WORLD CONFERENCE ON TIMBER ENGINEERING 2025
BRISBANE, AUSTRALIA
Advancing Timber for the Future Built Environment

EXPLORING CORRELATIONS BETWEEN NON-DESTRUCTIVE AND DESTRUCTIVE TESTS FOR THE MECHANICAL CHARACTERIZATION OF EXISTING TIMBER STRUCTURES

Dante Marranzini[1], Giacomo Iovane[1], Salvatore Verre[2], Michele Brunetti[3], Michela Nocetti[3], Nicola Ruggieri[4], Marco Togni[5], Luciano Ombres[6], Beatrice Faggiano[1]

ABSTRACT: The paper focuses on the mechanical characterization and assessment of the state of preservation of existing timber structures. Non-destructive tests (NDT) have great potential in estimating the mechanical properties of wood through in-situ investigations, offering an alternative to destructive laboratory tests. However, their effectiveness depends on the presence of reliable correlations between the NDT parameters and the physical and mechanical properties of wood estimated through destructive test (DT). In this study, a statistical analysis of data obtained from NDT and DT on a sample of ancient timber members in structural dimension from South Italy is presented and the corresponding correlations are showed. The paper includes a brief description of the sample, a focus on the statistical methodology and the results. It also offers a critical analysis of the correlation laws, highlighting those most reliable for in situ investigation.

KEYWORDS: Timber structures; in situ assessment of timber structures; mechanical characterization of existing timber members; non-destructive and destructive tests; NDT-DT statistical correlations.

1 – INTRODUCTION

In order to assess the safety conditions of timber structures the evaluation of actual mechanical properties is a fundamental step towards diagnosis, structural analysis and design of possible retrofit interventions. Compared to other construction materials, the mechanical characterization of timber is a challenging task, especially for ancient timber members. The main approach for on site evaluation consists in Visual Strength Grading (VSG), which is based on the location and measurement of some wood features according to grading rules provided by national standards (in Italy UNI11119 [1]; UNI 11035-1 and 2 [2, 3]). Therefore a strength grade is attributed to the timber member depending on wood quality. Subsequently, through the EN 1912 standard [4], it is possible to identify a strength class, deriving the mechanical properties to be used in the structural analysis. In addition to this method, Non-Destructive Test (NDT) can be performed on-site. The main goal of NDT is to detect major wood defects and areas affected by decay, providing an indirect estimation of the mechanical properties of timber structures without compromising the structural integrity. In contrast, a comprehensive understanding of existing structures can be achieved through Destructive Tests (DT). However, these require the extraction of the whole structure or structural parts, in order to evaluate the mechanical properties in the laboratory. This approach is generally not feasible in the assessment of existing structures. Non-Destructive Testing (NDT) techniques play a crucial role

[1] Giacomo Iovane, [1] Beatrice Faggiano, Department of Structures for Engineering and Architecture, University of Naples Federico II, Napoli, Italia, giacomo.iovane@unina.it; faggiano@unina.it.

[2] University eCampus, Department of Engineering, via Isimbardi, 22060, Novedrate, Italy, salvatore.verre@uniecampus.it

[3] National Research Council of Italy, 10, Via Madonna del Piano, 50019, Sesto Fiorentino (FI), Italy, michele.brunetti@cnr.it, michela.nocetti@cnr.it

[4] Soprintendenza Archeologia Belle Arti e Paesaggio per la provincia di Cosenza, 87100, Cosenza, Italy, nicola.ruggieri@cultura.gov.it

[5] University of Florence, Dept. of Agriculture, Food, Environment and Forestry (DAGRI), 13, Via San Bonaventura, 50145, Florence, Italy, marco.togni@unifi.it

