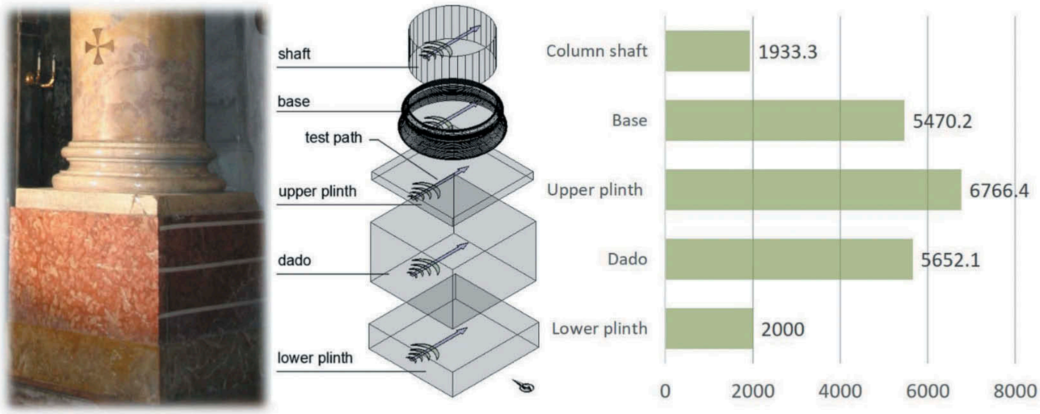

Figure 8. Example of calibration applied for a direct sonic test carried out on different elements composing a classic order (data elaborated by the authors).

their results is further described. Two different masonry structures were investigated by direct sonic tests. The north façade wall, tested by internal-external trajectories, covering a distance of 93 cm, showed a uniform distribution of the sonic velocities (see Figure 9). The north-east pillar, tested by using east-west trajectories, covering a distance of 156 cm, was characterised by not uniform values (see Figure 9). In the first case, the mean value of 1991 m/s can be assumed as reference velocity of a Byzantine brickwork presenting a solid connection among the internal nucleus and the external layers. In the second case, two ranges of velocity can be associated to a different composition of the massive pillar: the exter-nal bricks coating maintains a velocity similar to the previous case, equal to 1920 m/s, whereas the rest of the tested area presents a mean sonic velocity of about 1330 m/s, indicating a different organization of the masonry section. According to the building techniques used for massive structure, the masonry section could be composed of multiple leaves.

5. The sonic tests analysis on Santa Fosca and La Cattolica

The tests calibration in the two churches was arranged as follows:

a. testing using direct sonic configuration areas that were supposed to be representative for the multiple leaf structure and not deeply modified, according to the historical analysis;
b. measuring the sonic speed of a single brick by using direct, indirect and semi-direct configuration, in order to catch the characteristic sonic velocity of the main components;
c. acquiring some extra-data by using diagonal semi-direct testing path, in order to evaluate the impact of the distance between emission and receiving points with the multiple leaf masonry section.

5.1. Santa Fosca experimental campaign

For Santa Fosca, the historical analysis compared to the analysis of masonry pattern had shown that modifications occurred to the whole masonry complex and that the south wall showed interesting traces comparable to the first building period. Reused bricks of several dimensions compose the areas considered as belonging to the first phase of the building. Some Roman sesquipedalian bricks were even found (Figure 10). The joints present a height ranging between 1 cm and 1.5 cm.

During restoration works that were ongoing into the sacristy, a cavity in the wall was documented after the removal of some bricks for the realization of new technological systems. The direct sonic tests were expected to identify the areas hiding the cavity from the influence of the presence of air on wave propagation: three square grids 6 × 6 were reported on the two surfaces of the wall, with points 15 cm distant from each other (Figure 11). From the analysis of the masonry wall (already seen in Figure 5), it can be observed that the portions chosen for the sonic tests have not been reconstructed during Rupolo's or Forlati's intervention. On the other hand, it is worth recalling that although part of the analysed wall (FS1 and SF2) is made of reused bricks that might characterise the first phase of the church, it is not possible to determine their construction period.

Figures 12 and 13 show the main characteristics of the surfaces of the walls, with the position of the grids, for both sides.

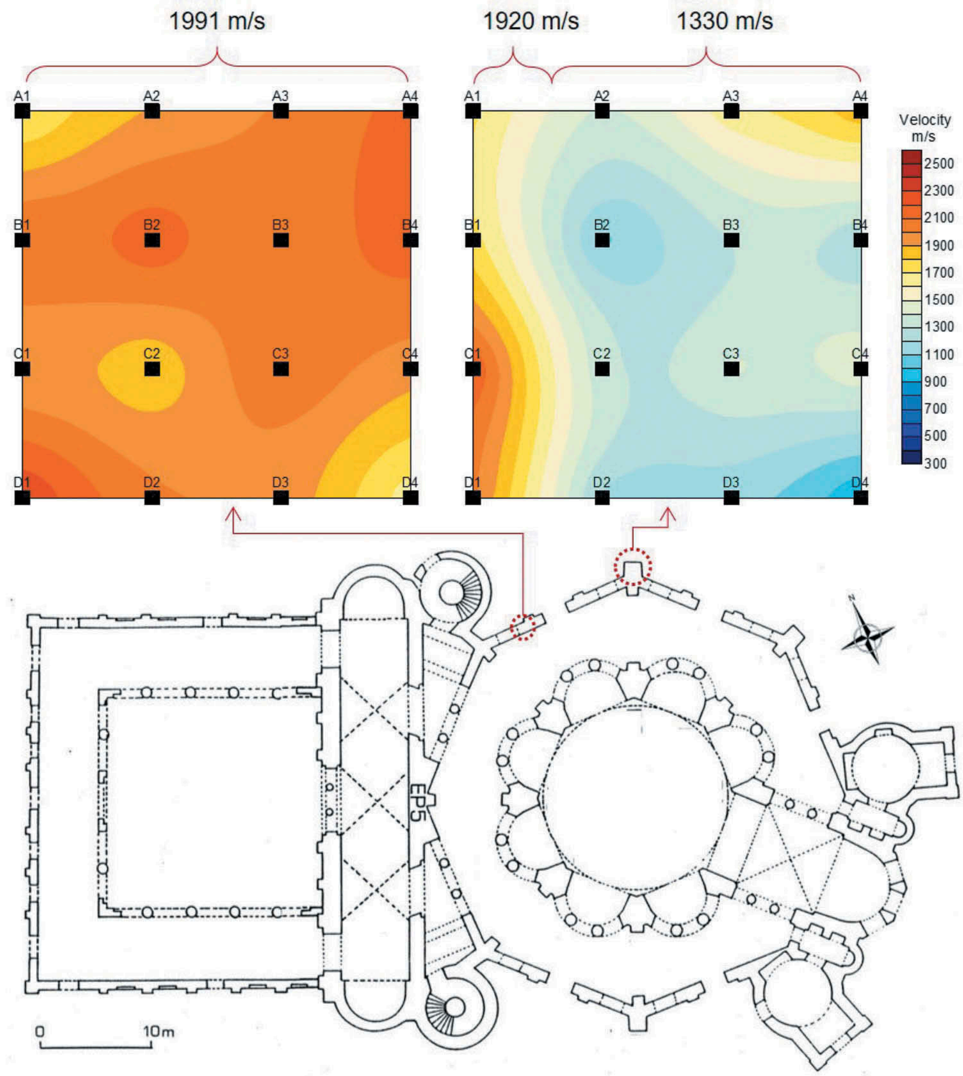

Figure 9. Comparison between sonic tests carried out on the north wall and on the north pillar of the San Vitale Basilica in Ravenna (data were a courtesy of professor Luigia Binda and the elaboration was made by the authors).

