Correlation between thermal and density properties of chestnuts: preliminary results of experimental non-destructive testing

Archives of Civil and Mechanical Engineering (2024) 24:157
https://doi.org/10.1007/s43452-024-00969-8

ORIGINAL ARTICLE

Correlation between thermal and density properties of chestnuts: preliminary results of experimental non-destructive testing

Vittoria Borghese[1] · Luca Santoro[2] · Silvia Santini[1] · Raffaella Sesana[2]

Received: 9 January 2024 / Revised: 23 April 2024 / Accepted: 28 April 2024

Abstract

This study presents the preliminary outcomes of a methodology for the physical and mechanical characterization of various chestnut elements in different states of preservation. Strategizing conservation and retrofit interventions for timber is necessary, and to do this, it is necessary to establish an estimation of physical (transmissivity, thermal conductivity, humidity level, etc.) and mechanical properties (density, compressive or bending strength, etc.). This essential information is typically associated with timber defects, but there are lack of correlations. The primary objective is to establish correlations between thermal and density properties with the aim of preserving original assets. The investigation delves into the relationship between timber density and thermal properties through experimental non-destructive testing (NDT). Two NDTs were employed with the aim of correlating: penetrometric testing and active thermography investigations. The parametric study on the excitation period yielded valuable insights into the temporal dynamics of heat transfer within the timber, underscoring the significance of selecting appropriate excitation periods to capture precise thermal properties. Tabular data on relative humidity for salified, dried, and new samples provided a quantitative backdrop to these observations, unveiling the nuanced effects of humidity on the timber's thermal response. The results of this study are positioned to inform future conservation efforts by laying the groundwork for a comprehensive understanding of timber's mechanical properties. Particularly, the challenge lies in accurately estimating density, where surface tests are often less reliable than in-depth ones. Therefore, it is crucial to seek validation through other NDT tests, such as thermographic analysis and visual inspection, and hygrometric tests recognizing their importance in enhancing the reliability of density assessments. This approach will contribute to the development of more discerning preservation strategies.

Keywords Timber · NDT · Active thermography · Density

1 Introduction

Timber is an orthotropic material, as defined [1] and it is uniquely characterized as "alive" due to continuous water exchanges with the surrounding environment. Each timber sample exhibits diverse physical and mechanical traits, introducing uncertainties and variability in correlations discovered through experimental testing, even when compared to other samples of the same timber species or geographic origin [2]. The distinctive nature of timber, with its inherent variability, often leads to it being understudied. Consequently, replacing timber components becomes a more straightforward task than diagnosing and maintaining them. Consequently, there are few well-preserved ancient timber structures today, despite many components tracing their origins back to previous centuries and undergoing modifications over time [3].

Luca Santoro, Silvia Santini and Raffaella Sesana contributed equally to this work.

Luca Santoro
luca.santoro@polito.it

Vittoria Borghese
vittoria.borghese@uniroma3.it

Silvia Santini
silvia.santini@uniroma3.it

Raffaella Sesana
raffaella.sesana@polito.it

1 Department of Architecture, Roma Tre University, Via Aldo Manuzio, 68 L, Rome 00153, Italy

2 Department of Mechanical and Aerospace Engineering, Politecnico di Torino, Corso Duca degli Abruzzi, 24, Turin 10129, Italy

Published online: 24 May 2024

The challenge associated with replacing timber structural elements is often linked to external appearances, reflecting intrinsic surface defects due to the material's nature or external loads. Modern timber elements attempt to overcome these challenges through specific processes, reducing defects significantly. However, this industrial processing raises sustainability considerations [4, 5].

In addition to the issues posed by historical timber, an under-explored area is the study of timber reuse or recycling for structural solutions. Properly treated timber, when reused, holds the potential to provide high performance, reduce consumption, and minimize waste. Although examples of historic timber reuse are scarce in the literature, the Green Building Council in Italy provides one such instance: the restoration of the Church of San Giuseppe dei Falegnami. After the roof collapse, truss elements were repurposed, maintaining their original functions or transformed, such as from purlins to braces [6].

The scarcity of preserved and reused timber often leads to new designs. These designs, conforming to safety coefficients imposed by Italian regulations (Technical Standards: Norme Tecniche per le Costruzioni 2018) [7], may result in reduced structural resistance, necessitating over-sizing of structures. This, in turn, challenges existing technological solutions, increasing required thicknesses and causing material waste. timber is rarely preserved, and even more rarely is it reused because of the reliability of its mechanical properties. To address these issues, is relevant to deepen the analysis of different timber samples, exploring variations between standard and reused/treated timbers. The goal is to contribute to a broader understanding of sustainable and structurally viable timber applications.

Recognizing the necessity of preserving and reusing timber elements, this study advocates for the development of investigation methods that validate structural strength and material integrity without causing damage. This can be done through diagnostics and evaluation of degradation status with non-destructive tests (NDT). Non-destructive investigations aim to estimate the physical and mechanical characteristics of the material and structures without altering the samples. For these reasons, they can be carried out in situ if the elements are inspectable and reachable and do not cause (if not minimal) damage to the structure [8]. Various NDTs exist, differing in structure knowledge requirements, costs, materials investigated, and information obtained. Notably, density is a key property (as resistance and elastic modulus) determining the conservation status and reliability of timber as a structural element. In this research, the aim is to deepen the correlation between density and thermal properties through experimental NDT. Empirical data and correlation estimations are obtained in the laboratory, with the ultimate goal of proposing a valid methodology for on-site tests that preserve timber elements by understanding conservation status.

For density estimation, it is proposed to correlate measurements of penetrometric test with another NDT method: infrared thermography (IRT). This non-invasive approach allows remote surface temperature observation, avoiding physical contact and utilizing a device that analyzes emitted radiation. Research on NDT on timber elements is currently still limited and mainly focused on forestry. The uncertainty that distinguishes the results does not yet allow for reliable correlations. Research in the field of thermography as a non-destructive testing methodology for timber elements has witnessed significant developments, showcasing a diversification of approaches and methodologies over the years.

A relevant example of this progress is explored by Ref. [9] where the use of radiometry to non-destructively assess the density of timber elements provides a valuable alternative for historical structures. Another work applied active thermography to diagnose timber elements, focusing on determining the node area ratio in elements covered with paint [10]. This study highlights the technique's sensitivity in specific assessments, offering valuable insights into the condition of historical elements.

Reference [11] proposed an approach based on the equality of mechanical and non-destructive parameters to assess the in-situ strength properties of timber, emphasizing the importance of a methodology tailored to the needs of historical structures. Similarly, Ref. [12] addresses the structural health assessment of historical buildings through the combined application of non-destructive techniques, emphasizing the importance of a holistic approach for accurate diagnosis.

Other studies [13, 14] utilized infrared thermography to evaluate the deterioration status of timber elements, identifying issues such as moisture and damage caused by incompatible repairs. With some similarities, Ref. [15] resented an innovative methodology for detecting biodegradation and disintegration damage in timber structures wrapped in composites, underscoring the importance of advanced structural monitoring techniques.

Reference [16] proposed an active infrared thermography-based approach to assess the density and mechanical properties of ancient timber members, deepening the application of this technique to historically significant elements. The analysis of effect of density on the thermodynamic behavior of timber, contributing to a deeper understanding of the potential of infrared thermography in the physical characterization of the material is proposed in Ref. [17].