[6] University of Calabria, Dept. of Civil Engineering (Dinci), Rende, 87036, Cosenza, Italy, luciano.ombres@unical.it

https://doi.org/10.52202/080513-0414

in evaluating the mechanical properties of wood, particularly those methods that allow for the indirect estimation of such properties through correlations with Destructive Testing (DT) results. Today, a wide range of NDT techniques and instruments are available for evaluating structural wood. Comprehensive overviews can be found in numerous studies [5-8]. NDT methods are generally classified as either non-destructive or semi-destructive, based on the extent of damage they cause. Common semi-destructive techniques include resistance drilling, core drilling and screw withdrawal. These methods enable the measurement of parameters that can be used to indirectly estimate wood density, as demonstrated in studies on various wood species [5, 9-11]. Another important group of NDT methods involves stress wave-based techniques, primarily used to assess structural stiffness [5, 8-11]. These include sonic and ultrasonic stress wave methods, both of which rely on the propagation of sound waves through the material. Based on Time-of-Flight (TOF) measurements, these methods allow for the estimation of the Dynamic Modulus of Elasticity (MOE_{dyn}). Several studies investigated the relationship between static and dynamic elastic moduli, finding strong linear correlations across several wood species [12,13]. Vibration-based methods form another category of NDTs. These techniques are based on the natural frequency of timber, which is directly related to stiffness. Natural frequency is typically measured after inducing vibrations—often with a hammer impact—using commercial devices. From these measurements, MOE_{dyn} can be derived to predict the Modulus of Elasticity (MOE). Extensive literature supports the use of this technique for evaluating the mechanical properties of timber from various species [14-18]. Among the various studies on the mechanical characterization of wood, several authors carried out tests (NDT and DT) on ancient timber members extracted from buildings belonging to the Italian built heritage [10, 11, 19-24].

In this context, the present paper provides a statistical evaluation of data collected from both NDT and bending DT tests conducted on a sample of ancient structural timber elements [25, 26]. The study explores the relationships between the test results and offers a detailed analysis of the correlations. It includes an overview of the sample characteristics, emphasizes the statistical methods applied and discusses the main findings. Furthermore, the study critically examines various correlation models to identify the most reliable ones for on-site assessments.

2 – BACKGROUND

The work falls in the context of the research project DPC–ReLUIS, at the current edition 2024-2026, with regards to the reduction of the seismic vulnerability of existing buildings. To achieve a complete understanding of existing structures through testing, the most direct and effective approach is to carry out DT. However, the on-site prediction of the mechanical properties of wood can be performed through NDTs, exclusively, due to the need of conservation of ancient timber members belonging to historical buildings.

3 – PROJECT DESCRIPTION

The sample of study consists of 18 struts made of *Chestnut* (*Castanea sativa, CS,* 5 specimens) and *Corsican Pine* (*Pinus nigra* subsp. *laricio* (Poir.) Maire*, PNL,* 13 specimens), extracted from an historic building in Cosenza old town [25]. For the mechanical characterization of the timber member, the following investigations were carried out at the University of Calabria (Fig. 1): geometrical survey, VSG, NDTs (moisture content measurement, drilling resistance test, acoustic test and vibrational test) and DT in bending [25].

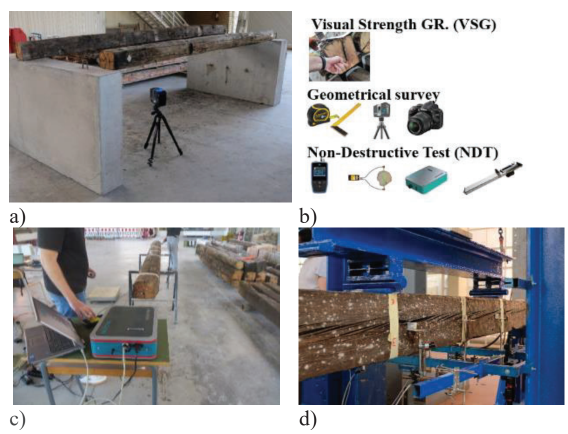


Figure 1. a) Geometrical survey; b) Used instruments, c) Non-Destructive Test; d) Destructive Test in bending.

The geometrical survey was carried out with both direct survey and indirect survey methods based on laser scanner and photogrammetric method. It was noted as the Chestnut specimens had a greater geometrical irregularity than Corsican pine. Subsequently, the VSG was performed according to the grading rules provided by the Italian National Standards [1-3] and then a strength class was assigned to each specimen [4]. For PNL, 9 specimens were graded above Grade III, specifically 7 specimens have Grade II and 2 specimens have Grade I, the other 4 specimens have Grade III. For CS, only one out of five specimens reached Grade II, with the remaining ones falling into the lowest grade (Grade III). Definitely, PNL showed a superior wood quality compared to CS. Most of the CS specimens were penalized due to the presence of large knots, whereas the worst grading criterion for PNL was the slope of the