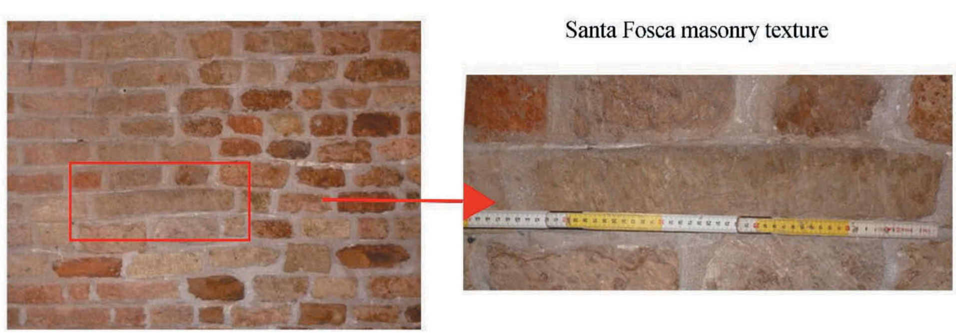

Figure 10. Analysis of the masonry texture of Santa Fosca in Venice.

The first grid (SF-S1) was located 2,29 m above the floor level, on a small square niche. It is worth noting that this grid crosses two different masonry patterns: as already mentioned, the lower is characterised by reused bricks different in colors and dimensions, whereas the upper one is composed of a regular and homogeneous pattern where bricks are similar to each other. The patterns diversity corresponds quite well to the pulse velocities resulting from the sonic tests. In fact, the velocity (referred to a path length of 70 cm, corresponding to the

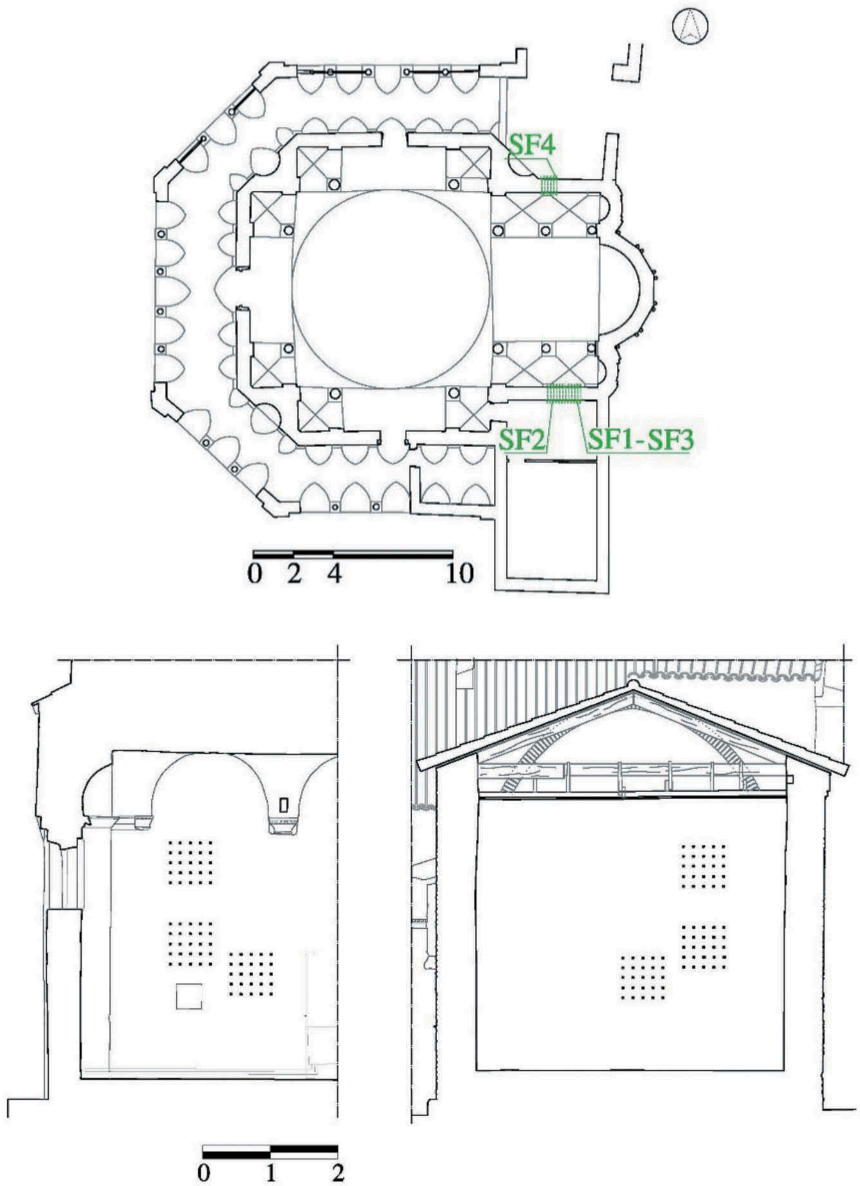

Figure 11. Localization of the direct sonic tests grids carried out in two areas on the south wall of the church.

wall section) varies between 520 and 1325 m/s. Especially the values between 520 and 800 m/s indicate a masonry section composed of stone elements, not well connected to each other (see Figure 14a).

Like in the case of grid SF-S2, also in this case the analysis has been conducted on two different masonry patterns, which probably correspond to two diverse stratigraphic units.

