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CHARACTERIZATION OF DECAY IN THE WOODEN ROOF OF THE S. AGATA CHURCH OF RAGUSA IBLA (SOUTHEASTERN SICILY) BY MEANS OF SONIC TOMOGRAPHY AND RESISTOGRAPH PENETRATION TESTS

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This article describes the results of a sonic tomography survey and penetration tests carried out inside the S. Agata Church of Ragusa Ibla, in southeastern Sicily (Italy). The purpose of this work was to evaluate the extent of decay in some of the ancient wooden trusses of the nave's roof, in view of possible strengthening interventions. Sonic tomography is entirely noninvasive and is suitable to investigate large portions of a structure, although qualitatively, whereas penetration tests are slighlty invasive as point measurements that enable high-resolution detection of wood decay and cracks. This study combined the two techniques to investigate the internal condition of four trusses that looked most deteriorated at a preliminary visual inspection. Results showed that decays occur mainly next to the walls, due to rainwater infiltration, and on the side of the timbers facing the rear of the nave, possibly for the higher level of moisture caused by lack of ventilation from that direction. In general, chords have worse mechanical properties than rafters.

KEY WORDS: wood, sonic tomography, penetration test, S. Agata Church of Ragusa Ibla

1. INTRODUCTION

Ragusa Ibla is a historical village of southeastern Sicily, included since the 2002 in the UNESCO World Heritage List as one of the *Late Baroque Towns of the Val di Noto*. At its southeastern edge stands the Church of S. Agata (Figures 1a–1b) that Sella (1944) reported to exist already at the beginning of the 14th century. In 1607, this church became a property of the Capuchin Friars who built a monastery adjacent to it. Several dates carved inside the two edifices testify periods of construction and rebuilding through time, some of these following the 1693 destructive earthquake: 1614, carved into one of the roof trusses (Figure 1c); 1715, on the chorus door; 1742, on the pavement right behind the entrance of the monastery (Sortino Trono, 1928).

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Figure 1. Photographs of (a) aerial view of the historical village of Ragusa Ibla, and (b) location of the S. Agata Church; (c) the date 1614 is carved into one of the roof trusses, probably referring to its construction (color figure available online).

The church of S. Agata, known also as *Capuchins' Church*, has a single nave with a roof made of 15 chestnut trusses. The aim of the present work was to evaluate the state of conservation of the roof. After a preliminary visual inspection aimed at identifying the problematic portions of the timbers, four trusses were selected with the largest evidence of deteriorations for further investigation with in-situ, non-destructive methods. First sonic tomography was carried out to obtain qualitative information about the extent of decay; afterwards penetration tests were performed to quantify the loss of material locally, and crosscheck the results obtained with tomography.

2. TECHNIQUES OF INVESTIGATION

2.1. Sonic Tomography

Sonic and ultrasonic tomography are entirely non-destructive techniques that are suitable to verify the integrity of a structure. Elastic pulses in the acoustic frequency range (≥20–20,000 Hz) are transmitted in the medium under investigation and recorded by an array of sensors deployed in contact with it, respectively. The time needed for the waves to travel from the energization points to the receivers—called *time of flight* (TOF)—is used to compute propagation velocity along different paths and reconstruct two-dimensional (2D) velocity images across the object. As mechanical wave velocity through a medium is directly proportional to its elastic modulus, the tomography image, called a *tomogram*, gives a picture of the mechanical conditions of the target object.

The spatial resolution of a tomography method refers to the size of the smallest feature detectable; it is directly related to the wavelength (λ) of the wave transmitted into the object, that in turn depends on velocity (v) and frequency (f) through the equation $\lambda = v/f$. The use of higher frequency (shorter wavelength) waves raises the resolution of the investigation. However, higher frequency waves have a shorter penetration depth because they attenuate rapidly as they travel through a medium. For this reason, ultrasonic tomography is most appropriate for compact materials and small structural elements such as beams and pillars, while sonic waves are preferable to examine anisotropic materials, where signal attenuation is an issue, and larger structures, although with less resolution.

Sonic and ultrasonic waves proved to be effective for decay detection in wooden structures and living trees; waves travel faster through sound wood than through a deteriorated wood (e.g., Berndt et al., 1999; Sandoz et al., 2000; Bucur, 2003; Socco et al., 2004; Ross et al., 2006; Palaia, 2007; Lin et al., 2008; Brazee et al., 2011).