https://doi.org/10.52202/080513-0414

grain. Hereafter, average values of results are reported. From NDT, the moisture content of the specimen was measured (MC_{CS}=14.7%; MC_{PNL}=17.2%), they being slightly higher than the reference value (MC:12%). In agreement with literature, high value of drilling resistance (R_m) was found for CS than PNL ones ($R_{m,CS}$=27.7%, $R_{m,PNL}$=20.2%,). The Acoustic test (A) was performed through both direct and indirect measures. From this test as well as from Vibrational test (V) the Dynamic Modulus of Elasticity MOE_{dyn} was calculated. From acoustic test similar value of MOE_{dyn} were found for both CS and PNL sample ($MOE_{dyn,A,CS}$=12800 MPa; $MOE_{dyn,A,PNL}$=12500 MPa). In contrast, vibrational tests showed that CS sample was on average stiffer than PNL ($MOE_{dyn,V,CS}$=11500 MPa; $MOE_{dyn,V,PNL}$=10800 MPa).
The density of the specimens was calculated by directly measuring the specimen's mass and volume (ρ_{CS}=612kg/m^3; ρ_{PNL}=590kg/m^3). Then, the bending tests were performed. The corresponding load-displacement (F-w) curves are shown in Figure 2.

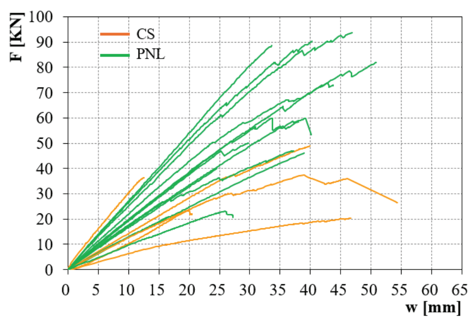


Figure 2. Bending tests: Load-displacement curves.

From the elastic test, Modulus of Elasticity for PNL was on average higher than for CS (MOE_{PNL}=8600 MPa; MOE_{CS}=6000 MPa). The same trend was found for strength ($f_{m,PNL}$=22.9MPa; $f_{m,CS}$=13.5MPa). Very low values were found for two (2/5) Chestnut specimen, due to the presence of large knots at the tension side. From the load-displacement (F-w) curves (Fig. 2), a fragile behavior up to collapse can be recognised. The following different types of failure occurred: in most specimens, fracture at the notched joint, placed at the tension side; fracture triggering near the large knots placed at the tension side. In general, low strength values corresponded to this type of failure. For six specimens a vertical crack triggered at the tension side. A sudden collapse occurred for specimen number 6 due to the presence of a large resin pocket in the cross section [26].

4 – DESIGN PROCESS

The experimental results of NDT and DT were evaluated using statistical methods. Based on NDT and DT parameters, a set of relationships was explored by using linear regression. These models could provide an estimation of the physical and mechanical properties of the material, considering the randomness of the data sample. Thus, the correlations were grouped into three classes: correlation between NDT, DT and NDT-DT parameters. Among them, the third group of models (NDT-DT correlations) is the most interesting for in-situ applications for predicting the mechanical properties of wood. Considering that ND Techniques are valuable for conducting structural health assessments of a timber structure without causing harm, correlations between NDT and DT measurements is surely a worthy mission. Generally, the quality of the fit is evaluated using the goodness-of-fit index, R^2, which is a summary metric to evaluate the linear model's fit to a given set of data. The linear regressions herein proposed are shown in Figure 3 with the corresponding R^2.

5 – RESULTS

5.1 NDT CORRELATIONS

The correlations between non-destructive parameters themselves, such as dynamic Modulus of Elasticity (MOE_{dyn}) vs mean drilling Resistance Measure (R_m), considering both Acoustic ($MOE_{dyn,A;}$ Fig. 3a) and Vibrational methods ($MOE_{dyn,V}$, Fig. 3b), were evaluated.

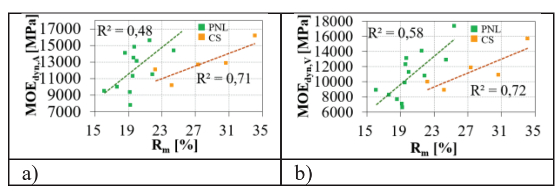


Figure 3. Prediction of dynamic Modulus of Elasticity with drilling resistance measure: a) $MOE_{dyn,A}$ from acoustic test; b) $MOE_{dyn,V}$ from vibrational test.

