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DETERMINATION OF SOME MECHANICAL PROPERTIES OF TIMBER OF DIFFERENT STRENGTH CLASSES BY NON-DESTRUCTIVE AND DESTRUCTIVE METHODS

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Abstract

Traditional destructive testing is used to determine the mechanical properties of construction timber. Although accurate results are obtained from these tests, they damage the material and render it unusable. As a result, the tested material cannot be reused, resulting in economic losses. In addition, destructive methods require a laboratory infrastructure to perform the tests and do not provide on-site evaluation. Due to these disadvantages of destructive testing, non-destructive testing methods have emerged. Non-destructive testing prevents cost loss by causing no or very little damage to the material, providing on-site testing, and enabling the material to be reused. This study aimed to ascertain the correlation of certain mechanical properties of timber from diverse strength classes through the utilization of non-destructive and destructive methodologies. Non-destructive tests, including screw withdrawal force, shear modulus, bending strength, and modulus of elasticity, were conducted on the timber samples. Furthermore, to develop a regression curve based on the results of destructive testing, additional destructive tests were carried out to determine the density, bending strength, and modulus of elasticity of the timber. A highly accurate regression curve was found using the data obtained as a result of the tests. The findings of this study demonstrate that non-destructive testing methods can be used as a reliable alternative in wood material evaluation processes.

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DETERMINATION OF SOME MECHANICAL PROPERTIES OF TIMBER OF DIFFERENT STRENGTH CLASSES BY NON-DESTRUCTIVE AND DESTRUCTIVE METHODS

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1. Introduction

Timber is produced in different quality classes in our country and the world, and timber quality is seen as the most important factor affecting the cost of materials such as CLT. When the timber quality classifications are examined today, most of them divide the wood material into three classes. However, the type of classification varies according to the intended use of the wood material and the purpose of the classification standard (Görgün, 2013). In the TS EN 14081-1 (2016) standard, the strength classification of timber structures-rectangular sawn building timbers is carried out by referring to the strength classes specified in the TS EN 338 European norm standard. According to TS EN 338 European norm; a strength classification has been made as 12 (C14, C16, C18, C20, C22, C24, C27, C30, C35, C40, C45, C50) for coniferous tree species and 8 groups (D18, D24, D30, D35, D40, D50, D60, D70) for leafy tree species. These classifications determine the quality of the timber and are the most important factor affecting the selling price.

The assessment and classification of the quality of wood raw material significantly impact maximizing yields. Financial, quantitative, and ecological reasons for increased yields are important. Globally, there is a major shift in forest management and logging intensity, which requires significantly faster and more accurate assessment of wood material properties. Wood has a wide range of physical and mechanical properties. These properties and their correlations vary from species to species and depend on growth conditions. When structural timber is produced, key properties must be assessed to ensure the material's structural safety and economic use (Ondrejka et al., 2021).

There are various methods for assessing wood. According to the degree of destruction of the material being evaluated, there are 1. destructive, 2. non-destructive, and 3. semi-destructive methods. Non-destructive and semi-destructive methods are more important in assessing wood (Ross et al. 1998). In contrast, semi-destructive techniques for assessing wood properties are defined as non-destructive test procedures concerning the structural element but destructive to the extracted sample (Kasal et al., 2003). Semi-destructive methods only partially damage the material without affecting its further use. They are mainly used to assess the properties of wood, timber, or historic roof structures (Kloiber et al., 2015).

Various techniques can be used for nondestructive evaluation of wood materials, generally classified as follows (Pellerin and Ross, 2002; Dündar, 2009).

- Visual Assessment: Examination of the material according to its color or defects
- Physical Tests: Examination of electrical resistivity, dielectric properties, vibrational properties, wave propagation, acoustic emission, and the effects of radioactive radiation, such as X-rays on materials,
- Chemical Tests: Wood chemical analysis of the composition of the wood material, as well as the presence and effectiveness of the preservatives and fire retardants used,

In this study, the objective was to ascertain the correlation of certain mechanical properties of timber from diverse strength classes through the utilization of non-destructive and destructive methodologies.

2. Materials and Methods

2.1. Wood Material

In this study, spruce (*Picea orientalis* L.), one of the most preferred coniferous wood species in wood buildings, was selected. In addition, alder (*Alnus glutinosa subsp.* Barbata (C.A. Mey.) Yalt.), one of the fast-growing species, was selected as a regional tree species.

