COMBINED NON-DESTRUCTIVE AND DESTRUCTIVE TESTS FOR THE MECHANICAL CHARACTERIZATION OF OLD STRUCTURAL TIMBER ELEMENTS

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ABSTRACT

The paper deals with the mechanical identification of old timber members in structural size, based on combined non-destructive (NDT) and destructive tests (DT). An experimental activity has included on one hand several NDT investigations, using hygrometric, ultrasonic, sclerometric and resistographic methods, and on the other hand static tests, in compression parallel to the grain and in bending. Correlations between NDT and DT parameters are given by means of linear regression model.

INTRODUCTION

In the field of restoration of ancient timber structures, in situ inspection by means of non-destructive techniques represents a first step towards diagnosis and structural analysis. Instrumental NDT techniques have evolved to evaluate physical and mechanical properties of wood, as ultrasonic and vibration methods (Global Test Methods), and detect internal defects by means electronic penetrometers and superficial hardness systems (Local Tests Methods). These techniques present several advantages, such as their easiness in practical utilization and tools transportation. However the effectiveness of such methods aimed at the structural identification should be aided through laboratory tests by studying the variability of the mechanical properties of the timber elements.

In this context, a research activity was developed in the framework of the Italian project PRIN 2006 *"Diagnosis techniques and totally removable low invasive strengthening methods for the structural rehabilitation and the seismic improvement of historical timber structures",* aiming to providing a methodology for *in situ* mechanical identification of timber elements by means of combined NDT techniques. An experimental campaign was carried out at the Laboratory of the Department of Structural Engineering (DIST) of the University of Naples "Federico II", including non-destructive investigations and destructive tests on full-scale specimens, made of old chestnut wood (*Castanea sativa* Mill.). The following NDT methods were used: hygrometric tests, ultrasonic investigations, sclerometric tests and resistographic measurements. Furthermore, compression tests in direction parallel to the grain and bending tests were carried out. In this paper testing equipment and set-up, together with the applied methodology for data processing and interpretation, are illustrated. Correlations of NDT parameters with wood density, modulus of elasticity and ultimate strength are provided, based on linear regression model.

MATERIAL AND METHODS

The experimental campaign was developed on structural members made of old chestnut wood, recently dismantled by timber roofing trusses of an ancient masonry building of Naples (Fig. 1a).

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From the king posts elements, a number of 14 specimens (type C) were obtained for compression tests. They had a nearly square cross-section, characterized by large rounded edges, with a mean equivalent diameter (D) ranging between 14.5-16 cm and a standard length of about 6D (Fig. 1b). From the trusses struts, 10 specimens (type B) were selected for bending tests. They had an irregular circular shape with mean diameter from 15 to 16.5 cm and standard length equal to about 19D (Fig. 1c), according to UNI EN 408 standard.

By means of the visual inspection, on the lateral surface of the members, several shape irregularities and extended degradation state of the base material were detected, as knots, longitudinal splitting, cracks, ring shakes, biological damage and holes, due to nails and insect attacks.

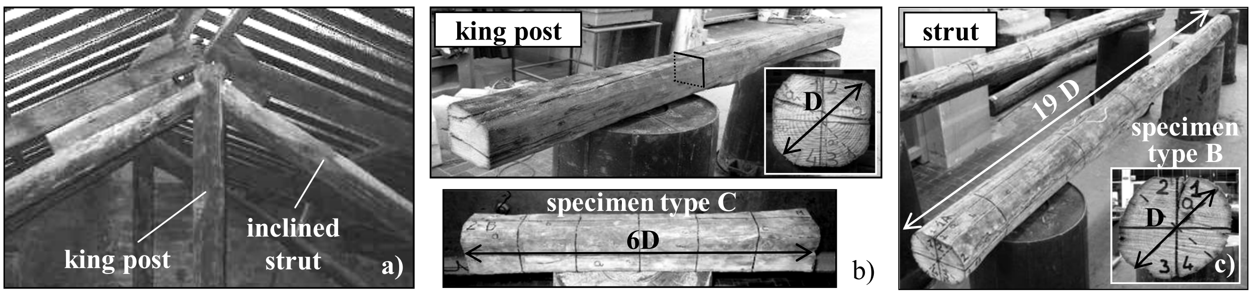

Fig. 1. Structural elements: a) Assembled trusses; b) Specimen type C; c) Specimen type B.

The following non-destructive methods were employed in the research activity: a) hygrometric tests, for the evaluation of the moisture content of wood, which severely affects its mechanical properties and its susceptibility to degradation by decay; b) ultrasonic investigations, through which a direct relationship between the stress wave speed and the elastic properties of the material can be defined, based on the theory of acoustic wave propagation; c) sclerometric tests, through which the quality and hardness of superficial layers of wood are estimated by the penetration depth of a blunt pin, fired into the wood; d) resistographic measurements, for the evaluation of the wood density by measuring the drilling resistance along the path of a small needle inserted into the wood. Full-scale static tests, in compression parallel to the grain and in bending, were carried out aiming at evaluating the structural behaviour of the timber elements in terms of stiffness, load bearing capacity and collapse mode, according to UNI EN 408 standard.

