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 paper a methodology based on resistographic NDTs is analysed. In particular, a wide 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 Countries of the Mediterranean area and particularly in Italy very large historical heritages have to be preserved. In particular, many timber structures, especially for floors and roofs, still exist and require to be refurbished or improved, both for static and functional reasons.

As wood is a natural material, it is subjected during its life to biological degradation phenomena connected to environmental conditions. Furthermore the ancient erection techniques often caused structural anomalies (i.e. splitting, shakes, cracking, etc.) in the timber members. Then the condition (from a structural point of view) of ancient timber structures can be very variable, 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.

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 integration of the first level inspection (visual survey) with non-destructive tests (NDT), carried out directly on the in-situ beams.

One of the most common NDT technique is the drilling investigation, which provide local in-depth information on deterioration condition, 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 (Bertolini et al. 1998, Feio et al. 2004, Kasal and Anthony 2004).
In this paper, 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 current paper, 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. (2006). Note that, in this wide experimental campaign, the resistance of the material and of the members have 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 spruce elements has been also carried out providing additional results which are useful for a better refinement of the proposed correlation procedure.

2 THE 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. 1a) 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 1x10^-3 mm of drilling.

Tests have been carried out on 3 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 length of about 450 mm and cross-section diameters variable in the range 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. 1b.

Tests on chestnut samples were performed in both longitudinal and transversal direction. 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.

Figure 1 : (a) Resistographic test; (b) typical defect pattern and degradation phenomena.

Figure 2 : Main dimensions of the tested samples.
The transversal NDTs were performed on the lateral surface of the beam, before its cutting in separate samples. They have been made along three different horizontal lines, corresponding to three chords of the transversal grid, the median line ($0_{\text{med}}$), one upper line ($3_{\text{sup}}$) and one bottom line ($1_{\text{inf}}$), 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 defects or degradation states of the wood along the perforation are highlighted by sudden reduction of $RA$ respect to its average value. Note that, being relative the resistance given by the Resistograph, the reported results are valid only for tests performed with the device above described, 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 Fig. 5 and 6 typical curves obtained from tests performed on chestnut samples in both longitudinal and transversal direction are reported. The curves show different conditions of the wood in different location of the same beam: good and constant quality of the material (Fig. 5a); wood with localized defect or degradation state (Fig. 5b and 6b); presence of knots along the drilling line (testified by localized higher values of $RA$) (Fig. 6a).

![Figure 3: Longitudinal resistographic tests on Sample 1.](image)

![Figure 4: Position of the transversal resistographic tests performed on the beam.](image)

![Figure 5: Typical longitudinal test results: (a) wood of good quality; (b) degraded zone from 150mm to 175mm of drilling depth.](image)
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, which have been carried out along the direction parallel to wood grain, provide rather uniform results, as it is shown in Fig. 5a, where the value of RA is practically constant along the whole drilling depth. Anyway 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:

$$
R_{ML} = \frac{\int_0^H RA \cdot dh}{H} \quad [%] \quad (1)
$$

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. 7a and 7b 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), has 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.

In order to correlate longitudinal and transversal resistographic tests, the mean values ($CMR_{ML,0}$) of $R_{ML,0}$ on each chord, along which transversal tests have been performed, have been also evaluated, as reported in Table 2 for all the edges of the samples. In Fig. 7c the $CMR_{ML,0}$ values are highlighted in a graph representing the distribution along the depth of the section of the mean values of $R_{ML,0}$ on all the chords of the max. edge of Sample 1.
### Table 1: Main values of longitudinal Resistographic measures.

<table>
<thead>
<tr>
<th>Samples</th>
<th>Section</th>
<th>Num. of tests</th>
<th>MRML,T [%]</th>
<th>DRML,T [%]</th>
<th>MRML,0 [%]</th>
<th>DRML,0 [%]</th>
<th>SMRML,0 [%]</th>
<th>SDRML,0 [%]</th>
<th>WMRML,0 [%]</th>
<th>WDRML,0 [%]</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>Max</td>
<td>60</td>
<td>26.17</td>
<td>7.82</td>
<td>29.71</td>
<td>7.20</td>
<td>28.79</td>
<td>5.74</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>65</td>
<td>26.06</td>
<td>6.34</td>
<td>27.86</td>
<td>3.95</td>
<td>32.36</td>
<td>4.32</td>
<td>33.15</td>
<td>4.80</td>
</tr>
<tr>
<td>2</td>
<td>Max</td>
<td>65</td>
<td>28.94</td>
<td>7.93</td>
<td>34.01</td>
<td>4.23</td>
<td>38.34</td>
<td>4.56</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>60</td>
<td>28.33</td>
<td>6.28</td>
<td>30.71</td>
<td>3.91</td>
<td>32.36</td>
<td>4.32</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Max</td>
<td>60</td>
<td>31.84</td>
<td>9.24</td>
<td>38.34</td>
<td>4.56</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>38.34</td>
<td>4.56</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 2: CMRML,0 values for all tested Samples.

