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# Experimental correlations between destructive and non-destructive tests on ancient timber elements

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ABSTRACT

The refurbishment of ancient timber structures requires an acquaintance of the residual structural capacity of members in order to design reliable repairing interventions. Such information cannot be obtained by means of destructive tests on sacrificial elements extracted from the existing structures, while non-destructive tests (NDT) are currently performed in situ on timber elements. In this article, a methodology based on resistographic NDTs is analysed. In particular, an experimental campaign of NDTs on ancient chestnut elements has been carried out for determining a correlation between NDT results and mechanical wood properties, previously obtained by means of destructive tests. Then, a numerical formulation between resistographic tests carried out along the direction parallel to the grain and the longitudinal ultimate compressive stress has been proposed. In addition, since in situ NDTs can be performed only along direction transversal to the growth rings, a correlation between longitudinal and transversal NDTs has been obtained. Finally, in order to validate the proposed procedures, a series of analogous tests have been carried out also on new spruce elements.



## 1. Introduction

In many European countries (central, northern and Mediterranean area), and in particular in Italy, a large historical heritage has to be preserved. In particular, many timber structures, especially in floors and roofs, still exist and require to be refurbished or improved, both for static and functional reasons.

As wood is a natural material, during its life it is subjected to biological degradation phenomena connected to environmental conditions. Furthermore, different structural anomalies (i.e. splitting, shakes, cracking, etc.) are often shown by timber members, also due to the ancient processes of workmanship. Then the condition (from a structural point of view) of ancient timber structures can be very variable, for it being strongly influenced by these causes. For these reasons, the evaluation of the structural capacity of existing timber structures and the definition of the necessary reinforcing interventions need a preventive reliable acquaintance of the physical and mechanical properties of wood and of the residual bearing capacity of members [1,2].

In case of historical structures, such information cannot be obtained by means of local or overall destructive tests on sacrificial elements, which should lead to the loss of the structural integrity. The best compromise seems to be the one based on the integration of the first level inspection (visual survey) with non-destructive tests (NDT), carried out directly on the in site beams.

One of the most common NDT technique is the drilling investigation, which provides local in-depth information on deterioration conditions, identifying also the effective section of degraded structural elements. Nowadays, several national and international research efforts are aiming at directly correlating NDT information with physical and mechanical properties of wood [1–4].

In this article, for ancient chestnut timber beams, a correlation between NDTs (carried out by means of the resistographic equipment) and destructive tests is presented, in order to define a methodology for obtaining the mechanical properties of the material and the bearing capacity of the timber elements directly from the resistographic measures (i.e. the drilling resistance).

NDTs have been specifically performed by the authors and described in the present article, while the destructive tests for both defect-free small specimens and beams in actual dimension (full-scale bending tests) are reported in Calderoni et al. [5]. Note that, in this wide experimental campaign, the resistance of the material and of the members has been determined taking into account also the effects of degradation conditions, structural defects and shape anomalies of ancient timber.

In order to further validate the proposed method also for wood of different species, analogous experimental activity on new

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**Nomenclature**

*The following notations are used in this article*

| | |
|---|---|
| NDT | Non-destructive test |
| RA | Relative resistance (%) |
| DD | Drilling depth (mm) |
| $R_{ML}$ | Longitudinal mean value of RA on the considered drilling depth $H$ |
| $R_{ML,T}$ | Mean value of RA considering the very low or null values of RA |
| $R_{ML,0}$ | Mean value of RA skipping the very low or null values of RA |
| $MR_{ML,0}$ | Mean value of $R_{ML,0}$ values for each end-section |
| $DR_{ML,0}$ | Standard deviation of $R_{ML,0}$ values for each end-section |
| $SMR_{ML,0}$ | Mean value of $R_{ML,0}$ values for each sample |
| $SDR_{ML,0}$ | Standard deviation of $R_{ML,0}$ values for each sample |
| $WMR_{ML,0}$ | Mean value of all the $R_{ML,0}$ values |
| $WDR_{ML,0}$ | Standard deviation of all the $R_{ML,0}$ values |
| $CMR_{ML,0}$ | Mean value of $R_{ML,0}$ values for each chord |
| $R_{MT}$ | Transversal mean value of RA on the considered drilling depth $H$ |
| $R_{MT,T}$ | Mean value of RA considering the RA values ranging 0–5% |
| $R_{MT,0}$ | Mean value of RA skipping the RA values ranging 0–5% |
| $C_{DEF}$ | $(R_{MT,0} - R_{MT,T})/R_{MT,0}$ |
| $CMR_{MT,T}$ | Mean value of $R_{MT,T}$ values for each chord |
| $CMR_{MT,0}$ | Mean value of $R_{MT,0}$ values for each chord |
| $WMR_{MT,0}$ | Mean value of all the $R_{MT,0}$ values |
| $K_{T,L}$ | $CMR_{MT,0}/CMR_{ML,0}$ |
| $f_{c,0}$ | Maximum compressive stress along grain direction |

spruce elements has been also carried out providing additional results which are useful for a better refinement of the proposed correlation procedure.

