Visual and Machine Strength Gradings of Scots and Red Pine Structural Timber Pieces from Türkiye

Fatih Kurul,* and Nusret As

Scots (*Pinus sylvestris* L.) and red pine (*Pinus brutia* Ten.) structural timbers (540 pieces) from Türkiye were first visually graded according to TS 1265 (2012). Then, non-destructive tests were conducted using vibration and time of flight (ToF) methods, followed by destructive tests on a four-point bending test setup according to EN 408 (2012). The vibration method showed a higher correlation than ToF with strength and stiffness. The dynamic modulus of elasticity (MOE_d) obtained by the vibration method was 12.3% and 15.4% lower in Scots and red pine, respectively, compared to the ToF method. Mechanical testing determined local MOE was 14% and 15% higher than global MOE for Scots and red pine, respectively. An alternative formula to the existing conversion formula in EN 384 (2018) was derived. The average bending strength of red pine was 7% higher than Scots pine. For visual strength grading, local and global MOE in Scots pine, class 1, 2, and 3 structural timbers were assigned to C35, C27, and C22, respectively. Red pine was assigned to C40, C27, and C24 for local MOE and C35, C24, and C22 for global MOE. In machine strength grading, the grade combination was C40-C30-C22-C16-R for both species. The best results were achieved in settings where vibration method and local MOE were used together. Machine strength grading achieved higher efficiency than visual strength grading.

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Keywords: Visual strength grading; Machine grading; Local and global modulus of elasticity; Scots pine; Red pine

*Contact information: Istanbul University-Cerrahpaşa Faculty of Forestry, Department of Wood Mechanics and Technology, Istanbul, Türkiye; *Corresponding author: fatihkurul@iuc.edu.tr*

INTRODUCTION

Wood is one of the oldest materials people have used since ancient times to meet their needs. In parallel with the developments in other branches of industry in recent years, the forest products industry has also shown rapid change and development. Accordingly, there has been a significant increase in demand for wood materials. In parallel with this increase, the consumption of forest assets is also increasing. Therefore, the efficient use of wood materials is essential. For efficient use of wood material, it is crucial to use it in the right area. To decide on the right area, it is necessary to know the wood material's physical, mechanical, and other technological properties. These properties will make comparing wooden materials with other materials easier and give ideas about their processing and usage features.

Wooden material, used in many parts of life, has also been used as a building material since people started to create spaces. Despite its low density, its high strength properties, being an renewable natural resource, providing good sound and heat insulation, and being aesthetic and recyclable, make wood stand out for structural use. However, as a natural material, wood has an anisotropic structure. Because of its various defects, wood can have various physical and mechanical properties (variation) even within the same species. Therefore, by the binding legal requirements of the countries, only wood with a designated strength class can be used for applications in the construction sector. Thus, it is aimed to ensure both structural safety and economical use of the material (Faria *et al*. 2012; Christoforo *et al*. 2015; Ridley-Ellis *et al*. 2016; Burawska-Kupniewska *et al*. 2020; Krzosek *et al*. 2020).

Each country has developed national standards to classify wood structurally, creating its structural grading system. Standard TS 1265 (2012) is used for the structural grading of coniferous tree species in Türkiye. National standards from some European countries, such as DIN 4074-1 (2021) in Germany, BS 4978:2007+A2:2017 (2007) in England, UNI 11035-1 (2022) in Italy, and UNE 56544 (2022) in Spain, are also used. Due to the wide variety of wood species, origins, and different grading rules, the European structural wood grading system is recommended. This system consists of harmonized EN 14081-1 (2019), EN 14081-2 (2022), EN 14081-3 (2022), and supporting standards. National standards must meet the minimum conditions. Structural timbers are divided into categories (strength classes) according to three essential features. These are strength (bending or tensile), stiffness (modulus of elasticity (MOE) in bending or tensile), and density. TS EN 338 (2016) standard specifies strength classes and properties, and the TS EN 1912 (2012) standard was created to facilitate the exchange of structural timber between different markets. These standards list how national visual grading standards relate to the strength classes in TS EN 338 (Stapel and Kuilen 2014; Ridley-Ellis *et al*. 2016; Barriola *et al*. 2020).

Mechanical tests on structural timbers are carried out according to the EN 408 (2012) standard. This standard defines two methods for modulus of elasticity adjustments *via* a four-point bending test. The global measurement of the modulus of elasticity is determined by the mid-span deflection of the supports ($E_{m,g}$). In contrast, the local measurement of the modulus of elasticity is determined in the middle third of the beam ($E_{m,l}$) by the relative deflection of the natural axis of the beam. Although $E_{m,l}$ and $E_{m,g}$ are related, they also contain essential differences (Ravenshorst *et al*. 2009; Nocetti *et al*. 2013; Gil-Moreno *et al*. 2016). For $E_{m,l}$, the deformation is recorded on the natural axis as the average displacement of two LVDTs placed on one side of the timber. In this region of the four-point bending test, the bending moment is constant and is, therefore, theoretically considered to be under “pure bending” with no shear effect (Ravenshorst *et al*. 2009; Gil-Moreno *et al*. 2016). On the other hand, for $E_{m,g}$, the deformation is measured at the center of the span, typically the center of the tensile zone. In this measurement, part of the deformation is due to the shear effect between the support and the load point. $E_{m,g}$ measurement is a more effortless testing procedure to perform. It is less sensitive to experimental error and allows the exact location of the worst defect. However, it often includes a compressive deformation component at the supports and loading points, which can significantly impact the results. So, the benefits of using $E_{m,g}$ can outweigh the disadvantages (Ravenshorst *et al*. 2009; Nocetti *et al*. 2013; Gil-Moreno *et al*. 2016) .