This survey acquired 28 sonic tomography profiles along 1.1-m segments of chords and rafters. Acoustic waves were generated by an instrumented hammer that worked also as a trigger to determine the TOF, and were recorded by 12 equally spaced (10-cm) piezoelectric transducers placed in contact with the timbers (Figures 2a–2b). Hammer and receivers were connected to the portable seismograph M.A.E. Eurosit A6000S (Figure 2c) equipped with an A/D 24-bit converter. The operation was in direct transmission mode, which means that energization points and receivers are paired on opposite sides of the timber as in Figures 2b and 2d.

In a wooden element, the propagation velocity of elastic waves varies depending on the direction of the fibers—it is faster along the fibers than across them. In this work, the timbers were hammered (i.e., waves propagate) transversely to the fibers of the wood. Measurements in this direction are most effective for detection of decay (Ross et al., 2006).

Data were processed in real time with the software SeisOpt@2D v5.0 (Optim, Inc., Reno, NV, USA) that uses the array geometry and the travel times of the first arrivals (longitudinal waves) to derive subsurface velocity. The tomography reconstruction method is a nonlinear optimization technique involving forward modeling. It creates test velocity models represented as discrete cells, each characterized by a constant velocity value, through which travel times are calculated and then compared with the observed TOFs. This process runs iteratively until a satisfactory match between calculated and observed times is obtained. The best solution is the model that minimizes (i.e., optimizes) the discrepancy between calculated and observed travel times. Final outputs of the processing are the best velocity model and the ray density diagram, this last displaying the number of rays that sampled each cell of the model.

The software SeisOpt@2D v5.0 allows the user to choose among five preset resolution levels based on the receivers spacing (rs) of the input data, which in this survey was 10 cm. We have selected the highest resolution level which corresponds to grid cells with horizontal and vertical size defined as $hx = 0.375 \cdot rs$ and $hz = 0.1875 \cdot rs$ (i.e., 3.75 and 1.87 cm, respectively).

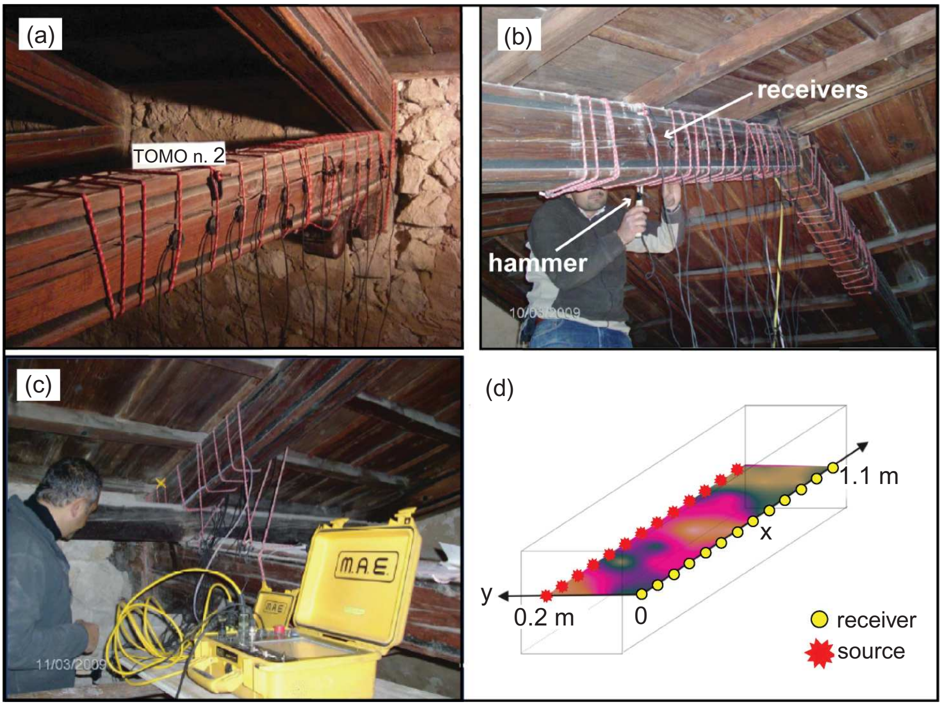

Figure 2. Photographs of the sonic tomography equipment along the chord (a) and the rafters (b, c); (d) scheme of the direct transmission configuration used in this survey (color figure available online).