Microwave reflectometry-based method was introduced by Ref. [18] for identifying buried anomalies in architectural structures, expanding the set of non-destructive techniques for structural analysis. Other advanced approaches are proposed by Ref. [19] with the combined ultrasound and thermography approach to identify internal defects in timber, offering effective solutions to enhance the quality of timber destined for processing. In Ref. [20], active thermography technique and lock-in stimulation technique is used for hidden defect evaluation demonstrating the capability of evaluating defects in low thermal diffusivity material such as reinforced polymers.

Some case study project are conducted by Ref. [21] on non-destructive tests on the Church of the Nativity in Bethlehem, combining approaches such as ultrasound detection and thermography, demonstrating the effectiveness of the integrated approach in diagnosing historical buildings. On the other hand, Ref. [22] conducted in-depth in-situ tests and analyzed the dynamic behavior of the Church of Santa Maria Maddalena, providing an example of integration between experimental data and numerical modeling for an accurate assessment of the structure.

Also, different works with different aims are proposed by Ref. [23] with the introduction of a multi-parameter analysis for the assessment of historical timber floors, using techniques such as acoustic emission and numerical modeling, demonstrating the effectiveness of multi-criteria analysis.

In the end, Ref. [24] proposed a health assessment method for timber columns using empirical mode decomposition and correlated Laplace filtering, offering a non-destructive alternative to ensure the safety and durability of electrical infrastructures.

1.1 Incidence of timber defects

The arboreal stem consists of essentially three tissues. The mechanical one is the most prevalent and consists of fibers parallel to each other united in bundles and serves to support the structure. The conductive tissue is for the transport of the lymphatic system and finally, the parenchymal is reserved. The mechanical fabric is the one that gives the mechanical properties of the material that, depending on how and where the sample is cut, offers a different response in the three main directions (longitudinal, transverse, and radial) defining orthotropic material [25].

This specification should be taken into account when carrying out the tests, as it causes repercussions in the data. The fibers respond differently to mechanical stress, but also cause problems in ultrasonic tests for example, where the longitudinal position of the probes returns more reliable results [26].

In addition to this heterogeneity of the material, it is, by its nature, composed of some defects (knots, or knots group, mechanical cracks, splits, ring shakes, and slope of the grain), which alter its physical and mechanical characteristics, adding a great variability of the results. Knots, for example, being points of increase in density, involve a point of discontinuity and consequent fragility of the structure. For this reason, particular reference is made to these in assessments, to avoid possible structural collapse [27, 28].

The main uncertainty of timber is the average density, as is also expressed by the European standard EN 338:2010 which identifies it as one of the three main factors for the classification of timber elements. Density can be estimated through penetrometric through the use of two instruments: the Woodpecker and Resistograph (not used in this work). Through these devices, it is possible to conduct punctual tests through the penetration of tips or needles inside the material. In the case of the second instrument, it is a depth test, allowing to obtain complete knowledge (even if always punctual) of the analyzed section. For the Woodpecker, it is possible to have a more widespread point map limited to the surface only.

The Resistograph was developed in the 80 s by Frank Rinn for forest studies, to know in detail the trend of the growth circles of trees and the presence or absence of internal insects or fungi. This instrument compares the penetration length with the percentage resistance that the material opposes concerning the rotation or the pressure of the needle. It is a roto-drilling instrument. Peaks or depressions of the graph serve to understand the presence of increases or decreases in density (similar to knots for peaks or the presence of biotic or fungal attacks for depressions) [29].

The Woodpecker instead is a tool that is used through the inflection of 9 points that form a grid at a distance of at least 2.5–3.0 cm. Each is fixed using five shots and is measured penetration through the subtraction of the original length (50 mm) relative to the ledge. Thanks to the curves provided by the producer, depending on the timber species, it is possible to correlate with the penetration depth and the surface density. These data are often less reliable, as the surface of the timber is often subject to degradation or deviation [30, 31].

2 Methodology

To carry out these tests, different chestnut samples provided by local woodworking company were examined. The samples have the peculiarity of being both standard and reused to be able to also propose the possible reuse of timber elements and structures. The idea behind the experiment is to overcome the absence of a specific regulatory standard for the reuse or recycling of timber elements, often not used for prejudices against poor mechanical reliability.

The timber samples analyzed are 8 (7 chestnuts, and 1 oak sample), of which some of them are of new production, and others are from reuse treated in different ways (vaporized, salified, and dried), to compare the results. The company's sawmill works only timber at km 0 with a supply radius of 20 km, for the timber essences: chestnut (*Castanea sativa* or fagaceo), oak (*Quercus robur*, *Quercus petranea*), and a small part resinous timber (as larch and fir, in negligible elm production, rural Ulmus).

The company produces timber products both for finishing and structural use starting from timber abandoned in the timbers due to natural causes (storms, landslides, old age of timber) and also beams belonging to ancient farmhouses or abandoned roofs, always with a recovery radius of, at most, 30 km from the site of our sawmill.

The processing of recovered and reused timber consists of vaporization, drying, or salification through: cleaning by iron brush, logs, and beams; passage with a metal detector for the relief of metal parts accumulated over time in the timber itself; sawing in our sawmill at a slow pace, to reduce the timber in boards; cooking by boiling the timber; second cooking, using earth and water vapor; drying to the hygrometric standards required by the timber standard for the various uses previously agreed. The following methodology is proposed.

1. Sample selection and preparation
   - Select a total of 8 timber samples, including 7 chestnut samples and 1 oak sample.
   - Distinguish between standard produced samples and reused and treated (vaporized, salificated, and dried).
   - Conduct a thorough visual inspection of each timber sample to identify external defects or anomalies and obtain the visual estimation of mechanical properties.
2. Penetrometric tests
   - Using Woodpecker to estimate the superficial density of the samples.
   - Correlation between Woodpecker density curves and penetration data obtained carrying out tests.
   - Perform a moisture content test (hygrometric test) to assess the water content within the timber.
3. Active infrared thermography
   - Implement IRT to assess thermal properties through phase investigation and identify disuniformity across the timber surface.
   - Use a specialized device for remote surface temperature excitation and observation.
4. Correlation and statistical analysis
   - Gather empirical data from visual inspections, moisture content tests, and NDT results.
   - Conduct statistical analyses to quantify the correlation between density and thermal properties.
   - Assess the impact of different treatments on the structural integrity of reused timber.

This research proposes a valid methodology for on-site tests that prioritize preservation and conservation status assessment without causing damage, encompassing a comprehensive approach that integrates NDT tests such as visual inspections, moisture content testing (also known as hygrometric test), penetrometric tests and active infrared thermography (specimen overview: Table 1).

3 Non-destructive tests setup

3.1 Visual inspection

The Italian standard UNI 11119:2004 [32] for visual inspection provides criteria for obtaining the visual strength and mechanical properties of on-site elements by the observation of superficial defects and cracks. The geometry (maximum dimensions and existence of wanes) and defects must be visually inspected by the standard.

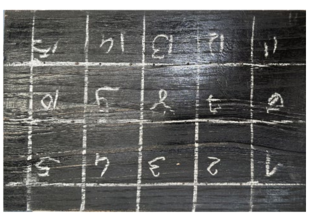
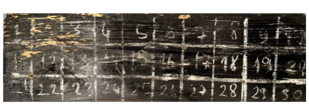
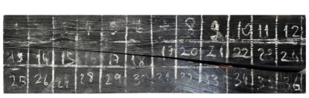
The UNI 11119 standard outlines the inspection's purpose: to gather pertinent details about each load-bearing timber member to assess its structural integrity and mechanical performance. This includes identifying the timber species, measuring moisture content and gradients, determining biological risk class, examining geometry and morphology for defects or damage, evaluating critical zone positions and dimensions (and their incidence on the total geometry of the face they are on), and grading strength. The standard so provides a correlation between the presence of defects and deterioration with mechanical properties also depending of the specimen of the sample.