Today, structural timber grading is done in two ways: visual grading and machine strength grading. Visual grading consists of measuring the defects of the wood that affect its strength, such as knots, fiber deviation, annual ring width, pith, and cracks (Stapel and Kuilen 2014; Barriola *et al*. 2020; Rosa *et al*. 2020; Arriaga *et al*. 2022). In machine grading, each sample is evaluated mechanically using non-destructive methods. “Indicative properties” (IP) are determined by measuring one or more physical-mechanical properties of the timber with a non-destructive device. Both grading methods are frequently preferred (Ridley-Ellis *et al*. 2016; Kovryga *et al*. 2017; Krzosek *et al*. 2020; Krzosek and Burawska 2022). However, the IP obtained by machine grading is a more accurate predictor of wood quality than those obtained by visual grading. The machine grading process is much faster, possible human errors are minimized, and the potential to obtain a higher strength class brings machine grading to the fore (Nocetti *et al*. 2010; Brunetti *et al*. 2016; Nocetti *et al*. 2016; Ravenshorst and Kuilen 2016; Ridley-Ellis *et al*. 2016; Kovryga *et al*. 2017; Krzosek *et al*. 2020; Krzosek and Burawska 2022; Krzosek *et al*. 2022; Moltini *et al*. 2022).

Compared to studies in Europe, only a few studies have been conducted in Türkiye to determine the strength classes of structural timbers using non-destructive and destructive methods. This study aims to determine and compare the strength class obtained from visual and machine grading for Scots and Red pine species growing in Türkiye. In addition, another objective of the study is to examine the relationships between local and global modulus of elasticities and compare them with the conversion formula given in EN 384 (2018).

EXPERIMENTAL

Wood Specimens

In this study, 540 specimens with three different cross-sections were used, including 270 Scots pine (*Pinus sylvestris* L.) and 270 red pine (*Pinus brutia* Ten.) pieces from Türkiye, as described in Table 1. The moisture contents of the specimens were measured using the electrical resistance method by following the procedure defined in EN 13183-2 (2002). The average moisture contents were 14.3% for Scots pine and 14.0% for red pine structural timber.

Table 1. Number of Tested Structural Timbers for Species, Visual Grade, and Cross-Sections

Species	Visual Grade	Cross-sections (mm)			Total
		50 x 100 x 1900	50 x 150 x 2900	50 x 200 x 3800	
Scots Pine	1	30	30	30	90
	2	30	30	30	90
	3	30	30	30	90
	Total	90	90	90	270
Red Pine	1	30	30	30	90
	2	30	30	30	90
	3	30	30	30	90
	Total	90	90	90	270
General Total		180	180	180	540

Visual Grading

All specimens used in this study were classified according to TS 1265 (2012). Visual grading criteria for structural timber are defined in Table 2. Therefore, knot dimensions were visually checked, and narrow diameters were measured through the length of specimens to calculate the knot diameter ratios (KDR) for each specimen (Fig. 1). Moreover, fiber deviation, annual ring width, and other defects were measured as specified in TS 1265 (2012). Then, all specimens were cut according to the location of critical knots to be placed in between the loading points.

Table 2. Visual Grading Criteria for Structural Timber According to TS 1265

Characteristics	Grades		
	Class 1	Class 2	Class 3
Knot The ratio of knot diameter to the width of the face on which the knot is visible must be max (Fig.1a).	The narrow diameter is no greater than 50 mm. 1/5	The narrow diameter is no greater than 70 mm. 1/3	No limitation 1/2
Knot cluster The ratio of the sum of knot diameters within the worst 150 mm length to the width of the face on which the knots are visible must be max (Fig.1b).	2/5	2/3	3/4
Slope of grain a) In case of presence of surface fissure b) In case of no surface fissure	Deviation in 1 m length is not greater than:		
	70 mm 100 mm	120 mm 200 mm	200 mm 300 mm
Annual ring width	Growth ring area bigger than 4 mm should not be greater than 1/2 of the whole cross-section.	No limitation	No limitation

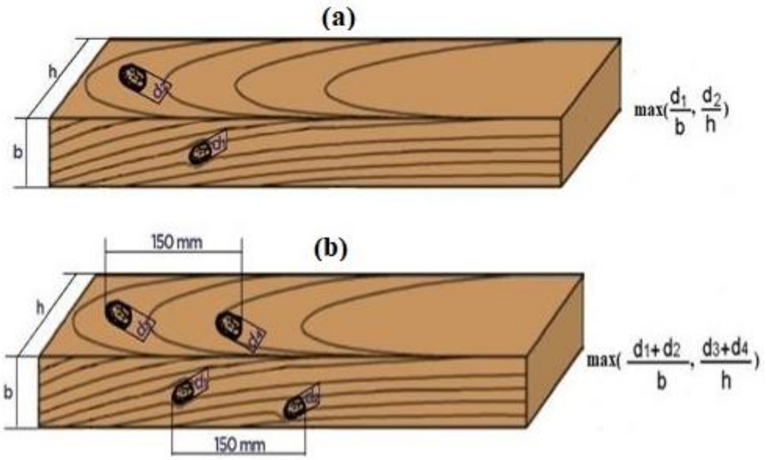

Fig. 1. Principles of measuring knots in structural timbers according to TS 1265 standard: (a) single knot, and (b) knot cluster

Non-destructive Tests

Following the visual grading, the dynamic modulus of elasticity (MOE_d) was determined for each specimen using the longitudinal vibration and time of flight (ToF) method. The longitudinal vibration method is based on measuring the natural frequency of longitudinal vibration produced by the impact at one end of the piece, which crosses in its entirety. The test setup is represented in Fig. 2(a). In the test procedure, the specimens are placed on two supports with soft polyurethane pillows to ensure that test pieces are vibration-free. One of these is simultaneously supported and balanced, recording the half mass of each piece. A hammer hits the end of a specimen, and the impact induces a stress wave of longitudinal vibration caught as sound by a microphone set close to the other end of the test piece. A fast Fourier transform (FFT) sound analyzer analyzes the sound's natural frequency. After that, the dynamic modulus of elasticity ($MOE_{\text{d,vib,\%12}}$) was calculated according to the following Eq. 1. The second method is a ToF with a portable microsecond stress-wave timer. Microsecond timer (23 kHz) has two piezoelectric-type transducers with 60 mm long spikes, as shown in Fig. 2(b). For the application, the source is selected as a simple hammer impact, and then the time of flight is measured. Then, stress wave velocity (m/s) was calculated using the distance between the transducers (l, m) and the time of flight taken from the device (t, μs) by Eqs. 1 and 2,

$$MOE_{d,vib,\%12} = \frac{(2f_0 l)^2 \rho}{1-0.01(u-12)} 10^{-6} \tag{1}$$

$$MOE_{d,ToF,\%12} = \frac{(\frac{l}{t}10^6)^2 \rho}{1-0.01(u-12)} \tag{2}$$

where $MOE_{\text{d,vib,\%12}}$ is the dynamic modulus of elasticity obtained from longitudinal vibration (MPa), $MOE_{\text{d,ToF,\%12}}$ is the dynamic modulus of elasticity obtained from ToF (MPa), f_0 is the natural frequency (Hz), l is the length of specimen (m), t is the time of flight taken from the device (μs), ρ is the specimen's density (kg/m^3), and u is the moisture content (%) obtained from electrical resistance method.

