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NDT for evaluation of volumetric water content in wood structures

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***Abstract* – The condition of the wood structure and its components should be carefully recorded before considering any action. The diagnosis of wood structures in heritage should precede any intervention. Is important to know preliminarily the construction and structural system, the decay condition and the causes. Furthermore, damage or structural failure should be considered. The diagnosis must be based principally on measurements of physical parameters using non-destructive testing (NDT), and if necessary on laboratory testing. Water is one of the principal causes of wood decay. In this study Ground-penetrating radar (GPR) and time domain reflectometry (TDR) was used to estimate the dielectric permittivity and successively the volumetric water content of several types of wood. An empirical relationship was found between the dielectric constant and volumetric water content. Results were applied to a case study: the Cathedral of Foggia.**

I. INTRODUCTION

The electromagnetic characteristics of the wood are of great interest within GPR prospecting related to the study of the conservation state of the wooden structures. In particular, these characteristics, if correctly retrieved, allow not only a correct time-depth conversion [1] but also a correct focusing of the buried targets (such as voids, knots, etc.) through migration or, more in general, an inversion algorithm [2].
Moreover, depending on the applications, the characteristics of the medium can be crucial in themselves and not only in relationship to the reconstruction and interpretation of the targets. This can happen, e.g. when the "final" quantity of interest is the water content of the wood [3]. In general, the dielectric permittivity and the electrical conductivity of the embedding medium depend in a meaningful way, but also in a complicated and often unknown way, on the chemical, physical and mineralogical properties mixture composing the wood at hand. This makes it quite hard to get a reliable a-priori knowledge of them. In particular, some experimental values or semi-empirical laws are available [1,4]; nevertheless, they should be considered reference-average quantities, which are helpful to test the likelihood of a measure in the field but should not replace it.
In particular, the measure of the dielectric permittivity of the wood can be performed from the same GPR data [5, 6], classically using the shape of the diffraction curves. Alternatively, the dielectric permittivity can be evaluated through the time domain reflectometry (TDR) technique [7].
In this paper, a comparative experimental evaluation of the dielectric permittivity of some wood samples is proposed. Results show an excellent agreement between the diffraction curve method analysis and the TDR measurements. An empirical relationship was found between dielectric constant and volumetric water content in the wood structures. Results were applied to a case study to study the conservation state of the wood beams of the Cathedral of Foggia (Apulia region, south Italy).

II. TDR MEASUREMENTS

The experimental setup for TDR measurements included a TDR unit (Campbell Scientific TDR100), a non-invasive three-rod probe and a 3.5 m-long 50 Ω-matched coaxial cable that connected the probe to the TDR unit. The TDR100 generates a step-pulse signal with a rise-time of 200 ps, which corresponds to a frequency bandwidth of approximately 1.7 GHz.
The wood samples have been dehydrated at 105 Celsius for 24 hours. In particular, drying wood prevents inhomogeneity due to possible gradients of moisture content. Moreover, dehydration also reduces the dependence of the permittivity on potential gradients of density. Successively the samples were immersed in water and saturated. The relative dielectric permittivity of the prepared sample was determined through the well-known TDR method [8]. In TDR measurement, the step-pulse signal generated by the TDR unit propagates along the probe inserted in the material under test; the reflected signal is acquired by the same TDR unit and displayed in terms of reflection coefficient, a function of the apparent distance in the air.

As detailed in ref. [9], for low-loss and low-dispersive materials, the relative dielectric permittivity can be evaluated through the following equation:

$$\varepsilon \cong \left(\frac{L_{app}}{L_{phys}} \right)^2 \qquad (1)$$

where Lapp is the apparent distance of the probe inserted in the sample under test (Lapp is calculated directly from the TDR waveform), and Lphys is the probe's physical (actual) length.

According to ref. [10], the accurate value of Lphys was evaluated through preliminary TDR measurements performed in air and distilled water (this was necessary because a tiny portion of the sensing element is contained in a Teflon cap, and this portion must be correctly subtracted to obtain the actual value of Lphys).

For the case considered herein, reference TDR measurements were performed using the non-invasive three-rod probe. For each acquisition, the instrumental averaging number was 128. The number of sample points for each waveform was 2,048.

For example, fig. 1 shows one of the acquired TDR waveforms and the corresponding first derivative curve. The derivative facilitates the evaluation of Lapp; in fact, the first peak of the derivative (occurring approximately at 6.2 cm) corresponds to the beginning of the probe, whereas the second one (occurring around 5.5 cm) corresponds to the open-ended probe termination.

