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SUSTAINABLE ASSESSMENT: A CONTRIBUTION TO IMPROVE THE RELIABILITY OF NDT ON OLD CHESTNUT PURLINS

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ABSTRACT: The aim of this study is to give an additional contribution to the improvement of a sustainable diagnostic practice to be used for the assessment of ancient wooden structures, in order to limit the damage of the existing ones through destructive tests, and to have a reliable prediction of old element properties, with their historical value, reducing demolition and substitution with consumption of new materials. To achieve this purpose, correlation laws and methodologies that can be used to facilitate the performance of non-destructive testing (NDT) in situ, will be highlighted. Seventeen chestnut purlins, dated between the 19th century and the 20th century and coming from the roof of the Cloister of Michelangelo at the Baths of Diocletian in Rome, are tested. As the first part of a wider experimentation, the aim is to identify the best practice for three relevant unknowns that characterize a wooden structural element: the geometry, through the survey and the BIM modelling; the density by means of the penetrometric tests (Resistograph and Woodpecker); the elastic module through direct and indirect ultra-sonic tests.

KEYWORDS: Assessment, chestnut, NDT

1 INTRODUCTION

The proposed research aims to combine the best diagnostic practices with the most recent dictates of sustainability, giving itself as a meeting point between the assessment commonly understood and the application of the best methodologies to preserve the environment.
Usually, a critical point is represented by the scheduled maintenance operations in order to protect the historical heritage and ensure greater sustainability of the restoration. The aim is to highlight sustainability in historic buildings through methodologies and correlations useful to facilitate the performance of non-destructive testing (NDT) *in situ* on existing timber structures without altering the characteristics of the analysed element and to limit the consumption of new materials or the damage of existing ones through destructive tests.
Moreover, several Countries have a wooden historical-artistic heritage plagued by aging and bad reworkings, all factors that aggravate its conservation. For this reason, it is important to provide a sustainable and reliable methodology for the assessment of this heritage developing procedures for the historical timber structures.
As the first phase of wider experimentation that includes destructive tests too, this study aims to develop the best practices for the estimation of three important unknowns that characterize a wooden structural element: the geometry, through the visual survey and the photogrammetry; the density by means of the penetrometric tests, such as the Resistograph and the Woodpecker [1]; the elastic module through direct and indirect ultra-sonic tests [2], thanks to the relationship that connects the static modulus with the dynamic one calculated by density and the stress wave speed parallel to the grain. However, at the moment, only the correlation between the direct and indirect measures was investigated To achieve this purpose, chestnut (*Castanea Sativa Mill.*) roof purlins were used, all dated between the 19th century and 20th century and coming from the Cloister of Michelangelo at the Baths of Diocletian in Rome (Figure 1).

Figure 1: *Reference sections and position of the penetrometric tests*

In conclusion, the aim of this study is to give an additional contribution, with new data and analysis, in order to improve a sustainable methodology, that can be used on-

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site, able to estimate these three fundamental characteristics of an ancient wooden structural element.

2 CASE STUDY

To carry out the proposed research, seventeen purlins coming from Michelangelo's Cloister of the Baths of Diocletian in Rome were examined.

2.1 CLOISTER OF MICHELANGELO

The Cloister of Michelangelo is part of the complex of the Diocletian's Baths in Rome, located near the Termini station [3].

The famous Baths of Diocletian were immediately considered witnesses of Roman greatness, built in 302 A. C. and they were the largest in Roman times by extension [4].

Each side of the internal Cloister consists of the ground floor of 25 spans of vaults and Tuscan columns in travertine. The structure ends with a roof inclined to a wooden pitch.

Since the 80s of the last century, the building of the Cloister has undergone many interventions of structural consolidation, due to the critical conditions of the supporting structure. The few diagnostic operations carried out in the last 40 years have led to low knowledge of the load-bearing capacity and countless consolidation interventions throughout the structure.

2.2 PREVIOUS WORKS

This research is the prosecution of two previous works carried out on the first part of the sample that originally counted 40 purlins. The first work addresses the issue of sustainability for interventions on ancient wooden structures, proposing a methodology of analysis of NDT, aimed at limiting the decommissioning and replacement of roofing, suggesting non-invasive methods of analysis to understand the bearing capacity of the primary elements [5].

The second work focuses on the assessment of the sustainability of the interventions carried out over the decades on the Cloister of Michelangelo. The aim is to demonstrate how the development of NDT can be more sustainable than the complete replacement but also compared with local structural reinforcement interventions carried out without careful analysis. Classic rehabilitation interventions are also compared and a multi-criteria Decision Analysis (MCDA) based method is provided to assess sustainability and establish a ranking of intervention alternatives [6].

3 GEOMETRY

3.1 SAMPLE PROPERTIES

The elements analyzed are in chestnut wood and date back a period included between 1865 and 1911 and had the function of purlins in the roof of the Cloister.

The purlins examined are seventeen. Eight of them are confined with an old metallic continuous spiral (from F6 to F15) while the others are free (from SF6 to SF21). All the specimens were submitted to the NDT. Section dimensions and length vary from one to the other and the average values are given in Table 1.