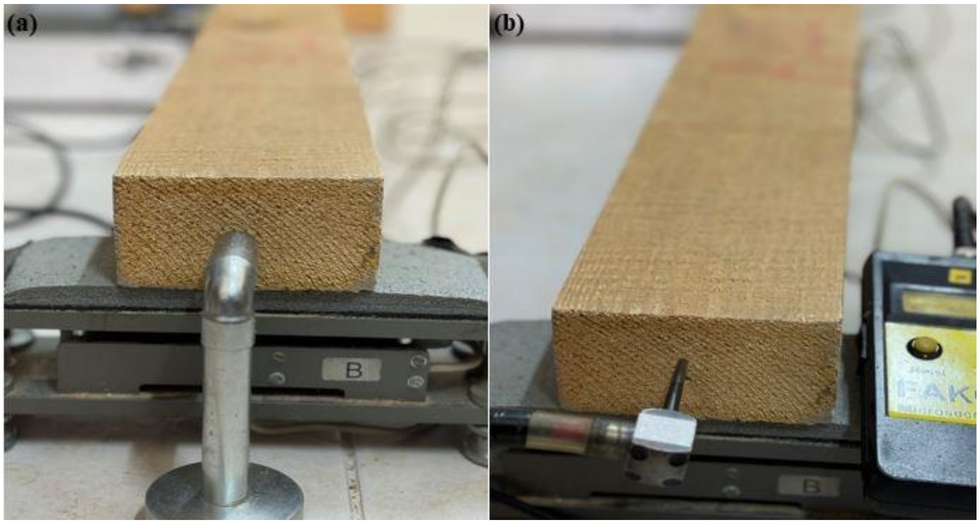

Fig. 2. Longitudinal vibration (a); and ToF (b) test-method setup

Mechanical Tests

After the non-destructive tests, 540 structural timbers were tested edgewise in a four-point bending test setup stipulated in EN 408 (2012) with an 18 × h span length. Tests were performed with the universal testing machine (BCO-DC300/LDL; BESMAK, Ankara, Türkiye), which was equipped with a load cell of 300 kN. Deformations (w) were measured on both sides' faces at the neutral axis and at the center of a central gauge length of five times the depth of the section (local). In addition, it was measured at the center of the span (global) (Fig. 3). Thereby, the local modulus of elasticity ($E_{\text{m,l}}$), global modulus of elasticity ($E_{\text{m,g}}$), and modulus of rupture (f_{m}) were determined by the following Eqs. 3 to 5,

$$E_{m,l} = \frac{a l_1^2 (F_2 - F_1)}{16 I (w_2 - w_1)} \text{ N/mm}^2 \tag{3}$$

$$E_{m,g} = \frac{3al^2 - 4a^3}{2bh^3\left(2\frac{w_2 - w_1}{F_2 - F_1} - \frac{6a}{5Gbh}\right)} \quad \text{N/mm}^2 \tag{4}$$

$$f_m = \frac{3Fa}{bh^2} \text{ N/mm}^2 \tag{5}$$

where $E_{m,l}$ is the local modulus of elasticity (MPa), $E_{m,g}$ is the global modulus of elasticity (MPa), f_m is the modulus of rupture (MPa), l_1 is the gauge length for the determination of modulus of elasticity (mm), I is the moment of inertia (mm^4), l is the span distance (mm), a is the distance between a loading position and the nearest support in a bending test (mm), $F2$ - $F1$ is the load difference at 10% and 40% of maximum load (N), w_2 - w_1 is the deflection difference at 10% and 40% of maximum load (mm), G is the shear modulus assumed as infinitive, b is the with (mm), and h is the height of samples (mm).

After the mechanical tests, each specimen’s defect-free density at the moisture content during the test was determined from a full cross-section piece of the timber cut as close to the location of the fracture after the experiments (Fig. 4a). Then, the pieces were immediately weighed with an accuracy of 0.01 g, and their dimensions were measured with an accuracy of 0.01 mm. Furthermore, the moisture contents were found with the same samples following the procedure defined in EN 13183-1 (2002) (Fig. 4b).

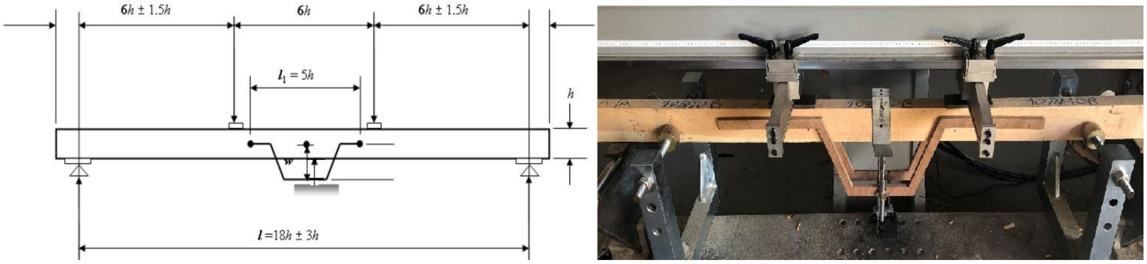

Fig. 3. 4-Point bending setup according to EN 408 (2018)

Fig. 4. (a) Moisture and density of sample cutting at the end of the test, and (b) oven drying for moisture content

Characteristic Value

According to EN 384 (2018) there are several adjustments required for obtaining characteristic values:

1) The experimental values for the modulus of elasticity and the density of specimens that were not at the reference moisture content, were adjusted using the following formulas (Eqs. 6 to 7),

$$MOE_{(12\%)} = MOE(u) \times \left[1 + 0.01 \times (u - u_{ref})\right] \tag{6}$$

$$\rho_{(12\%)} = \rho(u) \times \left[1 - 0.005 \times (u - u_{ref})\right] \tag{7}$$

where u is the moisture content at testing ($8\% \leq u \leq 18\%$), and u_{ref} is the reference moisture content (normally $u_{ref} = 12\%$).