## 2. Experimental activity on ancient chestnut elements

The experimental activity has been based on a number of resistographic NDTs performed by using a IML Resi F400® device (Fig. 1(a)) at "hardwood" level. It gives the resistance encountered by the bit of a 1.4 mm diameter drill, driven at a constant speed in the wood element. The resistance is recorded on a graph at each $1 \times 10^{-1}$ mm of drilling.

Tests have been carried out on three ancient chestnut samples, obtained by cutting circular timber beams, aged 1700–1800, which have been withdrawn from a floor slab of an ancient masonry building of the historical centre of Naples. The samples had a length of about 450 mm and cross-section diameters varied in the range of 240–260 mm (Fig. 2). They show defect pattern and in-depth degradation state common for such type of elements (i.e. knots, shakes, shrinkage, cracking, holes, etc.), as shown in Fig. 1(b).

Tests on chestnut samples were performed in both longitudinal and transversal directions. In particular, the longitudinal NDTs have been carried out at both edges of the samples for a drilling depth of about 200 mm, in order to have complete information on the whole length of the specimen. The perforations have been made on a 20 mm square grid (about 60 measures for side), as indicated in Fig. 3 for both edges (named max and min) of Sample 1.

The transversal NDTs were performed on the lateral surface of the beam, before cutting it into separate samples. They have been made along three different horizontal lines, corresponding to three chords of the transversal grid, the median line ($0_{med}$), one upper line ($3_{sup}$) and one bottom line ($1_{inf}$), in different transversal sections spaced of about 170 mm (Fig. 4).

Each resistographic test gives a relative resistance (RA (%)) vs. drilling depth (DD (mm)) curve, in which the defects or degradation states of the wood along the perforation are highlighted by sudden reduction of RA with respect to its average value. Note that, being relative to the resistance given by the resistograph, the reported results are valid only for tests performed with the above-described device, while the use of a different equipment requires a specific calibration with reference to wood species for which the mechanical properties are already known.

In Figs. 5 and 6, typical curves obtained from tests performed on the chestnut samples in both longitudinal and transversal direction are reported. The curves show different conditions of the wood in different locations of the same beam: good and constant quality of the material (Fig. 5(a)); wood with localized defect or degradation state (Figs. 5(b) and 6(b)); presence of knots along the drilling line (testified by localized higher values of RA, Fig. 6(a)).

As expected, in an ancient timber element defects and degradation states largely vary in location, extension and typology, depending on both the specific original and natural features of the trunk and the environmental conditions existing during the life of the structure. For these reasons, the variability of the wood quality is quite random and extremely complex to be defined.

## 3. Assessment of test results

### 3.1. Longitudinal tests

Longitudinal resistographic tests (total number of about 400 on six edge sections of three chestnut samples), which have been carried out along the direction parallel to wood grain, provide rather uniform results, as it is shown in Fig. 5(a), where the value of RA is practically constant along the whole drilling depth. However, each test has been assessed by evaluating an unique parameter $R_{ML}$, which is the mean value of RA on the considered drilling depth ($H$), defined as:

$$R_{ML} = \frac{\int_0^H \mathrm{RA} \cdot \mathrm{d}h}{H} \ (\%). \quad (1)$$

The parameter $R_{ML}$ has been calculated either considering ($R_{ML,T}$) or skipping ($R_{ML,0}$) the very low or null values of RA, which represent the existence of either very degraded zones or holes.

In Fig. 7(a), (b) the $R_{ML,0}$ values of each test performed on the max edge of the Sample 1 are reported in a 3-D graph, together with the corresponding density of probability curve, which practically gives a Gaussian distribution with a mean value ($MR_{ML,0}$) of 29.71 and a standard deviation ($DR_{ML,0}$) of 7.20. In Table 1, the mean value and the standard deviation of $R_{ML,T}$ and $R_{ML,0}$ are reported for both the edges of all tested specimens.

Note that the correlation between the $MR_{ML,0}$ and $MR_{ML,T}$ values can give a measure of the defectiveness of the analysed specimen in longitudinal direction, which in this specific case seems to be not very high.

In Table 1, the mean values ($SMR_{ML,0}$) and the standard deviation ($SDR_{ML,0}$) of $R_{ML,0}$ for each sample, evaluated considering all longitudinal tests performed (about 310), have been reported too, together with both the overall mean ($WMR_{ML,0}$) and standard deviation ($WDR_{ML,0}$) values.

The low values of $SDR_{ML,0}$ made the authors confident on the possibility to correlate these results with the actual mechanical properties of the defect-free wood, obtained from destructive tests performed on clear small specimens, as reported in Section 5.