<table>
<thead>
<tr>
<th>Section</th>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>max</td>
<td>min</td>
<td>Mean</td>
</tr>
</tbody>
</table>
| chord 3
sup | 27.09    | 25.31    | 26.20    | 25.31    | 28.60    | 33.70    |
| chord 0
med | 24.84    | 23.65    | 24.25    | 29.53    | 36.19    | 36.89    |
| chord 1
inf | 27.58    | 26.48    | 27.03    | 31.81    | 30.94    | 41.30    |
|         | 25.83    | 30.95    | 37.30    |

Figure 7: The 3-D $R_{ML,0}$ distribution (a), the corresponding Gaussian graph (b) and $CMR_{ML,0}$ values (c) for the max. end-beam of Sample 1.

3.2 Transversal tests

Contrary to the longitudinal ones, the results of the transversal Resistographic tests almost always showed not negligible variation along the drilling depth (Fig. 6), with $RA$ values significantly fluctuating respect to the mean value $R_{MT}$. The smaller and more frequent variations are due to the passage through the growth ring interface, while the more significant increasing or decreasing of $RA$ correspond respectively to knot presence or to degraded zones or holes. This means that the smaller variations are not correlated to the quality of the material; besides, due to their quite constant frequency, they do not practically affect the mean value of the measures ($R_{MT}$). On the contrary when $RA$ becomes suddenly very low (in the range 0-5%), a defect surely exists and can be considered in judging the wood quality.

At this aim the mean value of $RA$ along the whole drilling depth has been determined in two different ways. In the first one all the $RA$ values have been considered ($R_{MT,T}$), while in the second one the mean value has been evaluated skipping the $RA$ values ranging 0-5% ($R_{MT,0}$) (Fig. 8). Consequently the ratio $C_{DEF}=(R_{MT,0}/R_{MT,T})*100$ has been here considered as a measure of the local defectiveness of the wood.

This ratio can also be used to reduce the width of the cross-section when carrying out shear checks. As an example, for the test showed in Fig. 9, the width reduction of cross-section to be applied is about 29%, which is the corresponding value of $C_{DEF}$. Note that, for this aim, the sin-
gle test has to be referred to, since the mean value of many tests is not significant for a local check.

In Table 3 the mean values of $R_{MT,T}$ and $R_{MT,0}$ evaluated for each sample with reference to each investigated chord (named $CMR_{MT,T}$ and $CMR_{MT,0}$ respectively), are reported, together with the corresponding values of $C_{DEF}$. Note that for Sample 1 and 2 and the median chord, the values of $C_{DEF}$ are significantly higher than the other ones, due to the presence of a sub-horizontal longitudinal crack in the middle of the cross section. On the contrary the low values of $C_{DEF}$ for the other chords confirm the absence of significant defect or holes in that zones.

It seems to be also possible to correlate the mean value of the results of the transversal tests (for a section, a sample or a whole trunk) with some mechanical properties of the wood. At this aim the mean values ($R_{MT,0}$), evaluated skipping the very low $RA$ values, have to be used. Particularly the shear resistance of timber can be derived directly from the results of the transversal tests, while the ultimate compressive stress parallel to the grain can be obtained by correlating the results of the transversal tests with the ones of the longitudinal tests, as illustrated in the next Section.

<table>
<thead>
<tr>
<th>Chords</th>
<th>Sample 1</th>
<th></th>
<th></th>
<th>Sample 2</th>
<th></th>
<th></th>
<th>Sample 3</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$CMR_{MT,T}$</td>
<td>$CMR_{MT,0}$</td>
<td>$C_{DEF}$</td>
<td>$CMR_{MT,T}$</td>
<td>$CMR_{MT,0}$</td>
<td>$C_{DEF}$</td>
<td>$CMR_{MT,T}$</td>
<td>$CMR_{MT,0}$</td>
</tr>
<tr>
<td>$3^{sup}$</td>
<td>26.70</td>
<td>28.67</td>
<td>6.88</td>
<td>37.99</td>
<td>39.03</td>
<td>2.65</td>
<td>40.03</td>
<td>40.78</td>
</tr>
<tr>
<td>$\theta_{med}$</td>
<td>24.63</td>
<td>29.16</td>
<td>15.53</td>
<td>21.03</td>
<td>26.62</td>
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<td>$I_{inf}$</td>
<td>28.10</td>
<td>29.90</td>
<td>6.01</td>
<td>34.21</td>
<td>35.73</td>
<td>4.26</td>
<td>27.67</td>
<td>28.65</td>
</tr>
<tr>
<td>Mean values</td>
<td></td>
<td></td>
<td></td>
<td>29.24</td>
<td>33.79</td>
<td>33.39</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 8: A transversal Resistographic analysis: $R_{MT,T}$ and $R_{MT,0}$ values.

### 3.3 Correlation between longitudinal and transversal tests

Commonly the NDTs can be performed in-situ only in transversal direction, due to the impossibility of directly inspecting cross-sections of the beam without destroying it. The edges of the beam usually cannot also be tested longitudinally, because they are hidden inside the supporting wall. On the other side, as already said, the performed longitudinal tests have shown a good uniformity of results, so that they can be reliably correlated to the mechanical properties of wood parallel to the grain. Therefore, it appears to be extremely important to correlate longitudinal and transversal NDT values. This correlation, being referred to the properties of wood, which is independent of the local defectiveness of timber, has to be made with reference to the mean values of test results evaluated without considering the very low values of $RA$.