NON-DESTRUCTIVE TESTS

Hygrometric Tests

The hygrometric tests were performed by means of the Tramex Professional device, which is a digital pin type resistance meter with built-in pins designed to take precise measurements of moisture content in wood. The professional tool gives moisture readings from 7% to 40% in 0.1% increments. The resistor pins were inserted into the lateral surface of the elements, for a total number of 10 readings per specimen.

Ultrasonic Investigations

Ultrasonic System CMS v.3.1 was used for ultrasonic tests, equipped by a data acquisition unit combined either with high-power piezoelectric transducers (>1.6 Kv), the transmitter TSG-20, fitted with threaded conic tips, and the cylinder-shape receiver RSG-55 (Fig. 2a).

Direct method was used, placing the transducers on two opposite faces of the same specimen. Two procedures were adopted: 1) direct method parallel to the grain; 2) direct method perpendicular to the grain. The transmission technique based on the parallel direct method allows a global evaluation of the dynamic mechanical properties of the material. In this case, the transducers were aligned along 5 longitudinal directions for each specimen. Regarding the perpendicular direct method, local transversal measurements were performed in different points of the lateral surface of the tested elements, in order to discover the presence of weak and critical zones. Eleven contiguous sections were investigated, coupling the sensors in 4 directions per section, for a total number of 44 transversal readings per specimen.

The recorder signals were analyzed in time (t)-Amplitude (A) diagrams in order to evaluate the wave propagation time, so called "Time of Flight" (TF; Fig. 2d). The velocity of the ultrasonic pulse, so-called Stress Wave Speed (SWS), was easily determined dividing the distance between the probes by the stress wave transmission time.

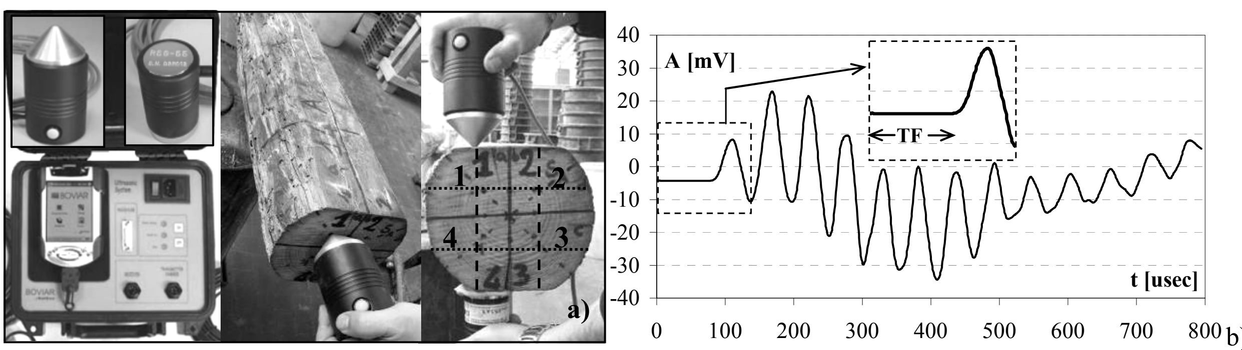

Fig. 2. Ultrasonic tests: a) Testing apparatus and set-up; b) Typical stress waveform.

Sclerometric Tests

The Wood Pecker mechanical test hammer for wood was used for sclerometric tests. The device allows to measure the penetration of a blunt metallic needle, 2.5 mm diameter and 50 mm length, shoot into the outer milimeters of wood surface by means of five spring blows (Fig. 3a).

Regular grids of nine points, 2.5 cm spacing, were used as single test areas (UNI EN 12504-2). Longitudinal tests were performed shooting the pins on the end cross-sections of each specimen, for a total of 18 tested points. On the other hand, the resistance to superficial penetration in the direction perpendicular to the grain was investigated by means of sclerometric shots on the lateral faces of the samples, in two transversal directions orthogonal each other, for a total of 10 test areas and 90 test points per specimen. In some cases, it was necessary to select shot locations so to avoid local defects, as deep shakes or superficial decay, and then slightly altering the results. The penetration depth (PD) is calculated by means of a comparator system which measures the pin outside length. Readings are given with 0.01 % accuracy (Fig. 3b).

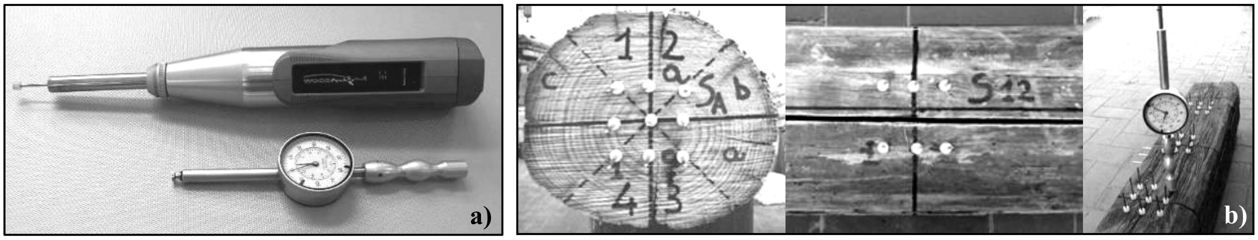

Fig. 3. Sclerometric tests: a) Testing apparatus; b) Experimental set-up.