This investigation is carried out to know the state of conservation of the chestnut elements, even if mainly indicated for inspection of new elements rather than of ancient ones.

If ancient structures are analyzed, the data obtained by the legislation may be less reliable and may provide an undercurrent of the mechanical characteristics. Since they are reused elements or new production, but processed before the distribution, it is easily applicable (also thanks to the absence of wanes, splits, and other defects).

However, the requirements for knots or knots groups remain valid. In addition to the visual inspection, two NDTs were conducted, a hygrometric, penetrometric test

Table 1 Sample name and dimensions

Photo	Sample	Process	Width [m]	Height [m]	Length [m]	Volume [m^3]	Weight [kg]
	1	Standard	0.028	0.320	0.160	0.0014	0.711
	2	Vaporized	0.062	0.511	0.177	0.0056	2.735
	3	Standard	0.024	0.207	0.130	0.0006	0.322
	4	Standard	0.028	0.236	0.182	0.0012	0.538
	5	Dried	0.062	0.280	0.175	0.0030	1.390
	6	Salified	0.065	0.454	0.183	0.0054	3.044
	7	Vaporized	0.065	0.505	0.140	0.0045	2.357
	8	Salified	0.064	0.610	0.154	0.0060	2.893

with Woodpecker and active thermography investigations. Species are provided together with a classification of the strength into three groups, along with the relative modulus of elasticity in bending (MoE) and the maximum permissible tension and compression stress values.

Regarding the chestnut samples, all of them are considered class I with a MoE of 10000 N/mm^2 as reported in the summary Table 2.

3.2 Penetrometric tests

The Woodpecker (WP) is a redesigned Schmidt hammer used to estimate density made by the Italian manufacturer DRC, composed of a steel needle (with a diameter of 2.5 mm) with a conical tip. The penetration depth (PD) is determined by measuring the needle's exposed portion after being inserted into the timber with five shots (with a pre-fixed interaxis of 25 or 30 mm) and subtracting it from the total (50 mm). The maker provides several correlation laws for PD, regarding various timber species, focusing on the link between penetration depth and superficial density.

The choice of using Woodpecker, instead of more accurate methods, is given by the intention of wanting to know the surface density and to correlate it to the thermal properties that are evident from the active thermographic tests, which analyze the outer part of the material.

Usually, during the test try to avoid the area that includes visible defects, having an average estimate corrected by excessive variations in density alters the test result. In this case, it is essential to create a grid that covers the entire surface of the sample and that allows you to have at various points the corresponding thermal data. However, the distance of 30 mm between the points has been maintained as shown in Fig. 1.

Also, hygrometric tests were carried out, using a hygrometer with superficial probes. The relative moisture content of the timber samples was measured in different positions using a Huepar M01 tester (scale G).

A grid of points distant 30 mm, as for WP tests, was reported on the samples, and humidity was measured in the nodes of the grid. Measurements were performed with room temperature equal to 24 °C and relative humidity equal to 0.265.

3.3 Active thermography

The use of thermography to investigate timber properties has been documented in the literature, with papers focusing on hygrometric [5], density [33], and mechanical [33] properties. This paper applies the Active Lock-In [34] [35] technique and analyses the phase plot of the processed thermograms using the setup shown in Fig. 2.

To avoid issues related to emissivity calibration, the sample surfaces were coated with a 0.1 mm thick black opaque spray paint. The emissivity was then set to 0.96. Two 500-W halogen lamps, 400 mm away from the surface of the samples, were used to send a heat input to the surface for 30 s, followed by 60 s of cooling. This process was repeated three times. An IR FLIR A6751sc thermal camera, with a sensitivity of less than 20 mK and a 3–5 m spectral range, was positioned 2000 mm away from the target to acquire the heating and cooling profile of the surface during the test. The thermograms were then processed to obtain phase maps.

The infrared camera captures the thermal response of an excited area, represented by a 3D matrix $T^m_{i,j}$, where m indexes time steps $t_m = m\Delta t$, with $\Delta t = 1/f$ as the sampling interval, i and j span the pixel rows and columns of the $H \times W$ frame. For a single pixel, the temperature sequence T^m reflects the thermal variation over time. Noise inherent in the camera

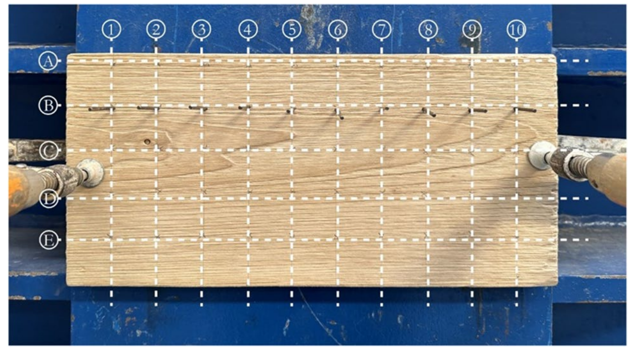


Fig. 1 The first line of the Woodpecker tests with the referring grid

sensor affects the temperature readings, which can be mitigated using filtering or decomposition methods, though some signal alteration is inevitable.

The sample's emissivity coefficient ϵ varies across the surface, influencing the absolute temperature readings but not the signal's temporal pattern. Frequency analysis of $T^m_{i,j}$ can yield accurate dynamics despite these uncertainties.

The Discrete Fourier Transform (DFT) translates the sampled temperature data into a frequency domain representation $\hat{T}_n$, given by

$$\hat{T}_n = \sum_{m=0}^{N-1} T^m e^{-\frac{i2\pi nm}{N}}, \quad n = 0, \dots, N-1.$$

The amplitudes $|\hat{T}_n|$ correspond to the signal's frequency components. Due to symmetry in the real-valued T^m, analysis is restricted to the first half of the DFT spectrum. Heat transfer alters the DFT amplitude at specific frequencies. Normalizing the DFT magnitude by the zero-frequency component $\hat{T}_0$, it is possible to define

$$\hat{T}'_n = \frac{|\hat{T}_n|}{\hat{T}_0}, \quad n = 1, \dots, \left\lceil \frac{N-1}{2} \right\rceil.$$

From an analytical point of view, in the literature [36], the 1D solution of temperature distribution in an isotropic semi-infinite specimen submitted to a modulated thermal source is given by

$$T(z,t) = T_0 \exp\left(-\frac{z}{\mu}\right)\cos\left(\frac{2\pi z}{\lambda} - \omega t\right) \tag{1}$$

where z is the coordinate along the thickness, t is the time, $\omega = 2\pi f(\mathrm{rad/s})$ is the modulated frequency, $f(\mathrm{Hz})$ is the heat wave frequency, and $\lambda = 2\pi\mu(m)$ is the thermal wavelength. The most important feature of this equation is $\mu = \sqrt{(\alpha/\pi f)}(m)$ and is expressed as thermal diffusion length, where /alpha is the thermal diffusivity. This value gives the rate of decay of the thermal wave as it penetrates

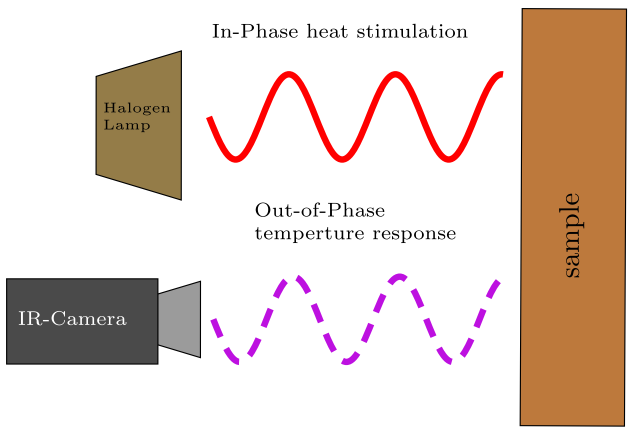


Fig. 2 Scheme of the experimental setup

Table 2 Sample dimensions, strength classes given by the visual grading, and comparison between real and estimated density

Sample	Process	Strength class	Density [kg/m^3]	WP Density estimation [kg/m^3]
1	Standard	I	495.9	425.4
2	Vaporized	I	487.7	419.7
3	Standard	I	498.6	473.6
4	Standard	I	447.3	428.9
5	Dried	I	457.5	415.8
6	Salified	I	563.6	445.7
7	Vaporized	I	512.8	432.5
8	Salified	I	481.2	420.9

trough the material. It is evident that thermal diffusivity has an influence in thermal signal amplitude and phase.