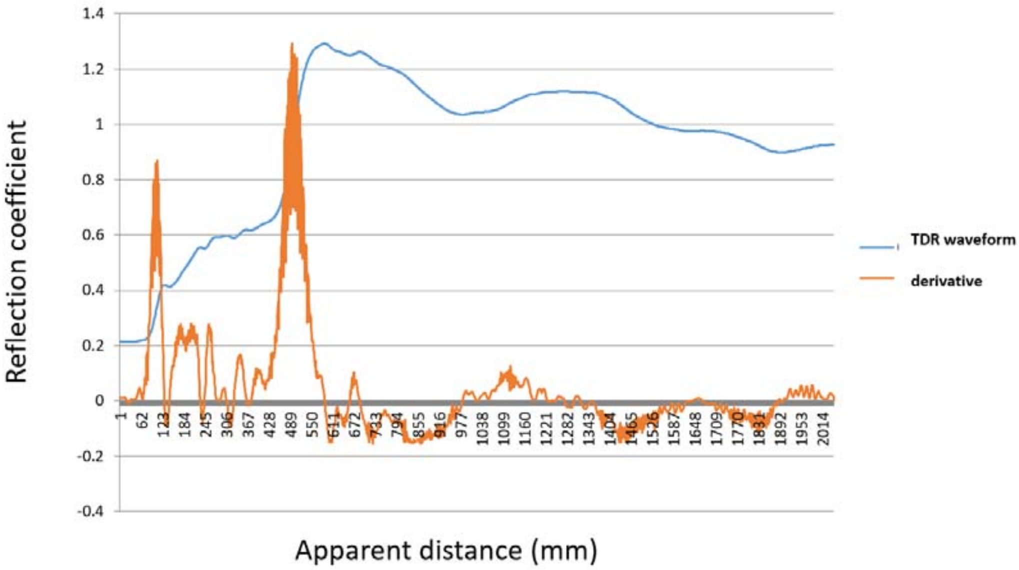

Fig. 1. The location of geophysical surveys TDR waveform (blue curve) and corresponding first derivative (orange curve) obtained for the wet maple

The relative dielectric permittivity of the wood, calculated through equation (1) and averaged over the four measurement points, is 4.01 (evaluated with a corresponding expanded uncertainty of 3%).

III. GPR MEASUREMENTS

The measurements have been performed with an IDS Ris Hi-mode system equipped with an antenna at a nominal central frequency of 2 GHz. Each B-scan has a time window of 32 ns, discretized using 2048 samples. When moving the antenna on the wood, extreme care was taken to pull the antenna at a constant velocity. The repetition of the scan along the same line three times has allowed a test about the uniformity of the antenna movement velocity. For GPR measurements, the experimental setup was a wooden sample on a metal rod (Fig. 2). This allows us to analyze the data using the diffraction curve method.

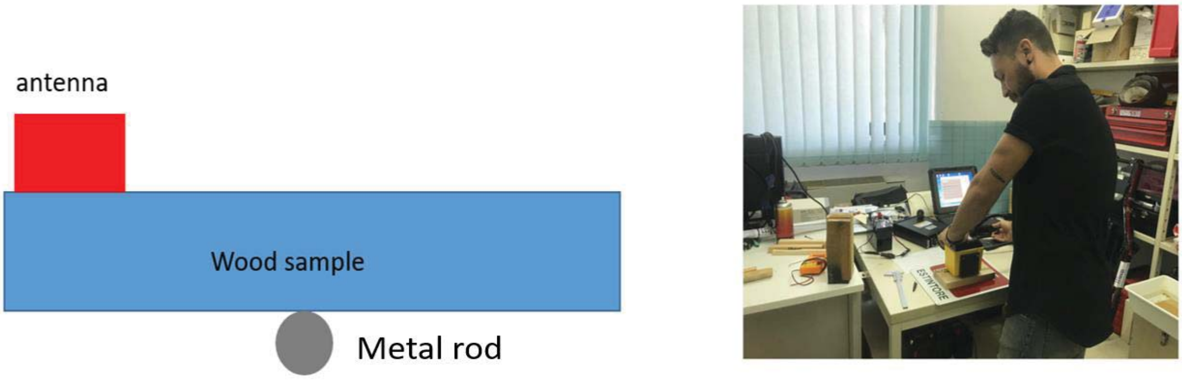

Fig. 2. GPR experimental setup

The diffraction curve method is based on the matching between the data and a model describing the two-way time of the GPR signal. This model provides a curve while considering the movement of the antenna over the target. In particular, given an electrically tiny target (in our case, the bar with the small cross-section in terms of the probing wavelength) at the abscissa x_o, if the offset between the transmitting and receiving antennas is neglected, concerning fig. 2, the model for the diffraction curve is given by

$$t = \frac{2}{c}\sqrt{(x - x_o)^2 + \left(\frac{ct_o}{2}\right)^2} \qquad (2)$$

where c is the propagation velocity in the soil, linked to the relative permittivity ε_{sr} by the well-known relationship,

$$c = \frac{c_o}{\sqrt{\varepsilon_{sr}}}$$

and t_o is the minimum recorded time, gathered when the source-observation point flies just over the target so that $x = x_o$.