Resistographic Measurements

IMLRESI F400 model was used for resistographic tests. It is a drilling resistance measuring system based on the energy used to introduce a needle through the wood. A drilling needle with a diameter of 1.5 mm to 3.0 mm penetrates into the wooden element with a regular advancing speed. The spent energy of the drilling device is measured electronically every 0,1 mm, as a value of the drilling resistance. Measurements in both directions parallel and perpendicular to the grain were carried out with an advancing speed of about 20 cm/minute (Fig. 4a). On each end section, the longitudinal perforations were undertaken on 5 test points, for a total number of 10 measures per specimen. Two transversal perforations were carried out in several test sections, previously selected for ultrasonic investigations, for a number of 22 transversal tests (Fig. 4a).

The experimental results were analyzed by means of graphic profiles relating the Drilling Depth (DD) and the drilling resistance, measured as Amplitude percentage (A; Fig. 4b). By examining the resistographic charts, it was possible to detect the presence of internal defects, as damaged zones, hollow areas, cracks and other decay patterns, which return by very low or null values of drilling resistance. Within the wood good parts, the longitudinal profiles show very similar values of amplitude which, on the contrary, is characterized by a strong variation in the transversal measurements, due to the crossing of the growth rings during the drilling path.

As unique parameter of the wood drilling resistance the mean value of the amplitude (A_m) was calculated. It represents the ratio between the integral of the diagram area and the depth of the needle path. It is worth noticing that, in presence of internal defects, the A_m values were evaluated on homogeneous parts, without considering low or null resistance measures (Fig. 4b).

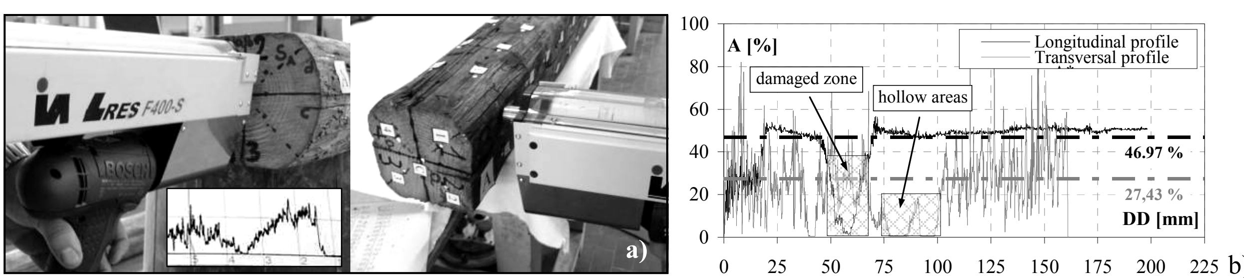

Fig. 4. Resistographic measures: a) Testing device and set-up; b) Typical graphic profiles.

Experimental Results

As NDT parameters, the average values of non-destructive measures are considered for each tested element. In Tables 1 and 2, the following longitudinal (L) and transversal (T) parameters are reported for the specimens type C and B, respectively: moisture content (MC), ultrasonic stress wave speed (SWS), sclerometric penetration depth (PD) and mean resistographic amplitude (A_m). Furthermore, statistical parameters, as arithmetic mean (Mean) and variation coefficient (CV) are determined for both specimens groups (Table 3).

Table 1. Results of non-destructive tests on specimens type C.

Specimens	**Hygr. [%]**	**Ultrasonic [m/sec]**		**Sclerometric [mm]**		**Resistographic [%]**	
Type C	MC	SWS_L	SWS_T	PD_L	PD_T	$A_{m,L}$	$A_{m,T}$
C1	11.3	5154	1848	16.44	15.97	51.49	57.58
C2	11.4	5137	1815	18.52	16.56	45.97	49.64
C3	12.1	5198	1679	17.43	17.35	46.65	49.54
C4	11.6	5128	1706	18.30	18.20	29.84	37.94
C5	11.4	5659	1661	20.28	18.84	36.78	32.06
C6	11.2	5633	1727	19.87	17.67	29.4	27.40
C7	12.0	4860	1602	18.36	18.32	25.21	35.63
C8	12.1	5645	1575	19.50	16.90	37.13	26.63
C9	11.2	5455	1668	20.10	18.71	38.37	26.81
C10	11.0	5471	1413	18.26	16.52	56.96	42.84
C11	11.0	5366	1623	17.17	16.71	47.73	53.43
C12	11.8	5113	1522	20.08	18.40	41.17	31.58
C13	12.2	5264	1605	18.64	16.34	32.71	40.56
C14	10.9	5178	1596	20.08	18.54	42.13	41.83

Table 2. Results of non-destructive tests on specimens type B.

Specimens	**Hygr. [%]**	**Ultrasonic [m/sec]**		**Sclerometric [mm]**		**Resistographic [%]**	
Type B	MC	SWS_L	SWS_T	PD_L	PD_T	$A_{m,L}$	$A_{m,T}$
B1	11.6	5358	1746	15.90	17.33	21.98	21.27
B2	12.3	5572	1644	14.47	14.27	55.63	54.18
B3	11.9	5322	1683	15.52	15.06	43.09	34.54
B4	12.1	5454	1670	12.72	12.99	49.85	42.46
B5	13.4	5353	1585	17.47	17.85	37.69	34.66
B6	11.7	4767	1658	12.90	13.62	44.64	38.74
B7	12.4	5409	1609	14.78	15.68	45.20	39.85
B8	11.2	5525	1560	16.62	17.82	34.82	31.07
B9	12.1	5292	1640	15.17	13.52	40.52	34.90
B10	10.4	5541	1551	15.73	17.25	37.62	38.73

Table 3. NDT statistic parameters for both specimens type C and B.