The timber used in this study was sourced from an industrial facility located within the immediate vicinity. Before supply, sample groups were extracted from the timber at the factory, and preliminary non-destructive testing was conducted using an acoustic testing device (Sylvatest 4) to determine the appropriate strength classes according to the TS EN 338 standard. These tests indicated that the spruce timber's strength classes ranged from C14 to C30, while the alder timber ranged from D18 to D40. Based on these findings, it was determined that the timbers could meet the requirements of six different strength classes. As a result, 24 m^3 (1620 pieces) of spruce timber and 24 m^3 (1620 pieces) of alder timber were commercially supplied. The dimensions of the timbers were 2400x100x25 mm, with a moisture content of 12±3%.

2.2. Non-Destructive Testing

2.2.1. Screw Withdrawal Force and Shear Modulus

Screw withdrawal force and shear strength tests were performed on all timbers (3240 pieces) at three different points on each timber as non-destructive. The screw withdrawal force values of the test samples were determined with the non-destructive screw withdrawal force meter developed by Fakopp (Figure 1). In addition, using the determined screw withdrawal force values, the shear modulus of the test specimens was calculated using the following formula (1).

$$G = 224\, F_{Screw} + 210 \quad (1)$$

where;
G: Shear modulus (MPa)
F_{Screw}: Screw withdrawal force (kN)

Figure 1: Non-destructive screw withdrawal force meter

2.2.2. Bending Strength and Modulus of Elasticity

In this study, non-destructive tests were carried out on all timber samples (totaling 3240 pieces) using the acoustic testing device Sylvatest 4 (Figure 2). As a result of these tests, bending strength and modulus of elasticity values were obtained. The instrument evaluates the mechanical properties of wood materials with fiber-directional measurements and can measure timber as well as other wood components, such as laminated timber. It is also capable of determining wood quality and strength properties on standing trees and logs. With this device, the strength classes of timber were determined according to the TS EN 338 standard.

Figure 2: Sylvatest 4 acoustic test device

The device measures the ultrasonic wave flight time through the wood material to calculate the bending strength and modulus of elasticity. This calculation is conducted using software, which subsequently displays the strength class in accordance with the relevant standard. Additionally, the device converts the obtained data into a graphical format, as illustrated in Figure 4.

Figure 3: Determination of strength classes of timber by acoustic test device

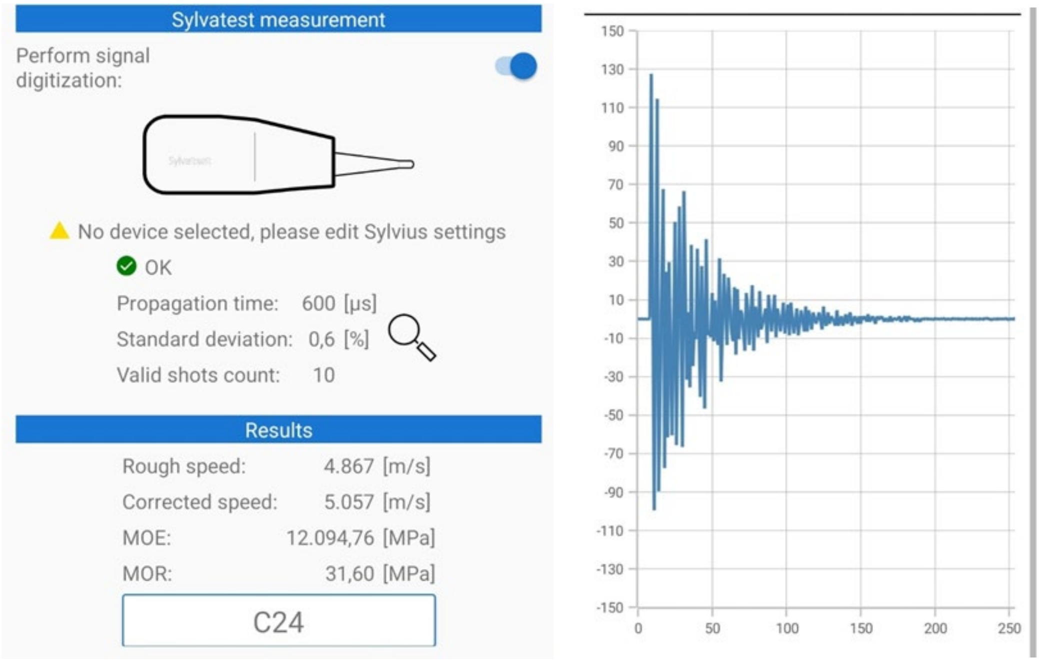

Figure 4: Acoustic tester software data

2.3. Destructive Tests

C16, C22, C30, and D18, D30, D40 strength classes were established based on data derived from non-destructive testing procedures. In each strength class category, bending strength and modulus of elasticity tests were conducted using destructive methods by the requirements of the TS EN 384 standard.