The second grid has been located on a lower area (point one is 1,85 m above the floor level) at a distance of 15 cm from grid SF-S1. On the wall side overlooking the sacristy, the grid is located next to the closed door, on the left. In this case, the velocities are even less homogenous than in the previous test (see Figure 14b). Some detailed considerations are:

- the area between points 25, 28, 32, 34 shows velocities comparable to the sound waves in the air. It is therefore possible that this part can hide a cavity inside the wall section or materials not well connected among each other;
- the area between points 1–5 and 19–23 shows velocities between 500 and 800 m/s. These velocities are related to a range of values comparable to a material, whose elements are not well assembled and connected to each other;

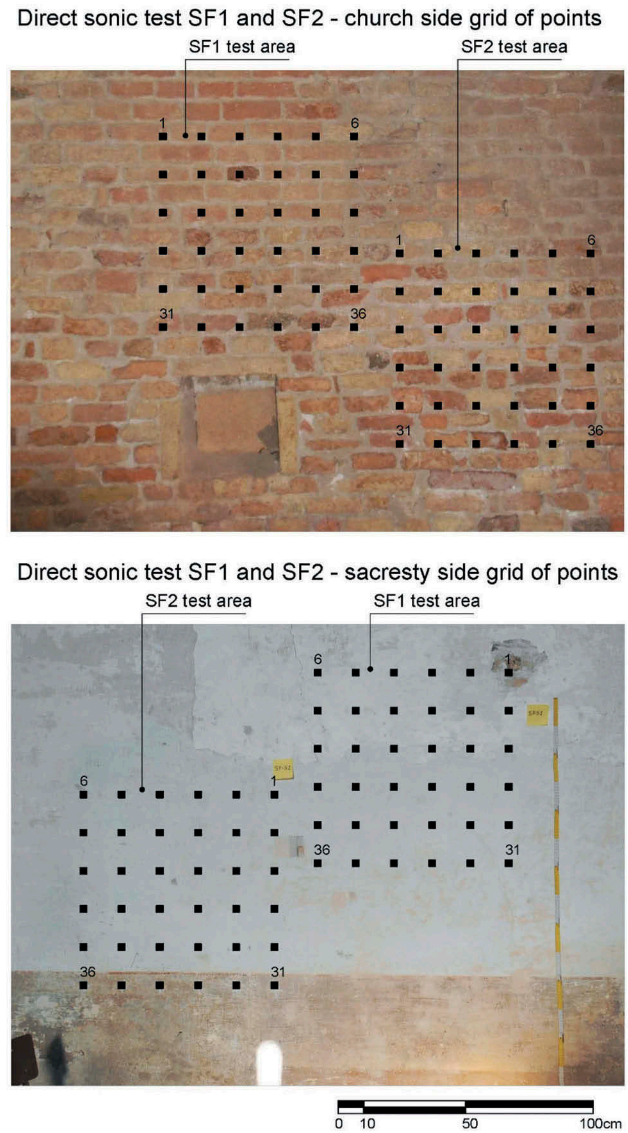

Figure 12. Localization of the direct sonic grids SF1 and SF2 on both sides of the wall.

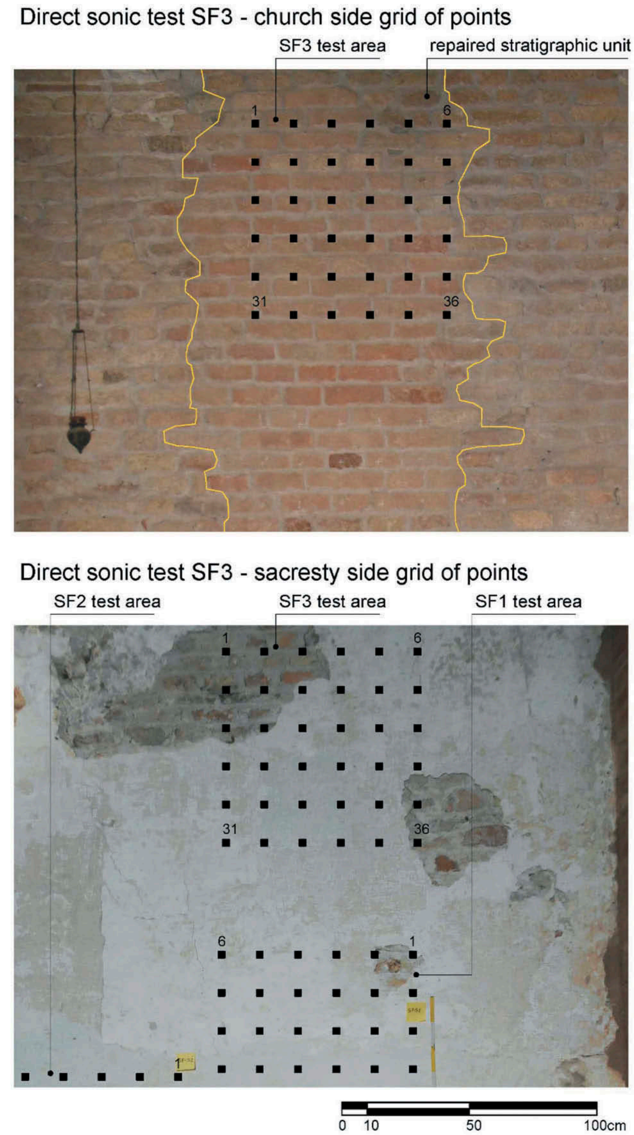

Figure 13. Localization of the direct sonic grid SF3 on both sides of the wall.

- the column of points between 6 and 36 shows velocity values higher than 1000 m/s and at points 12 and 36 even higher than 1700 m/s. This area shows densities greater than the other parts. This increase of the values, strictly depending on the higher density of this part, can be explained by looking at the masonry pattern on the surface overlooking the inside of the church. In fact, on the right of the grid, the masonry pattern drastically changes, probably due to a later intervention.

The sonic test SF-S3 has been carried out on a higher side of the masonry wall between the sacristy and the apse, 3,45 m above the floor level, slightly below a cavity discovered during a local inspection. At points 5 and 6 the velocity is close to the sound propagation velocity in the air (see Figure 14c). Most of the tested area is characterized by high velocity values close to 1400 m/s, which can be explained assuming that the material is compact and the elements are well interconnected. By observing the masonry pattern, values increase next to the changing of the supposed stratigraphic unit, as a result of a recent intervention.

The results indicate that the wall presents significant discontinuities. A velocity range of about 567–1365 m/s characterizes the areas where the masonry section maintains a load bearing function. The velocity distribution with values close to 400 m/s, found in the second test, can be associated to the presence of a cavity inside the wall. The vertical path followed by