Specimens	**Hygr. [%]**	**Ultrasonic [m/sec]**		**Sclerometric [mm]**		**Resistographic [%]**	
Type B	MC	SWS_L	SWS_T	PD_L	PD_T	$A_{m,L}$	$A_{m,T}$
Mean	11.7	5327	1641	17.26	16.68	40.52	38.49
CV [%]	5.41	4.36	5.63	13.13	10.32	22.01	24.37

DESTRUCTIVE TESTS

Compression Tests Parallel to the Grain

The compression tests were performed under force control using the Mohr Federhaff AG testing machine, with a loading cell HBM of 740 kN. The hydraulic press is constituted by a top fixed head and a movable base plate with an actuator of 5000 kN capacity (Fig. 5a).

For the determination of the elasticity modulus, LVDT1,2,3,4 were placed on the opposite faces of the specimen in order to measure the relative deformations over the central gauge length equal to 4 times the smaller cross-sectional size of the piece (Fig. 5a). A quasi-static loading procedure was applied in three elastic cycles up to 70, 140, 210 kN respectively. The experimental results were provided in F-Δw curves (Fig. 5b). Destructive tests were performed in different loading-reloading failure cycles, aiming at evaluating the maximum compression strength and the residual bearing capacity. LVDT5,6 were located on the machine loading-base plate, measuring the base displacements (w) of the sample (Fig. 5a). In each step, the load was increased up to failure and applied at a constant base plate speed, in such a way that maximum force is reached within 300±120 sec. The acquired data are represented in F-w curves, together with the envelope curve. As an example, in Figure 6a they are depicted with reference to the C8 specimen.

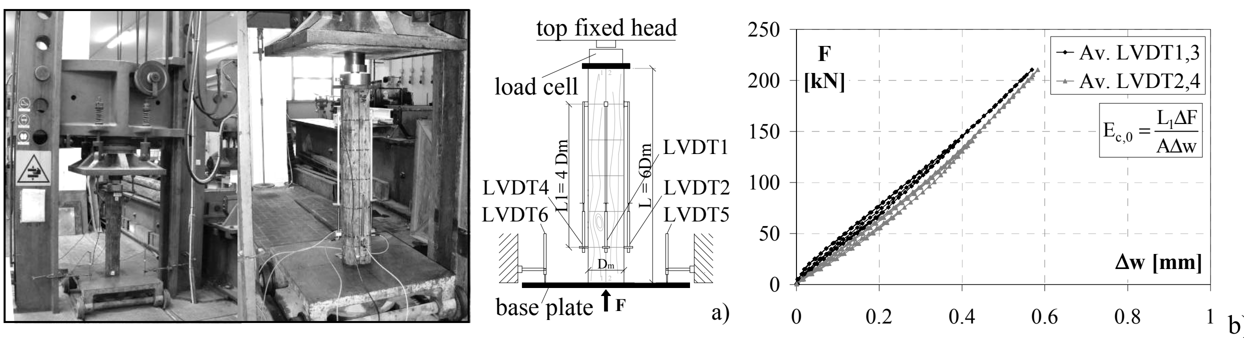

Fig. 5. Compression tests: a) Testing apparatus and set-up; b) Elastic F-Δw curves.

In Figure 6b the envelope curves for all the specimens in terms of stress (σ)-strain (ε) relationships are shown together with the mean curve, which is assumed to characterize the compression behaviour of the tested old chestnut timber. It can be observed that the global response appears more or less similar for all specimens. In fact, the curves show a linear elastic branch up to the peak load reached during the test. After that, the curves exhibit distinct non linearities with abrupt reduction of the stress carrying capacity. Similar collapse modes were observed for all tested specimens (Fig. 6c). Typical failure patterns consist in fractures in radial direction or in cleavages along the annual growth rings, which were developed together with the attainment of the splitting almost parallel to the grain with consequent buckling of the fibres.

