Density estimation of historical wooden elements through means of thermographic correlation approach

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Abstract
Ancient wooden artifacts are vulnerable to deterioration from a variety of environmental and human factors. It is challenging to comprehend the assessment when the wooden part is placed inside a construction without performing a diagnostic procedure. While working with ancient wooden structures, tradition and preservation of the architectural, technological, and historical heritage are crucial. A series of non-destructive tests (NDT) must be carried out and developed in order to preserve and determine the nature of the structure and comprehend how to maintain it because wood is also a significantly heterogeneous material. Thermographic techniques are well recognized to be non-destructive, contactless, complete field techniques and are already common in the artistic sector. However, there is the possibility of estimating the physical properties (for example transmissivity, thermal conductivity, humidity level, etc.) and mechanical characteristics (density, compressive or bending strength, etc.), critical information, linked usually with wooden defects, when it comes to planning interventions of conservation. This work presents the preliminary results of a physical and mechanical characterization methodology of different chestnut elements in different states of conservation, with the aim of correlating thermal and density properties, for the purpose of conserving artistic assets.

Keywords: thermography, wood, density, mechanical properties, characterization.

Introduction

Wood is a very particular material being heterogeneous, anisotropic and often also defined as orthotropic [1]. In contrast to other materials, each sample may exhibit radically different physical and mechanical traits from others, even when compared to other samples of the same woody species or geographic origin. These characteristics raise the uncertainties and variability of the correlations discovered through experimental testing [2]. Architectural history includes also the study of connections, interventions, and connecting components [3].

The modern woods used in architecture for structural use, defined as engineering, try to overcome the intrinsic problems with particular processes, reducing them considerably [4]. It is necessary to develop non-destructive tests (NDT) methods of investigation that can validate the strength of the structures and the material, without damaging the existing historical elements.

The arboreal stem consists of essentially three tissues. The mechanical one is the most prevalent and consists of fibers parallel to each other and 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 fibers respond differently to mechanical stress. In addition to this heterogeneity of the material, it is, by its nature, composed of some defects (knots, or knots clusters, mechanical cracks, splits, ring shakes and slope of the grain), which alter its physical and mechanical characteristics, adding a great variability of the results. For this reason, particular reference is made to these in assessments, in order to avoid possible structural collapse [5], [6].

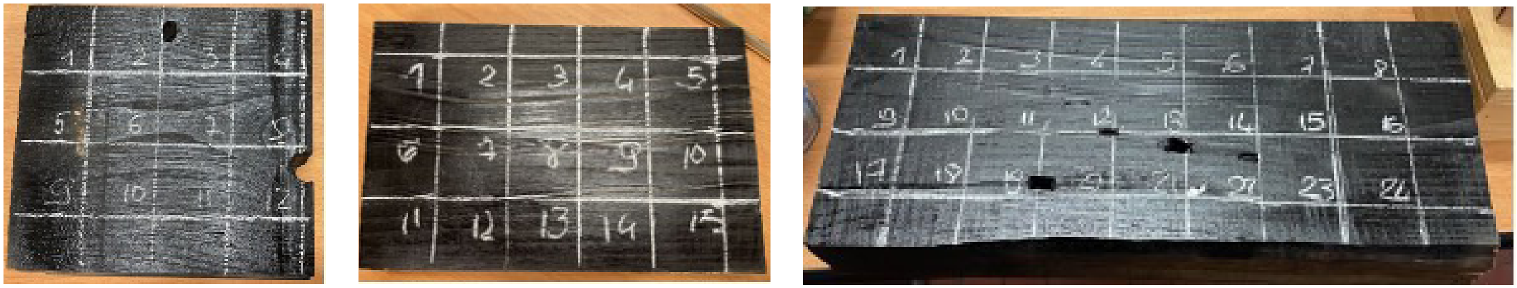
In this research, the authors aim to investigate and deepen the correlation between density and thermal properties of timber, through experimental NDT. In order to estimate density, an NDT method is proposed, to check and assess wooden constructions without causing damage: infrared thermography (IRT). Different chestnut samples provided by Brondello Erminio company of Cuneo were examined. The samples have the peculiarity of being both standard and reused with the aim of being able to also propose the possible reuse of wood elements and structures. This paper is presented as a first work of a wider and more complex research that will also evaluate the deepening of sustainability through a quantitative evaluation and an innovative approach to the material.

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

Sample	Strength Class	Width [mm]	Hight [mm]	Lenght [mm]
1 - New	I	50	200	200
2 – Old salified	I	50	450	200
3 -Old dried	I	50	180	200

Materials and methods

The company's sawmill works only wood at km 0 with a supply radius of 20 km, for local wood essences. The company produces wooden products both for finishing and structural use starting from wood abandoned in the woods due to natural causes (storms, landslides, old age of wood) and also beams belonging to ancient farmhouses or abandoned roofs. The processing of recovered and reused wood consists of vaporization, drying or salification. The analyzed chestnut wood samples are 3, of which one of new production and two are from reuse, one salified and one dried, in order to compare



a b c

Figure 1: wood samples: new (a), old salified (b) and old dried (c)

the results. Regarding the chestnut samples (Table 1), all of them are considered as class I with a MoE of 10000 N/mm^2 according to UNI 11138:2004. In addition to the visual inspection two NDTs were conducted, hygrometric test and active thermography investigations. For the hygrometric tests, a hygrometer with superficial probes was used. The relative hygrometric test of the wood samples was performed in different positions by means of a Huepar M01 tester (scale G). A grid of points distant 50 mm was reported on the samples (Figure 1) 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 26,5%

