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Assessment of mechanical properties for ancient timber through visual and ND methods

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ABSTRACT: The Italian built heritage is characterized by an extensive use of timber as building material, realizing floor and roof structures of palace, churches and buildings. Conservation and restoration are needed for the safeguard of the timber-built heritage. However, given the lack of knowledge about the mechanical capabilities of the ancient structural members, often the blind removal takes place. In this context a research program for the mechanical characterization of ancient timber elements through an experimental campaign is ongoing at the University of Calabria, through a cooperation with the University of Naples Federico II, the University of Florence and the National Research Council. In particular, 18 ancient timber members are studied through the application of innovative survey methods, visual strength grading, non-destructive, destructive and long-term bending tests. In this paper a first part of the experimental work concerning survey, visual strength grading and non-destructive tests on 8 specimen is presented.

1 INTRODUCTION

In Italy most of the built-up consists of masonry buildings that are generally characterized by timber floors and roofs structures. Timber was already used in advanced systems since the Roman times (Stellacci and Rato, 2021). In southern Italy, during the Borbone reign, it even realized the first example of anti-seismic construction technique (Ruggieri, 2022). Furthermore, since the ancient times timber was widely used for medium and large span structures in churches and prestigious buildings (Faggiano et al., 2018). The conservation of the architectural heritage is a policy of protection, recently also raised to a social relaunch of territorial context as the Italian inner areas (Rossitti et al., 2022). At the same time, since Italy is heavily exposed to seismic and hydrogeological risks, conservation also aims at reducing the vulnerability of the built-up. Further to the structural function, also the authenticity, both ideal and material, in a condition of sufficient safety (ICOMOS, 1999; Tampone and Ruggieri, 2016) should be conserved.

Interventions on existing structures need adequate knowledge of material and structure characteristics, as well as of survey and diagnostic techniques. Therefore a preliminary assessment aiming at defining history, geometry and mechanics of timber structures is required (Cruz et al., 2015). In particular ancient timber is usually affected by defects, irregular geometries and degradations that influence the behavior, so that the lack of knowledge often directs the design choices towards the replacement of members, causing economic, cultural and environmental losses.

Inspired by this motivation a research program for the mechanical characterization of ancient timber members is ongoing at the University of Calabria, through a cooperation with the

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University of Naples Federico II, the University of Florence and the National Research Council. In particular, the experimental campaign aims at the *in-situ* determination of the mechanical properties of timber members through the application of smart non-destructive technologies. In particular the following methods and techniques are included: visual strength grading, also aided by laser scanner acquisitions, non-destructive tests, like stress waves propagation, vibration and drilling resistance tests, destructive bending tests and long-term bending tests.

The first part of the experimental work regarding the survey, visual strength grading (VSG) and non-destructive test (NDT) on 8 specimens (ID: 2, 7, 9, 10, 11, 13, 17, 18) is herein presented.

2 VSG AND NDT FOR MECHANICAL CHARACTERIZATION OF ANCIENT TIMBER MEMBERS

2.1 *The sample features*

The 18 timber specimens in structural dimensions are part of the rafters extracted from the roof trusses of the XIX century building, the lyceum gymnasium Bernardino Telesio, in the historic center of Cosenza (Italy; Ruggieri and Serra, 2019). The specimens date back approximately to the mid eighteenth century, since after the Cosenza earthquake (1854) the roof was reconstructed. In 2020 the timber trusses were replaced and the 18 rafters were deposited at the “DINCI” Laboratory for tests on materials and structures of the University of Calabria, in Rende (Cosenza).

Rafters have an average 4.00 m length with an approximately square cross section, with an average size of 20 cm. The sample timber species identification was performed through the visual analysis: most of the members (13) are in Corsican Pine (*Pinus nigra* subsp. *laricio* (Poir.) Maire); the others (5) in Chestnut *(Castanea Sativa).* In particular Corsican Pine (PNL) is characterized by resinous and rounded knots having modest dimensions, as well as by differentiated heartwood in the transversal cross section; while Chestnut (CS) is characterized by large and elliptical knots, porous rings and the typical flaming appearance of the grain on the tangential section.

Figure 1. a) Timber trusses extracted from the lyceum gymnasium Bernardino Telesio, Cosenza (Italy); b) Timber rafters stored in the DINCI Laboratory, Rende (CS); c) Survey of two rafters with laser scanner.