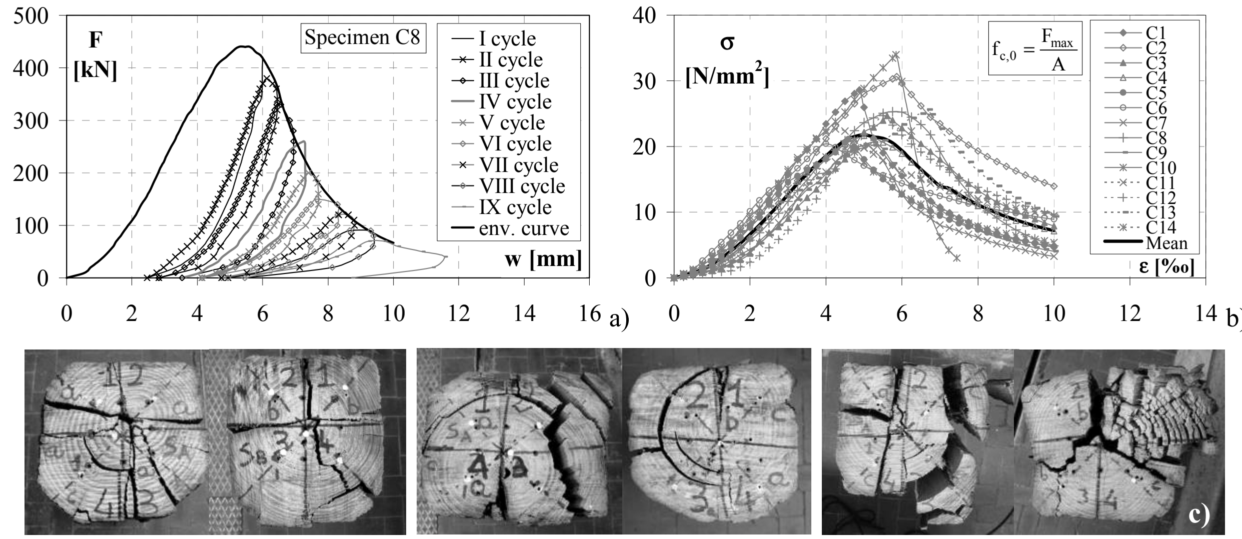

Fig. 6. Compression tests: a) Failure F-w curves; b) σ-ε curves; c) Failure modes.

Bending Tests

The Mohr Federhaff AG testing machine with a loading capacity of 5000 kN was used for the force controlled tests. According to the four-points static scheme, the tested beams were loaded with two symmetric concentrated forces, applied in the third of the beam span by interposing a rigid steel profile between the actuator and the test specimen (Fig. 7a). For the determination of the local modulus of elasticity, LVDT1,2,3 were placed on the specimen at the neutral axis in order to measure the deformations over the central gauge length equal to 5 times the depth of the section. Furthermore, aiming at evaluating the global elasticity modulus, LVDT4 measured the deflections at the mid-span of the beam, at the centre of the tension side edge (Fig. 7a). Three cycles in elastic ranges, up to 3-6-9 kN were carried out, fitting the elastic deformations (w) and the corresponding applied load (F) in F-w curves (Fig. 7b).

After the elastic cycles, it was also possible to obtain the bending strength increasing the load up to failure in several loading-reloading cycles, reaching the maximum force within 300±120 sec. Destructive tests results are provided in terms of applied force (F) versus loading-actuator displacement (w; Fig. 8a). In Figure 8b the F-w envelope curves of all tested beams are provided. It is generally observed that the initial growing branch presents a linear behaviour up to the maximum applied load. Furthermore, after the second or third cycle, an evident reduction of strength occurs, together with important actuator displacements. Typical failure modes observed during the tests are shown in Figure 8c. For almost all the specimens the rupture mechanism was triggered around large knots located at the central zone and at the tensile edge of the beam cross-section, manifested by tearing of the more stressed fibres. In any cases an evident buckling of the compressed fibres was observed, followed by the propagation of slip phenomena.

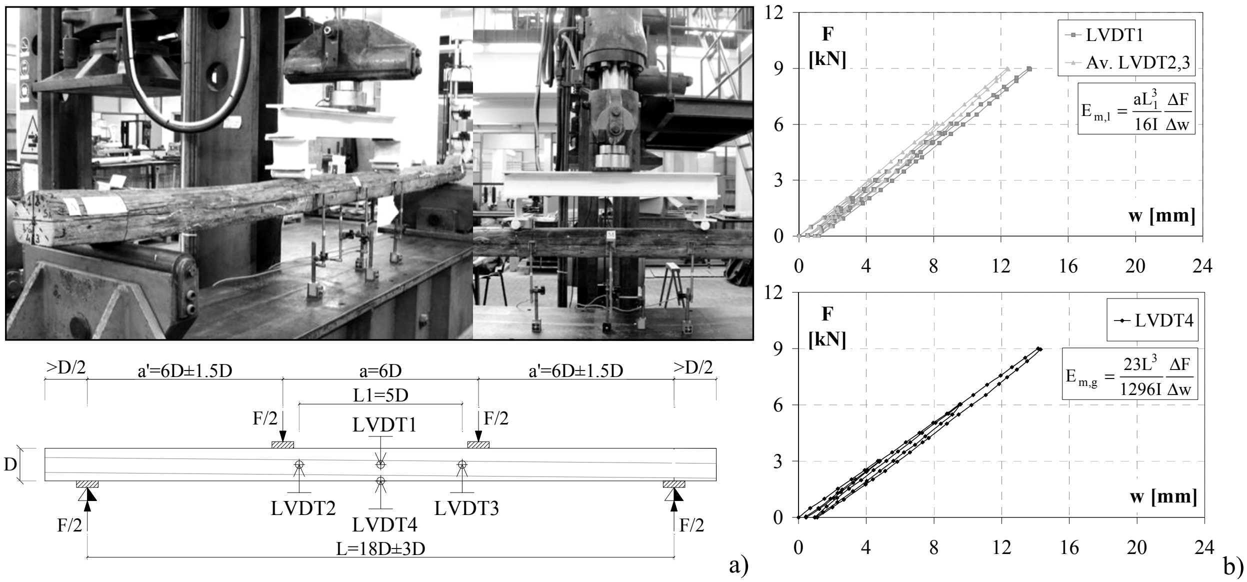

Fig. 7. Bending tests: a) Testing apparatus and set-up; b) Elastic F-w curves.