2.3.1. Density, Bending Strength and Modulus of Elasticity

The density, bending strength, and modulus of elasticity of the timber were evaluated for structural dimensions in accordance with the TS EN 408 standard, as referenced in TS EN 384. Bending strength and modulus of elasticity tests were performed six repetitions for strength classes C16, C22, C30, D18, D30, and D40. Additionally, density tests were performed on 20 samples for each strength class.

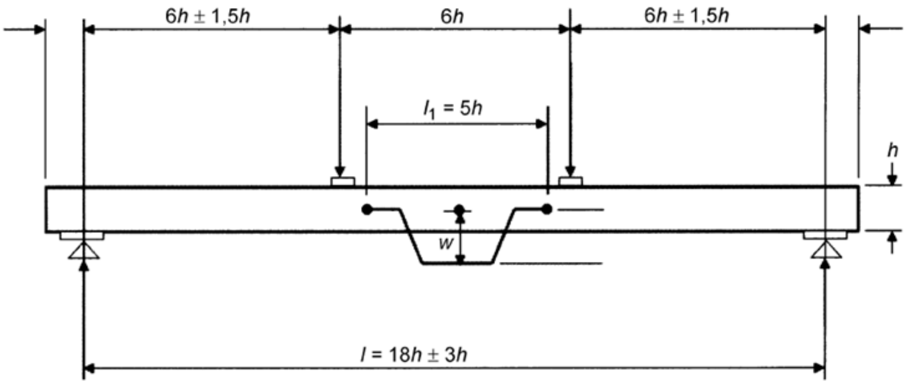

Figure 5: Bending strength and modulus of elasticity in bending test setup (TS EN 408, 2016)

Bending strength and modulus of elasticity are given by the equations,

$$Bending\ strength\ (N/mm^2) = \frac{FL}{bd^2} \quad (2)$$

$$\text{Modulus of elasticity } (N/mm^2) : \frac{al_1{}^2(F_2-F_1)}{16I(w_2-w_1)} \quad (3)$$

Where F is the load at a given point on the load deflection curve, in N, L is the support span, in mm, b is the width of the test specimens, in mm, and d is the depth of the test specimens, in mm.

3. Results

3.1. Findings of Non-Destructive Tests

3.1.1. Screw Withdrawal Force and Shear Modulus

The screw withdrawal force and shear modulus data, obtained through non-destructive tests, for each group the spruce group (C16, C22, C30) and alder group (D18, D30, D40) timber strength classes determined in this study, were subjected to a multiple analysis of variance (ANOVA) within using the Student-Newman-Keuls test. The results were statistically significant at the 99% confidence level. The tables presenting the mean values and homogeneity groups for these tests are provided in Tables 1 and 2.

Table 1: Mean values and homogeneity groups of screw withdrawal force determined by non-destructive method

Wood Species	Strength Classes	Screw withdrawal force (kN)		Homogeneity Group*
		Mean	Standard Deviation	
Spruce	C16	1,50	0,22	a
	C22	1,61	0,21	a
	C30	1,85	0,28	b
Alder	D18	2,53	0,25	a
	D30	2,69	0,29	a
	D40	2,83	0,40	a

*Note: The same letters in the group (Spruce, Alder) indicate that there is no statistical difference.

Table 2: Mean values and homogeneity groups of shear modulus determined by non-destructive method

Wood Species	Strength Classes	Shear Modulus (MPa)		Homogeneity Group*
		Mean	Standard Deviation	
Spruce	C16	545,22	48,92	a
	C22	571,29	46,17	b
	C30	633,74	81,43	c
Alder	D18	777,44	56,18	a
	D30	812,09	64,99	a
	D40	844,07	89,54	a

*Note: The same letters in the group (Spruce, Alder) indicate no statistical difference.