3.2 VISUAL INSPECTION

Wood is a living material defined, which has continuous exchanges with the external environment, heterogeneous and anisotropic (also defined as orthotropic). It is a complex material to analyze and it presents defects that are part of its nature and that are partially eliminated in innovative engineered timber elements, but that are present in historic ones. Wood defects produce a material discontinuity that causes a change in physical and mechanical characteristics, resulting in the formation of critical zones that affect the overall strength.

In Italy, there is a specific standard, the UNI 11119:2004, that provides criteria for the visual strength grading of the ancient timber elements when they are still in place [7].

The Standard requires a visual survey of the geometry (maximum dimensions and presence of wanes) and the defects (knots, knot clusters, mechanical cracks, splits, ring shakes and slope of the grain). It is returned, by tree species, a classification in three different categories of strength with the relative modulus of elasticity in bending (MoE) and allowable tension and compression stress values. Regarding the purlins, 7 samples were classified in class II with a corresponding MoE value of 9000 N/mm^2 and the remaining 10 in class I with a MoE of 10000 N/mm^2.

The visual grading was made excluding the section wanes, since the geometrical limitations provided by the standard are considered too penalizing for historical timber elements.

Table 1: *Purlin dimensions and strength-classes given by the visual grading*

Purlin	Strength Class	Width (cm)	Hight (cm)	Lenght (cm)
F06	II	16,0	18,0	262
F07	II	14,0	13,0	265
F08	II	18,0	16,0	264
F09	I	14,0	15,0	263
F11	II	12,0	10,5	301
F12	I	13,0	12,0	255
F13	I	13,0	14,5	299
F15	I	11,5	15,5	297
SF06	I	15,0	13,0	263
SF07	I	15,5	19,0	263
SF09	II	16,0	15,0	260
SF10	I	15,5	15,5	306
SF12	II	12,5	12,5	271
SF13	II	17,5	17,0	263
SF14	I	16,0	16,0	240
SF15	I	13,0	18,0	263
SF21	I	18,5	13,0	306

3.3 VOLUME ESTIMATION

In order to estimate the correlation laws between the NDT and the chestnut density, it is required to determine the density of the 17 purlins. For this purpose, it is necessary to derive the actual volume and weight, the latter measured by a dynamometer, of the specimens. For the volume the task is more complex, being the beams very irregular in every direction. Two measurement methods were applied. The first one detects a detailed geometry in several sections approximating the variations in shape along the purlin. The sections were recreated in the HBIM environment, linking them and obtaining the volume (Figure 2a). The second one employs the photogrammetric technique creating a PointCloud dataset of points, giving a very accurate geometry elaborated with a Matlab code and also with the identification of cracks [8] (Figure 2b).

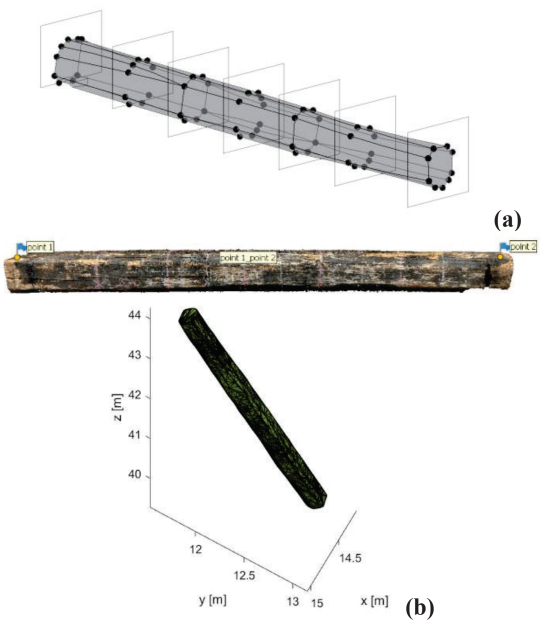

Figure 2: (a) *BIM element created by sections****; (b)*** *Photogrammetry Point Cloud and MatLab elaboration*

In Table 2 the volumes and the resulting densities obtained by the two methods (V_{BIM}, V_{PHG}, ρ_{BIM}, ρ_{PHG}) are reported and compared. However, the photogrammetric method was applied to the purlins without confinement only, since the presence of the metal band causes an important alteration of the computed volume. The change in density associated with the change in the volume estimation is expressed as a percentage variation and may have significant values included between 3% and 21%.
In the following, the density obtained by sections and then computed for the whole sample will be considered as the actual density ρ on which to estimate the correlation laws.

4 DENSITY

4.1 PENETROMETRIC METHODS

The penetrometric methods include all those tests performed with devices that involve penetrating the wood with a needle. The needle can be short or long. In the first case the superficial layer is involved only, while in the second case the entire section can be crossed. In any case, these types of tests cause little damage to the material and then they can be counted among the non-destructive methods (NDT). For the actual experimentation the Woodpecker and the Resistograph were employed both alone and by combining the results.