4 Results and discussion

4.1 Penetrometric tests

Table 2 provides a summary of the obtained results, showcasing both the actual density and the density estimated through NDT testing for each sample.

It is noteworthy that the estimated value consistently falls below the actual density, as previously explained. This discrepancy arises from the instrumentation being calibrated for new timber rather than aged as shown in Table 2.

After removing sample 3, considered an outlier also for its nature (walnut) different from the others, the scatter plot shows a general positive trend between real density D and Woodpecker D_{WP} estimated density that is superficial. The equation of the regression line and the R^2 value provide further insights into the correlation:

$$D_{\mathrm{WP}} = 0.298D + 277.8$$

With the reverse formula, it is possible to obtain the real density from WP tests:

$$D = (D_{\mathrm{WP}} - 277.8)/0.298$$

The Pearson coefficient r, which measures the goodness of fit of the model, is $r = 0.98$. This suggests that the linear regression equation fits well the experimental data, indicating a significant correlation between the two variables 3. However, it is important to note that the population is limited and the removal of a sample can impact the analysis, and further assessments are advisable in the future. The fact that the surface density estimated by the Woodpecker (WP) is lower could also be attributed to surface degradation and fiber detachment.

The regression line starting by the elaboration of the data is obtained in order to check the reliability between the real density and the estimated one as shown in Fig. 3.

4.2 Active thermography

4.2.1 Effect of the excitation period

This study's cornerstone involved a pixel-by-pixel analysis of the thermal images obtained from various historical timber samples. This approach allowed us to discern subtle, yet significant, discrepancies in the data, potentially indicative of underlying variations in timber density and moisture content.

Notable differences in color and intensity were observed across the thermal images. These variations corresponded with hypothesized changes in the timber's mechanical properties, particularly in areas exhibiting higher moisture content or differing density, potentially due to structural anomalies like knots or internal fissures.

Certain regions displayed distinct thermal patterns, suggesting localized variations in the timber's physical structure. These findings are critical in hypothesizing about the historical treatment and condition of the timber elements. In Fig. 4, the sequence of thermographic phase plots for sample 1 presents a comprehensive overview of the material's response to a range of excitation periods.

The temporal evolution captured in these images is a testament to the intricate interplay between thermal energy input and the sample's intrinsic properties. At the outset, the brief excitation periods of 2 s and 4 s yield phase plots with localized thermal responses, which likely represent rapid heat exchanges at the surface. The undefined nature of the thermal patterns at these intervals suggests a dominance of swift thermal diffusion, with limited penetration into the deeper layers of the sample.

As the excitation period extends to 10 s and beyond, the phase images begin to exhibit more defined and widespread patterns, signifying the progression of thermal waves deeper into the timber. This change in depth and clarity of the thermal response provides valuable insights into the thermal inertia and the temporal characteristics of heat transfer within the material. The transition from the initial chaotic patterns to more coherent and stable interference fringes at the longer excitation periods of 30 s and 60 s implies a move towards a steady-state regime of thermal conduction. These orderly patterns not only reflect the timber's homogeneity but also have the potential to reveal internal defects or variations in density.

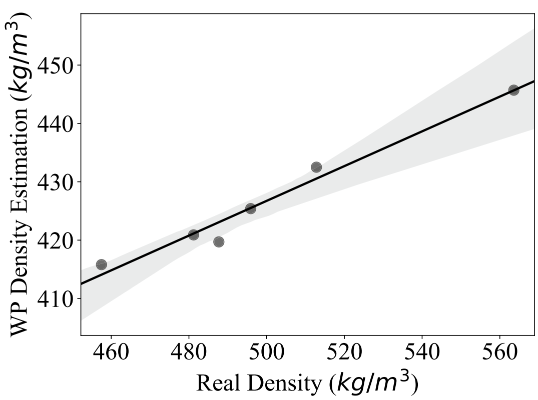


Fig. 3 Scatter plot illustrating the correlation between real timber density and WP density estimation

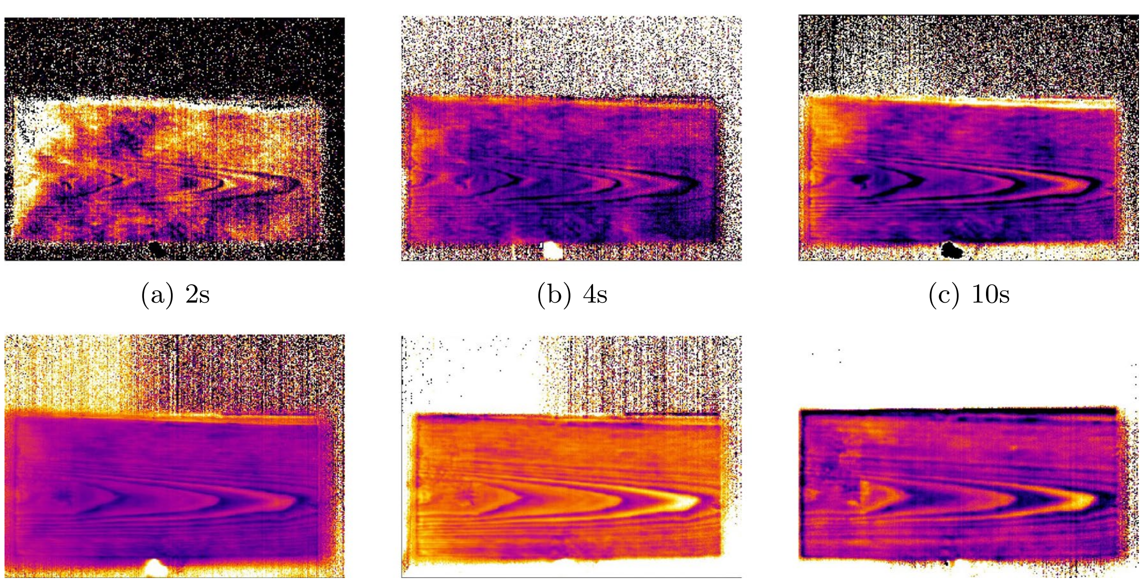
Notably, the phase plot captured at the 30 s mark stands out as particularly informative. It appears to strike an optimal balance between the thermal response time of the sample and the clarity of the thermal patterns, which may be critical for the non-destructive density estimation of historical timber elements. It is at this intermediate excitation period that the thermographic technique demonstrates a significant capacity to differentiate between uniform and variable density regions within the timber.

This parametric study on the excitation period is a crucial step toward refining the protocols for non-destructive testing of historical timber elements. The discerned patterns within the phase plots will not only guide the selection of appropriate excitation periods for future assessments but also ensure that such evaluations accurately reflect the material's true condition.