When the tables are examined, the non-destructive screw withdrawal force values of the C30 strength class group of spruce timbers were found to be statistically higher than the other strength class groups. There was no statistical difference between the strength class groups in alder timbers. In a study conducted by Akyıldız and Malkoçoğlu (2001), it was stated that although the screw withdrawal force values of coniferous tree species showed larger values than coniferous tree species, they also showed differences among themselves as a function of their specific gravity and the screw withdrawal force increased as the specific gravity value increased. Similarly, the non-destructive shear modulus values of the C30 strength class group of spruce timbers were statistically higher than those of the other strength class groups. In the case of alder lumber, no statistical difference was found between the strength class groups.

3.1.2. Bending Strength and Modulus of Elasticity

The bending strength and modulus of elasticity data of the timber obtained by non-destructive methods were subjected to multiple analyses of variance. The results were found to be statistically significant at a 99% confidence level. The tables of mean values and homogeneity groups of the mentioned tests are given in Tables 3 and 4 below.

Table 3: Mean values and homogeneity groups of bending strength determined by non-destructive method

Wood Species	Strength Classes	Bending Strength (N/mm²)		Homogeneity Group*
		Mean	Standard Deviation	
Spruce	C16	16,97	0,55	a
	C22	22,80	0,57	b
	C30	31,12	0,82	c
Alder	D18	18,98	0,57	a
	D30	31,26	0,88	b
	D40	41,79	1,22	c

*Note: The same letters in the group (Spruce, Alder) indicate no statistical difference.

Table 4: Mean values and homogeneity groups of modulus of elasticity determined by the non-destructive method

Wood Species	Strength Classes	Modulus of Elasticity (N/mm²)		Homogeneity Group*
		Mean	Standard Deviation	
Spruce	C16	8544,52	299,67	a
	C22	10619,69	230,81	b
	C30	12299,42	214,30	c
Alder	D18	9747,75	141,42	a
	D30	11323,83	245,32	b
	D40	13207,32	121,04	c

*Note: The same letters in the group (Spruce, Alder) indicate no statistical difference.

Similarly, the non-destructive bending strength and modulus of elasticity values of the C30 strength class group of spruce timbers were statistically higher than those of the other strength class groups. The highest bending strength and modulus of elasticity values of alder timbers were found statistically in the D40 strength class group. Yin et al. (2024) analyzed 600 pieces of timber to determine density and modulus of elasticity by the non-destructive method and found a relationship between density and mechanical properties. However, it was stated that density alone was not sufficient to predict the modulus of elasticity of timber, which is also due to defects randomly distributed on the timber. In another study, it was determined that mechanical properties will increase with increasing density (Wang et al., 2017). Olsson and Abdeljaber (2024) used a non-destructive method to supply C35/C18 combination and C24 grade timber for the production of hybrid CLT panels and observed that the strength class increased with the increase in timber density.

3.2. Findings of Destructive Tests

3.2.1. Density, Bending Strength and Modulus of Elasticity

Multiple variance analysis was performed on the density, bending strength, and modulus of elasticity data obtained from destructive tests, and the results were found statistically significant at a 99% confidence level. The tables of mean values and homogeneity groups of the specified tests are given in Tables 5-7 below.

Table 5: Mean values and homogeneity groups of density determined by the destructive method

Wood Species	Strength Classes	Density (gr/cm³)		Homogeneity Group*
		Mean	Standard Deviation	
Spruce	C16	0,425	0,019	a
	C22	0,469	0,016	b
	C30	0,452	0,011	b
Alder	D18	0,519	0,013	a
	D30	0,571	0,014	b
	D40	0,571	0,016	b

*Note: The same letters in the group (Spruce, Alder) indicate no statistical difference.

Table 6: Mean values and homogeneity groups of bending strength determined by the destructive method

Wood Species	Strength Classes	Bending Strength (N/mm^2)		Homogeneity Group*
		Mean	Standard Deviation	
Spruce	C16	15,40	2,34	a
	C22	20,99	4,06	b
	C30	27,00	0,99	c
Alder	D18	17,83	2,82	a
	D30	25,77	4,07	b
	D40	33,03	2,91	c

*Note: The same letters in the group (Spruce, Alder) indicate no statistical difference.