Table 2: *Volume, density and percentage variation results for the third and fourth methods.*

Purlins	V_{BIM} (m^3)	ρ_{BIM} (Kg/mc)	V_{PHG} (m^3)	ρ_{PHG} (Kg/mc)	ρ_{BIM}/ρ_{PHG} (%)
F06	0,068	524	-	-	-
F07	0,055	545	-	-	-
F08	0,069	560	-	-	-
F09	0,059	588	-	-	-
F11	0,053	618	-	-	-
F12	0,042	602	-	-	-
F13	0,055	547	-	-	-
F15	0,061	595	-	-	-
SF6	0,057	676	0.055	658	3%
SF7	0,073	569	0.081	512	11%
SF9	0,061	597	0.067	546	9%
SF10	0,050	595	0.052	578	3%
SF12	0,054	518	0.061	461	12%
SF13	0,068	639	0.072	608	5%
SF14	0,059	631	0.067	563	12%
SF15	0,065	610	0.078	505	21%
SF21	0,082	630	0.088	583	8%

Considering the medium purlin length and the intention to perform bending tests in the future, three reference sections have been chosen in order to execute the penetrometric tests: the central one and the two sections delimiting the middle third as illustrated in Figure 3.

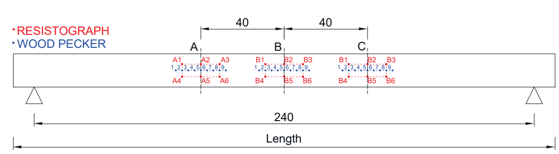

Figure 3: *Reference sections and position of the penetrometric tests*

4.1.1 Woodpecker

The Woodpecker (WP), produced by the Italian company DRC, is a modified Schmidt hammer. On the percussion, the rod was added a removable needle in hardened steel with a conical tip, a diameter of 2,5 mm and a total length of 50 mm. The test is to insert the needle into the wood with a given number of shots. Then, the penetration depth (*PD*) is obtained by measuring the exposed part of the needle.
The penetration depth is related to the superficial density of the wooden element and the manufacturer gives some correlation laws *PD*-ρ concerning different wood species,

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including chestnut. These relationships were estimated on the basis of experimental research conducted on a limited number of new timber specimens with dimensions 80x80x1300 mm [9]

In order to use these results, the manufacturer recommends to drive the needle with 5 consecutive shots and to execute at least 9 insertions in the same area following a grid with 25÷30 mm interaxis. Obviously, the test must be performed by choosing a possible defect-free area along the wooden surface.

Few studies have been performed on the reliability of the WP up to now. Lliana et al. 2018 [10] utilized twelve Norway spruce joist specimens, extracted from a dismantled 19th century building, in order to compare four different test methodologies suitable for *in-situ* density estimation: the needle penetration resistance (NPR) including both the Woodpecker and the Pylodin, the screw withdrawal resistance (SWR), the core drilling (CD) and the drilling chips extraction (DCE). Concerning the WP, the authors evaluated the test results driving the needle with one, three and five shots. The last option, which is the one recommended by the manufacturer, gave the best correlation with density with a coefficient of determination of 0,33. This value is higher than the one obtained with the Pylodin, but lower than those related to the other three test methodologies.

Similarly, Osuna-Sequera et al. 2019 [11] compared the NPR, SWR and DCE methods in order to optimize the number of measurements to be performed along extended wooden elements where the density variation, due to the growth of the original tree, becomes important from one end to the other. Then, they demonstrate that the penetration depth measured with the WP is considerably influenced by the position of the test area reaching differences up to 5 mm between the bottom of the original tree and a section 10 meters high. Anyway, performing ten measurements along the element they obtain R^2=0,55. In this case, the coefficient of determination is higher than the one obtained with the Pylodin and with the SWR method too.

Regarding chestnut, Faggiano et al. [12] used the WP upon 24 wooden elements extracted from a dismantled roof of an ancient building in Naples. In this case, the authors made the tests following the producer's recommendations. In detail, they performed 10 tests, including 9 measurements each, along with all the specimens.

According to the description they gave, the surface conditions of the 24 elements seem to be very similar to the actual ones with an extended decay due to the attacks of xylophagous insects in addition to the presence of defects as knots, cracks and holes. The correlation that they found between the penetration depth and the density was quite low with R^2 = 0,30 and the regression line was:

$$\rho = -11{,}40 \times PD + 777{,}69 \tag{1}$$

where *PD* is included in the range 13÷19 mm, while the manufacturer's correlation law, calibrated on new chestnut samples, covers a depth range between 9 and 14 mm.

Besides, it seems to be obvious that the superficial decay makes the cortical layer of an old wooden element softer, permitting the needle of the WP to penetrate deeper. This is a very crucial factor since it is not easy to quantify the amount of this decay and the way it is distributed along the surface, being inhomogeneous.

In order to investigate, with more data, the relationship between the penetration depth and the density of old chestnut structural elements, 6 tests, with 9 measurements each, were performed along the 17 purlins. The test grids were located next to the three central reference sections and on two opposite sides of the specimen (Figure 3). The spacing of the grid was about 30 mm and the area with the best superficial condition, without knots and at least 25 mm far from any crack or hole was chosen.

4.1.2 Resistograph

The Resistograph was developed from the second half of 80s by a german researcher: Frank Rinn. The device is characterized by a thin needle that can be 400 mm long and penetrates, like the tip of a drill, inside the wood. Then, the drilling resistance is measured, registered and displayed by a graph that highlights density variations due to the annual growth circles of the trunk and to the presence of eventual defects as cracks or decay with a sharp drop in resistance, or knots with peaks of resistance. Moreover, the relationship between the drill resistance and the density of the wood was demonstrated in 1996 by comparison with some X-ray tests [13].