2.2. Penetration Tests

Penetration tests provide high-resolution, point measurements of wood quality, and are little invasive (e.g., Ross et al., 2006; Palaia, 2007; Lear et al., 2011). Tests consist in entering the wood with tiny metal tips to measure the differential resistance to drilling that is diagnostic of density changes along the drilling path. Apart from the inherent heterogeneity of wood, density changes are caused by structural defects, alterations due to fungi or insects that are often present in old timbers, voids and fractures.

The Resistograph (IML, Inc., Orange Park, FL, USA) is a common tool for these tests. It is portable, battery-operated and easy to handle, and can reach parts of a structure that are not accessible with other techniques. Further, damage to the investigated structure is minimal due to the thinness of the tip. The advancement speed is set on the basis of the expected wood quality and is held constant by an electronic control unit.

The output of a test performed with the Resistograph is a profile, called a resistogram, where density behavior is displayed as amplitude of resistance to drilling vs. the depth progressively reached by the tip. A resistogram illustrates the natural heterogeneity of wood and the presence of decay and fractures, as in the example of Figure 3a. It is dominated by series of positive and negative peaks due to the annual rings growth—minimum peaks corresponding to early wood portions formed during springtime, maximum peaks corresponding to late wood rings formed during fall. Decayed wood has a lower resistance to drilling with respect to sound wood; knots correspond to the highest resistance amplitude. In case of fractures or voids, as well as total decay, the resistance profile goes to zero.

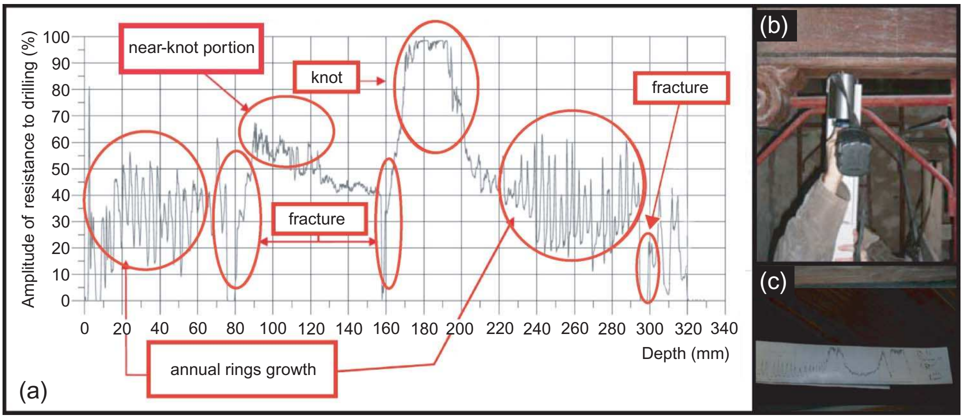

Figure 3. (a) Chart of example profile of resistance to drilling and interpretation of the density behavior; (b) photograph of the penetration test equipment; (c) printout of a resistogram obtained in this survey (color figure available online).

In the present work, 15 tests were performed, 12 on chords and three on rafters, using the Resistograph IML-RESI F400 system with a needle of 3 mm in diameter (Figure 3b). Drilling depth ranges between 16 and 24 cm depending on the thickness of the timber in the drilling direction, vertical or horizontal. With this instrument, data are recorded digitally on a computer and printed in real time on a wax paper strip at 1:1 scale, to allow a direct comparison with the structure under test (Figure 3c). In the digital recordings, quality assessment is automatically provided, as data are displayed, with a sequence of colored bars distinguishing portions of wood characterized by similar response to drilling.

3. RESULTS

For each of the four trusses under investigation, we have carried out seven tomography profiles and three to four penetration tests, some of which crossing the tomography sections. Tomograms with related ray density diagrams and resistograms obtained for each truss are shown in Figures 4–7. Tomograms image horizontal cross sections of the timbers oriented toward the church's entrance. As for the penetration tests, most of the horizontal drillings point toward the entrance, while all vertical drillings point upwards.

In the truss # 3 (Figure 4) sonic velocity ranges from 900 to 3,400 m/s along the rafters (Tr1-Tr4) and from 1,000 to 2,600 m/s along the chord (Tc1-Tc3), this last characterized by the largest low-velocity anomalies. In the rafters, Vp is predominantly higher than 2,000 m/s (red to brown), indicating the presence of sound wood, with sparse low velocity areas (blue) indicating the presence of decay in the first centimeters of depth. The high-velocity spots imaged in Tc1 are interpreted with the presence of knots.