2) f_m shall be adjusted to 150 mm depth by dividing with the factor k_h as described in the formula. Therefore, the bending strength values obtained from the samples with a depth of nominal 100 mm were adjusted to 150 mm depth by dividing by the factor k_h (Eq. 8):

$$k_h = Min\begin{cases}\left(\frac{150}{h}\right)^{0.2}\\ 1.3\end{cases} \tag{8}$$

3) $E_{m,g}$ shall be adjusted to the modulus of elasticity E_0 by using the following formula (Eq. 9):

$$E_0 = E_{m,g\%12} \times 1.3 - 2690 \tag{9}$$

After completing the required adjustments, the 5-percentile strength values $f_{05,i,}$ defect-free density $\rho_{05,i,}$ and the mean stiffness values were determined for each grade of Scots and Red pine species as stimulated in EN 14358 (2016), where bending strength was assumed as logarithmically distributed and modulus of elasticity and density were assumed as normally distributed. Thus, the parametric method was used to calculate the 5-percentile values of bending strength and density. The coefficient of the subsample was neglected.

Machine Strength Grading

Machine strength grading was made according to the EN 14081-2 (2022) standard. While bending strength, stiffness (local and global), and density values were used as the grade-determining properties (GDP), dynamic modulus of elasticity ($MOE_{d,vib}$ and $MOE_{d,ToF}$) values were used as the indicating properties (IP). Although the standard only recommends the vibration method, calculations were also made for the ToF method using the same procedures. For ToF measurement, the density value of 450 kg/m^3, prescribed by the standard for devices that do not measure weight, was used.

First, a group of structural timber was assigned to a strength class when that group's characteristic values met the class's requirement in EN 338 (2018). The characteristic values were the fifth percentile (ranking method) for bending strength and density, and the mean value for MOE was calculated according to EN 384 (2016). The k_v factor provided by EN 384 (2016) for machine grading was 1.12 when $f_{m,k}$ was equal to or less than 30 N/mm^2. Additionally, the requirement for the modulus of elasticity was 95% of the characteristic modulus of the class for all groups. Second, the machine settings were calculated. For each grade to be graded together (grade combination), a threshold of IP values was determined to achieve the required GDPs. Finally, the cost analysis was performed in three steps.

1. A size matrix was calculated for grade combination, giving the number of pieces in each of the optimum and assigned grades for the total sample.
2. An elementary cost matrix was determined, giving the costs of wrongly upgraded and downgraded pieces according to EN 14081-2 (2022).
3. A global cost matrix was calculated by multiplying each cell in the size matrix by the corresponding cell in the elementary cost matrix and dividing the result by the total number of pieces in the assigned grade.

A check was made that none of the cells corresponding to wrongly upgraded pieces in this global cost matrix exceeded 0.4.

In addition to visual and machine strength grading, the differences between means between groups were evaluated at a 95% confidence level ($p \leq 0.05$) (IBM SPSS 21.0 software) using an independent sample t-test for species comparison, and analysis of variance (ANOVA) for all other groups.

RESULTS AND DISCUSSION

The non-destructive and destructive test results were used for ANOVA to detect whether any significant differences exist statistically within $MOE_{\mathrm{d,\ vib\%12}}$, $MOE_{\mathrm{d,\ ToF\%12}}$, $E_{\mathrm{m,\ l\%12}}$, $E_{\mathrm{m,\ g\%12}}$, and f_{m}, considering the visual grades and cross-section of the specimens. Average values for moisture content, ρ_{12}, $MOE_{\mathrm{d,\ vib\%12}}$, $MOE_{\mathrm{d,\ ToF\%12}}$, $E_{\mathrm{m,\ l\%12}}$, $E_{\mathrm{m,\ g\%12}}$, and f_{m} are given separately for each visual grade and cross-section in Table 3 for Scots and Red pine species. Furthermore, the coefficient of variation values are given in parentheses. Afterward, the Duncan test was applied to the variables with significant differences and grouped them with lower-case letters and numbers over the mean values.

Table 3. Non-destructive and Destructive Test Results and ANOVA for Scots and Red Pine Structural Timbers