Given the results of the test, the Resistograph is very suitable to detect possible states of decay hidden inside a wooden element and then not identifiable by a visual survey. However, given also the relationship with the material density, several attempts to correlate the outcome of the test directly with the density and even with the mechanical properties of the wood, as the elastic and the rupture modulus, were done. In fact, if *DR* (%) is the drilling resistance, expressed as a percentage of the amplitude, and *h* (mm) is the progressive drilling depth up to *H*, a medium rate (DR_m) may be calculated by the integral of the graph (Figure 4):

$$DR_m = \frac{\int_0^H DR \cdot dh}{H} \tag{2}$$

The outcomes of these correlation attempts are very discordant [13]. On the other hand, the result of the test depends on several factors including, first of all, the tree species and then the moisture content, the drilling direction in relation to the growth circles, the model of the Resistograph, the drilling speed and many more.

Some experimental works aimed to find the correlation laws between the drilling resistance and the physical and mechanical properties of wood were made about chestnut too. With regard to density, processing the data obtained by Faggiano et al. [12] who tested 24 ancient chestnut beams by means of a Resistograph IML RESI F400, a correlation with R^2 = 0,43 was obtained, while the authors themselves, with the same device, found a correlation with R^2 = 0,32, performing the test along 9 purlins of the late nineteenth century [5].

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For the actual experimentation, a Resistograph IML RESI PD400 was employed. This tool can provide not only the drill rate (*DR*) but also the feed rate (*FR*). The outcomes are two different graphs where *DR* and *FR* are both expressed in percentage of the amplitude. In either case, it is possible to detect an eventual decay within the wooden element and to calculate a medium rate, however, the drill rate is generally affected by the friction that develops between the needle and the wood during the test. This friction is affected by several factors as the tree species, the density, the moisture content and the penetration depth. In any case, a very simple linear model, with friction depending only on the drilling depth, can be assumed. In this way, the drill graph can be easily corrected just by subtracting the increasing friction along the path [14] (Figure 4).

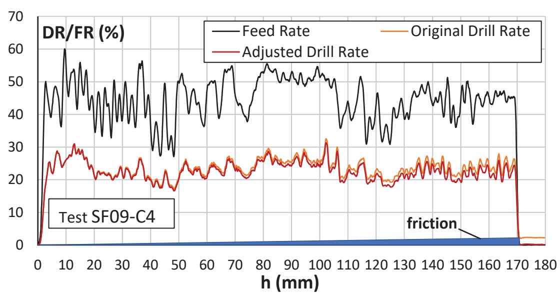

Figure 4: *Resistograph - Comparison between the original drill rate graph, the adjusted one and the federate graph*

The comparison between the correlations found for the feed rate and the drill rate with the mechanical and physical properties of four tree species developed by Sharapov et al. [15] suggests that *DR* is more reliable than FR. In detail, about the relationship *DR*-ρ, coefficient of determinations generally higher than 0,76 were found.

In a similar way, the tests performed along the 17 purlins were processed considering both the drill rate and the feed rate (Figure 4). For each element, 6 tests around the three reference sections, were executed, for a total of 18 tests (Figure 3). The rotational speed was set at 3000 rpm, while the feed speed at 100 cm/min.

When processing, both FR_m and DR_m were calculated, the latter having subtracted the friction component. In both cases the medium resistance was computed excluding all the inhomogeneous parts of the graphs as peaks or drops due to the presence of knots, cracks or decay.

4.1.3 Combined method

The superficial decay that generally affects the ancient timber structural elements and its randomness compromise the reliability of the Woodpecker, since this kind of test involves just a thin layer of material close to the surface. On the other hand, the Resistograph involves all section thickness, but any correlation laws with density are strictly connected with the model of the instrument and with the drilling speed. In order to overcome these limits, it is proposed to combine the two methods as already suggested by the authors [5], although in place of the Woodpecker, the Pylodin was used.

If the WP producer law is considered reliable enough for any value of the penetration depth, the resulting density (ρ_{WP}) can be related with the medium resistance computed along the initial or the final section of the Resistograph graph for a length equal to PD_m ($R_{m,PD}$). Then, the following ratio can be calculated;

$$C = \frac{\rho_{WP}}{R_{m,PD}} \tag{3}$$

Assuming that this ratio remains constant along the entire section thickness, the wood density can be estimated multiplying the coefficient C by the medium resistance computed on the remaining part of the graph:

$$\rho_{comb} = C \cdot R_{m,(H-PD)} \tag{4}$$

Obviously, both tests must be executed close to each other so that their combination makes sense. In fact, regarding the 17 purlins, the two tests were performed at the three reference sections (Figure 3). Then, the WP was executed both on the inlet and outlet side of the Resistograph so that both the initial and final parts of the feed rate and drill rate graphs were considered.

4.2 RESULTS

Regarding the WP, the mean penetration depth of one purlin is calculated as the average value of the six tests outcomes, while the single test result is evaluated as the mean value of 9 measures. In Table 3, the mean penetration depths (PD_m) and the related coefficients of variation (*CV*) are reported for each purlin, together with the maximum and minimum values (PD_{min} and PD_{max}) registered by the six tests.