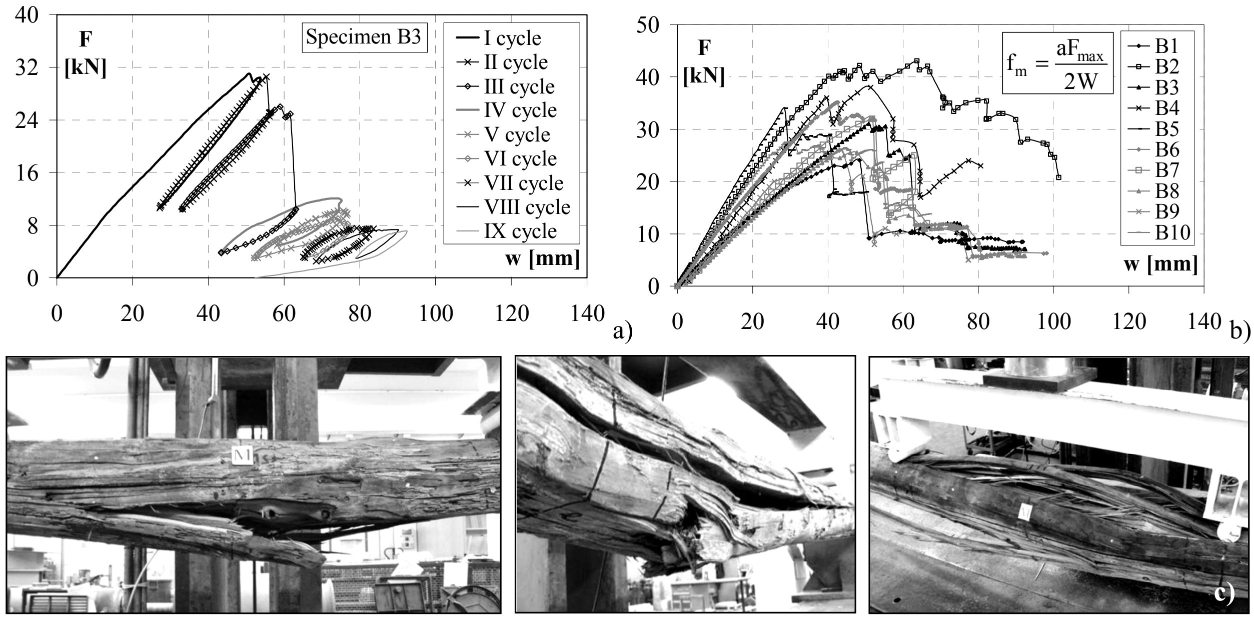

Fig. 8. Bending tests: a) Failure F-w curves; b) Envelope curves; c) Failure modes.

Experimental Results

In Table 4 the experimental results of the compression tests in direction parallel to the grain are given in terms of both stiffness ($E_{c,0}$) and strength ($f_{c,0}$) characteristics. For the bending tests, the values of the local ($E_{m,l}$) and global ($E_{m,g}$) modulus of elasticity, together with the maximum bending strength (f_m), are provided in Table 5. The density values (ρ) are reported too. They were determined on the basis of the measured sizes and weight of the timber elements, for a moisture content of about 12%. In addition, the dynamic modulus of elasticity (E_{dyn}) are calculated, according to the theoretical relationship for homogenous and isotropic elements

($E_{dyn}=SWS^2\rho$). The main statistical parameters are also presented, including the average values (Mean) and the variation coefficients (CV) of the obtained mechanical properties.

Table 4. Compression tests results.

Spec. Type C	ρ [kg/m^3]	E_{dyn} [N/mm^2]	$E_{c,0}$ [N/mm^2]	$f_{c,0}$ [N/mm^2]
C1	617	16385	9552	28.58
C2	618	16305	8887	30.62
C3	578	15620	7213	24.65
C4	542	14247	7742	21.84
C5	565	18080	10600	21.12
C6	530	16828	10945	20.66
C7	545	12866	8175	20.13
C8	550	17537	9000	25.29
C9	595	17714	7961	20.78
C10	642	19207	9491	33.97
C11	610	17561	8341	22.98
C12	554	14496	8088	24.77
C13	577	15988	10078	25.62
C14	582	15602	10428	19.98
Mean	579	16317	9036	24.36
CV [%]	5.80	10.39	12.98	17.44

Table 5. Bending tests results.

Spec. Type B	ρ [kg/m^3]	E_{dyn} [N/mm^2]	$E_{m,l}$ [N/mm^2]	$E_{m,g}$ [N/mm^2]	f_m [N/mm^2]
B1	526	15085	11257	10885	32.23
B2	638	19809	15291	15374	46.91
B3	574	16247	11029	11465	42.00
B4	614	18252	12683	12912	44.44
B5	604	17303	12162	13910	38.29
B6	622	14133	11023	12509	46.72
B7	634	18539	12647	13577	40.37
B8	554	16915	13120	13146	44.87
B9	605	16936	12278	11023	36.58
B10	627	19257	13858	13685	38.52
Mean	600	17248	12535	12849	41.09
CV [%]	6.18	10.38	10.67	11.02	11.63

MECHANICAL IDENTIFICATION BY NDT-DT COMBINED METHODS

The experimental results have been statistically analyzed correlating the non-destructive parameters (NDT; ultrasonic, sclerometric and resistographic) with the mechanical properties obtained by destructive tests (DT) in compression parallel to the grain (specimens type C) and in bending (specimens type B). In this way, by means of linear regression model, it was possible to predict through NDT investigations the wood density, modulus of elasticity and strength of the tested old chestnut timber. The regression coefficients (R^2) between the variables involved in the model are provided in Table 6.