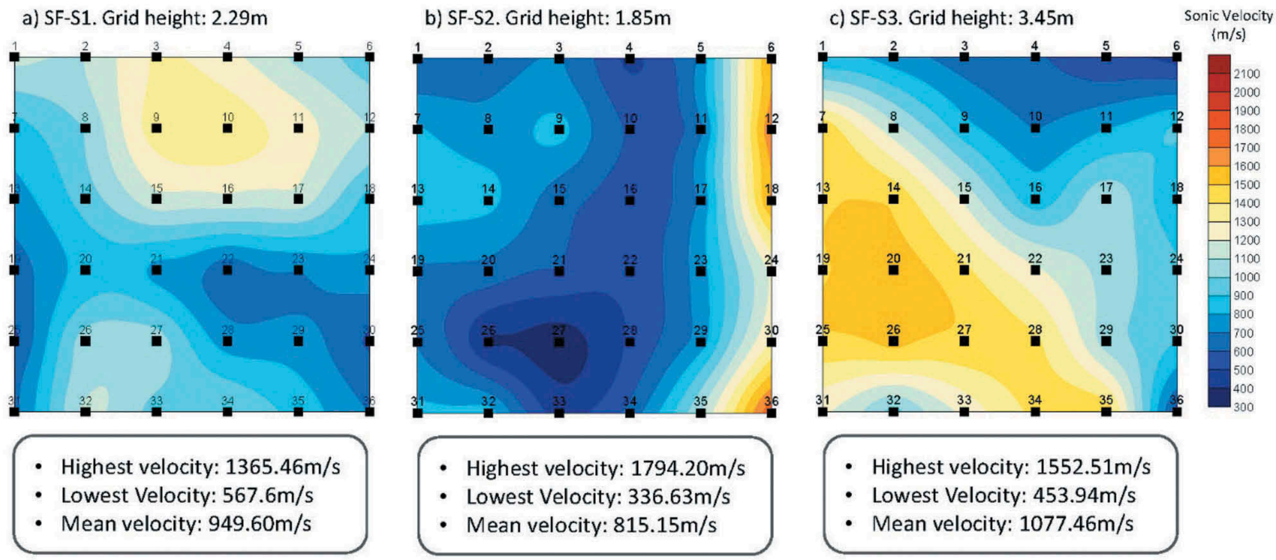

Figure 14. Map velocity distribution of the three areas of the south wall investigated by direct sonic tests with the obtained main results.

the low velocities describes a precise geometry, observing the grid reported in Figure 15b, that can even indicate the inclusion of a different material in the masonry wall. Thanks to this qualitative indication, a further and localized direct inspection can verify the characteristics of the structure: in this case, a vertical cavity hosting the traces of a timber element was discovered.

5.2. La Cattolica experimental campaign

Moving to the case of Stilo, two sonic tests were carried out on the south wall. In this case, the frescos on the internal walls and the position of the church along the slope of the mountain prevented the assessment of most sides of the building. Only two areas along the south side were tested by direct sonic tests. In this case, two main materials were identified: bricks of about 43 × 23 × 4cm or 22 × 15 × 8 cm while the height of the mortar joint varies between 2 and 2.5 cm. The masonry texture shows a prevalent use of headers 22 × 15 × 8 cm in all the courses, with some less frequent stretchers placement. One or two listed courses are also present, formed by the flat 43 × 23 × 4 cm bricks (Figure 15). From the architectural survey of the external prospects, one listed course appears at about one third in elevation in the south, east and north façades, whilst it is not present on the west façade.

Compared to the case of Santa Fosca, the walls of La Cattolica have lower thickness, thus regularity of the masonry texture should characterize the wall sections. Considering the various uses of the building during its long history, a qualitative control of the vertical structures seemed appropriate. In this case, direct access to both wall sides was possible only at the south wall. A homogeneous

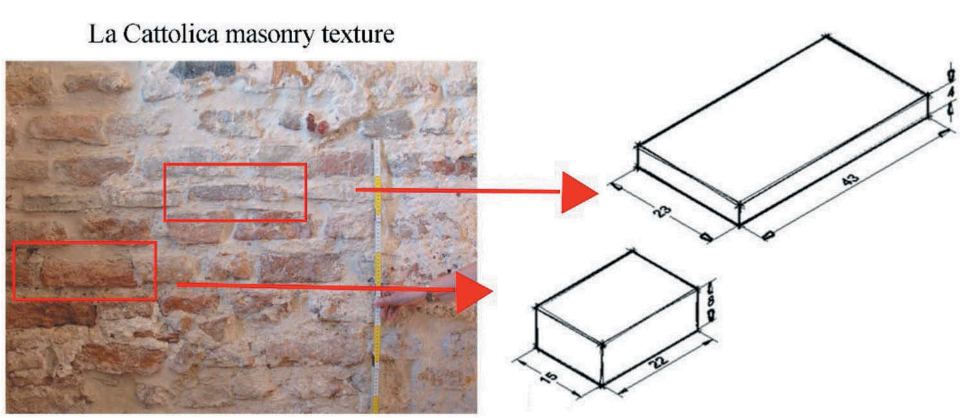

Figure 15. Analysis of the masonry apparatus of La Cattolica in Stilo.

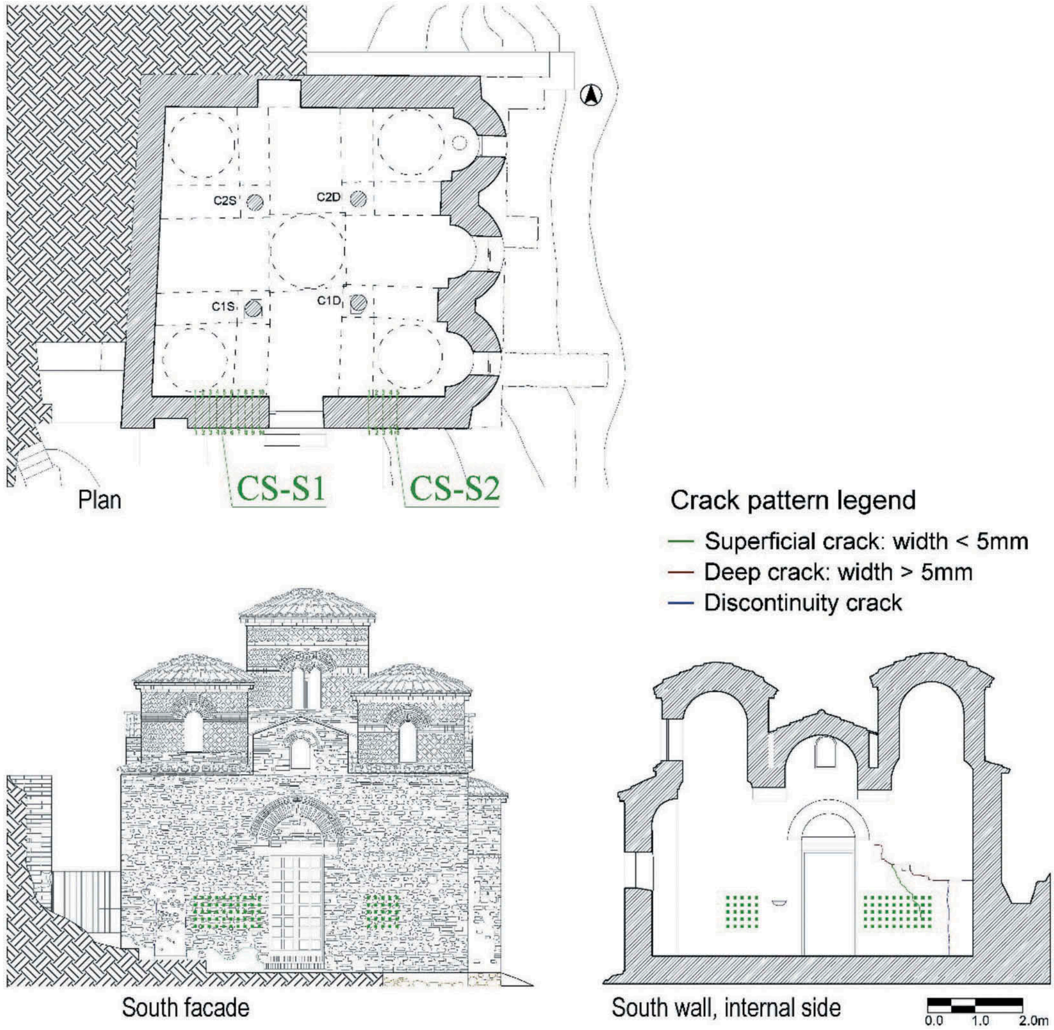

Figure 16. Localization of the direct sonic tests grids carried out in two areas on the south wall of the church.