Table 3: *Wood Pecker tests results*

Purlin	PD_m (mm)	*CV* (%)	PD_{min} (mm)	PD_{max} (mm)
F06	18,83	10,9	17,02	22,89
F07	18,02	1,8	17,50	18,38
F08	17,63	4,9	16,30	18,52
F09	16,52	2,0	15,94	16,84
F11	17,89	9,4	16,39	20,71
F12	16,88	3,4	16,46	17,97
F13	19,07	3,7	17,94	19,66
F15	17,96	7,4	16,66	20,49
SF06	18,04	7,8	15,60	19,40
SF07	16,94	6,5	15,61	18,44
SF09	16,29	5,6	15,46	17,64
SF10	16,54	3,6	17,58	16,83
SF12	20,18	6,2	17,92	21,64
SF13	16,95	10,2	15,67	19,31
SF14	17,10	5,9	16,37	18,88
SF15	17,04	7,3	15,74	19,21
SF21	16,19	5,9	15,52	18,06

It can be observed, that the mean penetration depths are included between 16,2 mm and 20,2 mm, while the results of the single tests have a wider range from 15,5 mm to 23

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mm. The coefficients of variation, as well as the minimum and maximum depths, highlight that the experimental data are quite scattered along the same purlin, probably due to the inhomogeneity of the surface decay. In addition, the conditions of the cortical layer make completely inadequate the producer's law as illustrated in Figure 5.

On the other hand, Figure 6 shows the regression line built on the actual data (ρ and PD_m) with the related 95% confidence and prediction intervals. The purlin SF06 was excluded from the analysis, since the related data seems to be an outlier (Figure 5). The coefficient of determination is $R^2 = 0,55$.

The actual regression line is compared with the one obtained by Faggiano et al. [12] (Eq. (1)). The two lines have a quite different slopes, however they are strictly connected considering that the second one falls almost completely within the confidence limits of the first one. Anyway, the general randomness of the superficial decay and the lack of knowledge about the sample that Faggiano et al. used, does not encourage data to be merged to achieve a single law.

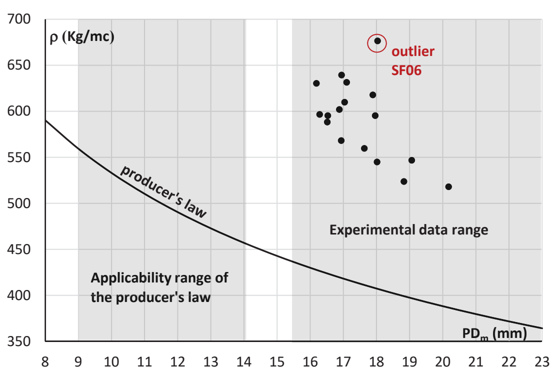

Figure 5: WP - Comparison between the experimental data and the producer's law

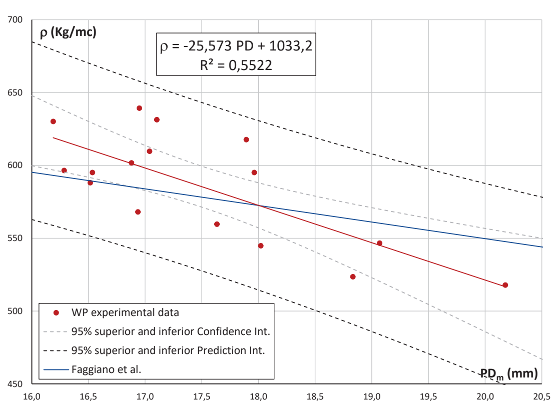

Figure 6: WP - Correlation between the penetration depth and the actual density

Better results are obtained by means of the Resistograph, probably because this method involves the entire section, rather than just the cortical layer, and therefore the superficial decay is irrelevant.

In Table 4 the medium feed rate (FR_m) and the medium drill rate (DR_m) are reported together with the respective coefficient of variation (CV_{FR} and CV_{DR}).

Table 4: *Resistograph tests results*

Purlin	FR_m (%)	CV_{FR} (%)	DR_m (%)	CV_{DR} (%)
F06	32,1	5,3	18,8	10,9
F07	38,8	14,2	18,0	13,4
F08	39,3	4,3	18,7	5,6
F09	44,9	8,3	20,4	8,7
F11	47,2	5,3	22,0	10,9
F12	44,7	10,0	20,9	10,8
F13	39,2	11,8	17,3	8,9
F15	41,5	7,3	19,3	7,1
SF06	53,4	6,1	25,9	8,4
SF07	38,9	7,7	18,0	5,5
SF09	42,6	6,5	20,8	10,9
SF10	38,8	6,8	17,9	5,9
SF12	30,7	11,2	14,6	8,7
SF13	46,2	4,3	21,9	6,6
SF14	47,5	9,5	22,8	11,2
SF15	46,3	4,0	22,2	5,7
SF21	46,8	8,1	22,0	9,6

In both cases, the correlations between FR_m and DR_m and the actual density of the purlins are strong. However, the regression line FR_m - ρ is slightly more reliable than the other one with a coefficient of determination $R^2 = 0,89$ versus $R^2 = 0,82$. In Figures 7 a/b the regression lines with the related 95% confidence and prediction intervals are reported. Then, the chestnut density may be estimated through the following relationships:

$$\rho = 7{,}011 \cdot FR_m + 294{,}26 \mp 37 \left(\frac{Kg}{mc}\right) \qquad (5)$$

$$\rho = 14{,}71 \cdot DR_m + 295{,}15 \mp 47 \left(\frac{Kg}{mc}\right) \qquad (6)$$

Finally, it is necessary to point out that these correlation laws may be considered a reference just if the tests are performed with the Resistograph IML RESI PD400 with the same rotational and feed velocities set.