Table 7: Mean values and homogeneity groups of modulus of elasticity determined by the destructive method

Wood Species	Strength Classes	Modulus of Elasticity (N/mm^2)		Homogeneity Group*
		Mean	Standard Deviation	
Spruce	C16	8286,52	343,94	a
	C22	11039,03	801,48	b
	C30	12606,42	790,62	c
Alder	D18	10899,34	494,80	a
	D30	12326,48	962,54	b
	D40	14300,12	997,38	c

*Note: The same letters in the group (Spruce, Alder) indicate no statistical difference.

When the tables are analyzed, the destructive density values of the C22 and C30 strength class groups of spruce timber were statistically higher than those of the C16 strength class group. In alder lumber, the highest density values were found statistically in the D30 and D40 strength class groups. When the destructive bending strength and modulus of elasticity values were analyzed, it was found that the C30 strength class group of spruce timbers was statistically higher than the other strength class groups. The highest bending strength and modulus of elasticity values of alder timbers were statistically found in the D40 strength class group.

3.3. Regression analysis of destructive and non-destructive tests

Regression analysis was performed to reveal the relationship between the data obtained by destructive and non-destructive tests on spruce and alder timbers, and it was determined that the results of destructive and non-destructive tests were highly compatible. In addition to the acoustic test device (Sylvatest 4) used in the project for the calculation of the bending strength and modulus of elasticity values found as a result of non-destructive tests, the results determined by the screw holding device, which is another non-destructive measurement tool, were also used to determine the agreement between the data. As a result of the regression analyses, it was observed that there was a high agreement between the destructive and non-destructive test data. The graphs of the regression analysis of the destructive and non-destructive test data obtained from the timber are given below.