Since the chord exhibited the worse mechanical conditions, penetration tests were performed on this element only. The drilling sensitivity level, tentatively chosen for a "hard" wood type in the first measurement R1, was set to a "soft" wood type in the remaining tests. R1 was drilled next to the right end of Tc3 that is characterized by intermediate Vp values. Consistently, this test displays a medium-quality wood for most of the path. The highest drilling resistance between 15.7 and 17.0 cm is due to the presence of a knot. The

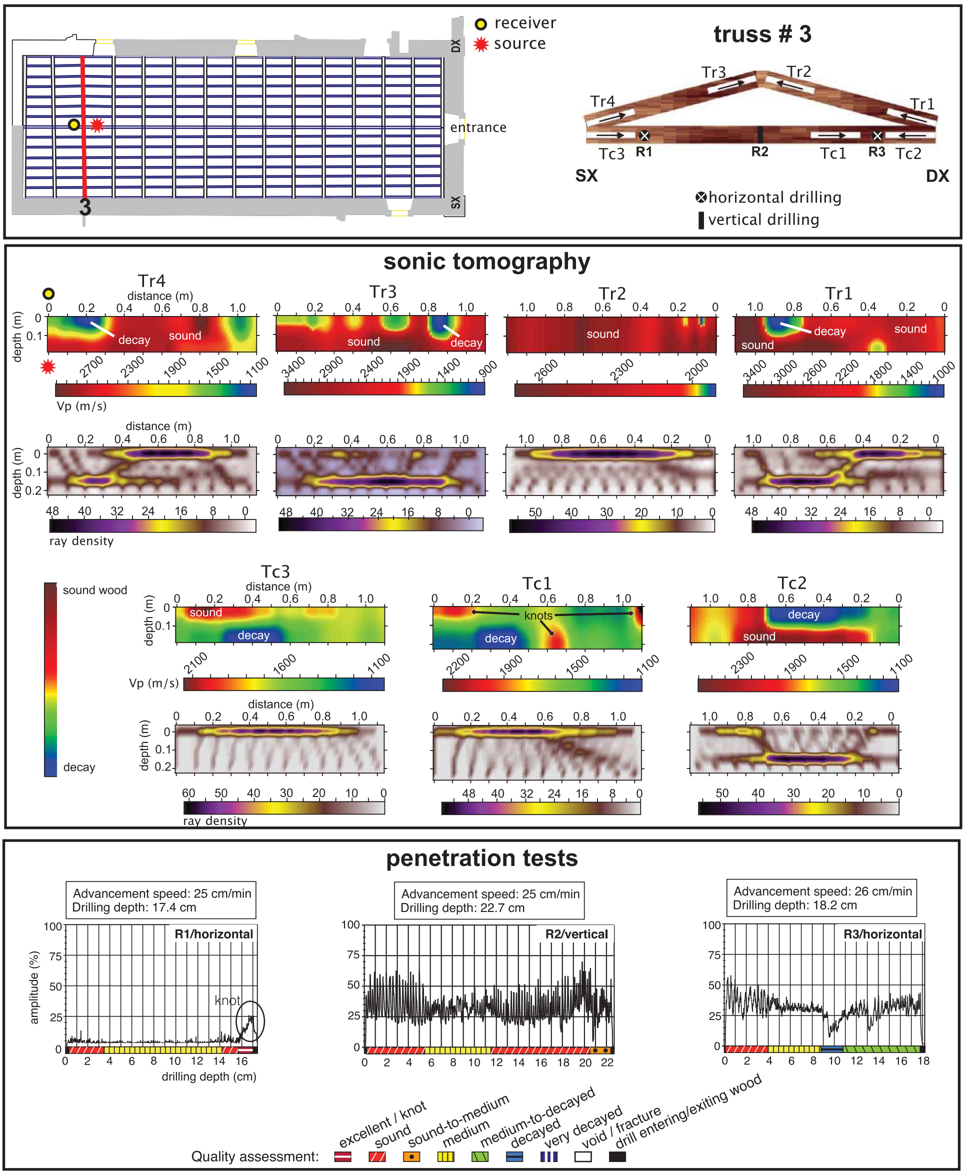

Figure 4. Upper panel: (left) plan of the S. Agata Church; the truss under test is highlighted; the position of sources and receivers used for tomography following the configuration of Figure 2d is indicated; (right) truss outline with the position of penetration tests (circles indicate horizontal drillings, bars indicate vertical drillings) and tomography profiles (the rightward or leftward sense of acquisition is due to logistic reasons). Middle panel: sonic tomograms and corresponding ray density diagrams. Tomograms image horizontal slices of the timbers with the y–axis (depth) increasing toward the church's entrance. They illustrate wood quality with graduated shading. Ray density diagrams indicate the number of rays sampling each cell of the velocity model. Lower panel: profiles of resistance to penetration vs. drilling depth. Patterned bars along the x–axis indicate wood quality. Depth varies between 16 and 24 cm depending on the thickness of the timber in the drilling direction. Horizontal tests are drilled toward the entrance of the church; vertical tests are drilled upwards. The resistogram R1 was obtained using a low drilling sensitivity, raised in the following tests (color figure available online).