Regarding the combined method, for each section, the average values of all densities estimated by combining the penetration depth with the inlet and outlet sections of both the feed rate ($\rho_{comb,FR}$) and drill rate ($\rho_{comb,DR}$) graphs were computed. During processing, those combined densities that were lower than the ones estimated with the Wood Pecker only were excluded, as well as those ones higher than 700 Kg/mc. In Table 5 the combined densities estimated with both the graphs and the relative coefficients of variation are reported. These last highlight an important dispersion of the data.

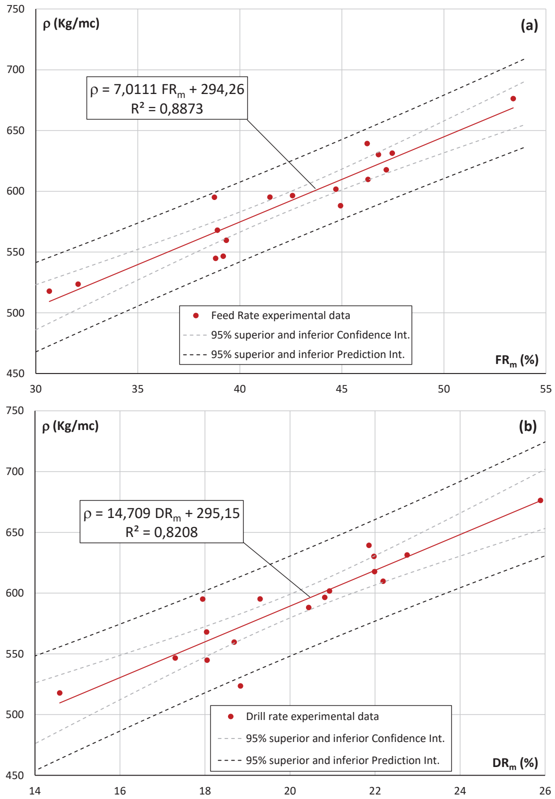

Figure 7: *Resistograph - Correlation between the Feed Rate (a) and the Drill Rate (b) and the actual density*

Table 5: *Combined method results*

Purlin	$\rho_{comb,FR}$ (Kg/mc)	CV_{FR} (%)	$\rho_{comb,DR}$ (Kg/mc)	CV_{DR} (%)
F06	491	9,5	468	8,1
F07	476	11,7	491	14,5
F08	469	11,6	493	10,7
F09	503	11,1	507	11,3
F11	491	12,5	505	13,4
F12	499	12,4	509	11,9
F13	490	13,0	485	14,2
F15	480	9,5	509	15,8
SF06	520	16,5	520	14,1
SF07	500	10,0	493	12,3
SF09	475	12,8	513	16,0
SF10	486	11,2	502	9,8
SF12	430	7,6	430	6,7
SF13	575	13,8	558	14,4
SF14	491	10,9	498	13,6
SF15	509	12,3	538	15,8
SF21	502	14,7	476	10,4

As can be seen from Table 5, the estimated densities are very conservative, anyway, the correlation between the actual densities and the ones evaluated through the drill rate graph has some interesting aspects. Considering the whole sample, the regression line is quite parallel to the equality one ($\rho_{comb,DR} = \rho$) with $R^2 = 0,48$ (Figure 8). Anyway, the data concerning the specimens SF06 and SF21 can be considered outlier and then they can be excluded from the correlation. In this case, the coefficient of determination increases up to 0,69, while the regression line slightly lowers keeping the slope almost the same. Considering the 95% prediction intervals, it can be assumed that:

$$\rho = 1{,}0838 \cdot \rho_{comb,DR} + 40{,}4 \mp 57 \; (\frac{Kg}{mc}) \qquad (7)$$

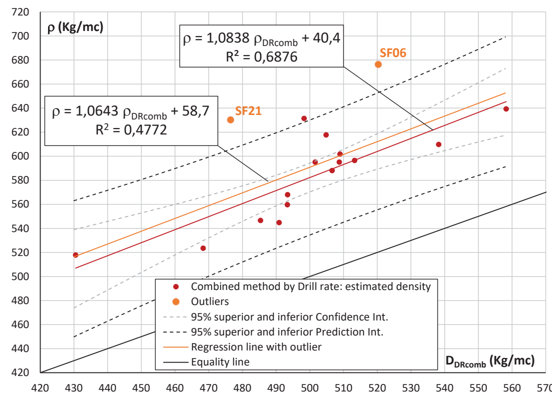

Figure 8: *Combined method - Correlation between the estimated densities evaluated through the Drill Rate graph and the actual densities*

5 MODULUS OF ELASTICITY

5.1 ULTRASONIC PULSE VELOCITY

The elastic properties of wood may be estimated through the so-called dynamic methods including the ultrasonic pulse velocity measurement (V). This velocity is strictly connected with the density of wood (ρ), with its dynamic modulus of elasticity (E_{dyn}) and with the Poisson modulus (ν). Since the latter is often ignored, the relationship between the remaining quantities becomes very simple:

$$V = \sqrt{\frac{E_{dyn}}{\rho}} \qquad (8)$$

However, the correct application of the method and the subsequent interpretation of the data is not as simple.