Species	Visual Grade	Cross-sections (cm)	N	M.C. (%)	ρ_{12} (kg/m^3)	$MOE_{\mathrm{d,\ vib,\%12}}$ (N/mm^2)	$MOE_{\mathrm{d,\ ToF,\%12}}$ (N/mm^2)	$E_{\mathrm{m,\ l,\%12}}$ (N/mm^2)	$E_{\mathrm{m,\ g,\%12}}$ (N/mm^2)	f_{m} (N/mm^2)
Scots Pine	1	-	90	14.7 (7.2)	524 (9.5)	13,746 ^{a} (13.1)	14,821^{a} (12.3)	14,103^{a} (17.0)	12,233^{a} (14.4)	53.9^{a} (18.4)
	2		90	14.7 (6.8)	508 (9.4)	12,382^{b} (12.6)	14,007^{b} (11.7)	12,905^{b} (15.6)	11,319^{b} (14.7)	46.9^{b} (19.5)
	3		90	14.5 (6.6)	502 (10.3)	11,233^{c} (14.2)	13,117^{c} (13.1)	11,381^{c} (19.3)	10,193^{c} (15.4)	40.0^{c} (25.5)
	-	5x10	90	13.7 (4.0)	503 (10.0)	12,294^{1} (17.8)	13,649^{1} (14.5)	12,927^{12} (22.7)	10,624^{1} (18.4)	48.4^{1} (26.5)
		5x15	90	15.3 (5.1)	509 (8.9)	12,446^{1} (14.5)	13,963^{12} (13.0)	12,307^{1} (17.6)	11,285^{2} (14.9)	46.0^{1} (22.5)
		5x20	90	14.9 (5.7)	522 (10.5)	12,621^{1} (14.5)	14,334^{2} (12.0)	13,154^{2} (16.5)	11,837^{3} (14.8)	46.4^{1} (22.6)
	General Total		270	14.6 (6.9)	511 (9.9)	12,453^{x} (15.6)	13,982^{x} (13.3)	12,796^{x} (19.3)	11,248 ^{x} (16.5)	46.9^{x} (24.1)
Red Pine	1	-	90	14.2 (6.1)	568 (13.5)	12,872^{a} (14.8)	14,307^{a} (13.3)	14,337^{a} (19.4)	12,160^{a} (15.1)	60.0^{a} (18.9)
	2		90	14.3 (6.0)	548 (12.1)	11,456^{b} (12.9)	13,282^{b} (11.0)	12,316^{b} (15.7)	10,814^{b} (13.3)	47.7^{b} (22.8)
	3		90	14.3 (6.9)	553 (9.8)	11,077^{b} (14.0)	13,268^{b} (12.8)	11,546^{c} (16.7)	10,264^{c} (14.0)	43.0^{c} (26.3)
	-	5x10	90	13.8 (4.8)	550 (13.6)	11,519^{1} (18.7)	13,341^{1} (13.8)	12,500^{1} (22.7)	10,677^{1} (18.5)	53.4^{2} (25.4)
		5x15	90	14.7 (4.9)	549 (9.1)	11,905^{1} (13.5)	13,735^{1} (11.8)	13,055^{1} (21.5)	11,125^{12} (15.3)	49.9^{1} (24.9)
		5x20	90	14.3 (7.3)	570 (12.4)	11,981^{1} (13.7)	13,781^{1} (13.1)	12,609^{1} (14.6)	11,437^{2} (13.3)	47.4^{1} (27.9)
	General Total		270	14.3 (6.3)	556 (12.0)	11,802^{y} (15.4)	13,619^{y} (12.9)	12,721^{x} (19.9)	11,079^{x} (15.9)	50.2^{y} (26.4)

*Values in parenthesis show the coefficient of variation. Different small letters above numbers in the related column show that there is a difference for each test value ($p < 0.05$) for visual grading. Different small numbers above numbers in the related column show that there is a difference for each test value ($p < 0.05$) for cross-sections.

The average $MOE_{\mathrm{d,\ vib,\%12}}$ values of Scots pine and red pine structural timbers were determined as 12,500 and 11,800 N/mm^2, respectively. Scots pine value was approximately 5.5% higher than red pine. Hassan *et al*. (2013) determined the dynamic modulus of elasticity as 11,000 N/mm^2 in small-clear Scots pine samples. In studies conducted on structural Scots pine timbers, Montero *et al*. (2015) found 9,680 N/mm^2 at 12% moisture content, Arriaga *et al*. (2012) found 10,900 N/mm^2, and Llana *et al*. (2018) found approximately 11,100 N/mm^2. Güntekin *et al*. (2013, 2014) found the dynamic modulus of elasticity as 9,840 N/mm^2 using the vibration method for Turkish red pine structural timbers at 27.1% moisture content.

The average $MOE_{\mathrm{d,\ ToF,\%12}}$ values of Scots pine and red pine structural timbers were determined as 14,000 and 13,600 N/mm^2, respectively. Scots pine was approximately 2.5% higher than red pine. Hassan *et al*. (2013), determined the dynamic modulus of elasticity as 11805 N/mm^2 in small-clear Scots pine samples using an ultrasonic device. Montero *et al*. (2015) and Llana *et al*. (2018) found 11,200 and 14,600 N/mm^2 in structural Scots pine timber, respectively. Güntekin and Aydin (2016) and Güntekin *et al*. (2015) found the dynamic modulus of elasticity as 11,100 and 13,200 N/mm^2 using an ultrasonic device for small-clear Red pine samples at 12.5% and 13.4% moisture content, respectively. The high amount of resin in Turkish red pine structural timber increases its density compared to Scots pine. However, the presence of resin causes lower frequency values to be obtained during vibration and an increase in the sound transmission time. Therefore, lower velocity values are obtained in red pine for both methods. The dynamic modulus of elasticity is calculated by multiplying the square of the velocity and the timber density. Therefore, it is understood that the increase in velocity is more effective than the increase in density. Therefore, Scots pine has a higher dynamic modulus of elasticity.

The average $E_{\mathrm{m,l,\%12}}$ values in Scots pine and red pine structural timbers were determined as 12,800 and 12,700 N/mm^2, respectively. Fundova *et al*. (2020) found the average local modulus of elasticity as 8500 N/mm^2, Fátharta *et al*. (2020) as 9240 N/mm^2, McLean (2019) as 9310 N/mm^2, and Burawska-Kupniewska *et al*. (2020) as 12,700 N/mm^2 on Scots pine. In addition, Moltini *et al*. (2022) determined 10,800, 11,500, 10,700, and 12,200 N/mm^2 in Scots pine structural timber obtained from four different regions of Spain, and the average of all regions was 11,300 N/mm^2.

The average $E_{\mathrm{m,g,\%12}}$ values of Scots pine and red pine structural timber values were 11,200 and 11,100 N/mm^2, respectively. Fundova *et al*. (2020) found the average global modulus of elasticity as 7900 N/mm^2, and Fátharta *et al*. (2020) found it in the 9100 to 12400 N/mm^2 range. In addition, Ranta-Maunus *et al*. (2011) determined that the average values for Scots pine growing in different countries were 12,400, 10,900, and 9100 N/mm^2. In their research on Scots pine, Arriaga *et al*. (2012) determined the average global modulus of elasticity as 10,440 N/mm^2. It is thought that the differences in the studies are due to the differences in the growing areas and the defect rates of the structural timbers. No study on Red pine structural timber by EN 408 (2012) test procedures has been found in the literature. When the average local and global modulus of elasticity for both species was compared with the independent sample t-test, it was determined that the averages did not differ at the 95% confidence level.