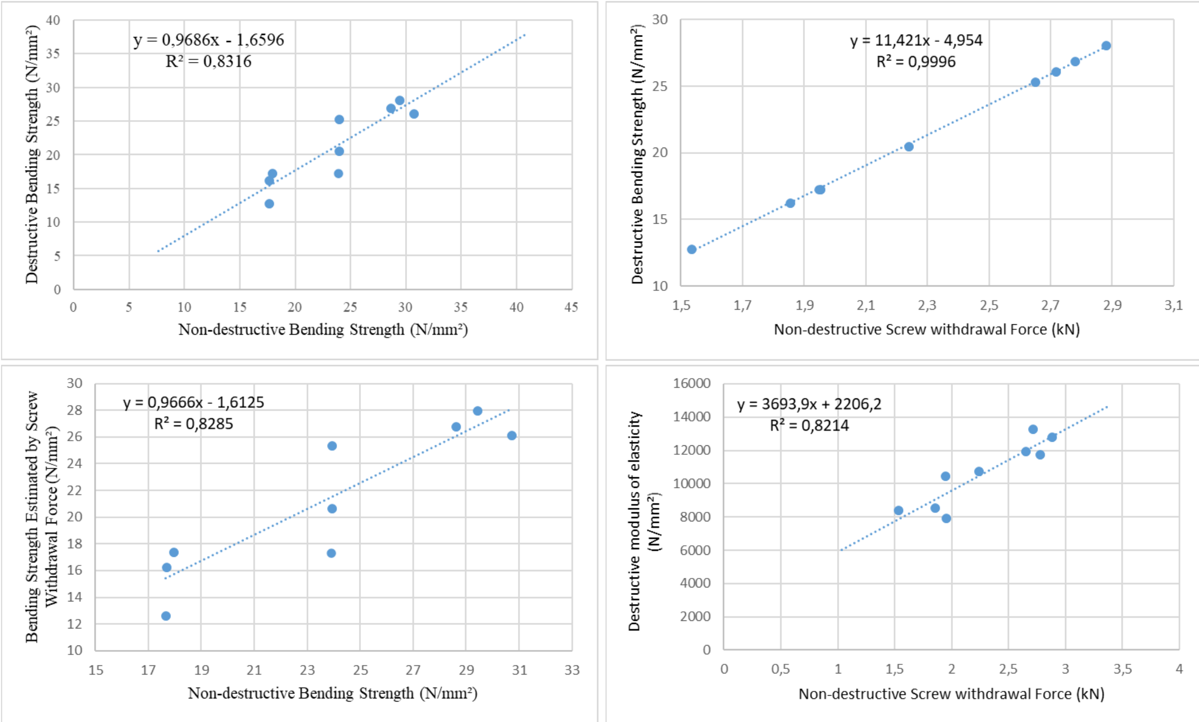

Figure 6: Regression plots of spruce timber

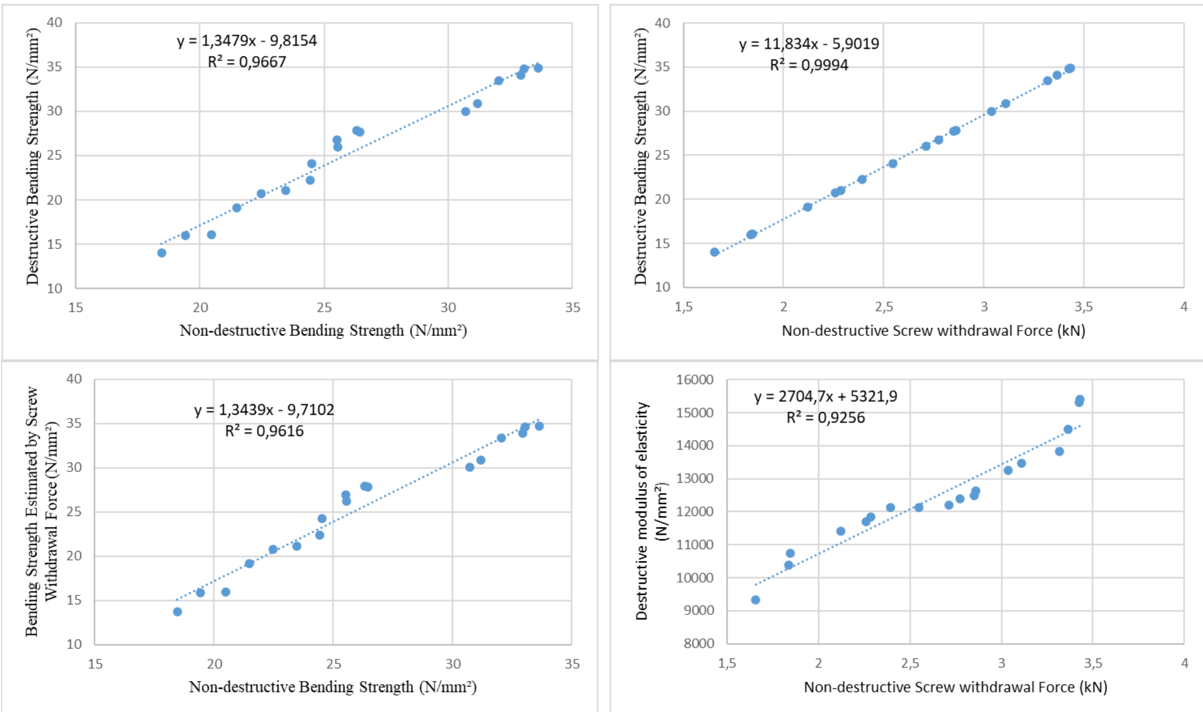

Figure 7: Regression plots of alder timber

The findings revealed that the R^2 values obtained from alder timber were higher, and the established models were more reliable compared to the existing literature on the subject. In addition, the non-destructively calculated modulus of elasticity values were in good agreement with the modulus of elasticity values calculated by the regression models (Figure 8).

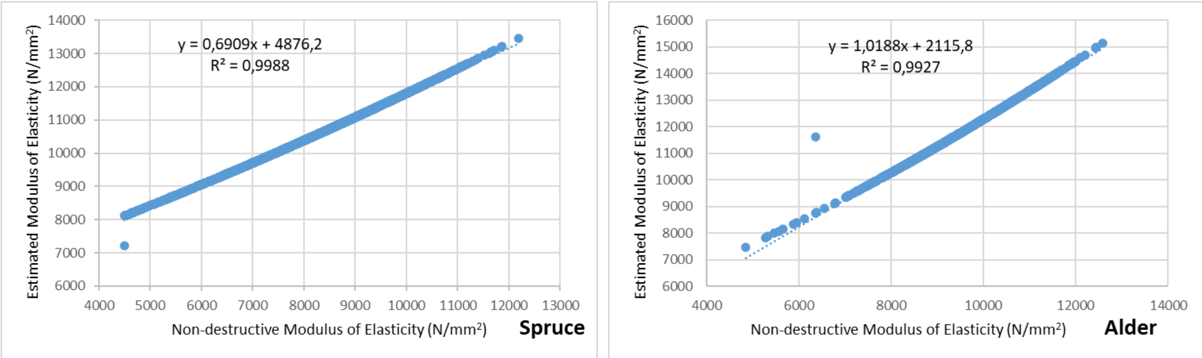

Figure 8: Comparison of the modulus of elasticity values calculated by the regression models with non-destructive methods