The diffraction curve analysis (Fig. 3) allows esteeming the electromagnetic wave velocity and successively the dielectric constant.

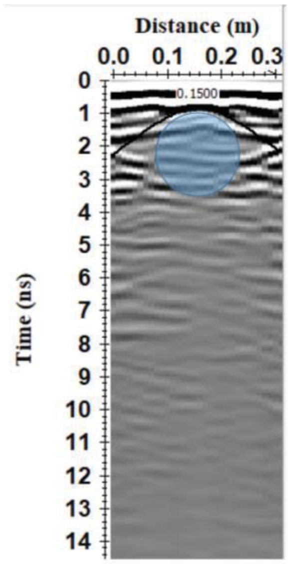

Fig. 3. GPR radar section with the diffraction curve analysis

The diffraction curve adaptation done a velocity of 0.15m/ns. Using the relationship is possible to calculate the dielectric constant. In this case, a ε=4 is obtained.

Analyzing the results obtained on the different samples with TDR and GPR, the relationship between dielectric constant and volumetric content in water is obtained (Fig. 4).

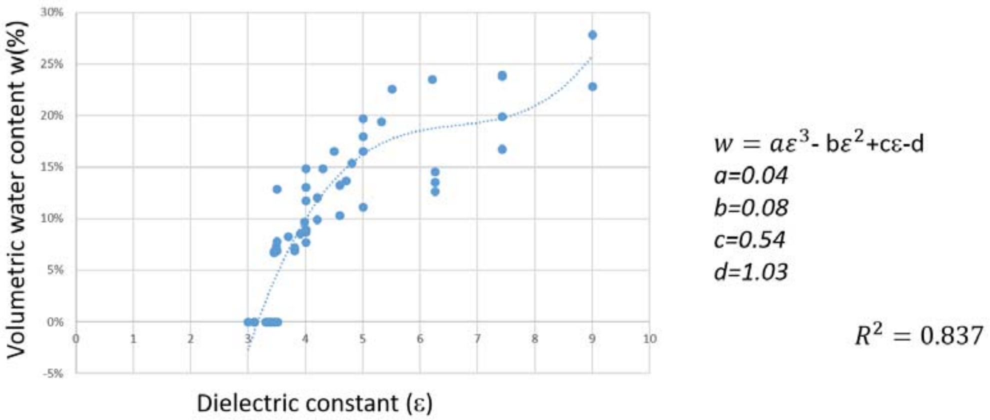

Fig. 4. Relationship between dielectric constant and volumetric water content

IV. THE CASE STUDY: THE CATHEDRAL OF FOGGIA

The Cathedral of Santa Maria de Fovea, which is directly linked with the patron saint "Madonna dei Sette Veli" (Madonna of the Seven Veils) in Foggia (Fig.5), of purely Baroque style, was restored after the earthquake of 1731 that almost destroyed the structure. The Cathedral of Foggia is strictly connected to discovering the Icona Vetere religious object, a table that depicts a rare portrait of the Virgin Kiriotissa with seven veils (from which the name of the Madonna with Seven Veils). It was built in 1170 in Romanesque-Apulian style and rebuilt in Baroque style. In 2011, an intervention related to the restoration work of the roof required an in situ investigation campaign aimed at assessing the conservation status of the wooden elements constituting the roofing of the Cathedral. To investigate the quality (compactness, number of nodes, voids, microfractures, etc.) of wooden pieces, ground-penetrating radar (GPR) investigations and resistographic tests were performed. Furthermore, a xylotomic study was also conducted to identify the species of the wooden elements constituting the timber.

Fig. 5. The Cathedral of Foggia

For this work were used, the GPR IDS-Hi Mod was with a 2GHz antenna.