The average f_{m} was 46.9 and 50.2 N/mm^2 in Scots pine and Red pine structural timbers at 14.6% and 14.3% moisture content, respectively. Fundova *et al.* (2020) determined the average bending strength as 31.8 N/mm^2, Fátharta *et al*. (2020) as 38.0 N/mm^2, and Moore *et al*. (2008) as 44.5 N/mm^2. In addition, Ranta-Maunus *et al*. (2011) determined the average values for Scots pine growing in different countries as 42.0, 36.5, and 37.8 N/mm^2.

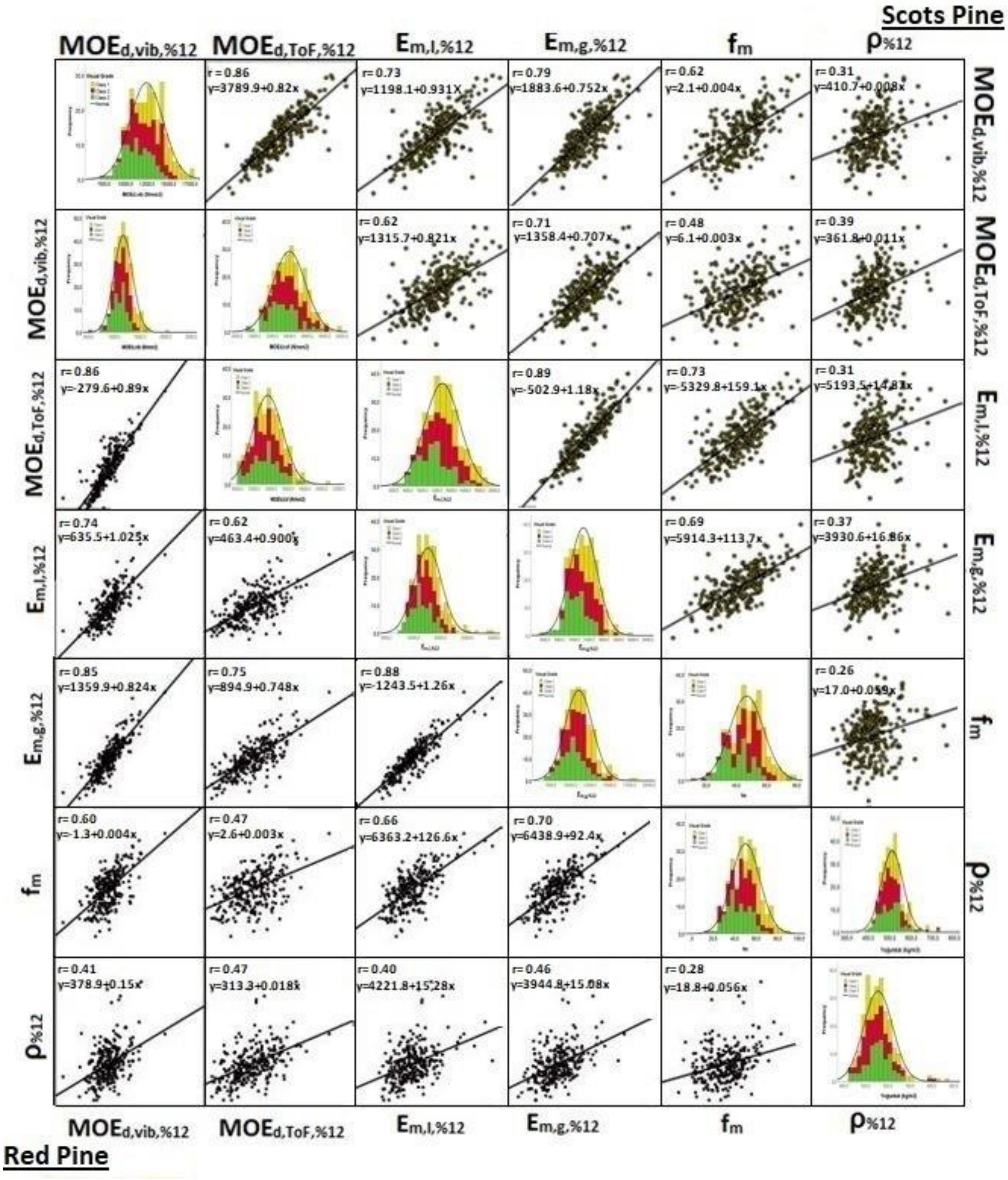

Fig. 5. Regression matrices of $MOE_{d,\ vib\%12}$, $MOE_{d,\ ToF\%12}$, $E_{m,\ l\%12}$, $E_{m,\ g\%12}$, f_m, and ρ_{12} for Scots and red pine

In their research on structural Scots pine timbers, Arriaga *et al*. (2012) determined the average bending strength value as 39.4 N/mm^2, and Burawska-Kupniewska *et al*. (2020) determined it as 47.0 N/mm^2. It is thought that the differences in the studies are due to the different growing conditions and the defect rates of the structural timbers. When the average bending strength of Scots pine and Red pine timber was compared with the independent sample t-test, it was determined that the averages differed at the 95% confidence level. It was determined that the average bending strength of Red pine structural timbers was approximately 7.0% higher than Scots pine timbers.

The frequency histograms of specimens and regression matrix of mechanical properties were plotted using dynamic modulus of elasticity-static modulus of elasticity, bending strength and density, static modulus of elasticity-bending strength and density, and bending strength-density for both species. Linear regression matrices for $MOE_{\mathrm{d,\ vib\%12}}$, $MOE_{\mathrm{d,\ ToF\%12}}$, $E_{\mathrm{m,\ l\%12}}$, $E_{\mathrm{m,\ g\%12}}$, f_{m}, and ρ_{12} are shown in Fig. 5 for Scots and Red pine. In the matrix, histograms were located at the points where the variables coincided with each other. Additionally, in the histogram graph, the yellow color indicates class 1, the red color class 2, and the green color indicates class 3 for both species.