First of all, wood is an orthotropic and inhomogeneous material with very different structural characteristics depending on the species. Then, the stress wave speed is influenced by the direction, the internal "architecture" of the material, the presence of any defect as knots, cracks or decay, as well as by the moisture content and even by the equipment employed for the test. Therefore, also among the same species, the ultrasonic pulse velocity measurement can vary greatly depending on the test conditions, compromising the reliability of the dynamic modulus estimation.

Second, the existing relationship between the dynamic modulus of elasticity and the static one is still discussed.

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With regard to chestnut, some studies have been conducted on old structural elements with different results. Faggiano et al. [12] found a strong correlation between E_{dyn} and the bending modulus (E_b) with $R^2 = 0,76$ as well as Santini et al. [5] although in this case, the correlation involved the compression modulus ($E_{C,0}$). On the other hand, Koca et al. [16] found a weak correlation between E_{dyn} and E_b with $R^2 = 0,32$.
In any case, the stress wave speed is generally measured parallel to the grain (V_L). In fact, along this direction, it reaches the highest value and it is less influenced by local defects and by the arrangement of the growth circles of the wood since there is an important difference between the velocity along the radial or the tangential direction ($V_R \approx 1/2 V_L$ and $V_T \approx 1/3 V_L$) [17]. Then, a practical problem is added. During *in-situ* surveys, the ends of the investigated wooden elements are often not accessible making it impossible to measure the longitudinal pulse velocity by direct way.
In this case, a solution may be given by the indirect measure (V_{ind}), placing the two transducers along the same face of the element with an appropriate distance between them. Some studies highlighted that in this way it is possible to obtain a good approximation of the longitudinal velocity. Oh [18] finds out, by some tests performed on spruce lumber specimens, that the ratio V_{ind}/V_L increases with the distance (d) asymptotically tending to 0,87 for d = 20 cm. However, Machado et al. [19] demonstrate that when some superficial defects occur it is important to further increase the distance in order to involve deeper wood layers in the propagation path. In this case, they obtained a ratio V_{ind}/V_L greater than 0,90 with d = 40 cm.
These studies are all performed on small clear wood specimens without defects or with planned defects. On the contrary, the ultrasonic tests executed on the 17 purlins are aimed to estimate the ratio V_{ind}/V_L when the indirect method is applied directly on site and to evaluate the best methodology to perform it. The equipment employed is an ultrasonic system CMS HLF-P SG02_0128 series with 55 kHz piezoelectric transducers equipped with tips.
The direct longitudinal velocity was calculated for each purlin as the average value of five tests performed between the ends: one in the middle of the section and the others close to the four edges (Figure 9).
The indirect measures were executed along the four sides of each element and the transducers were placed at both a distance of 40 cm ($V_{ind,40}$) and 60 cm ($V_{ind,60}$) as illustrated in Figure 9. The chosen paths were apparently free from macroscopic defects as knots and holes or important decay and they were not cut by significant fractures.

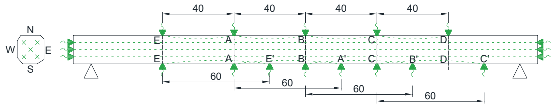

Figure 9: *Direct and indirect measures of the ultrasonic pulse velocity*

5.2 RESULTS

Following the tests, with regard to the choice of the distance between the transducers, it was observed that:
- the ratio V_{ind}/V_L remains approximately the same despite the variation of the distance ($V_{ind,40}/V_L$=0,85 - $V_{ind,60}/V_L$=0,86);
- it is more difficult to find a path with a length of 60 cm free of defects than one of 40 cm;
- the attenuation of the signal over 60 cm makes sometimes too difficult to read the time of flight of the stress wave.

For all these reasons the authors chose to deepen and analyse only the method that provide the shortest distance. The results of the direct (V_L) and indirect tests ($V_{ind,40}$) are given in Table 6. The indirect velocity is the medium value computed on 12÷15 different paths (N) for each purlin. In fact, despite a careful choice of the wave trajectory, the indirect velocities along the same element may be quite scattered with a coefficient of variation (CV) that can rise up to 10,63% (specimen F09). On the other hand, a relatively high number of measurements allows to maintain stable enough the ratio $V_{ind,40}/V_L$ with a CV less than 2%.

Table 6: *Direct and indirect ultrasonic tests results*

Purlin	V_L (m/s)	N	$V_{ind,40}$ (m/s)	CV (%)	$V_{ind,40}/V_L$
F06	5181	13	4521	5,55	0,873
F07	5264	12	4460	7,75	0,847
F08	5548	12	4653	5,69	0,839
F09	5392	12	4603	10,63	0,854
F11	5345	12	4597	4,67	0,860
F12	4948	12	4199	9,01	0,849
F13	5113	12	4530	7,80	0,886
F15	5358	12	4427	9,91	0,826
SF06	4944	12	4290	4,67	0,868
SF07	5316	12	4398	6,18	0,827
SF09	5248	12	4400	8,27	0,838
SF10	5397	12	4620	8,88	0,856
SF12	4944	12	4291	8,50	0,868
SF13	5638	15	4737	4,46	0,840
SF14	5645	13	4744	4,82	0,840
SF15	5379	14	4547	9,04	0,845
SF21	5260	12	4597	6,06	0,874
Medium value of the ratio $V_{ind,40}/V_L$					0,852
CV of the ratio $V_{ind,40}/V_L$ (%)					1,94

Figure 10 shows the correlation between the direct and the indirect readings. The coefficient of determination (R^2) is good and particularly it may be observed that there is quite no difference between the best fit regression line and the one forced to pass through the origin. Then, the latter may be considered reliable enough and, according to the related 95% prediction intervals, the longitudinal velocity can be estimated through the following relationship:

$$V_L = 1{,}174 \cdot V_{ind,40} \mp 229 \left(\frac{m}{s}\right) \tag{9}$$

where the slope is given by the ratio $V_L/V_{ind,40}$, which is 1/0,852.