At this aim, for each sample, the mean values ($CMR_{MT,0}$) of the transversal tests, performed along the analysed chords, have been correlated to the analogous values ($CMR_{ML,0}$) of the longitudinal ones (see Tables 2, 3), obtaining a correlation coefficient ($K_{TL} = CMR_{MT,0}/CMR_{ML,0}$) whose mean value ranges from 0.91 to 1.13. Therefore it seems to be reasonable to assume 1.00
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The correlation coefficient $K_{TL}$ is equal to about 1.00 even if the correlation is made on the base of the overall mean values of both longitudinal ($WMR_{ML,0} = 33.15\%$) and transversal ($WMR_{MT,0} = 32.15\%$) test results.

This means that, for chestnut species, the result of transversal tests, when they are depurated of the local defectiveness of wood, is numerically coincident to the one of the corresponding longitudinal tests. For this reason it seems to be possible avoiding longitudinal tests at all, since the same information can be obtained directly from transversal tests.

4 THE EXPERIMENTAL ACTIVITY ON NEW SPRUCE DEFECT-FREE SAMPLES

In order to validate the consideration above made on the NDT results also for different wood species and to define more correctly a correlation between longitudinal tests and mechanical properties of wood, destructive and not-destructive tests have been performed on white spruce defect-free elements too. Particularly, on 20 small samples (sized 50 mm x 50 mm x 100 mm), resistographic tests (3 along grain direction and 3 along transversal direction per sample) and longitudinal compressive tests have been carried out.

As it could be expected, quite uniform $RA$ values have been given by longitudinal tests for all specimens, obtaining an overall mean value $WMR_{ML,0} = 8.65\%$. On the other hand, transversal tests have shown significantly variable $RA$ values with $WMR_{MT,0} = 9.42\%$. It is worth noting that the overall correlation coefficient ($K_{TL}$) is about 1.1, which is in good agreement with the case of chestnut, even if for spruce the Resistograph results have been characterized by a greater standard deviation in the whole.

Obviously, the absolute value of the calculated parameters for chestnut resulted greater than those obtained for spruce, according to its worse mechanical properties, as confirmed by the compressive tests. In fact these tests, which have been performed in force control according to Italian and European regulations (UNI-ISO 3787), have given a mean value of ultimate compressive stress ($f_{c,0}$) equal to about 30 MPa, while for chestnut a value of 48 MPa was obtained (Mazzolani et al. 2004a).

5 CORRELATION BETWEEN MECHANICAL PROPERTIES AND NDTs

The relationship between results of longitudinal resistographic tests ($SMR_{ML,0}$) and the corresponding compressive strength ($f_{c,0}$) along the grain direction, obtained from the destructive tests on defect-free specimens, is given in Fig. 9, where the square and the triangular dots represent the results for chestnut and spruce wooden species respectively. Note that $SMR_{ML,0}$ is the mean value of all the $R_{ML,0}$ obtained for each tested sample.

On the same graph the best fitting line (linear regression performed by means of the least squares method) is also drawn. The limited spread of the dots with respect to this line shows the possibility to adopt the corresponding equation ($f_{c,0} = 0.75SMR_{ML,0} + 22.50$ [MPa]) for a numerical prediction of the compressive strength of clear wood based on the longitudinal resistographic results. Considered that, as described in 3.3 and 4, it is also possible to correlate longitudinal and transversal test results (by means of the coefficient $K_{LT}$), the compressive resistance of wood could be directly determined by means of in-situ non-destructive tests.

Analogous correlation could be established between resistographic transversal test results and actual shear resistance of timber. But at the moment the available data are not sufficient to obtain a reliable numerical formulation. In fact the results of shear destructive tests on actual structural element performed by the authors (Mazzolani et al. 2004b) are relative only to chestnut beams and data relative to new spruce actual beams are not yet available. Anyway note that the shear resistance of chestnut timber resulted of about 3.5 MPa, which should correspond to an overall mean value of the resistographic tests $WMR_{MT,0} = 32.15\%$. Further experimental activity on this topic is in progress.
6 CONCLUSIONS

A wide experimental campaign based on resistographic tests has been carried out on ancient chestnut elements in order to correlate NDTs resistance with the mechanical properties of wood obtained from destructive tests. Analogous tests have been performed also on new spruce defect-free specimens.

By means of the obtained results a formulation providing the compressive ultimate stress of wood starting from the resistographic longitudinal test results has been defined. Besides, a correlation between transversal and longitudinal tests has been also obtained in order to derive the wood resistance directly from non-destructive tests, which can be carried out in a simple way on existing structural elements.

Furthermore a \( C_{DEF} \) coefficient has been defined on the base of the transversal test results, which can be useful to reduce the width of the cross-section of the timber elements when performing shear verifications.

Further developments will be mainly devoted to carry out a wider experimental activity also on different wood species, in order to validate the proposed formulation and to allow a correlation with the shear resistance as well.

REFERENCES