2.2 *Sample survey*

Visual inspection and size measurement were carried out, they being fundamental steps in the assessment of historic timber structures. Visual inspection provides information about the overall state of conservation of the structure, as well as the presence of any sign of mechanical damage or decay, whereas size measurement aims at defining geometry and main dimensions of timber members. In general these analyses are performed through on-site observation and traditional survey techniques. However, thanks to the technological progress, innovative survey techniques are spreading. Indeed, laser scanners and photogrammetry have been recently used (Riggio et al., 2015; Nocetti et al., 2021; Abraldes et al., 2022) for the evaluation of wooden elements: from morphological, geometric and mechanical aspects to visual and degradation aspects. Therefore, as part of the experimental campaign, both 3D acquisition methodologies were applied, in order to generate three-dimensional models useful for the mechanical characterization of the study specimen. In particular, the accurate geometry of the specimens was surveyed, allowing the determination of volumes, as well as attention was paid to the restitution of textures useful for carrying out visual classification (VSG) even remotely.

2.3 *Visual Strength Grading (VSG)*

For the on-site mechanical characterization of timber members the visual strength grading (VSG) approach was firstly applied. It allows to attribute a strength grade to the members according to the visual criteria defined by regulations (Piazza and Riggio, 2008). Grading rules take into account macroscopic features of timber, such as size of knots, slope of grain and presence of shake. In Italy two national standards are available for VSG: UNI 11119 providing procedures for the on-site classification and UNI 11035 used for newly sawn structural timber, although it is used also for ancient timber. According to UNI 11119 three visual grades (I, II, III) can be assigned both to Corsican Pine and Chestnut, whereas according to UNI 11035 three (S1, S2, S3) and only one (S) visual grades can be respectively assigned to Corsican Pine and Chestnut. Both standards provide a strength class, in terms of allowable stresses (UNI 11119) or characteristic values (UNI 11035), as function of the assigned visual grade.

During the experimental campaign 8 rafters were graded according to the aforementioned standards. VSG was performed considering only the macroscopic characteristics located in the middle third of each member, since this part mostly affect the bending behavior of the member. VSG was performed both in laboratory and in-remote, using the high-resolution images acquired with photogrammetry survey (Figure 2). The latter methodology was found to be advantageous as it allowed the research group to share information and work even remotely.

More in detail, the 3D acquisition methodologies applied were phase-difference ToF laser scanner (LS) survey and close-range photogrammetric (P) survey, for which FARO Technologies, Inc. Focus Plus 150 laser scanner and a Fujifilm X-T2 nonmetric camera combined with Fujifilm XF 18-55 f/2.8-4R LM OIS lens were used, respectively.

The laser scanner survey was carried out for all the specimens under daylight ambient light conditions, in two stages: point detection and HDR frame acquisition. Scan registration and point cloud orientation operations were performed using SCENE software by FARO. After the cleanup actions, a point cloud of about 13 million points, with a density of 1.75 points/mm^2 was obtained for each specimen. The clouds were then processed to obtain meshes in Geomagic Wrap 2021 by 3D Systems, Inc. The cloud was sampled to make the point density homogeneous. The resulting meshes possessed approximately 10 million triangles per specimen.

The close-range photogrammetry was applied in conjunction with Structure from Motion software, only for specimens 16-P, 17-P, which were surveyed individually under daylight ambient light conditions. An average of 420 frames per specimen were taken. Photogrammetric processing was done using Metashape Professional produced by Agisoft LLC. Point clouds of about 45 million points per specimen with a density of 13.1 points/mm^2 were obtained. Meshes generated have approximately 10 million polygons. The 3D models were textured with high-definition.

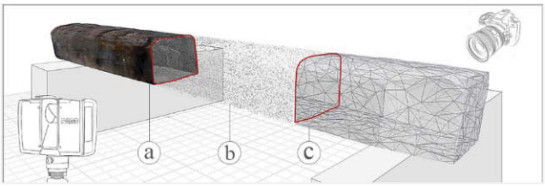

Figure 2. High-definition 3D model obtained by laser scanning and photogrammetry: a) Model textured; b) Point Cloud; c) Model Wireframe.

2.4 *Non-Destructive Techniques (NDT)*

Non-destructive techniques (NDT) are complementary to VSG. They are frequently used in professional practice and research fields, in order to collect information, principally about the state of conservation and the mechanical properties of timber members. The most common techniques can be grouped in three different categories: probing, acoustic and vibration techniques (Llana et al., 2020). Probing category includes drilling resistance method (Nowak et al., 2015; Faggiano et al., 2011), needle penetration, screw withdrawal and core drilling tests. Acoustic methods are based on the propagation of stress waves through material in order to estimate the timber member stiffness. Generally, two types of waves are used: sonic stress waves for frequencies within the audible range and ultrasonic stress waves at frequencies above 20 kHz (Dackerman et al., 2014). Vibration methods are based on natural frequency of timber member, which is directly related to the stiffness. Both acoustic and vibration methods are used to estimate the dynamic modulus of elasticity (MOE_{dyn}) from which static modulus of elasticity (MOE) can be derived through linear regression laws (Nocetti et al., 2010; Brunetti et al., 2013).