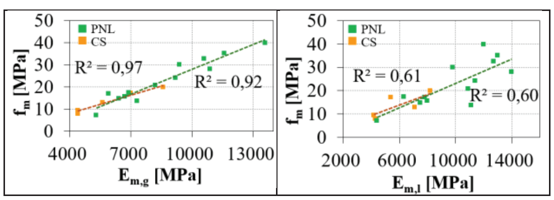
For both $MOE_{dyn,A}$ and $MOE_{dyn,V}$, quite good correlations with R_m were found. For $MOE_{dyn,A}$ vs R_m, R^2 values equal to 0.71 and 0.48 were obtained for Chestnut and Corsican Pine, respectively. For $MOE_{dyn,V}$ vs R_m slightly better correlations were found, with R^2 values equal to 0.72 and 0.58 for CS and PNL respectively. For CS, the good prediction of MOE_{dyn} by means of drilling resistance measurement (R_m) was probably due to the good correlation between R_m and density (R^2=0.92) which was used for MOE_{dyn} calculation.

5.2 DT CORRELATIONS

The correlations between the destructive parameters themselves were evaluated, considering the bending strength and the global and local moduli of elasticity, also as respect to wood density.

https://doi.org/10.52202/080513-0414

The regression analysis between DT parameters provided very interesting results. An almost perfectly linear relationship was found between bending strength (f_m) and global Modulus of Elasticity ($E_{m,g}$, Fig. 4a). In detail, for CS and PNL, R^2 values are equal to 0.97 and 0.92 respectively. This direct proportionality between strength and stiffness also emerges from Figure 2, where it can be seen that the curve showing the highest failure loads at the same time are the steepest ones (i.e., with the highest Modulus of Elasticity). Similarly, also the correlations between bending strength (f_m) and Local Modulus of Elasticity ($E_{m,l}$, Fig. 4b) are good, with R^2 equal to 0.61 for CS and 0.60 for PNL. Furthermore, from Figure 4 it is evident that the regression lines for the two wood species are almost overlapping and consequently the correlation equations are very close. Therefore, it can be stated that for the examined sample, the linear relationship between local/global elastic moduli and strength is independent of the wood species.

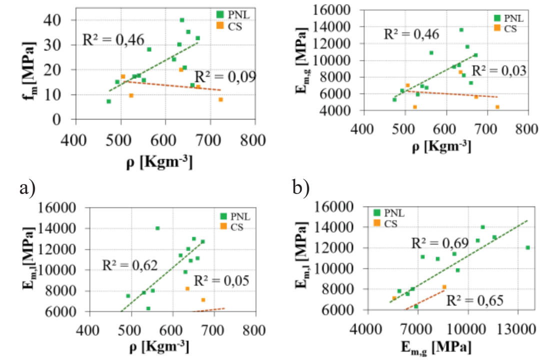


a) b)

Figure 4. Prediction of bending strength f_m from a) global $E_{m,g}$ and b) local $E_{m,l}$ Modulus of Elasticity.

As regards bending strength, the correlation with density was evaluated. Quite good results were found for PNL, with R^2 equal to 0.46, whereas a very poor correlation was noted for CS (Fig. 5a). Furthermore, it can be observed that the f_m, $E_{m,l}$ and $E_{m,g}$ vs ρ relationships are almost inversely proportional for Chestnut (Figg. 5a-c), which is contrary to what is well known in the scientific literature. Indeed, the regression laws are strongly influenced by an outlier (i.e. specimen n.2), which showed high value of density (ρ), but at the same time low values of f_m, $E_{m,g}$ and $E_{m,l}$ (obtained from the bending test), due to the presence of large knots at tension side [26]. On the contrary, for PNL, quite good and good correlations were found: R^2=0.46 (f_m vs ρ), R^2=0.46 ($E_{m,g}$ vs ρ) and R^2=0.62 ($E_{m,l}$ vs ρ).