In previous studies, it was found that there were strong relationships between the destructive and non-destructive test methods obtained (Gerhards, 1982a; Gerhards, 1982b; Sandoz, 1989; Sandoz, 1991; Bucur, 2003; Güntekin and Yılmaz, 2012). Görgüm and Dündar (2016) conducted a study that applied stress wave and longitudinal vibration methods from non-destructive test methods, as well as static bending strength and elastic modulus tests from destructive test methods, on black pine (*Pinus nigra* var. pallasiana Arnold.) timber. The relationship between the values obtained with non-destructive test methods and the static elastic modulus values obtained with destructive test methods was determined to be highly accurate. The R2 values of the prediction models obtained from this study agreed with the limit values specified in the literature. Llana et al. (2020) conducted a study in which destructive and non-destructive tests were applied to samples obtained from alder, ash, birch, and plane trees. The coefficients of determination (R^2) values obtained from the study were subsequently calculated, yielding values ranging from 0.02 to 0.83 for the elasticity modulus and from 0.03 to 0.81 for bending strength. The coefficients of determination (R^2) calculated at high rates proved that the relationship between the destructive and non-destructive test data obtained was successful. In addition, the non-destructively calculated modulus of elasticity values were found to be in good agreement with the modulus of elasticity values calculated by the regression models.

4. Conclusion

The non-destructive screw withdrawal force values for the C30 strength class of spruce timbers were found to be statistically higher than those of the other strength classes. In contrast, no statistically significant differences were observed among the strength classes in alder timbers. Similarly, the non-destructive shear modulus values of the C30 strength class in spruce timbers were statistically superior to those of the other strength classes. In contrast, no significant differences were detected among the strength classes in alder timbers.

The C30 strength class of spruce timbers exhibited significantly higher non-destructive bending strength and modulus of elasticity than other strength classes. In alder timbers, the highest bending strength and modulus of elasticity were statistically recorded in the D40 strength class.

The destructive density values of spruce timbers in the C22 and C30 strength classes were statistically higher than those in the C16 strength class. For alder timbers, the highest density values were statistically observed in the D30 and D40 strength classes. Similarly, the destructive bending strength and modulus of elasticity of spruce timbers were significantly higher in the C30 strength class compared to other strength classes. In alder timbers, the highest bending strength and modulus of elasticity were statistically found in the D40 strength class.

A regression analysis was performed to assess the relationship between destructive and non-destructive test results. The analysis revealed a strong correlation, indicating a high degree of compatibility between the two testing methods. These findings highlight the reliability of non-destructive methods in predicting the mechanical properties of spruce and alder timbers and emphasize the impact of strength classification on their overall performance.

Engineering design is vital for efficiently utilizing and classifying available material and its economic use. Structural engineers consider timber strength grades as a fundamental principle. Timber quality classifications in Europe are currently incorporating the requirements of building regulations, making continuous improvements and revisions to improve the application of standards (Ridley-Ellis et al., 2016).

This study established that the data obtained by non-destructive testing methods exhibited a high level of compliance with destructive testing methods in evaluating and classifying timber quality. Furthermore, it was revealed that the developed regression model contributed to faster and more effective structural health monitoring. These findings demonstrate that nondestructive testing methods can be used as a reliable alternative in wood material evaluation processes. The durability of wooden structures may decrease over time due to environmental effects and mechanical loads; as such, non-destructive testing methods have become increasingly important in recent years. These methods determine the mechanical and physical properties of load-bearing elements without causing damage to the structure, thus rendering restoration and maintenance processes more reliable and economical. The critical role of non-destructive testing in the performance monitoring of historical and modern wooden structures is well-documented, with numerous studies highlighting its contribution to enhancing safety and extending the lifespan of these structures.

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Disclosure Statement

No potential conflict of interest was reported by the authors.