4.2.2 Effect of surface coating

The thermographic phase plots depicted in Fig. 5 offer a stark visual contrast between the thermal behavior of painted and unpainted samples of historical timber, providing critical insights into the impact of surface coatings on heat transfer properties.

In the unpainted sample, the phase plot reveals a clear and uninterrupted pattern of thermal wave propagation. This clarity suggests that the absence of paint allows for a more direct assessment of the timber's intrinsic thermal response, free from the influence of external coatings. The visible interference fringes are indicative of the timber's natural



(a) 2s (b) 4s (c) 10s

(d) 20s (e) 30s (f) 60s

Fig. 4 Parametric study on phase plot quality varying the excitation period—sample 1 density variations and could potentially highlight areas of degradation or internal defects.

Conversely, the painted sample displays a markedly different thermal signature. The presence of paint introduces a layer of complexity, as it acts as an additional barrier to thermal penetration and diffusion. The resulting phase plot is less defined, with the paint's insulating properties dampening the thermal patterns. This dampening effect can obscure finer details of the timber's underlying condition, making it challenging to discern the same level of detail as seen in the unpainted sample. The comparison between the two plots underscores the significant role that surface coatings play in thermographic analysis. Paint, often used in historical timber for preservation or esthetic purposes, can significantly alter the thermal dynamics observed. The insulating characteristics of the paint must, therefore, be carefully considered when interpreting thermographic data, as they can mask or alter the natural thermal behavior of the timber.

This study on the effect of surface coating is pivotal for the development of accurate non-destructive testing protocols for historical timber conservation. It highlights the necessity for calibration or correction factors in thermographic analysis when dealing with painted timber artifacts. Recognizing the influence of paint on thermal readings ensures that conservationists and restorers can make informed decisions, accounting for the modifications that coatings introduce to the thermal assessment process.

4.2.3 Effect of the excitation source distance

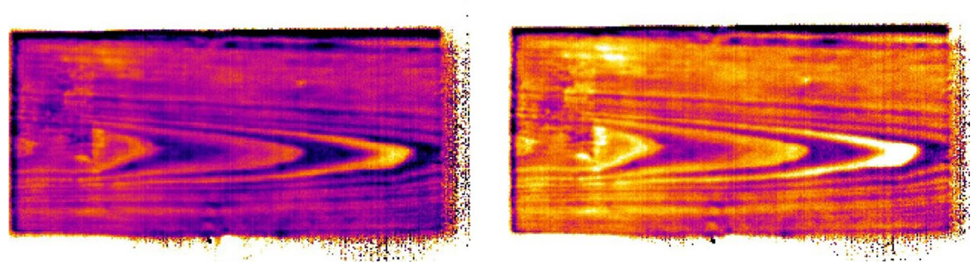
In Fig. 6, the thermographic images of sample 1 offer an intriguing comparison between the effects of proximity and distance of a heat source on the detectability of thermal patterns in both near and distant settings.

The thermogram at the closer distance of 200 mm (a) reveals a detailed and concentrated heat distribution across the sample's surface. The nearness of the heat source allows for a high-resolution capture of the thermal behavior, showcasing the natural thermal patterns of the timber with greater clarity. This proximity enables the detection of fine details within the timber, which could indicate variations in material density, possible defects, or moisture content.

Conversely, the thermogram at 1500 mm (b) displays a starkly contrasting image. The increased distance results in a broader dispersion of heat, with a consequent reduction in the intensity of the thermal footprint. This dispersal makes it significantly more challenging to detect the nuanced differences in the timber's thermal response. The image becomes coarser, and the finer details are lost, highlighting the inverse relationship between distance and resolution in thermographic imaging.

The comparative analysis of these two distances illustrates the critical role that the positioning of the heat source plays in thermographic diagnostics. The findings indicate that the proximity of the heat source is integral to the level of detail that can be resolved in a thermogram. For practitioners in the field of historical timber conservation, this underscores the necessity of adjusting the distance of the heating source to suit the required resolution and sensitivity for accurate assessments.

This study also has broader implications for the standards and practices of thermographic inspection in the conservation of historical artifacts. The ability to discern detailed thermal patterns is essential for non-destructive evaluation, and the data from this study serve as a guide for calibrating thermographic techniques based on the distance of the heat source. The results demonstrate the importance of careful planning and execution of thermographic procedures to ensure that the nuances of a sample's thermal properties are accurately captured and interpreted.



(a) Not painted (b) Painted

Fig. 5 Comparison between painted and raw sample—sample 1

4.2.4 On the relative contribution of density and humidity

Figure 7 showcases the intricate interplay between the density and humidity of new timber samples and their thermal signatures, as captured through thermographic imaging. The phase maps juxtaposed against the density and humidity maps for sample 2 offer a visual representation of how these physical properties manifest in thermal imaging.

The phase map correlated with the density map (a) reveals geometric patterns that resonate with the intrinsic density variations within the timber. These patterns correspond to the natural growth rings and the grain structure, which are fundamental determinants of the timber's density.

The sharp contrasts in the thermographic image highlight areas of different densities, suggesting regions where the timber may have varying structural integrity or mechanical properties. The clarity of these patterns is a testament to the sensitivity of thermographic techniques in detecting subtle variations in density within timber materials.

In contrast, the phase map aligned with the humidity map (b) displays a more fluid and gradient-like pattern, indicative of the moisture distribution across the sample. The variations in color intensity within the thermal image suggest regions of varying water content, which can significantly impact the timber's thermal response. Moisture in timber can affect its thermal conductivity and capacity, and these thermographic images vividly depict the heterogeneity of moisture within the sample.

The study captured in these images is crucial for understanding the contributions of density and humidity to the thermal characteristics of new timber. The distinct thermal footprints associated with each physical property illustrate the potential of thermographic analysis in assessing the condition of timber in a non-destructive manner.

For conservationists and materials scientists, the ability to accurately map these properties is invaluable, as it allows for the early detection of potential issues related to material degradation or suitability for use in various applications.

Moreover, these thermographic maps serve as a guide for future conservation efforts, where understanding the material properties of timber is essential for making informed decisions regarding preservation treatments and interventions. The detailed visual information provided by these images can aid in the development of targeted conservation strategies that account for the unique characteristics of each timber artifact or structure.

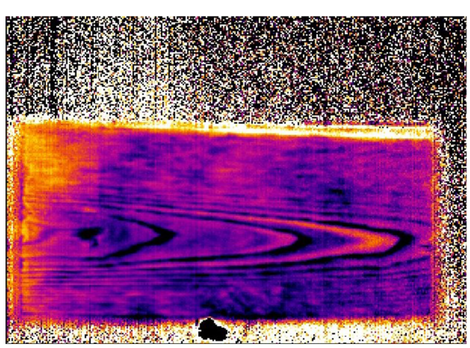
Additionally, the results for the dried and salified timber are presented. Figure 8, in conjunction with the accompanying Tables 3, 4 and 5, presents a detailed examination of the phase maps vis-à-vis the density variations across three different timber samples, considering their relative humidity levels. The phase maps and tabular data together provide a multidimensional perspective on how humidity interacts with the density to influence the thermal characteristics of the timber.

Sample 5 (a) shows a phase map with clear, geometric thermal patterns that correlate well with the timber's density attributes. The distinct thermal signatures correspond to the growth rings and are potentially indicative of the material's structural integrity. When cross-referenced with the tabular data on humidity, the variations in the phase map can be partially attributed to the fluctuating moisture levels within the sample, which inherently affect its thermal response.