Finally, for both wood species, a good correlation was found between the global and local Moduli of Elasticity, R^2 values being equal to 0.65 and 0.69 for CS and PNL, respectively. In Figure 5d the two regression lines are shown. They are almost parallel, meaning that the relationship between Global and Local Moduli has the same proportionality for both species, although the stiffness in PNL greater than in CS was noted.

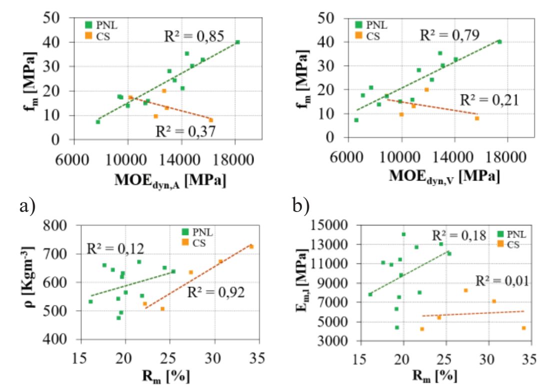


a) b) c) d)

Figure 5. DT Correlations: a) bending strength f_m - density ρ; b) Local Modulus of Elasticity $E_{m,l}$ - density ρ; c) Global Modulus of Elasticity $E_{m,g}$ - density ρ; d) Local Modulus of Elasticity $E_{m,l}$ - Global Modulus of Elasticity $E_{m,g}$.

5.3 NDT - DT CORRELATIONS

The relationships between non-destructive and destructive parameters are the most interesting for on-site application in the structural health monitoring of timber structures. Therefore, many correlations were analyzed, considering all the mechanical and physical parameters shown so far. Generally, the correlations found for PNL are more reliable than those for CS. As it is apparent from Figures 6a and b the relationships f_m vs $MOE_{dyn,A}$ and f_m vs $MOE_{dyn,V}$ are inversely proportional for Chestnut, due to the outlier of specimen n.2, as previously discussed, which showed high values of R_m, $MOE_{dyn,A}$, $MOE_{dyn,V}$, and ρ, but at the same time low values of f_m, $E_{m,g}$ and $E_{m,l}$ [26].



a) b) c) d)

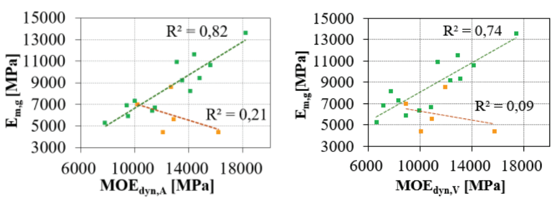
Figure 6. NDT-DT Correlations: a) bending strength f_m - MOE_{dyn} from acoustic test; b) bending strength f_m - MOE_{dyn} from vibrational test; c) density ρ - mean drilling resistance R_m; d) local modulus of elasticity $E_{m,l}$ - mean resistance drilling measure R_m.

However, in agreement with literature, a strong correlation was found for CS between density and drilling resistance measure (R^2=0.92; Fig. 6c), while it is very poor for PNL (R^2=0.12). However, for PNL good correlations were found for the remaining parameters. In

https://doi.org/10.52202/080513-0414

fact, the correlations between bending strength (f_m) and the Dynamic Modulus of Elasticity obtained from acoustic tests ($MOE_{dyn,A}$) and the vibrational test ($MOE_{dyn,V}$) showed R^2 values of 0.85 (Fig. 6a) and 0.79 (Fig. 6b), respectively.

For both the wood species poor to very poor correlations were found for $E_{m,l}$ vs R_m (R^2_{PNL}=0.18; R^2_{CS}=0.01). for Considering the prediction of the global Modulus of Elasticity $E_{m,g}$ (Fig. 7) through acoustic ($E_{m,g}$ vs $MOE_{dyn,A}$: R^2=0.82) and vibrational methods ($E_{m,g}$ vs $MOE_{dyn,V}$: R^2=0.74) good correlation are found for PNL with R^2=0.82 and R^2=0.74, while for CS poor correlations were found due to the presence of an outlier.



a) b)

Figure 7. NDT-DT Correlations: Global Modulus of Elasticity $E_{m,g}$ vs a) $MOE_{dyn,A}$ from acoustic test; b) $MOE_{dyn,V}$ from vibrational test.