According to Fig. 5, very high, positive (r = 0.86 and r = 0.86, respectively), and significant relationship at a 95% confidence level was found between the dynamic modulus of elasticity obtained by the vibration and the ToF methods in Scots pine and Red pine structural timbers. It was determined that the MOE_{d} values obtained in the vibration method compared to the ToF method were 12.3% lower in Scots pine and 15.4% lower in Red pine. Montero *et al*. (2015) found MOE_{d} at 16.0%, Llana *et al.* (2018) at 30.8%, and Görgün and Dündar (2018) at 14.4% higher in the ToF method compared to the vibration method. The reason for this could be that in the ToF method, the created stress wave travels by covering the shortest distance between the two sensors. In contrast, in the vibration method, the vibration created progresses by traveling through the entire volume of the timbers.

According to Fig. 5 very high and high, positive (r = 0.73 to 0.74 and r = 0.62 to 0.62, respectively), and significant relationships at a 95% confidence level were found between the local MOE and the MOE_{d} obtained by vibration and ToF methods in Scots and Red pine structural timbers. Fátharta *et al.* (2020), Ranta-Maunus *et al*. (2011), Krzosek *et al*. (2022), Ravenshorst (2015), and Nocetti *et al*. (2010) found very high positive and significant relationships between the vibration method and the local modulus of elasticity (r = 0.79, 0.92, 0.88, 0.83, and 0.73, respectively). No study in the literature has shown the relationship between the ToF method and the local MOE. For global MOE, very high, positive (r = 0.79 to 0.85 and r = 0.71 to 0.75, respectively), and significant relationships at a 95% confidence level were found between the global modulus of elasticity and the MOE_{d} obtained by vibration and ToF methods in Scots and Red pine structural timbers, respectively. Arriaga *et al*. (2012), Ravenshorst (2015), Gil-Moreno *et al*. (2022), Nocetti *et al*. (2010), and Görgün and Dündar (2018) found very high, positive, and significant relationships between the vibration method and global modulus elasticity in their studies (r = 0.85, 0.81, 0.83 to 0.89, 0.87, and 0.93, respectively). Further, Arriaga *et al*. (2022) and Görgün and Dündar (2018) found that there were high and very high, positive (r = 0.66 and 0.80, respectively) and significant relationships between the ToF method and the global modulus of elasticity.

According to Fig. 5, high and moderate, positive (r = 0.62 to 0.60 and r = 0.48 to 0.47, respectively), and significant relationships at a 95% confidence level were found between the bending strength and MOE_{d} obtained by vibration and ToF methods in pine structural timbers, respectively. Arriaga *et al*. (2012), Fátharta *et al*. (2020), Ravenshorst (2015), Ranta-Maunus *et al*. (2011), Gil-Moreno *et al*. (2022), Nocetti *et al*. (2010), and Görgün and Dündar (2018) found moderate, high, and very high, positive, and significant relationships between the vibration method and bending strength in their studies (r = 0.78, 0.66, 0.69, 0.71, 0.51 to 0.63, 0.49, and 0.79, respectively). Moreover, Arriaga *et al*. (2022) and Görgün and Dündar (2018) found that there were medium and high, positive (r = 0.58 and 0.61, respectively), and significant relationships between the ToF method and bending strength.

From Fig. 5, a moderate, positive (r = 0.31 to 0.41 and r = 0.39 to 0.47, respectively), and significant relationships at a 95% confidence level were found between density and MOE_{d} obtained by vibration and ToF methods in studied pine structural timbers. Fátharta *et al*. (2020), Ranta-Maunus *et al*. (2011), Krzosek *et al*. (2022), Nocetti *et al*. (2010), and Görgün and Dündar (2018) found moderate and very high positive correlations between the vibration method and density in their studies (r = 0.53, 0.73, 0.71, 0.48, and 0.74, respectively). Görgün and Dündar (2018) found a very high, positive (r = 0.72), and significant relationship between the ToF method and density in their study.

Figure 5 indicates a very high, positive (r = 0.89 and r = 0.88, respectively), and significant relationships at a 95% confidence level were found between local and global modulus of elasticity in pine structural timbers. Ravenshorst (2015), Gil-Moreno (2018), and Nocetti *et al*. (2010) also found very high, positive (r = 0.88, 0.95 to 0.93 to 0.95 to 0.94, and 0.87, respectively), and significant relationships in their studies. The local elasticity modulus / global elasticity modulus ratios in Scots pine and Red pine were determined as 1.14/1.00 and 1.15/1.00, respectively. Ravenshorst and Van de Kuilen (2009) found a ratio of 1.15, Solli (2000) and Nocetti *et al*. (2013) found it as 1.10, and Bostrom (1999) as 1.06. According to the EN 384 (2018) standard, the formula $E_{\mathrm{m,l}} = E_{\mathrm{m,g}} \times 1.22 - 834.2$ ($R^2 = 0.78$) was derived to convert the global modulus of elasticity into the local modulus of elasticity. The following formulas are available in the literature.

$E_{\mathrm{m,l}} = E_{\mathrm{m,g}} \times 1.13 - 800$ ($R^2 = 0.82$) Bostrom (1999)

$E_{\mathrm{m,l}} = E_{\mathrm{m,g}} \times 1.18 - 856$ ($R^2 = 0.89$) Solli (2000)

$E_{\mathrm{m,l}} = E_{\mathrm{m,g}} \times 1.28 + 2300$ ($R^2 = 0.88$) Nocetti *et al*. (2013)

$E_{\mathrm{m,l}} = E_{\mathrm{m,g}} \times 1.13 - 873$ ($R^2 = 0.88$) Gil-Moreno *et al*. (2016)

From Fig. 5 moderate, positive (r = 0.31 to 0.37 and r = 0.40 to 0.46, respectively), and significant relationships at a 95% confidence level were found between density and local and global modulus of elasticity in Scots pine and Red pine structural timbers. Ranta-Maunus *et al*. (2011), Krzosek *et al*. (2022), Gil-Moreno (2018), and Nocetti *et al*. (2010) reported moderate, high, and very high positive correlations between local modulus of elasticity and density (r = 0.73, 0.64, 0.73 to 0.69 to 0.40 to 0.53 and 0.30, respectively). Gil-Moreno (2018), Gil-Moreno *et al*. (2022) and Nocetti *et al*. (2010) reported moderate, high, and very high positive correlations between global modulus of elastic and density (r = 0.78 to 0.76 to 0.44 to 0.56, 0.53 to 0.49, and 0.37, respectively).