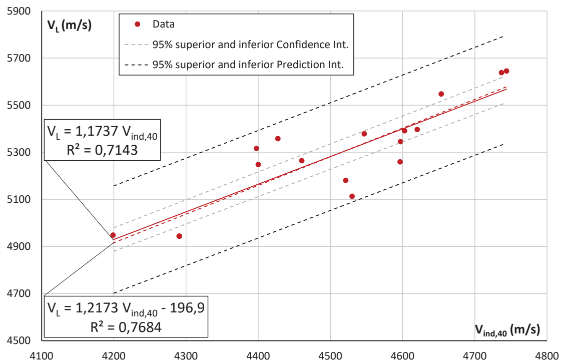

Figure 10: *Correlation between direct and indirect velocities*

6 SUSTAINABILITY CONSIDERATIONS

When addressing the issue of sustainability it is necessary to do so with full knowledge of the facts. In this research, authors talked about sustainability as material saving, but in reality, the considerations to be made are several.

In the first instance to conduct the experimental diagnostic operations on the samples were made of operations that have caused consumption and emissions that the proposed methodology offers to avoid. So the transport from the Diocletian Baths to the laboratory and the replacement of the elements are exactly the phases that, opting for non-destructive diagnostic operations, the research aims to avoid in the future.

On the basis of these considerations, it is necessary to think about actual consumption from a multi-parametric point of view, as carried out in previous research, as mentioned before. In this sense, NDT were analysed from an environmental, social, economic and structural point of view. There is no doubt, however, about savings in terms of assessment, transport, economics in the face of replacement works, and the social and cultural value of preserving not only the historical heritage but also the technology and materials.

This analysis compared various interventional alternatives, modelled using Heritage-Building Information Modelling (HBIM) technology, assessed using the multi-criteria decision analysis Analytic Hierarchy Process (AHP), and quantified sustainability using the multi-criteria Modelo Integrado de Valor para Evaluacin Sostenible (MIVES) methodology. To do this, the study offers a methodology to assess various interventions, including NDT diagnosis: i. replacement with the insertion of braces; ii. non-destructive testing and steel jacketing with shaped retaining profiles welded in situ; iii. non-destructive test and support beams bolted with braces; iv. NDT and simple braces addition.

Wood is a material that can be understood as a witness for such research and insights since it is often underestimated its strength in structural terms and the consequent economic and environmental savings resulting from its assessment.

Moreover, in the absence of many ancient wooden roof structures, it is also relevant for a cultural and architectural tradition that must be preserved and that must also be available to posterity.

7 CONCLUSIONS

The research aims to suggest a methodology that can provide a wide assessment examination for historic timber structures also taking into account sustainability, emphasizing the correlation that diagnostic tests can have with the environmental impact.

Non-destructive tests, given the low invasiveness, can be a set of scheduled maintenance operations that allow having a complete and constant overview of structural behavior over the years. Considering also the few analyses that are carried out on historic wooden buildings and the randomness of the results present due to the heterogeneity of the material, a procedural method is proposed in the research through combinations of different test results in order to obtain a complete assessment of the structure, without it being damaged or replaced.

The aim is to derive the estimates of the three unknowns concerning the wooden elements: geometry, density and elastic modulus.

The first, especially with regard to volume, is difficult to estimate on the construction site. The proposed analysis of several relevant techniques compared, allows having a general overview and a correlation between the data obtained. From the simple measurement of only the main dimensions to the photogrammetric survey, the authors have seen the influence that the estimated volume change can have on the density of the material.

The visual investigation deepens these analyses by providing a mechanical classification based on the defects observable from the outside.

The non-destructive tests provide estimation values of the physical and mechanical properties of the material, so the other two unknowns (density and elastic modulus) must be obtained through correlations that can make the results obtained reliably.

The correlations obtained from the proposed combined procedure, which are useful to derive the density estimate by comparing surface and depth results, have the limit of being able to be used only with the instrumentation used and with the same settings as those used in this research. In addition, the conservative state of the surface layer was also a key factor. Poor maintenance and deterioration of the wood surface layer is an important variable to consider especially with regard to surface testing.

For the modulus of elasticity through ultrasonic tests, instead, a comparison between estimated speeds based on the distance of the probes has been proposed, to understand which is more suitable for the use in situ.

The set of data and results obtained is useful in order to propose a useful methodology on site to carry out non-invasive diagnostic tests that can limit the consumption of material and maintain the historical value of ancient structures and technologies.

It is therefore intended to provide a method that can prevent the cultural, historical and architectural heritage

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too many invasive changes and alterations that prevent their preservation, through timely diagnostic operations.

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