Table 6. Regression-coefficients (R^2) between NDT and DT parameters.

Specimens	Mechanical properties		Ultrasonic [m/sec] SWS_L	Ultrasonic [m/sec] SWS_T	Sclerometric [mm] PD_L	Sclerometric [mm] PD_T	Resistographic [%] $A_{m,L}$	Resistographic [%] $A_{m,T}$
Type C+B	ρ	[kg/m3]	0.00	0.02	0.24	0.30	0.67	0.43
Type C	$E_{c,0}$	[N/mm^2]	0.23	0.00	0.12	0.00	0.00	0.02
Type B	$E_{m,l}$	[N/mm^2]	0.48	0.25	0.00	0.00	0.22	0.48
Type B	$E_{m,g}$	[N/mm^2]	0.16	0.33	0.00	0.01	0.33	0.56
Type C	$f_{c,0}$	[N/mm^2]	0.00	0.01	0.19	0.57	0.52	0.22
Type B	f_m	[N/mm^2]	0.02	0.05	0.27	0.20	0.58	0.49

On the basis of the statistical analysis, it appears that the sclerometric and resistographic techniques may be taken in practical applications for a quick and quantitative estimation of wood density (Fig. 9). In fact, high regression-coefficients between density and drill-resistance were found, for both longitudinal (R^2=0.67) and transversal (R^2=0.43) measurements (Fig. 9b). On the other hand, as the sclerometric tests are influenced by the conservation state of superficial wooden layers, often affected by insect attacks and biological damage, the regressions between density and pin penetration depth are characterized by larger scatter in the results (Fig. 9a).

The prediction of the stiffness mechanical properties could be allowed by means of ultrasonic investigations. Moderate regressions were found between the longitudinal stress wave speed and the static elasticity modulus, both in compression (R^2=0.23) and in bending (R^2=0.48; Fig. 10a). Besides, correlating the dynamic elasticity modulus with the static one, a strong linear agreement is provided with the local modulus in bending, as the high regression-coefficient emphasizes, R^2 being equal to 0.76 (Fig. 10b).

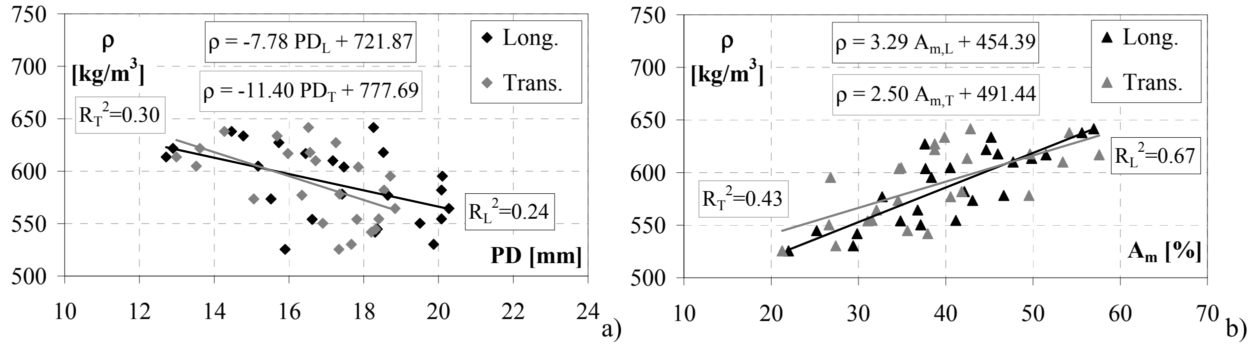

Fig. 9. Regressions with density (ρ): a) Penetration depth (PD); b) Mean amplitude (A_m).

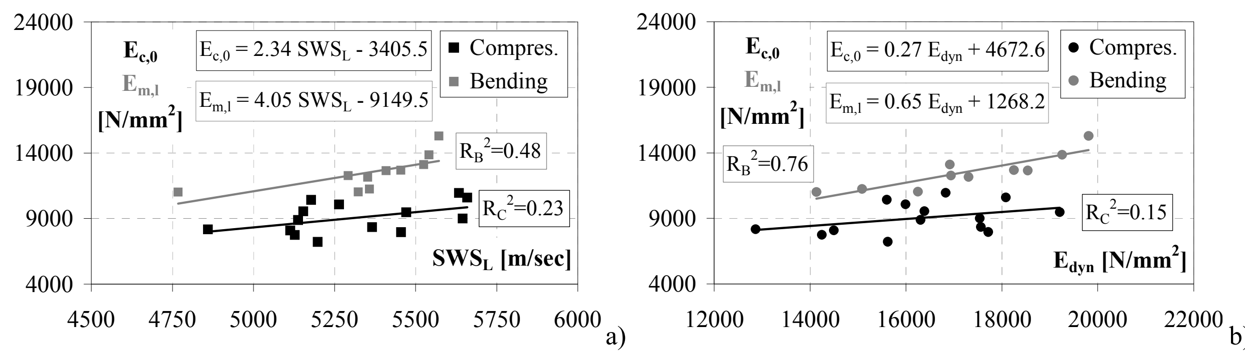

Fig. 10. Regressions with elasticity modulus in compression ($E_{c,0}$) and in bending ($E_{m,l}$): a) Stress wave speed (SWS_L); b) Dynamic modulus of elasticity (E_{dyn}).