texture was identified between the main door and an infilled opening near the west corner; a second area examined was on the other side near the main entrance, before the slope of the hill (see Figure 16). The south wall does not present an extended crack pattern. Few super-ficial cracks are visible on the internal side, but they are connected to some discontinuities (a closed opening) or are mainly referred to limited soil settlements, according to their diagonal path. The areas were also limited by the presence of some remains of fresco decorations on the internal side.

As observed in Santa Fosca, the walls of such ancient buildings present several modifications due to repair interventions along time, changes in the use of the building requiring some transformations, decays of the materials, with eventual replacement of the damaged bricks and repointing of the mortar joints. The restoration works carried out by M. Orsi in the first half of the 20th century, for example, used the repairing technique named "scuci-cuci" on the external surfaces of the wall for substituting bricks presenting hair cracks, erosion and powdering in limited areas. The internal side of the walls, characterized by frescoes or traces of decorations, used by experts of art for dating the building origins, did not require invasive repairing interventions and were preserved with cleaning and joint-repointing interventions.

A detailed view of the grids of points reported for each side of the wall is available in Figures 17 and 18.

The results showed a good distribution of homogenous values in both tested areas. The range of the sonic velocity here was between 1338 and 2293 m/s. In the first test some lower values were identified in the upper part of the grid of points; these could be the consequence of a crack system located near the scaffolding hole.

As shown in Figure 19, the main values of both tests are similar, indicating that the masonry cross section of the main façade presents homogenous characteristics. The velocities are close to those observed for regular

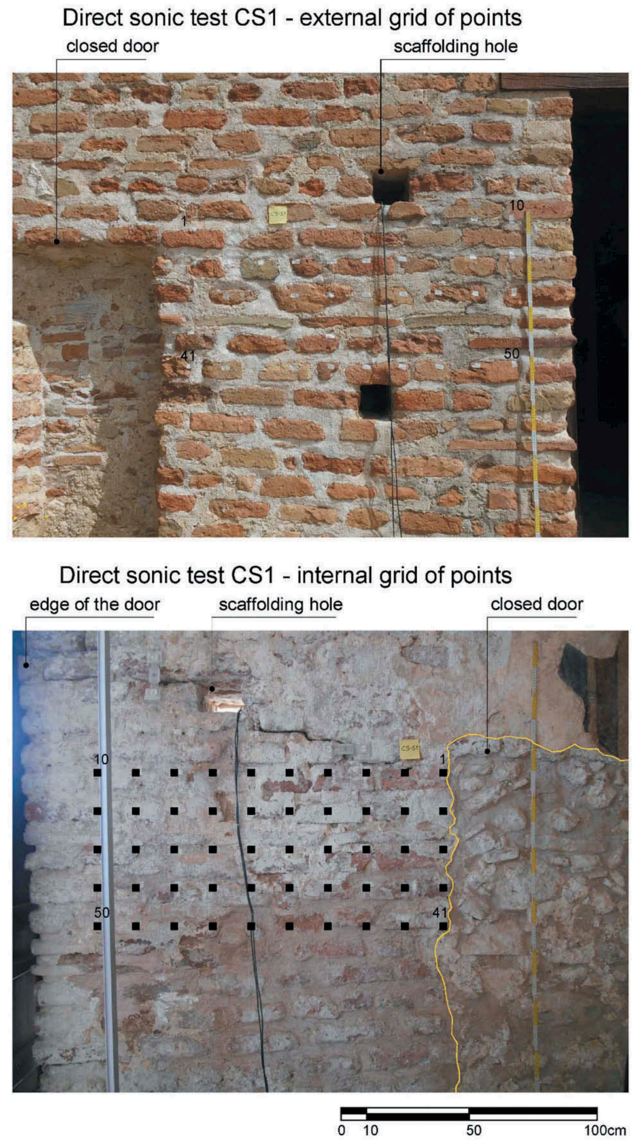

Figure 17. Localization of the direct sonic grid CS1 on both sides of the wall.

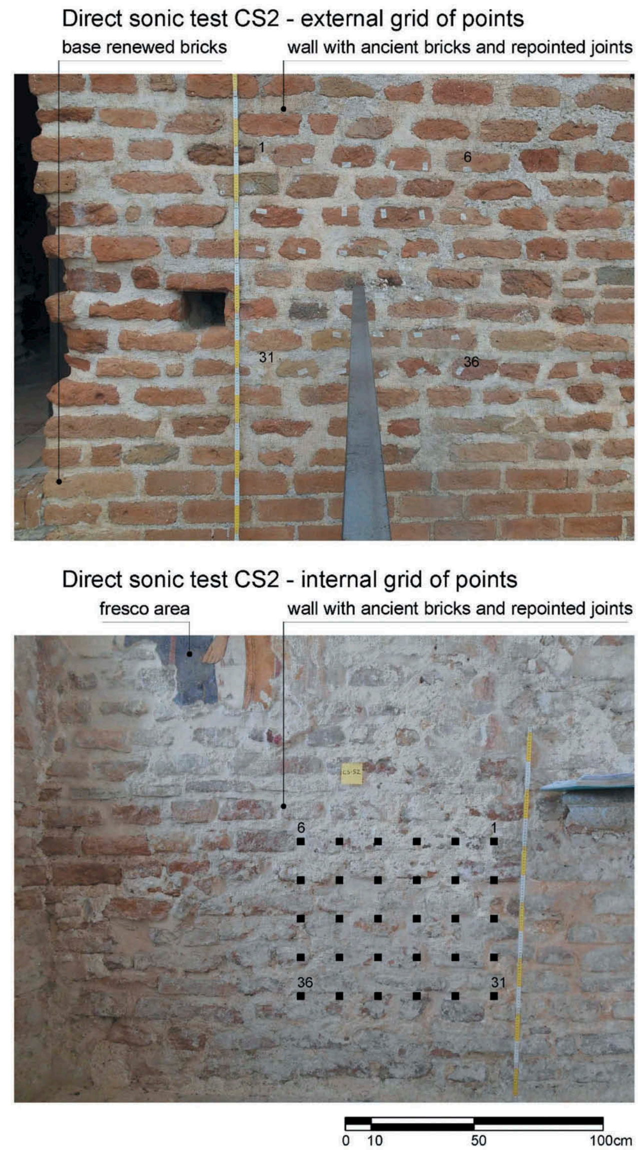

Figure 18. Localization of the direct sonic grid CS2 on both sides of the wall.

masonry sections composed of bricks and mortar. In this case, the tests identified a wall section presenting a correct connection among its component materials. Moreover, the results indicate that, in terms of state of conservation, the masonry wall maintains its original properties and damage is limited to thin cracks.