In this work drilling resistance, acoustic and vibration tests were carried out on the sample (Figure 3). Moisture content (MC) and mass were also measured. For each specimen a single MC measurement was taken on transversal face, through the hygrometer Hydromette CH 17 GANN, with a 60mm electrode length. Drilling resistance test was carried out using the Resi PD 400 Resistograph®. The penetration length and the average resistance to drilling (R_m) are the outputs provided by the device. For each specimen two measurements transversal to the grain were taken at each face, near the specimen end. The R_m measure was evaluated excluding the zones of the chart with no resistance. The device FAKOPP Microsecond timer® was used for acoustic test. It measures the time of flight of an acoustic stress wave induced by a hammer excitation. For each specimen five measurements were carried out using different sensor placement arrangements: one direct measurement (parallel to the grain) and four indirect measurements (one for each specimen face, placing sensors on the face with a same angle orientation (about 60°). During the test the length between sensors was measured in order to obtain the stress wave speed (SWS) through the time of flight (TOF) evaluated by the device. In the end, vibration test was conducted using the VISCAN Portable® Microtec device. It measures the natural frequency of vibration in the longitudinal direction of a timber piece by a laser interferometer exciting the specimen with a hammer (Berti et al., 2015). For each timber rafter one measurement was done in longitudinal direction.

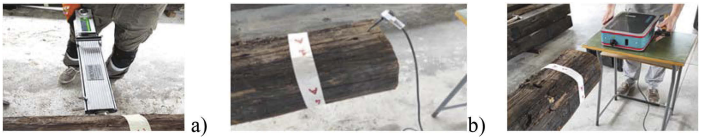
a) b) c)

Figure 3. Application of NDTs: a) the drilling resistance (DRM); b) acoustic; c) vibrational methods.

3 RESULTS

3.1 *Visual Strength Grading (VSG)*

Through visual inspection mechanical cracks were detected at the head of 4 members, probably caused by an excess of compressive stress at the joint between rafters and tie-beams. Other typical aspects of ancient timber noticed are the irregular geometry of the cross section (wanes and distortions) along the specimen length, double piths (on 4 specimens), iron stain discoloration on CS members, sign of superficial decay due to insect attacks (Cerambicidi*, Hylotrupes bajulus;* Anobium*, Anobiidae*), ring shakes at the member ends for most of the specimens. It is worth to notice that for VSG, defects as ring shakes, double piths and insect attacks are not taken into account, they being outside the specimen middle third. Moreover, geometrical irregularities were also not considered, because they would be very penalizing for the specimens, they being a widespread peculiarity of ancient timber structural members of the Mediterranean area.

The main geometric features of the specimens have been extracted from the 3D models generated through LS and P survey (Table 1). Given the irregular geometry of the specimens, the size of the cross section have been referred to a nominal section. Furthermore volume measured with both LS and P survey methods led to similar values, ranging from 132 dm^3 to 193 dm^3. Textured 3D models obtained from P survey has been used for VSG.

In order to assign a strength grade to the specimens, quantitative evaluations were carried out. For Chestnut specimens 2, 7, 9, large knots are inside the middle third, specimen 10 only shows insect damage also inside the middle third. Thus, three specimens (2, 9, 10) are classified as grade III (UNI 11119), while specimen 7 as grade II. According to UNI 11035 specimen 7 falls into grade S, while specimens 2, 9,10 are not classifiable as timber structural members, since they show defects above the prescribed limits. Corsican Pine specimens 7, 13, 17 are characterized by a grain slope up to 14%, specimen 18 has knots with diameter larger than 70mm. Thus, according to UNI 11119 three rafters (13, 17, 18) are classified as grade III and specimen 7 as grade II. At the same time specimens 13, 17, 18 are graded as S3 and specimen 7 as S2 according to UNI 11035.

3.2 *Non-destructive methods (NDT)*

In general, the moisture content (MC) of the specimen is higher than the normal content: the average value of MC is about 14.6% (maximum value is 23% for specimen 7). This is the consequence of unprotected storage of material until it was transported to the laboratory. The density ρ is similar for both wood species, being in average approximately equal to 600kg for CS and 550kg for PNL (maximum value is 723kg/m^3 for CS specimen 2). A slight data dispersion is recorded for CS (COV:17%) than PNL (COV:12%). Higher value of density for CS are probably due to the widespread presence of large knots.