6 – CONCLUSION

This study investigated the potential of non-destructive testing (NDT) techniques as tools for predicting the physical and mechanical properties of timber, through the development and analysis of statistical correlations with destructive testing (DT) parameters. By performing linear regression analyses across NDT-NDT, DT-DT, and NDT-DT datasets, several relationships were identified, offering insights into the structural behavior of Chestnut (CS) and Corsican Pine (PNL) wood species. Among the NDT correlations, strong relationships were found between drilling resistance measurements (R_m) and Dynamic Modulus of Elasticity (MOE_{dyn}), particularly using vibrational methods. DT correlations confirmed well-established mechanical behavior, with very high linearity observed between bending strength (f_m) and Global Modulus of Elasticity ($E_{m,g}$) for both species. The most promising outcomes emerged from NDT-DT correlations, which are vital for practical applications such as diagnosis and structural health monitoring of existing structures. For PNL, high coefficients of determination (R^2) were consistently observed between Dynamic Modulus of Elasticity (MOE_{dyn}) and both bending strength (f_m) and Global Modulus of Elasticity ($E_{m,g}$), indicating the effectiveness of acoustic and vibrational methods in capturing mechanical behavior. Conversely, for CS, the presence of an outlier notably reduced correlation strength, emphasizing the need for an extension of the sample and for potential outlier mitigation in future studies. In the end, the findings suggest that NDT methods, especially when correlated with reliable DT data, can serve as effective proxies for mechanical characterization in on site assessment of existing timber structures. Future work should focus on refining the statistical models by reprocessing the dataset with appropriate outlier detection and removal techniques, which could significantly enhance the robustness and predictive accuracy of the correlations, particularly for species such as Chestnut. Additional efforts may also include expanding the sample size and validating the proposed models.

Acknowledgments

The research project DPC–ReLUIS 2024-2026–WP12 and RETURN project are acknowledged.

7 – REFERENCES

[1] UNI 11119:2004. Cultural heritage – Wooden artefacts – Load bearing structures of buildings – On site inspection for the diagnosis of timber members.

[2] UNI 11035-1:2022. Structural timber - Visual strength grading of structural timber - Part 1: Softwood of rectangular cross section.

[3] UNI 11035-2:2022. Structural timber - strength grading of structural timber - Part 2: Broadleaf and rectangular cross-section.

[4] EN 1912:2012. Structural Timber - Strength classes - Assignment of visual grades and species.

[5] B. Faggiano, M.R. Grippa, A. Marzo, F.M. "Mazzolani. Mechanical identification by NDT of old chestnut structural timber". In: Protection of Historical Buildings. vol. 1 (2009), pp. 295-300, Rome, 21-24 June 2009. London: CRC Press, ISBN: 9780415558037.

[6] M. Riggio, RW. Anthony, F. Augelli, B. Kasal, T. Lechner, W. Muller, T. Tannert. "In situ assessment of structural timber using non-destructive techniques". In: Materials and structures (2014), 47, 749-766.

[7] T. Tannert, RW. Anthony, B. Kasal, M. Kloiber, M. Piazza, M. Riggio, F. Rinn, R. Widmann, N. Yamaguchi. "In situ assessment of structural timber using semi-destructive techniques". In: Materials and structures (2014), 47, 767-785.

[8] U. Dackermann, K. Crews, B. Kasal, J. Li, M. Riggio, F. Rinn, T. Tannert. "In situ assessment of structural timber using stress-wave measurements". In: Materials and structures (2014), 47, 787-803.

[9] M. Grippa, B., Faggiano, A. Marzo, F.M. Mazzolani. “Combined methods for in situ mechanical identification of ancient timber structures based on non-destructive tests”. In: World Conference on Timber Structures. Riva del Garda (TN), 20-24 June (2010).

[10] B. Faggiano, M.R. Grippa, A. Marzo, F.M. Mazzolani. “Experimental analysis on old chestnut timber by means of non-destructive techniques”. In: World Conference on Timber Structures. Riva del Garda (TN), 20-24 June (2010).

[11] B. Faggiano, M.R. Grippa, A. Marzo, F.M. Mazzolani. “Structural grading of old chestnut elements by bending and compression tests”. In: World Conference on Timber Structures. Riva del Garda (TN), 20-24 June (2010).