6. Interpretation of the masonry characteristics

The results described in the previous paragraphs provide a qualitative response of the masonry properties. By comparing the range of the sonic speed recorded for the different points of the grids, and making reference to the Byzantine building techniques, a qualitative interpretation of the section of the wall can be outlined. To this aim, sonic test no. 2 carried out in La Cattolica and sonic test no. 3 from Santa Fosca were compared, considering selected results recorded in specific points, in order to sketch out the hypothetical transversal pattern of the masonry section.

The graphs describing the velocity distribution showed an important dispersion of the results for the third grid of points used in Torcello, whilst the second test performed in Stilo was characterized by fairly uniform results. The homogeneous distribution of the sonic velocity is commonly associated to a regular composition of the masonry section. Taking into account the same row of points, from 19 to 24, both tests were compared by using the data of each single velocity measured between each emitter-receiver path.

If the masonry pattern of the walls is visible, like in Stilo (for both sides) and in Torcello (only for one side),

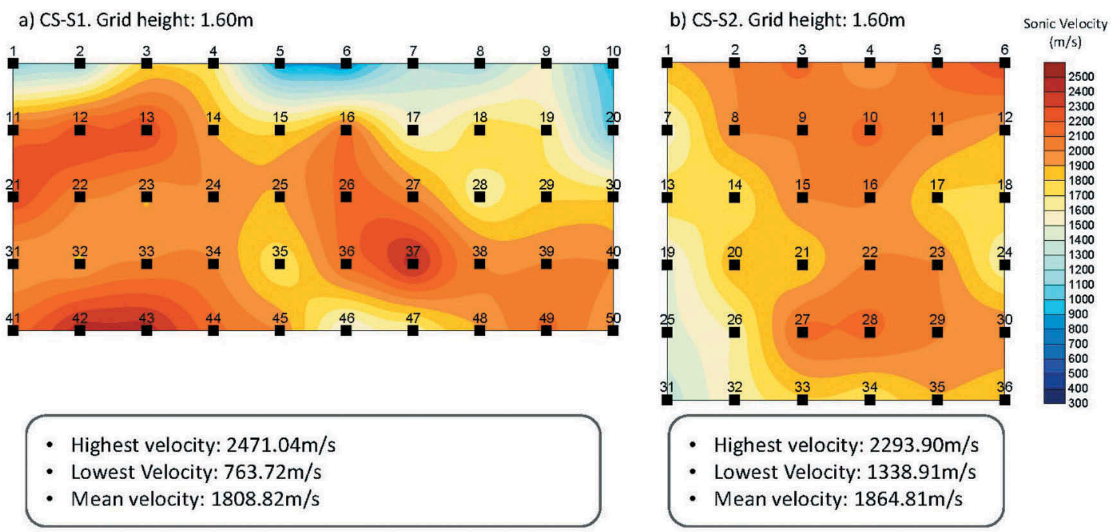

Figure 19. Distribution of the sonic velocities obtained by two direct sonic tests carried out on the south façade of La Cattolica church.

and a direct inspection of the brick dimensions (at least 20 measurements) can be carried out, a hypothetical layout of the masonry section can be proposed. Figure 20 shows the possible masonry typologies identified in Santa Fosca and in La Cattolica according to these parameters:

a. Dimension of the wall thickness;
b. Geometry and material consistency of the masonry apparatus;
c. Sonic speed propagation.

The interpretation drives to a graphic representation proposing the arrangement of the materials composing the masonry for the considered rows (points 19–24) of the testing grid. This layout refers to an assumed distribution of the internal density of the masonry section on the horizontal plane, characterized in both churches by several head-breaks on the external surfaces. Observing the sonic velocity, each variation among the results can be justified by a different organization of the materials in the nucleus of the section: well-connected elements, separated by a limited number of joints, can justify higher velocities. On the contrary, the presence of rubble materials or a higher number of joints between the components can cause a sensible reduction of the sonic speed.

Following the experimental identifications of masonry wall characteristics, a final crucial step would require the definition of the corresponding mechanical properties, as premise to structural analysis and, finally, to safety assessment. This last should be checked with reference to both vertical permanent loads and the horizontal actions due to seismic motion. The mechanical parameters representing compression and shear strength should therefore be determined, in addition to the elastic modulus. Obvious constraints on destructive testing are clearly in contrast with such a need, limiting the knowledge of masonry properties to a qualitative level. Even under such conditions, however, some indications on structural safety can be given, based on few general considerations.

Good health conditions, ascertained from visual inspection, result directly into a positive safety assessment in the case of old structures; the residual life expectation, depending on the decay process affecting both structural materials and components, can be estimated on the basis of non-destructive experimental techniques, as previously described. For both the churches here discussed, present health conditions appear to be satisfactory, and the structural decay process seems in a stable condition, as a consequence of previous restoration interventions.

In both cases, and mainly in the case of La Cattolica, the limited dimensions of the structural layout result into reduced levels of compression stress in normal conditions. Looking at local data for seismic hazard, in Santa Fosca shear stresses, which might be induced into the masonry walls by an earthquake, should be relatively limited. For la Cattolica, in a much higher seismicity condition, its small dimensions and compactness should favour a positive global seismic behaviour. A more reliable condition assessment of the vertical structures could be obtained by complementary investigations, using local inspections with the video-endoscope or ground penetrating radar and future calibrations could take into account a validation of the results based on a multi-scale diagnostic campaign based on ND and MD tests.