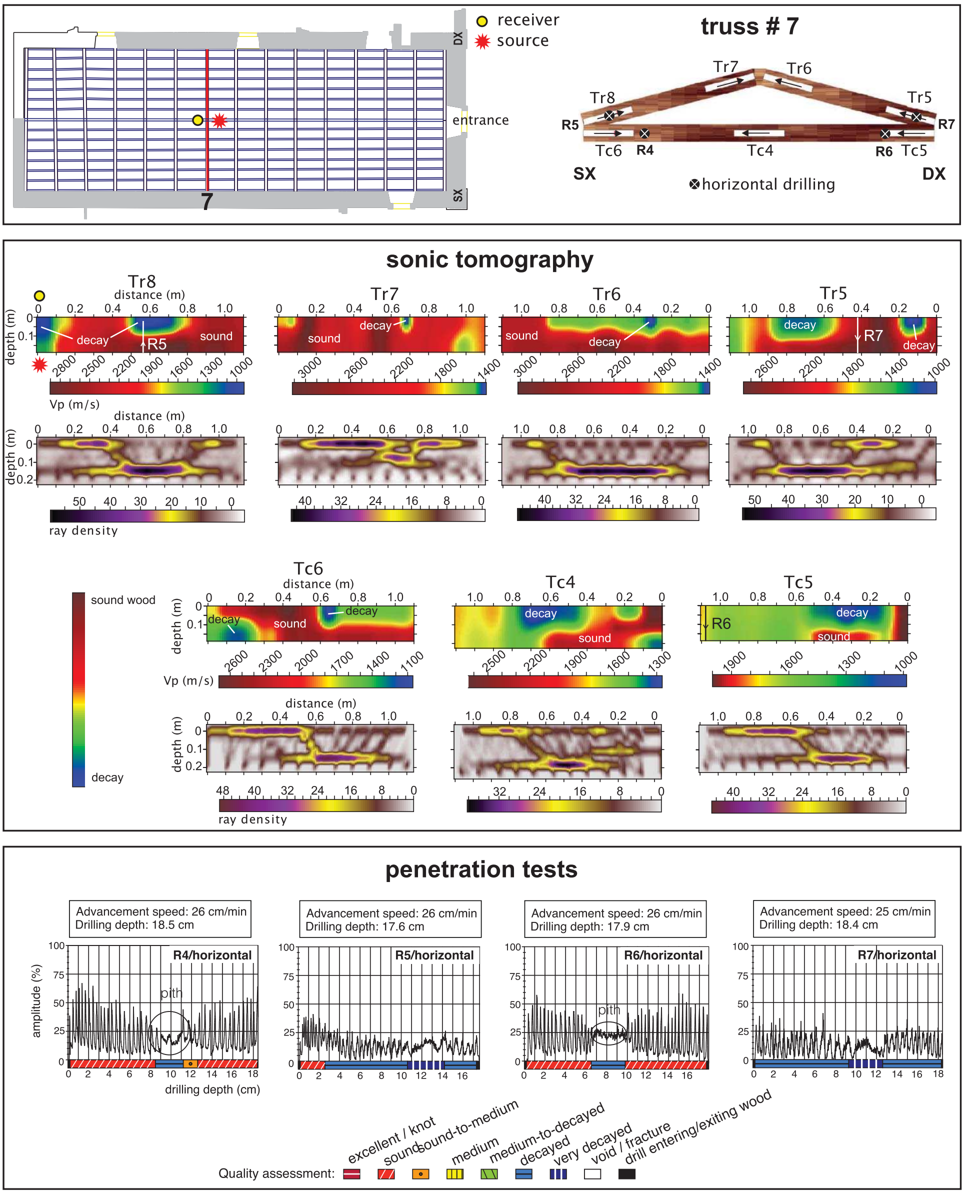

Figure 5. As in Figure 4, except that results refer to truss # 7. In the middle panel, lines crossing the tomograms along-depth indicate horizontal drillings (orientation is given by the arrow) (color figure available online).

test R2, drilled vertically in the middle of the chord, in a point that looked intact at the surface, confirmed the presence of a good-to-medium quality wood. In R3 wood quality is variable from sound to decayed.

In the truss # 7 sonic velocity is lower and deteriorations are larger in the chord than in the rafters (Figure 5), as in the truss # 3. Sound wood is drilled in the chord along R4 and R6, this last crossing the tomogram Tc5 in a point of almost absent ray coverage. R4 and R6 intersected the pith area between 8.5 and 11.2 cm and 6.5 and 9.8 cm, respectively. Pith