Correlating the NDT parameters with both compression and bending strength, the wood test hammer and drill-resistance methods appear mostly suitable for a non-destructive estimation of timber strength. In particular, good regressions are found between transversal sclerometric penetration depth and compression strength (R^2=0.57; Fig. 11), as well as between longitudinal resistographic measurement and bending strength (R^2=0.58; Fig. 12).

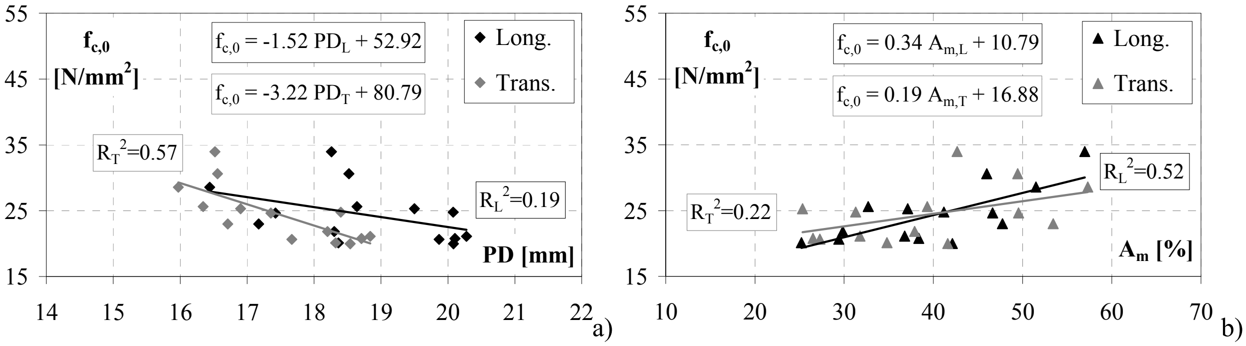

Fig. 11. Regressions with compression strength ($f_{c,0}$): a) Penetration depth (PD); b) Mean amplitude (A_m).

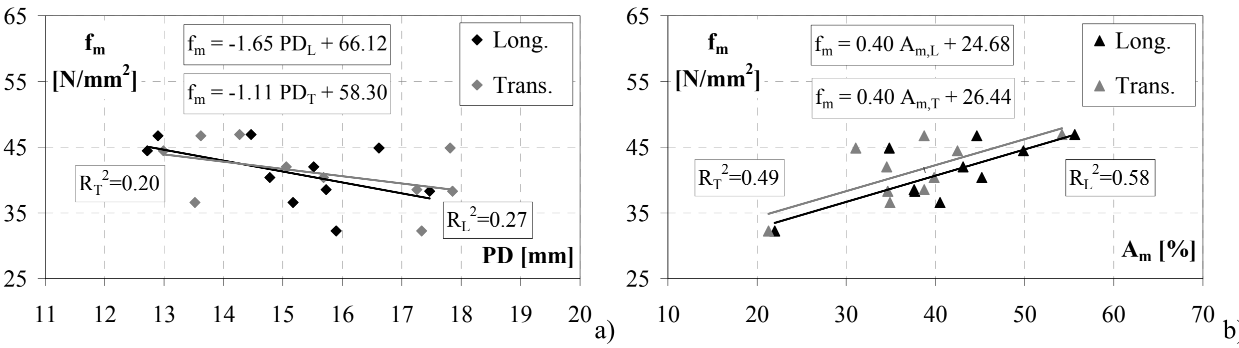

Fig. 12. Regressions with bending strength (f_m): a) Penetration depth (PD); b) Mean amplitude (A_m).

CONCLUSION

This paper presents the results of a wide experimental campaign which included non-destructive (NDT) and destructive tests (DT) on structural elements made of old chestnut wood. Ultrasonic, sclerometric and resistographic methods were used and static tests in compression parallel to the grain and in bending were carried out. By means of linear regression model, NDT-DT parameters are correlated each other to predict the wood density, modulus of elasticity and strength. The statistical analysis shows that the wood test hammer and the drill-resistance techniques seem to be the most adequate ones for a quantitative estimations of both wood density and strength. Whereas the dynamic properties, obtained by ultrasonic tests, appear a useful supplement to evaluate the stiffness properties of timber elements. In particular, a good linear-regression is provided relating the dynamic and the static modulus of elasticity in bending. Therefore, a great efficiency and reliability is demonstrated by NDT methods as practical applications for diagnosis and assessment of timber members and structures.

The experimental campaign is still going on by extending the investigations on both structural and small defect-free specimens, aiming at achieving a reliable methodological process for *in situ* mechanical identification by means of non-destructive techniques, based on statistical analysis and evaluation.

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