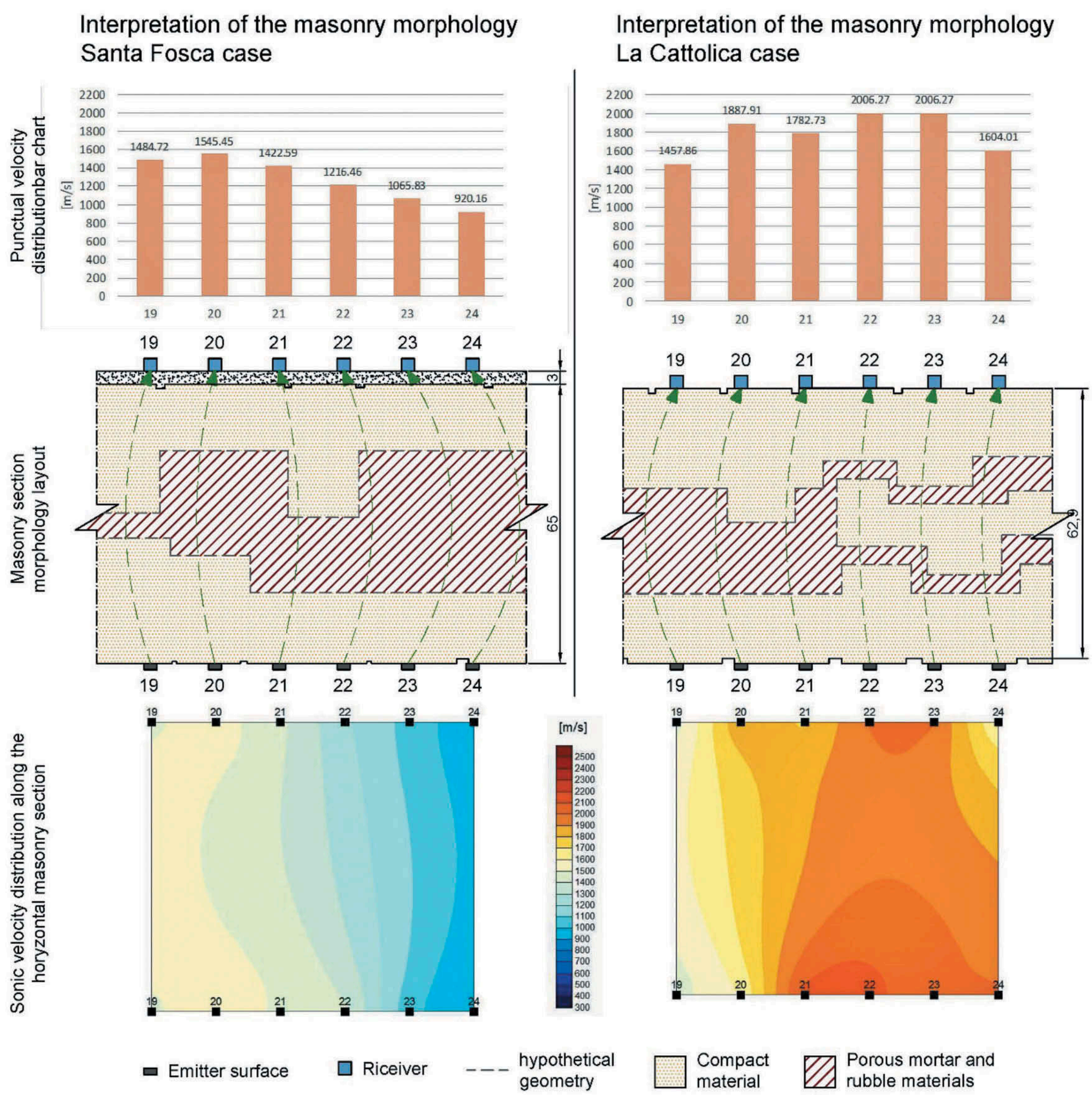

Figure 20. Interpretation of the results obtained for a specific row of the grid of points used for the tests: hypothetic layout of the masonry horizontal sections.

Attention should be focused on the possible activation of local failures, i.e., the collapse of the most deteriorated column in the case of La Cattolica and a sudden increase of local ground settlement in the case of Santa Fosca. Special interventions should be defined and carried out in relation to these specific issues.

7. Conclusions

The deep impact of Byzantine culture on the building techniques, developed in two different Italian regions, was here studied by considering Santa Fosca on Torcello Island (Venice) and La Cattolica in Stilo (Reggio Calabria). This work proposed a study approach based on the analyses of the historical evolution of the buildings compared with the onsite investigation of the masonry pattern with the support of direct sonic tests. The response obtained by this non-destructive investigation allows a further evaluation of the main structural properties of the considered buildings.

The qualitative results obtained by direct sonic tests, thanks to a detailed elaboration of the data, were used for deriving a reliable interpretation of the morphology of the walls cross sections. Within this framework, a higher quality of the masonry characteristics was identified for La Cattolica, a more compact and contained building compared to Santa Fosca, where the values showed a less reliable building technique. These results can reveal a different way of building, depending on local environmental conditions, like earthquakes or earth subsidence. In fact, despite these churches are both representative of the so-called

Middle-Byzantine period in Italy, their differences were observed at typological configuration level as well as considering the constructive techniques, strictly related to the local tradition depending on the geographical context.

An extension of the diagnostic testing, possibly resorting also to MDT, would be advisable for reducing uncertainties as well as for estimating mechanical properties for structural behaviour analysis. The results obtained from this first campaign, however, in spite of limitations associated to the high protection state for the two buildings and to the scope of the project, have offered a deep insight of the two buildings, and the possibility of an interpretation.

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Disclosure statement

No potential conflict of interest was reported by the authors.

References

Arena, M., D. Colistra, and D. Medaiti. 2015. La cattolica di stilo. 8 (15):1-14.

ASTM- D 2845–00. 2000. Standard test method for laboratory determination of pulse velocities and ultrasonic elastic constants of rock.

ASTM-C597–02. 2002. Standard test method for pulse velocity through concrete.

Baronio, G., L. Binda, and N. Lombardini. 1996. The role of brick pebbles and dust in conglomerates based on hydrated lime and crushed bricks. Proceedings of the Seventh North American Masonry Conference, Notre Dame (USA), June 2–5, 799–810.

Bettini, S. 1940. Aspetti bizantineggianti dell'architettura di Torcello. In *Torcello*, ed. M. Brunetti, 45–71. Venezia: Libreria serenissima.

Binda, L., and G. Baronio. 1996b. Byzantine concretes: The role of thick masonry joints containing crushed bricks. Proc. of the RILEM Int. Conf. on 'Concrete: from Material to Structure, Arles, France, 289–309.

Binda, L., L. Cantini, G. Cardani, A. Saisi, and C. Tiraboschi. 2007. Use of Flat-Jack and sonic tests for the qualification of historic masonry. 10th Tenth North American Masonry Conference (10NAMC), St. Louis, Missouri, June 3–6. doi: 10.1094/PDIS-91-4-0467B.

Binda, L., N. Lombardini, and F. Guzzetti. 1996a. St. Vitale in Ravenna: A survey on materials and structures. International Conf. Historical Buildings and Ensembles, Karlsruhe, 113–24.

Bouras, C. 2001. Βυζαντινή και μεταβυζαντινή αρχιτεκτονική στην Ελλάδα, Melissa, Atene (Engl. transl. Byzantine and Post-Byzantine Architecture in Greece, Melissa, Athens 2006).

Cameron, A. 2009. Greek East and Latin West. The Church, AD 681–1071. In *The journal of ecclesiastical history*, ed. A. Louth, (The Church in History, 3.), Xvii +382. Crestwood, NY: St Vladimir's Seminary Press, 2007. 978 0 88141 320 5; 1938 8306.

Cameron, A. 2011. The anxiety of images: Meanings and material objects. In *Images of the Byzantine World: Visions, massages and meanings. Studies presented to Leslie Bribaker*, ed. A. Lymberopoulou. Farnham: Ashgate, 47-56.