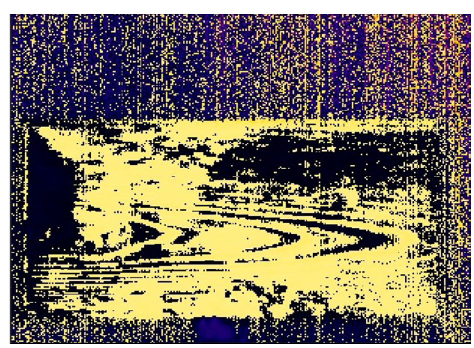
Sample 6 (b) displays a phase map with a relatively homogenous thermal pattern, suggesting a more consistent density throughout the sample. However, the table of relative humidity for a salified sample (Table 3) indicates variations in moisture content, which seem to have a less pronounced effect on the thermal imaging compared to sample 5. This could be due to the salification process potentially stabilizing the moisture distribution or affecting the timber's thermal conductivity.

Sample 3 (c) presents a phase map that appears to have a gradient of thermal patterns, likely reflecting a gradient in the timber's density. The circles visible in the thermal image suggest the presence of features or inclusions within the timber that have distinct thermal properties from the surrounding matrix, possibly due to differences in material composition or localized changes in density.

Fig. 6 Comparison between near and distant—sample 1

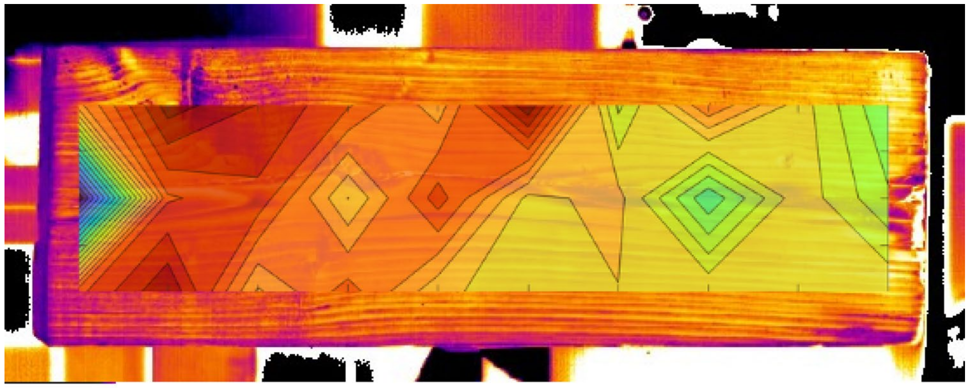


(a) distance=200mm

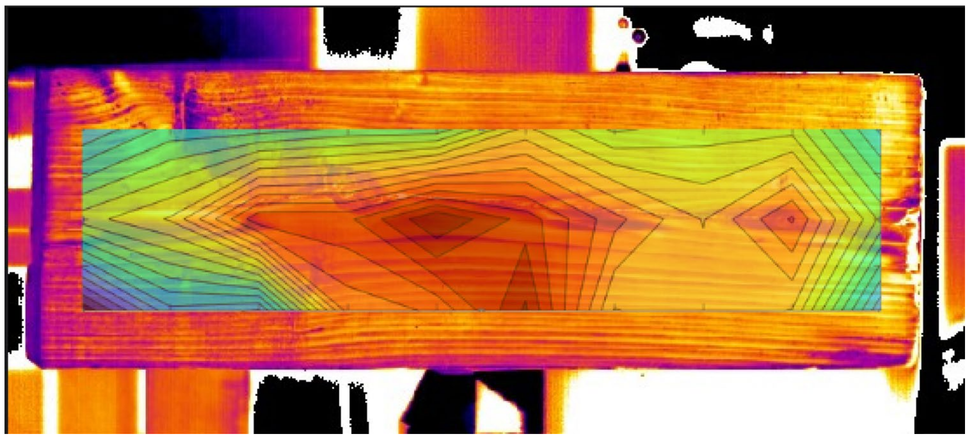


(b) distance=1500mm

Fig. 7 Study on contribution of density and humidity for new timber—sample 2



(a) Phase Map VS Density map



(b) Phase Map VS humidity map

The tabular data provided for dried samples (Table 4) and new samples (Table 5) offer additional context to the phase maps, indicating that lower humidity levels, as seen in the dried and new samples, result in more uniform thermal patterns. This uniformity is likely due to the reduced impact of moisture on the thermal conductivity of the timber, leading to a more consistent thermal response that is primarily dictated by the timber's density.

The combination of thermographic imaging and precise humidity measurements allows for a nuanced understanding of the timber's condition. For instance, areas within sample 5 that align with higher humidity readings may correspond to darker areas on the phase map, indicating cooler regions due to moisture's impact on thermal diffusivity. Similarly, the uniformity in sample 6's phase map might be the result of the salification treatment evening out the moisture content, leading to a more homogenous thermal response.

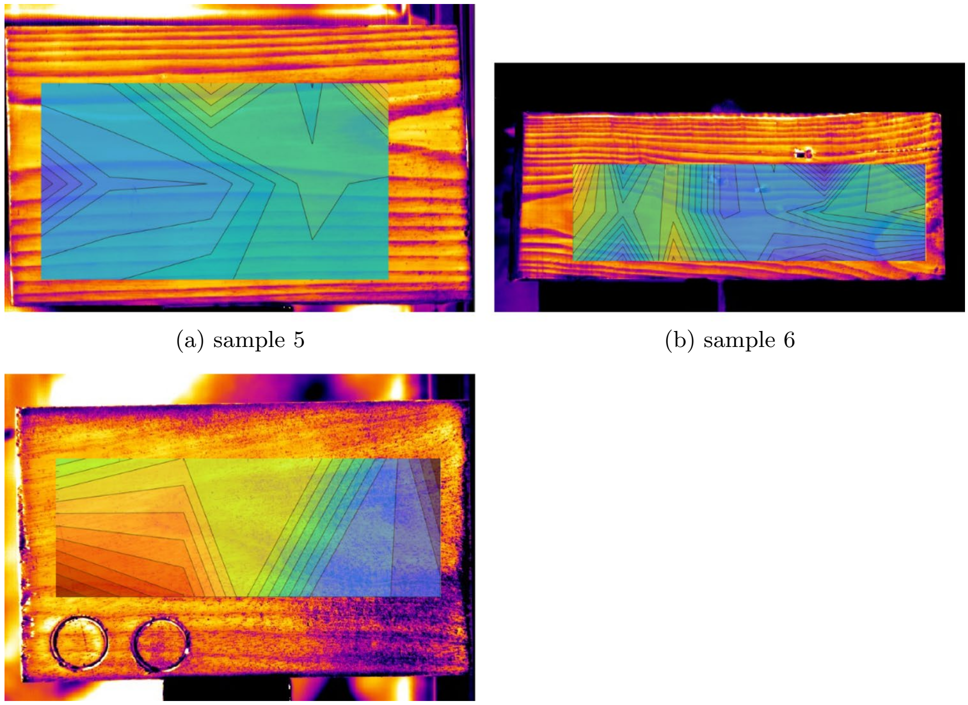
These insights emphasize the importance of considering both density and humidity in the assessment of timber's condition. The thermographic technique, when calibrated against known moisture levels, can be a powerful tool for non-destructively evaluating the integrity and suitability of timber for conservation or structural applications. The data from these studies serve as a critical reference for developing protocols that account for the complex interplay between timber's physical properties and its thermal behavior.

In Tables 3, 4 and 5, the relative humidity data are reported. The same data were plotted in Figs. 8a–c, with the corresponding phase contours.