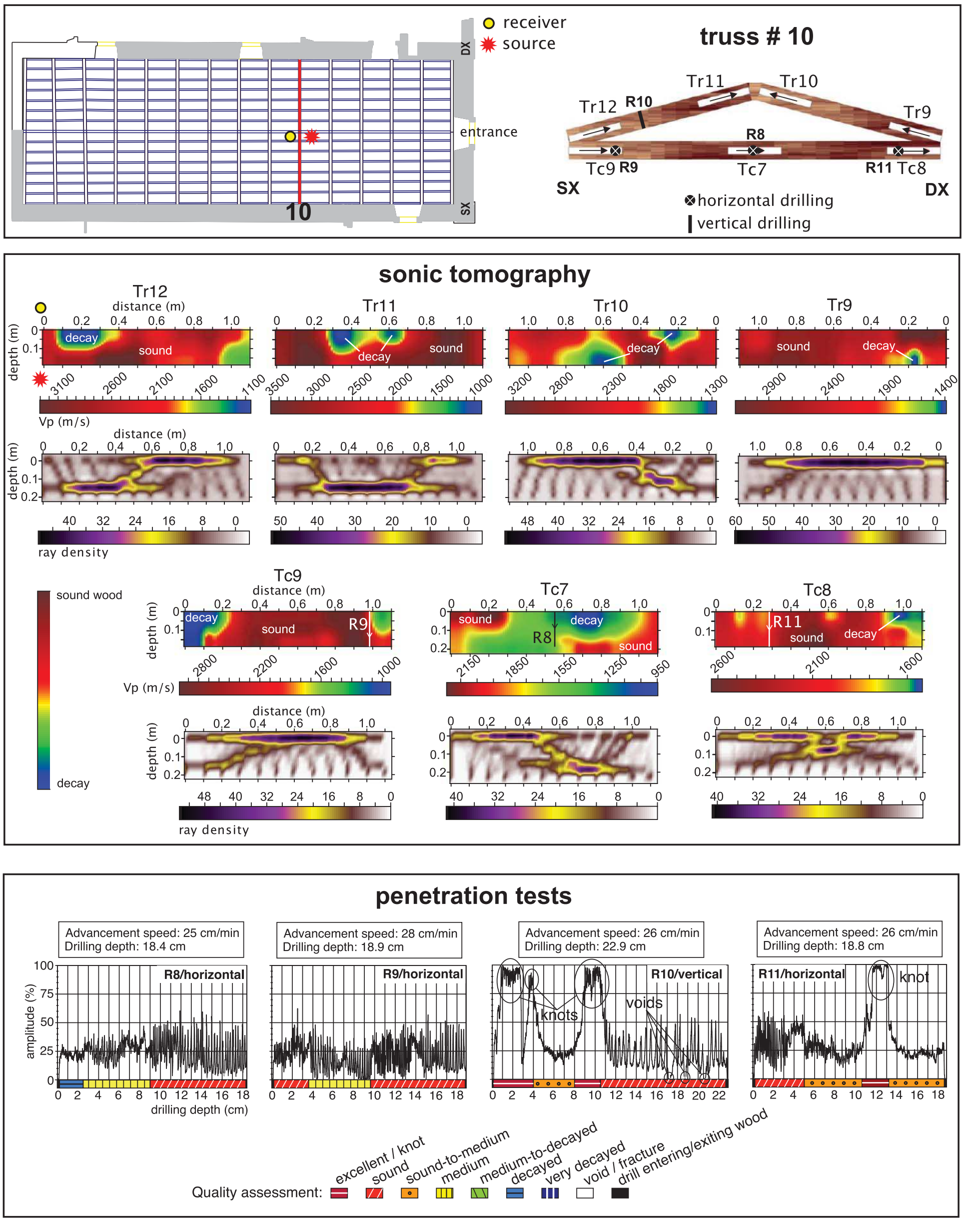

Figure 6. As in Figure 4, except that results refer to truss # 10. In the middle panel, lines crossing the tomograms along–depth indicate horizontal drillings (orientation is given by the arrow) (color figure available online).

is a spongy tissue offering a lower resistance to drilling with respect to adjacent areas; for such reason this portion of R4 and R6 was assessed erroneously as "decayed wood" by the Resistograph.

R5 and R7 tested the rafters across the tomography profiles Tr8 and Tr5, respectively. R5 detected a wood quality variable from sound to decayed, in agreement with the velocity