All GPR profiles were performed on wooden structures (Fig. 6) and acquired at 1024 samples/track; the other acquisition parameters were optimized on-site and held constant for each profile. To eliminate the noise component present in the data, facilitating the interpretation, processing was realized whose phases are listed below: i) background removal; ii) migration. The presence of various anomalies due to small inhomogeneities, such as nodes and fractures, make possible a rapid and accurate analysis of the velocity of propagation of electromagnetic waves and allowed to obtain the depth of the anomalies. The study of the GPR data (Fig. 7) show that: the radar signal has an excellent penetration and crosses the element investigated for all its thickness; the surface portion of the wooden structures, for a thickness varying from 2 to 5-6 cm, is generally characterized by refl ections of weak amplitude, and this testifi es to a net decrease in the density of the wood, probably related to both the activity of wood-eating insects and chemical attack; this anomaly appears to be more extensive on the extrados of the chains where the infiltration of rainwater, in the presence of significant accumulations of guano, may have generated a corrosive action resulting in breakdown of the cellular elements of the wood; the numerous reflections in the shape of hyperbole, placed at various depths indicate hardening of woody tissue that, in size and shape, can be related to nodes, single or in groups, their number, sometimes high, determines an average density including between 1.4 and 5.9 nodes per meter, but in some elements of the apse area will reach higher values; reflections with continuous development are generated by sub-horizontal fissures almost always oriented in the direction of the grain; their width is generally close to 1 cm; in some of the trusses wood elements B, C, F, G, L of the nave the presence of cavities with dimensions of the order of 5 cm was recorded, probably due to biological attack. Similar anomalies, presumably correlated to fracture larger than those usually identified, were detected in the trusses L1 (chain, strut right Monaco), L3 (chain), L5 (chain) and L6 (chain). The longitudinal development of these inhomogeneities varies from 15 to 35 cm.

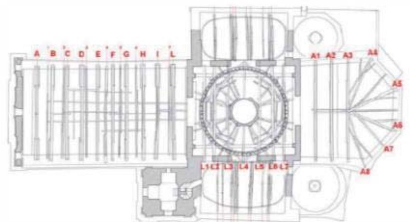

Fig. 6. The roof planimetry: the red letters refer to the position of the wooden structures

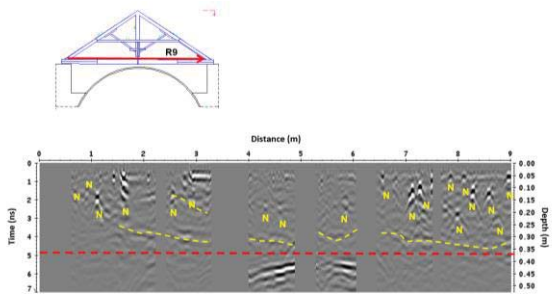

Fig. 7. The processed radar section

Using a point-source reflection from a buried object to determine the average velocity and the use of the relationship shown in Fig. 4 gives an accurate (qualitative) estimate of the volumetric water content (Fig. 8).

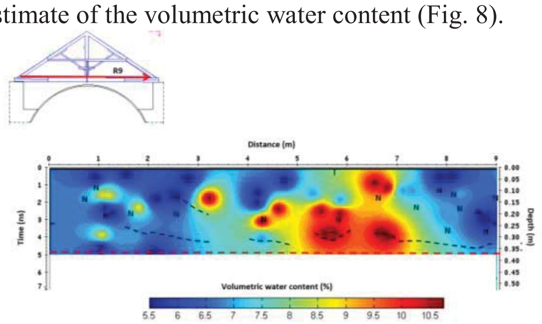

Fig. 8. The distribution of volumetric water content

The average volumetric water content of the wood varies from about 5% to 10% (Fig. 8). Water content was also measured through a direct mode using a wooden core, and the results agree with those obtained using our relationship.

V. CONCLUSIONS

In this paper, an experimental comparison between GPR and TDR measurements to determine the dielectric permittivity of a series of wood samples was proposed. A good correspondence, especially because (as it is easily calculable) was found between GPR and TDR measurements. A relationship between dielectric constant and volumetric water content was found. The GPR measurements on the case study allowed the presence of various abnormalities that correspond to nodes and/or slots, making possible a rapid and accurate analysis of the electromagnetic waves velocity of propagation and thus obtaining the depth of these anomalies. Among the main obtained data, it is worth stressing the following: the surface portion of the beams, for a thickness varying from 2 to 5-6 cm, is characterized by abnormalities related to the activity of wood-eating insects and chemical attacks due to pigeon droppings; the numerous reflections in the form of hyperbole, located at various depths, indicate that hardening of woody tissue can be mapped, both in size and shape, as nodes; the continuous reflections with a sub-horizontal development are generated by fissures almost always oriented in the direction of wood fibres; in some of the trusses wooden elements of the nave has recorded the presence of cavities with dimensions of about 5 cm.

Volumetric water content analysis shows an approximately homogeneous distribution of the moisture in the analyzed woods elements.

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