The following observations can be reported: the phase plot mimics the timber fiber distribution; the humidity appears to be lower where fibers are denser and higher where fibers are less dense; the phase contrast between fibers is almost constant; humidity is more uniform in dried sample while it shows large differences in salified samples; the average value of salified sample humidity is higher than in dried sample.

The 3D phase map, processed from thermal data obtained during lock-in stimulation of samples, is related to the local conductivity value [37]. In the present research, a plane white heat source was used in place of a monochromatic laser spot. The heat in this case propagates from the surface to the inner part if the material is homogeneous. If the surface is composed by is non-homogeneous material, different material absorbance and transmittance generate thermal differences at different points of the surface. The heat capacity of the timber fibers can be affected by the influence of water presence [5].

Fig. 8 Phase maps vs density maps



(a) sample 5 (b) sample 6

(c) sample 3

Table 3 Relative humidity, salified sample

Grid node	1	2	3	4	5	6	7	8
Humidity	19	20.1	14.1	12.6	13.7	12.6	12.4	12
Grid node	9	10	11	12	13	14	15	16
Humidity	18.5	18.3	14.3	14	12.8	14.7	12.5	12.2
Grid node	17	18	19	20	21	22	23	24
Humidity	17.7	15.2	13.3	13.7	13.9	14.6	13.8	13

Table 4 Relative humidity, dried sample

Grid node	1	2	3	4	5
Humidity	11.4	11.4	11.3	11.6	12.5
Grid node	6	7	8	9	10
Humidity	12.2	11.8	11.8	11.7	11.6
Grid node	11	12	13	14	15
Humidity	11.7	11.7	11.6	11.9	12.5

These thermal differences can generate heat diffusion and heat fluxes between points on the surfaces; then the phase diagram provides information on diffusivity both toward the internal volume and between different points of the surface. Water has a high absorbance and low transmittance in the IR spectrum and then, the different distribution of water between fibers can affect the surface temperature distribution and consequently the phase plot.

As discussed in Sect. 3.3, the phase is proportional to thermal diffusivity. The intrinsic heterogeneity of wood makes difficult to assess quantitatively the contribution of density or humidity to thermal signal, however, it is

Table 5 Relative humidity, new sample

Grid node	1	2	3	4
Humidity	11	11	11.1	11
Grid node	5	6	7	8
Humidity	11.3	11.3	110.9	10.8
Grid node	9	10	11	12
Humidity	11.5	11.4	11.2	11.1

demonstrated that active thermography is a powerful technique to non-destructively evaluate the timber structures and artifacts.

5 Conclusions

Timber is a material that poses challenges in mechanical comprehension, and its physical and mechanical properties are difficult to estimate, especially when dealing with structural elements that are not newly manufactured. Additionally, it is crucial to acknowledge that standards do not offer guidance in this regard. Therefore, an experimental campaign was undertaken on both newly produced and reused timber samples to establish correlations between various NDT methods. Penetrometric tests for surface density estimation, hygrometric tests, and thermographic investigations were conducted.

A qualitative correlation was identified between surface density and actual density.

The analysis of thermographic phase images has revealed a rich tapestry of density and moisture variations across the samples. This study has demonstrated the profound impact of these variations on the thermal behavior of the timber, as well as the influence of external factors such as surface coatings and the proximity of heat sources. The comparative analysis between painted and unpainted samples highlighted the insulating effect of surface treatments and their potential to mask the thermal patterns that signify the underlying state of the timber. Similarly, the distance of the heating source from the sample was shown to be a critical factor, with closer proximity enabling a more detailed and acute representation of thermal characteristics.

Moreover, examining the impact of different excitation periods on heat transfer within the timber yielded crucial insights. This underscores the significance of choosing suitable excitation periods for precise thermal property capture. Notably, clear thermal patterns emerged during intermediate excitation periods, indicating an optimal balance for assessing density in historical timber elements.

Analyzing phase maps in comparison with density and humidity maps provided valuable information about the internal composition and integrity of the samples. Distinct geometric patterns in certain samples directly aligned with the timber's growth rings and structural variations, while gradient patterns in others indicated diversity in density and moisture content. Tabular data on relative humidity for salified, dried, and new samples quantitatively supported these observations, revealing the nuanced effects of humidity on the timber's thermal response.

This research has underscored the versatility and precision of thermographic techniques in the non-destructive evaluation of historical timber. It has provided a foundation for refining testing protocols and has advanced the understanding of how various factors contribute to thermal imaging results. The ability to non-destructively visualize and quantify the internal properties of timber is relevant, not only for the preservation of cultural heritage but also for the broader field of materials science and engineering.

Acknowledgements The authors acknowledge Brondello Erminio sas for supporting the research by providing the wooden samples.

Funding Open access funding provided by Politecnico di Torino within the CRUI-CARE Agreement. The research has been possible thanks to Fondazione CRC granting, project "Enhancement of the local forest heritage for the energy efficiency of homes" (RIF.2023.1134 - ID 73844).

Declarations

Conflict of interest The authors declare that there are no conflict of interest regarding the publication of this paper. No financial or personal relationships have influenced the outcomes of this study.