References

Akyıldız H. and Malkoçoğlu A. (2001). Screw holding resistance of some important woods growing in the Eastern Black Sea Region. Artvin Çoruh University Journal of Forestry Faculty, 2(1), 54-60.

Bucur V. (2003). Nondestructive characterization and imaging of wood. Springer Science & Business Media.

Dong Q., Xing K. and Zhang H. (2017). Artificial neural network for assessment of energy consumption and cost for cross laminated timber office building in severe cold regions. Sustainability, 10(1), 84.

Dündar T. (2009). Lecture Note on Nondestructive Test Methods in Building Materials (Unpublished), Department of Forest Industry Engineering, Istanbul University, Istanbul.

Gerhards C. (1982a). Effects of conts on stress waves in lumber. Res Pap 384. Forest Products Laboratory, USDA, Washington DC.

Gerhards C. (1982b). Longitudinal stress waves for lumber stress grading. Factors affecting applications: state of the art. Forest Products Journal, 32(2), 20-25.

Gorgun H.V. and Dundar T. (2016). Comparison Of Acoustic-Based Nondestructive Test Methods for Assessing the Bending Properties of Lumbers. Kastamonu University Journal of Forestry Faculty, 16(2), 616-621.

Görgün H.V. (2013). Determination of Bending Strength and Modulus of Elasticity in Wooden Beams by Nondestructive and Destructive Test Methods. Master Thesis. Istanbul University Institute of Science and Technology. Istanbul.

Güntekin E. and Yılmaz T. (2012). Strength classification for red pine (*Pinus brutia* Ten.) timber. Journal of SDU Faculty of Forestry, 13, 140-142.

Kasal B., Drdacky M. and Jirovsky I. (2003). Semi-destructive methods for evaluation of timber structures. WIT Transactions on the Built Environment. 66, 835-842.

Kloiber M., Drdácký M., Machado J.S., Piazza M. and Yamaguchi N. (2015). Prediction of mechanical properties by means of semi-destructive methods: A review. Construction and Building Materials. 101, 1215-1234.

Llana D.F., Short I., and Harte A.M. (2020). Use of non-destructive test methods on Irish hardwood standing trees and small-diameter round timber for prediction of mechanical properties. Annals of forest science, 77, 1-13.

Olsson A. and Abdeljaber O. (2024). Predicting out-of-plane bending strength of cross laminated timber: Finite element simulation and experimental validation of homogeneous and inhomogeneous CLT. Engineering Structures, 308, 118032.

Ondrejka V., Gergeľ T., Bucha T. and Pástor M. (2021). Innovative methods of non-destructive evaluation of log quality. Central European Forestry Journal, 67(1), 3-13.

Pellerin R.F. and Ross R.J. (2002). Nondestructive Evaluation of Wood, Forest Products Society Publication, Madiosun, USA, 1-892529-26-2.

Ridley-Ellis D., Stapel P. and Baño V. (2016). Strength grading of sawn timber in Europe: an explanation for engineers and researchers. European journal of wood and wood products, 74, 291-306.

Ross R.J., Brashew B.K. and Pellerin R.F. (1998). Nondestructive evaluation of wood. Forest Products Journal, 48(1). 14-19.

Sandoz J.L. (1989). Grading of construction timber by ultrasound. Wood Sci Technol, 23, 95- 108.

Sandoz J.L. (1991). Form and treatment effects on conical roundwood tested in bending. Wood Science and Technology, 25, 203-214.

TS EN 14081. (2019). Timber structures-Strength classification of rectangular sawn building timbers-Part 1: General requirements. Turkish Standards Institute.

TS EN 338 (2016). Construction timber - Strength classes. Turkish Standards Institute.

TS EN 384 (2022). Construction timber - Determination of characteristic values of mechanical properties and density. Turkish Standards Institute.

TS EN 408 (2016). Wooden Structures - Building Timber and Glued Laminated Timber - Determination of Some Physical and Mechanical Properties. Turkish Standards Institute.

Wang Z., Fu H., Gong M., Luo J., Dong W., Wang,T. and Chui Y.H. (2017). Planar shear and bending properties of hybrid CLT fabricated with lumber and LVL. Construction and Building Materials, 151, 172-177.

Yin T., He L., Huang Q., Gong Y., Wang Z. and Gong M. (2024). Effect of lamination grade on bending and shear properties of CLT made from fast-growing Chinese fir. Industrial Crops and Products, 207, 117741.