[12] F. Arriaga, C. Osuna-Sequera, I. Bobadilla, M. Esteban. “Prediction of the mechanical properties of timber members in existing structures using the dynamic modulus of elasticity and visual grading parameters”. In: Construction and Building Materials (2022), 322, 126512.

[13] SY. Wang, JH. Chen, MJ. Tsai, CJ. Lin, TH. Yang. “Grading of softwood lumber using non-destructive techniques”. In: Journal of materials processing technology (2008), 208(1-3), 149-158.

[14] M. Nocetti, M. Bacher, S. Berti, M. Brunetti, P. Burato. “Machine grading of chestnut structural timber with wane”. In: Proceedings of the 4rd International Scientific Conference on Hardwood Processing (2013), pp. 7-9.

[15] M. Nocetti, M. Brunetti, M. Bacher. “Efficiency of the machine grading of chestnut structural timber: prediction of strength classes by dry and wet measurements”. In: Materials and Structures (2016), 49, 4439-4450.

[16] M. Brunetti, M., M. Nocetti, M., B. Pizzo, C. Cremonini, F. Negro, R. Zanuttini, M. Ramagnoli, G. Scarascia Mugnozza. “Structural products made of beech wood: quality assessment of the raw material”. In: European Journal of Wood and Wood Products (2020), 78, 961–970.

[17] M. Nocetti, G. Aminti, C.B. Wessels, M. Brunetti. “Applying Machine Strength Grading System to Round Timber Used in Hydraulic Engineering Works”. In: Forests (2021), 12(3), 281.

[18] M. Sciomenta, L. Spera, A. Peditto, E. Ciuffetelli, F. Savini, C. Bedon, M. Romagnoli, M. Nocetti, M. Brunetti, M. Fragiacomo. “Mechanical characterization of homogeneous and hybrid beech-Corsican pine glue-laminated timber beams”. In: Engineering Structures (2022), 264, 114450.

[19] B. Faggiano, M.R. Grippa, A. Marzo, F.M. Mazzolani. “Experimental study for non-destructive mechanical evaluation of ancient chestnut timber”. In: Journal of Civil Structural Health Monitoring (2011), 1, 103-112.

[20] B. Faggiano, A. Marzo, F.M. Mazzolani. “The Diplomatic Hall of the Royal Palace of Naples: Structural characterization of the timber roof by in situ ND investigations”. In: Construction and Building Materials (2018), 171, 1005-1016.

[21] A. Cavalli and M. Togni. “Combining NDT and visual strength grading to assess ancient timber beams stiffness to evaluate strengthening interventions suitability”. In: Wood NDT Proceeding-17th International Nondestructive Testing and Evaluation of Wood Symposium (2011), pp. 593-601. University of West Hungary-Sopron.

[22] M. Nocetti, M. Mannucci, M., M. Brunetti. “Automatic assessment of insect degradation depth in structural solid wood elements by drilling resistance measurements”. In: Construction and Building Materials (2023), 366, 130273.

[23] M. Nocetti, G. Aminti, M. Vicario, M. Brunetti. “Mechanical properties of ancient wood structural elements assessed by visual and machine strength grading”. In: Construction and Building Materials (2024), 411, 134418.

[24] M. Brunetti, G. Aminti, M. Vicario, M. Nocetti. “Density estimation by drilling resistance technique to determine the dynamic modulus of elasticity of wooden members in historic structures”. In: Forests (2023), 14(6), 1107.

[25] S. Verre, GF. Cauteruccio, G. Fortunato, AA. Zappani, L. Ombres, M. Brunetti, M. Nocetti, N. Ruggieri, M. Togni, D. Marranzini, G. Iovane, B. Faggiano. “Assessment of mechanical properties for ancient timber through visual and ND methods”. In: 8th International Symposium on Life-Cycle Civil Engineering, IALCCE 2023 Milan, Italy 2-6 July 2023. doi:10.1201/9781003323020-481.

[26] D. Marranzini, S. Verre, G. Iovane, N. Ruggieri, M. Brunetti, M. Nocetti, M. Togni, L. Ombres, B. Faggiano. “Mechanical characterization of ancient timber members through destructive test in bending”. In: Protection of Historical Constructions: Proceedings of PROHITECH 2025, Vol. 2., Naples, 26-28 March, Italy.

 https://doi.org/10.52202/080513-0414