In Table 1 the average value of the drilling resistance measures (R_m) are shown. It is apparent that for CS R_m values are higher (R_m:27.0%) than for PNL (R_m:21%). The higher value is for specimen 2 (R_m: 34.1%), it being closely related to the high density of the member. From drill charts it is also apparent that rafters 7, 9 and 18 belonged to very old trees, since they have a large number of rings. The acoustic tests and vibrational tests results are also given in Table 1. It is apparent that for both wood species stress wave speed (SWS) is directly proportional to density. The mean value of SWS is equal to 4,392 m/s for CS and to 4,264m/s for PNL. However, the values are much more dispersed for PNL (COV:17%) than for CS (COV:4%). The dynamic elastic modulus (MOE_{dyn}) calculated has average values equal to 11,600 MPa for CS and 10,500 MPa for PNL. Again, a greater dispersion characterizes PNL (COV:47%) as respect to CS (COV:26%).

With regards to vibrational tests, it is noted that for the whole sample frequencies are quite close and equally distributed, with an average value of 531Hz for CS and 511Hz for PNL. Unlike the acoustic test, for CS sample the average value of MOE_{dyn} is lower than for PNL (10,400 MPa and 11,100MPa, respectively). MOE_{dyn} values obtained from acoustic and vibration techniques vary by a maximum of 10%. Only for the CS specimens 2 and 10 there is a variation ranging from 20% to 25%. Also, in this case for PNL specimens MOE_{dyn} is statistically more dispersed than Chestnut (COV:51% versus 17%). Furthermore, it is worth to notice that for specimen 7 the MOE_{dyn} values are not affected by the high MC values. This is probably due to the good characteristic of the member that has been graded as II and S2 in VSG.

Table 1. Strength grading and non-destructive test results.

Wood Species	Density		DRM		Acoustic test				Vibrational test			
	Density		R_m		SWS		MOE_{dyn}		Frequency		MOE_{dyn}	
	Kg/m^3		%		m/s		MPa		Hz		MPa	
	Av.	Cov	Av.	Cov	Av.	Cov	Av.	Cov	Av.	Cov	Av.	Cov
CS	597	17%	27.0	19%	4.39	4%	11.60	26%	531	6%	10.40	17%
PNL	552	12%	21.0	0%	4.26	17%	10.50	47%	511	13%	11.10	51%

(CS: *Castanea Sativa*, PNL: *Pinus Nigra* subs. *Laricio*, DRM: drilling resistance method, R_m: average drilling resistance, SWS: stress wave speed; Av.: Average, Cov: coefficient of variation)

4 CONCLUSIVE REMARKS

In this paper the first part of a larger experimental campaign is showed. The work involved the application of innovative survey method, visual strength grading and non-destructive test on a sample of ancient timber members. The following conclusive remarks can be drawn:

– Innovative survey methods are effective methods to support the assessment of ancient timber members. Photogrammetry has produced 3D models with extremely precise and accurate geometry (useful for section extraction, volume measurements, etc.) and characterized by high resolution texture, which makes the technique more suitable for carrying out the VSG (useful for measuring knots, slope of the grain, etc.). 3D models, generated from data acquired by laser scanner adopted, resulted in less detailed meshes than photogrammetry, but there were no appreciable differences in volume and section measurements; texture quality proved to be unsuitable for visual analysis (due to the colorimetric characteristics of the specimens and ambient brightness). The computational and time burdens of acquisition by laser technique are lower than those by photogrammetric technique. The photogrammetry returns a textured model more suitable for carrying out the VSG. Visual strength grading performed on textured model is an effective methodology for working in a team even remotely. However, the survey of wane and cracks is a more time-consuming operation than standard Visual Inspection;
– Typical aspects of the ancient timber (double pith, biological decay, ring shake, mechanical damage) were identified through visual inspection, as well as LS and P. However, the criterion that considerably limits the VSG of ancient timber is the presence of wane. Indeed, this criterion has not been considered in the present work; large knots and slope of the grain have been the most recurrent defects respectively for Chestnut and Corsican Pine;
– From the application of NDT, it has been found that R_m and SWS are strictly correlated to timber density both for Chestnut and Pine. At the same time frequency seems to be not density dependent. Furthermore, for each specimen different values of MOE_{dyn} were determined by means of the application of acoustic and vibrational tests. However, in most cases the relative variation is less than 10%. A greater dispersion of MOE_{dyn} has been found for Corsican Pine. It is probably due to the heterogeneity of the quality of the material. Furthermore, for specimen 7 (PNL) MOE_{dyn} value was not affected by the high MC. This is probably due to the good characteristic of the member, as shown by the VSG results.

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