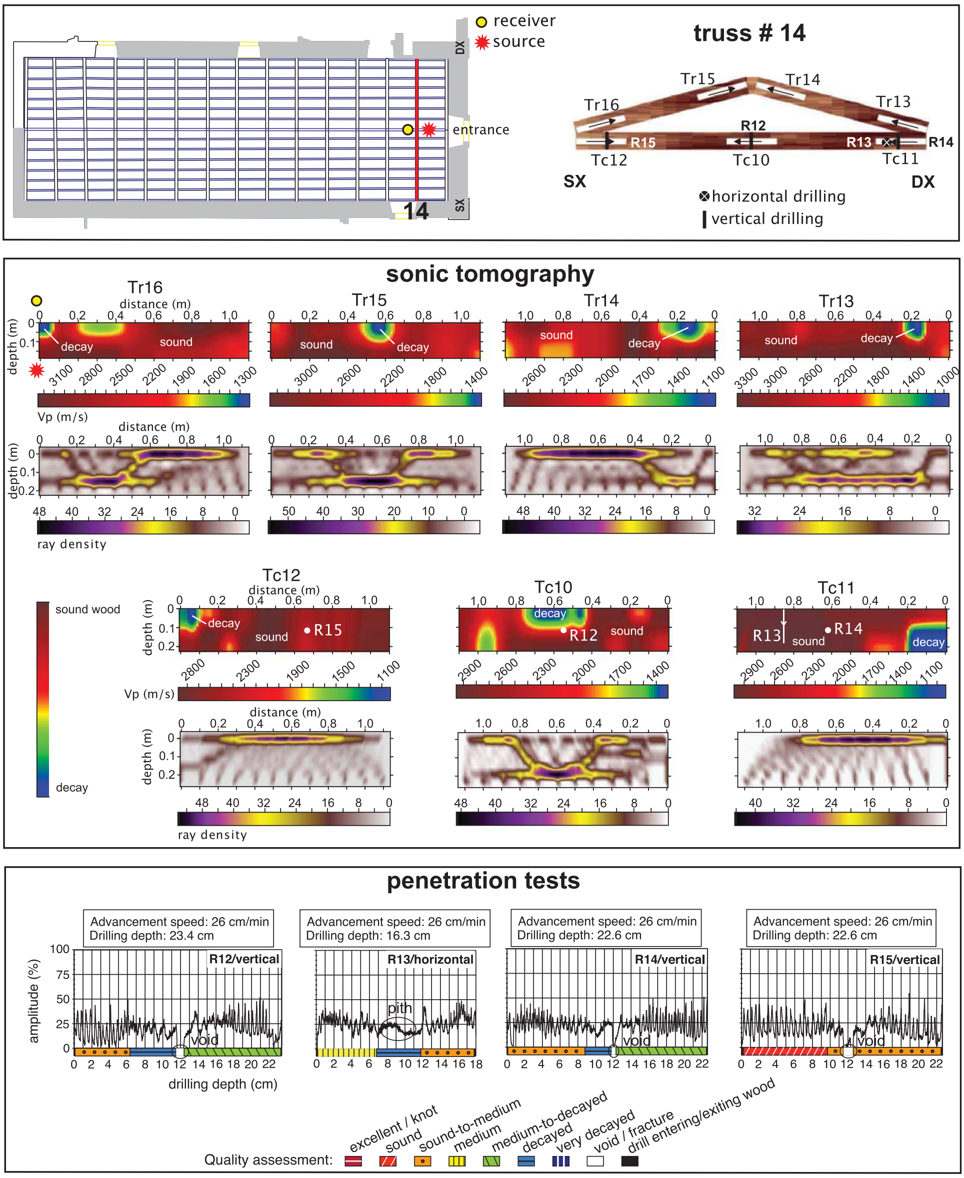

Figure 7. As in Figure 4, except that results refer to truss # 14. In the middle panel, lines crossing the tomograms along-depth indicate horizontal drillings (orientation is given by the arrow); circles indicate the position of vertical drillings (color figure available online).

imaged in Tr8; in contrast, the low amplitude displayed by R7 is not consistent with the high velocity values imaged in Tr5.

The chord of the truss # 10 (Figure 6) has better mechanical conditions than trusses # 3 and 7, but velocity is still lower than in the rafters. Deteriorations are present at the ends of the chord (tomograms Tc8 and Tc9).

Penetration tests R8, R9 and R11 were drilled horizontally into the chord, crossing three tomography sections. Results are consistent: R9 and R11 detected good-quality wood across areas of high velocity in Tc9 and Tc8, respectively, while R8 detected a variable quality in the middle of the chord, as imaged in Tc7. The 1-cm knot drilled by R11 was not resolved in the tomography image. Across the left rafter, R10 drilled a good-quality wood with centimetric portions of maximum resistance to drillings (knots). Few micro-voids were picked out next to the upper side of the timber (at 17.0, 18.6, and 20.5 cm).

Truss # 14 is mostly characterized by high velocity with small decayed areas in the upper 10 cm of the sections (Figure 7). The larger low-velocity anomaly imaged at the right end of the chord (Tc11) is poorly constrained. Three vertical drillings, equally spaced along the chord from one end to the other, detected a small cavity (few mm to 1 cm) at the same depth; this is suggestive of a linear continuous feature, possibly a microcrack, extending along the entire length of the timber.

4. CONCLUSIONS

The wood is an anisotropic and natural material often used to construct bearing structures in historical buildings. In the present work, we have applied two in-situ, non-destructive techniques, penetration tests and sonic tomography, to assess the extent of decay in some of the 15 chestnut trusses sustaining the roof of the S. Agata Church, in Ragusa Ibla.