References

1. Yang G, Kabel J, Van Rietbergen B, Odgaard A, Huiskes R, Cowin SC. Anisotropic Hooke's law for cancellous bone and wood. J Elast. 1998;53(2):125–46. https://doi.org/10.1023/A:1007575322693.
2. Moshtaghin AF, Franke S, Keller T, Vassilopoulos AP. Experimental characterization of longitudinal mechanical properties of clear timber: Random spatial variability and size effects. Constr Build Mater. 2016;120:432–41. https://doi.org/10.1016/j.conbuildmat.2016.05.109.
3. Li S, Zhou Z, Luo H, Milani G, Abruzzese D. Behavior of traditional Chinese mortise-tenon joints: experimental and numerical insight for coupled vertical and reversed cyclic horizontal loads. J Build Eng. 2020;2020:30. https://doi.org/10.1016/j.jobe.2020.101257.
4. Ratsch N, Böhm S, Voß M, Kaufmann M, Vallée T. Influence of imperfections on the load capacity and stiffness of glued-in rod connections. Constr Build Mater. 2019;226:200–11. https://doi.org/10.1016/j.conbuildmat.2019.07.278.
5. Lolli N, Fufa SM, Kjendseth Wiik M. An assessment of greenhouse gas emissions from CLT and glulam in two residential nearly zero energy buildings. Wood Mat Sci Eng. 2019;14(5):342–54. https://doi.org/10.1080/17480272.2019.1655792.
6. Santini S, Borghese V, Baggio C. HBIM-based decision-making approach for sustainable diagnosis and conservation of historical timber structures. Sustain (Switzerl). 2023;15(4):3003. https://doi.org/10.3390/su15043003.
7. Vagnon F, Bonetto SMR, Ferrero AM, Migliazza MR, Umili G. Rock-engineering design and ntc2018: some open questions. In: Calvetti F, Cotecchia F, Galli A, Jommi C, editors. Geotechnical research for land protection and development. Cham: Springer; 2020. p. 519–28.
8. Rodrigues LG, Sousa HS. Influence of an in-situ inspection on the reliability analysis of an ancient timber roof. Lecture Notes Civ Eng. 2021;153:417–29. https://doi.org/10.1007/978-3-030-73616-3_31.
9. Posta J, Dolejs J. Non-destructive assessment of timber elements with an emphasis on radiometry. Int J Architect Heritage 2015;9(6):655–64. https://doi.org/10.1080/15583058.2015.1041192 (Rubner Holzbau; Rothoblaas; Bovair; Trentino Network; Univ Trento, Dept Civil Engn & Mech Engn; CNR IVALSA, Trees & Timber Inst; European Corp Sci & Technol. 2nd International Conference on Structural Health Assessment of Timber Structures (SHATIS), Trento, ITALY, SEP 04-06) (2013).
10. Kucharska M, Jaskowska-Lemanska J. Active thermography in diagnostics of timber elements covered with polychrome. Materials. 2021;14:5. https://doi.org/10.3390/ma14051134.
11. Josifovski A, Todorovic N, Milosevic J, Veizovic M, Pantelic F, Askrabic M, Vasov M, Rajcic A. An approach to in situ evaluation of timber structures based on equalization of non-destructive and mechanical test parameters. Buildings. 2023;13:6. https://doi.org/10.3390/buildings13061405.
12. Riggio M, Macchioni N, Riminesi C. Structural health assessment of historical timber structures combining non-destructive techniques: the roof of giotto's bell tower in florence. Struct Control Health Monitor. 2017;24:7. https://doi.org/10.1002/stc.1935.
13. Kandemir-Yucel A, Tavukcuoglu A, Caner-Saltik EN. In situ assessment of structural timber elements of a historic building by infrared thermography and ultrasonic velocity. Infrared Phys Technol. 2007;49(3):243–8. https://doi.org/10.1016/j.infrared.2006.06.012. (**8th International Workshop on Advanced Infrared Technology and Applications (AITA), Rome, ITALY, SEP 07-09, .2005**).
14. Lopez G, Basterra LA, Acuna L. Estimation of wood density using infrared thermography. Constr Build Mater. 2013;42:29–32. https://doi.org/10.1016/j.conbuildmat.2013.01.001.
15. Nassr AA, El-Dakhakhni WW, Ahmed WH. Biodegradation and debonding detection of composite-wrapped wood structures. J Reinforced Plast Composit. 2010;29(15):2296–305. https://doi.org/10.1177/0731684409347598.
16. Xin Z, Guan C, Zhang H, Yu Y, Liu F, Zhou L, Shen Y. Assessing the density and mechanical properties of ancient timber members based on the active infrared thermography. Constr Build Mater. 2021;2021:304. https://doi.org/10.1016/j.conbuildmat.2021.124614.
17. Lopez G, Basterra L-A, Acuna L. Infrared thermography for wood density estimation. Infrared Phys Technol. 2018;89:242–6. https://doi.org/10.1016/j.infrared.2018.01.015.
18. Beni S, Micheletti F, Olmi R, Riminesi C. Time-domain approach for non-destructive assessment of embedded anomalies in architectural structures based on microwave reflectometry. In: 2015 8th international workshop on advanced ground penetrating Radar (IWAGPR), IEEE. IEEE 8th international workshop on advanced ground penetrating Radar (IWAGPR), Firenze. 2015.
19. Taskhiri MS, Hafezi MH, Harle R, Williams D, Kundu T, Turner P. Ultrasonic and thermal testing to non-destructively identify internal defects in plantation eucalypts. Comput Electron Agric. 2020;2020:173. https://doi.org/10.1016/j.compag.2020.105396.
20. Matarrese T, Palumbo D, Galietti U. Comparison in the transient regime of four lock-in thermography algorithms by means of synthetic and experimental data on CFRP. NDT and E Int. 2023;139:102925. https://doi.org/10.1016/j.ndteint.2023.102925.
21. Faella G, Frunzio G, Guadagnuolo M, Donadio A, Ferri L. The church of the nativity in bethlehem: non-destructive tests for the structural knowledge. J Cult Herit. 2012;13(4):27–41. https://doi.org/10.1016/j.culher.2012.10.014.
22. Celano T, Ceroni F, Fabbrocino G, Rainieri C, Casapulla C. Thermographic investigations and dynamic identification tests for non-destructive structural assessment and enhanced fe modelling of a historical iron-strengthened masonry church. J Civ Struct Heal Monit. 2023;13(4):901–24. https://doi.org/10.1007/s13349-022-00645-6.
23. Cruz C, Gaju M, Gallego A, Rescalvo F, Suarez E. Non-destructive multi-feature analysis of a historic wooden floor. Buildings. 2022;12:12. https://doi.org/10.3390/buildings12122193.
24. Zhang X, Yang J, Zhu W, Li G. A non-destructive health evaluation method for wooden utility poles with frequency-modulated empirical mode decomposition and laplace wavelet correlation filtering. Sensors. 2022;22:11. https://doi.org/10.3390/s22114007.
25. Fratzl P, Weinkamer R. Nature's hierarchical materials. Prog Mater Sci. 2007;52(8):1263–334. https://doi.org/10.1016/J.PMATSCI.2007.06.001.
26. Borghese V, Santini S, Sguerri L. Sustainable assessment: a contribution to improve the reliability of ndt on old chestnut purlins. In: World conference on timber engineering 2023 (WCTE2023). 2023. https://doi.org/10.52202/069179-0131.
27. Qu H, Chen M, Hu Y, Lyu J. Effect of trees knot defects on wood quality: a review. IOP Conf Ser: Mater Sci Eng. 2020;738(1):012027. https://doi.org/10.1088/1757-899X/738/1/012027.
28. Szabolcs K, Sandor F, Jozsef A, Taschner R. Effect of knots on the bending strength and the modulus of elasticity of wood. Wood Res. 2013;58(4):617–26.
29. Içel B, Güler G. Nondestructive determination of spruce lumber wood density using drilling resistance (Resistograph) method. Turk J Agric For. 2016;40(6):900–7. https://doi.org/10.3906/tar-1606-76.
30. Fundova I, Funda T, Wu HX. Non-destructive wood density assessment of Scots pine (Pinus sylvestris L.) using resistograph

and pilodyn. PLoS ONE. 2018;13(9):0204518. https://doi.org/10.1371/journal.pone.0204518.
31. Santini S, Baggio C, Sguerri L. Sustainable interventions: conservation of old timber roof of Michelangelo's cloister in Diocletian's baths. Int J Archit Heritage. 2023;17(3):500–17. https://doi.org/10.1080/15583058.2021.1938747.
32. Unificazione ENI. 11119:2004 cultural heritage—wooden artefacts—load-bearing structures—on site inspections for the diagnosis of timber members. 2004.
33. Aversa P, Daniotti B, Dotelli G, Marzo A, Tripepi C, Sabbadini S, Lauriola P, Luprano VAM. Thermo-hygrometric behavior of hempcrete walls for sustainable building construction in the Mediterranean area. IOP Conf Ser Earth Env Sci. 2019;296:785. https://doi.org/10.1088/1755-1315/296/1/012020.
34. Sesana R, Santoro L, Curà F, Molica Nardo R, Pagano P. Assessing thermal properties of multipass weld beads using active thermography: microstructural variations and anisotropy analysis. Int J Adv Manuf Technol. 2023. https://doi.org/10.1007/s00170-023-11951-8.
35. Santoro L, Razza V, De Maddis M. Frequency-based analysis of active laser thermography for spot weld quality assessment. Int J Adv Manuf Technol. 2023. https://doi.org/10.1007/s00170-023-12845-5.
36. Doshvarpassand S, Wu C, Wang X. An overview of corrosion defect characterization using active infrared thermography. Hobioken: Elsevier B.V.; 2019. https://doi.org/10.1016/j.infrared.2018.12.006.
37. Zubizarreta M, Cuadrado J, Orbe A, García H. Modeling the environmental sustainability of timber structures: a case study. Environ Impact Assess Rev. 2019;2019:78. https://doi.org/10.1016/j.eiar.2019.106286.