Cantini, L. 2016. The diagnostic investigations plan for historic masonry buildings: The role of sonic tests and other minor destructive techniques. In *Brick and block masonry. Trends, innovations and challenges*, ed. C. Modena, F. da Porto, and M. R. Valluzzi, 1469–76. London: Taylor & Francis Group, Balkema.

Cornaro, F. 1749. *Ecclesiae Torcellanae antiquis monumentis nunc etiam primum editis illustratae*, vol. 14. Venezia: Typis Jo. Baptistae Pasquali.

De Angelis D'Ossat, G. 1942. *Le influenze bizantine nell'architettura romanica*. Roma: Fratelli Palombi Editori.

Johnson, M. J., R. Ousterhout, and A. Papalexandrou, eds. 2012. *Approaches to Byzantine architecture and its decoration*. Ashgate.

Karaveziroglou, M., I. Papayianni, and G. Penelis. 1989. The dependent deformations of bricks masonry. Structural conservation of stone masonry, Athens: ICCROM, October 31, Athens, 247–54.

Krautheimer, R. 1965. *Early Christian and Byzantine architecture*. Baltimore: Yale University, Press Penguin Books.

Leciejewicz, L., ed. 2000. *Torcello. Nuove ricerche archeologiche*. Roma: G. Bretschneider Editore.

Lombardini, N. 2001. Some considerations on the IV-VI Centuries Rome, Milan, Ravenna and Istanbul Brick Masonries: The building technologies and the structural behaviour. Hagia Sophia. Surveying Project Conference, Tsukuba, 65–76.

Mango, C. 1974. *Architettura Bizantina*. Milano: Electa.

Mango, C. 1986. *Art of the Byzantine Empire, 252-1453: Sources and documents*. Toronto: University of Toronto Press.

Manzo, A. 2016. Santa Fosca in Torcello and the Middle Byzantine churches in Eastern Greece: Preliminary comparison and remarks on common features and differences. *Athens Journal of History* 2 (1):43–57. doi:10.30958/ajhis.2-1-3.

Manzo, A., and C. Chesi. 2016. Stability problems of the church of Santa Fosca on Torcello Island. In *Structural analysis of historical constructions structural analysis of historical constructions – Anamnesis, diagnosis, therapy,* *controls*, ed. K. Van Balen, and E. Verstrynge, 1728–35. London: Taylor & Francis Group.

Manzo, A., and C. Chesi. 2018. Building techniques and structural damage of historical constructions detected through the point cloud survey. In *Structural analysis of historical constructions, RILEM Bookseries*, ed. R. Aguilar, D. Torrealva, S. Moreira, M. A. Pando, L. F. Ramos, vol. 18, 275–84. Cham: Springer.

Megaw, A. H. S. 1964. Byzantine Reticulate Revetments. In *Χαριστηριον ειδ Αναστασιου*, ed. K. Ορλανδον III, Ethanai, 17–19. Athens.

Millet, G. 1899. *Le Monastère de Daphni* [The Daphni Monastery]. Paris: E. Leroux.

Miltiadou-Fezans, A. 2008. A multidisciplinary approach for the structural restoration of the Katholikon of Dafni Monastery in Attica Greece. In *Structural analysis of historic construction*, ed. D. D'Ayala, and E. Fodde, 71–86. London: Taylor & Francis Group.

Miltiadou-Fezans, A., E. Vintzileou, and N. Delinikolas. 2010. Pathology of the Katholikon of Hosios Loukas and preliminary structural analysis. *Advanced Materials Research* 133–134:319–24. doi:10.4028/www.scientific.net/AMR.133-134.319.

Miranda, L., L. Cantini, J. Guedes, and C. Anibal. 2015. Assessment of mechanical properties of full-scale masonry panels through sonic methods. Comparison with mechanical destructive tests. *Structural Control and Health Monitoring* 23 (3):503–16. doi:10.1002/stc.1783.

Orsi, P. 1929. *Le chiese basiliane della Calabria*. Firenze: Vallecchi.

Ousterhout, R. 1996. An Apologia for Byzantine architecture. *Gesta* 35 (1):21–33. doi:10.2307/767224.

Palieraki, V., E. Vintzileou, A. Miltiadou, and N. Delinikolas. 2008. The use of radar techniques and boroscopy in investigation of old masonry: The case of Dafni monastery. *International Journal of Architectural Heritage* 2:155–86. doi:10.1080/15583050701646711.

Pevser, N. 2002. *Storia dell'architettura europea*. Laterza: Roma-Bari.

Polacco, R. 1984. *La Cattedrale di Torcello*. Venezia: L'altra Riva.

Psycharis, I. N., H. P. Mouzakis, A. Miltiadou-Fezans, E. P. Pavlopoulou, and M. I. Taflampas. 2010. Investigation of the seismic response of a Byzantine Church and evaluation of the effectiveness of proposed interventions. *Earthquake Spectra* 26 (2):473–97. doi:10.1193/1.338948.

Spagnesi, P. 2008. *Chios medievale - Storia architettonica di un'isola della Grecia Bizantina*. Roma: Casa Editrice Università La Sapienza.

Stravrakakis, E., C. Ignatakis, B. A. Mathew, and G. Penelis. 1995. Masonry under biaxial compression analytical parametric investigation using F.E.M. In *Computer methods in structural masonry*, vol. 3, 78–87. J. Middleton and G. N. Pande. Lisbon.

Taliercio, A., and L. Binda. 2006. Stress analysis of San Vitale's Basilica in Ravenna: Current state and mid-term predictions. In *Structural analysis of historical constructions*, ed. P. B. Lourenço, P. Roca, C. Modena, and S. Agrawal, 2005–12. New Delhi. Balkema.

Teodoru, H. 1930. Les eglises a cinq coupoles en Calabrie: S. Marco de Rossano et la Catholique de Stilo. Ephemeris Dacoromana IV.Roma, Libreria di Scienze e Lettere.

Valluzzi, M. R., E. Cescatti, G. Cardani, L. Cantini, L. Zanzi, C. Colla, and F. Casarin. 2018. Calibration of sonic pulse velocity tests for detection of variable conditions in masonry walls. *Construction and Building Materials* 192:272–86. doi:10.1016/j.conbuildmat.2018.10.073.

Venditti, A. 1969. *Architettura bizantina nell'Italia meridionale*. Campania. Calabria. Lucania: Napoli.

Vintzileou, E. N., I. G. Konteas, A. Manoledaki, V. Palieraki, and A. Miltiadou-Fezans. 2009. The Katholikon of Osios Loucas Monastery: In situ investigations. NDTCE'09, Non-Destructive Testing in Civil Engineering, Nantes, France, June 30th – July 3rd.

Zago, F. 2009. La Cattolica di Stilo e i suoi affreschi. *Zograf* 33:43–61. doi:10.2298/ZOG0933043Z.

Zanini, E. 1994. *Introduzione all'archeologia bizantina*. Roma: Carocci.

Zuliani, F., ed. 2008. *Veneto Romanico*. Milano: Editoriale Jaka Book Spa.