The use of in-situ techniques made possible to characterize the deterioration of the timbers in parts that are not at sight without removing the structure from its place. Moreover, the equipments used in this study allowed us to check the data in real time, which is a considerable advantage to set the acquisition parameters properly, and to analyze the results right after the tests.

The two techniques were combined because, even though the tomography method is suitable to investigate larger areas, it is unable to quantify the loss of material as penetration tests do. Further, micro-voids are not resolved by sonic waves (not even by the higher frequency ultrasonic waves), while the Resistograph detects them precisely. Nonetheless, it is always proper to crosscheck the results of an indirect imaging method with direct, high-resolution sampling.

In the four trusses selected for this study on the basis of their apparent conditions, tomography has confirmed the presence of deterioration. Decay is mostly found next to the walls of the nave, caused by rainwater infiltration, and on the side of the timbers facing the rear of the church, possibly for the higher level of moisture caused by lack of ventilation from that direction. Except for truss # 14 that displays the best mechanical conditions, chords are in a worse state of conservation with respect to rafters, and this finding is particularly evident in the trusses # 3 and 7.

The results of the penetration tests turned out to be in agreement with the wood quality inferred by sonic tomography, proving that tomography gives reliable information about the internal condition of wooden structures. Direct sampling of the timbers revealed that most of the drilling paths is characterized by medium-quality (37%) and sound (35%) wood; 7% has an excellent response to drilling; 20% is classified as decayed; 1% is represented by voids. The information derived from this study will help conservation experts to figure out whether a restoration intervention is appropriate or if a full replacement of the most deteriorated timbers is needed to prevent collapse.

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