Thermographic approach for wood properties investigation is documented in literature and papers focus on hygrometric [7], density [8] [9] and mechanical [8] properties. All cited references refer to Active Pulsed Thermography. In the present paper Active Lock-In technique is applied and the phase plot of processed thermograms are analysed. Preliminarily, the sample surfaces exposed to heat stimulation were coated with a 0,1 mm thick black opaque spray paint to avoid problems related to emissivity calibration. Emissivity was then set to 0.96. By means of two halogen lamps, 500 Watt each, distant 400mm from the surface of the samples, a heat input was sent to the surface for 30 seconds and then the lamps were switched off for 60 seconds. 3 impulses were applied. An IR FLIR A6751sc thermal camera, sensitivity of less than 20 mK and 3-5 m spectral range, positioned at 2000 mm from the target, acquired the heating and cooling profile of the surface during the test. The thermograms were then processed by means of dedicated algorithms to obtain phase maps.

Results and discussion

In Tables 2, 3 and 4 the relative humidity data are reported. The same data were plotted in Figures 2, 3, 4, with the corresponding phase contours.

The following observations can be reported: the phase plot mimics the wood fibre 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 [10]. In the present research a plane white heat source was used in place of a

Table 2: *% 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 3: *% 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

Table 4: *% 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

Figure 2: new sample phase plot (left) and humidity plot (right).

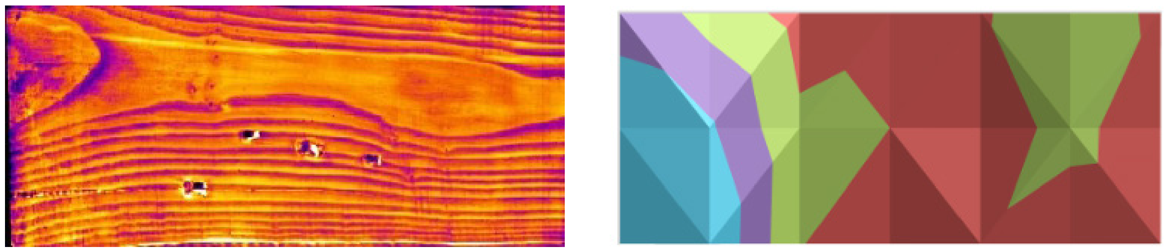


Figure 3: salified sample phase plot (left) and humidity plot (right).

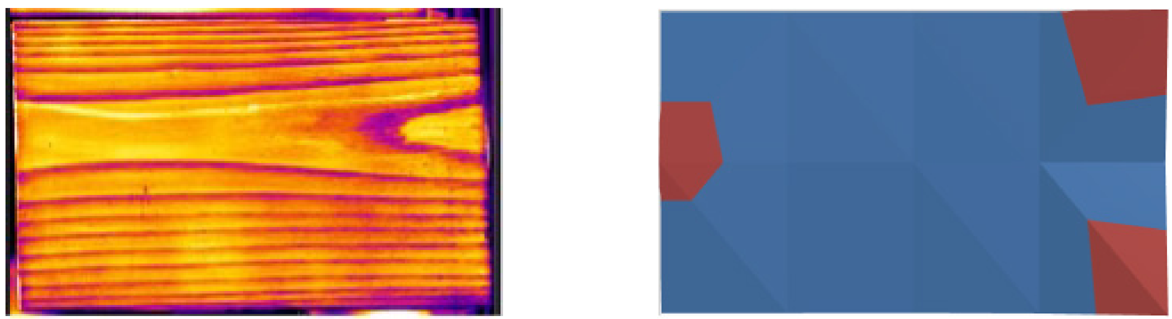


Figure 4: dried sample phase plot (left) and humidity plot (right).

monocromatic 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 in different points of the surface. The heat capacity of the wood fibres can be affected by the influence of water presence [7]. These thermal differences can generate heat diffusion and heat fluxes between points on the surfaces; then the phase diagram provides then 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.

Conclusions

Aim of this research was to develop methods of investigation to quantify the strength of the structures and the material, without damaging the existing historical elements. Diagnostics and evaluation of degradation status with non-destructive tests (NDT) well applies to this aim. By means of non-destructive investigations, and in particular hygrometric and active thermograpy techniques, three samples of Castanea sativa in different physical conditions, were investigated, without altering the samples. A clear correlation was found between humidity ratio and thermal phase plot. It has been found a full correspondence between the actual density and the estimated surface density and this step allows to continue the research in the next step through the correlation of the mapping of phase, humidity and density.

Analyzing the investigated physical properties in a timely manner, three correlations are obtained between the big unknowns of wood. Humidity is one of the most important factors of wood and is less often investigated due to seasonal and punctual variability in the sample. Variable behavior and heterogeneity make this investigation complex. On the other hand, the density is strictly connected to the percentage of humidity and is one of the fundamental requirements and unknowns that concern the existing wooden structures.

The correlation between these physical properties also leads to the mechanical knowledge of the wooden element. The research, still in progress, foresees this evolution so it is possible to have reliable curves and correlation maps that can be used for in situ work.

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