Figure 5 indicates high and very high, positive (r = 0.73 to 0.69 and r = 0.66 to 0.70, respectively), and significant relationships at a 95% confidence level between bending strength and local and global modulus elasticity in pine structural timbers. Ranta-Maunus *et al*. (2011), Krzosek *et al*. (2022), Gil-Moreno (2018), and Nocetti *et al*. (2010) reported moderate, high, and very high, positive correlations between local modulus of elasticity and bending strength (r = 0.73, 0.75, 0.8 to 0.78 to 0.77 to 0.77, and 0.60, respectively). Gil-Moreno (2018), Gil-Moreno *et al*. (2022), and Nocetti *et al*. (2010) reported high and very high, positive correlations between the global modulus of elasticity and bending strength (r = 0.79 to 0.77 to 0.75 to 0.79, 0.70 to 0.74 and 0.63, respectively).

Furthermore, low, positive (r = 0.26 and r = 0.28, respectively), and significant relationships at a 95% confidence level were found between density and bending strength in Scots pine and Red pine structural timbers. Ranta-Maunus *et al*. (2011), Krzosek *et al*. (2022), Gil-Moreno (2018), Gil-Moreno *et al*. (2022), and Nocetti *et al*. (2010) reported low, medium and high, positive correlations between density and bending strength (r = 0.46, 0.28, 0.62 to 0.60 to 0.39 to 0.43, 0.47 to 0.48, and 0.22, respectively).

The strength class CXX defines the bending strength of edgewise bended samples in the strength grading of Europe. After the 5 percentile values of bending strength and density, and mean value of modulus of elasticity were calculated, strength classes were declared by EN 338 (2016) for Scots and Red pine as shown in Table 4.

Table 4. Determination of Strength Classes for Scots and Red Pine According to Local and Global Modulus of Elasticity

Characteristic Values (5-percentile)			f_m (N/mm^2)				MOE (kN/mm^2)		Density (Kg/m^3)			Strength Classes
Species	Number	Visual Grade	Mean	CoV (%)	P/NP	$f_{05,i}$	$E_{0,mean}$	CoV (%)	Mean	CoV (%)	$\rho_{05,i}$	
Scots Pine	90	1	52.4	17.8	P	37.3	14.1^	17.0	524.7	9.5	435.1	C35
							13.2*	17.4				C35
	90	2	45.7	19.9	P	29.8	12.9^	15.6	507.6	9.4	422.6	C27
							12.0*	18.0				C27
	90	3	38.9	25.2	P	23.1	11.4^	19.3	501.8	10.3	408.9	C22
							10.6*	19.4				C22
Red Pine	90	1	58.3	18.3	P	41.0	14.3^	19.4	567.9	13.5	430.8	C40
							13.1*	18.2				C35
	90	2	46.3	22.4	P	29.5	12.3^	15.8	548.4	12.1	429.5	C27
							11.4*	16.4				C24
	90	3	41.8	26.2	P	24.2	11.5^	16.7	552.6	9.8	455.7	C24
							10.7*	17.5				C22

"^" Shows mean value of local modulus of elasticity and "*" shows mean value of global modulus of elasticity

Table 5. Machine Settings for Scots and Red Pine

IP	Species	GDP	R^2	Equation	F-statistic	Sig.
$MOE_{d, vib,\%12}$ + Knot Diameter Ratio (KDR)	Scots Pine	f_m	0.439	0.003×IP + 14.771 - 17.01×KDR	104.265	0.001
		$E_{m,l,\%12}$	0.539	0.931×IP + 1198.086	313.178	0.001
		$E_{m,g,\%12}$	0.617	0.752×IP + 1883.605	432.413	0.001
		$\rho_{\%12}$	0.096	0.008×IP + 410.7	28,607	0.001
	Red Pine	f_m	0.498	0.003×IP + 19.523 - 33.075×KDR	132.469	0.001
		$E_{m,l,\%12}$	0.542	1.025×IP + 623.470	317.105	0.001
		$E_{m,g,\%12}$	0.724	0.824×IP + 1359.86	703.185	0.001
		$\rho_{\%12}$	0.169	0.015×IP + 378.861	54.536	0.001
$MOE_{d, ToF,\%12}$ + Knot Diameter Ratio (KDR)	Scots Pine	f_m	0.305	0.002×IP + 27.733 - 30.241×KDR	58.555	0.001
		$E_{m,l,\%12}$	0.290	1.106×IP - 341.732	109.711	0.001
		$E_{m,g,\%12}$	0.330	0.889×IP + 684.929	131.989	0.001
		$\rho_{\%12}$	0.005	-	1.427	0.233
	Red Pine	f_m	0.416	0.004×IP + 19.287 - 39.76×KDR	95.282	0.001
		$E_{m,l,\%12}$	0.285	1.171×IP - 257.392	106.803	0.001
		$E_{m,g,\%12}$	0.376	0.935×IP + 720.159	161.313	0.001
		$\rho_{\%12}$	0.000	-	0.051	0.822

For local and global modulus of elasticities in Scots pine, class 1, class 2, and class 3 structural timbers are assigned to C35-C27-C22 strength classes, respectively. Red pine is assigned to strength classes C40-C27-C24 for local modulus of elasticity and C35-C24-C22 for global modulus of elasticity. The strength classes obtained in this study for Scots and Red pine species and presented in EN 1912 (2012) were compared. Red pine had higher strength classes than strength classes using EN 1912 (2012), where Class 1 = C35, Class 2 = C24, and Class 3 = C18. Unlike Red pine, the same strength classes were found for Scots pine in Class 1 = C35 and Class 2 = C27; however, a slight increase was found for Class 2 as equal to C22 compared to C20. Using the global modulus of elasticity may cause changes in strength classes, as seen in Red pine. In this study, the reason for reaching higher strength classes is that subsample groups were not included.

For Scots and red pine structural timbers, machine settings were determined separately using vibration and ToF methods as IP, local modulus of elasticity, and global modulus of elasticity as GDP. Ideal grade combinations were determined as C40-C30-C22-C16-R. Machine settings for both species are given in Table 5.

Characteristic values of grade combinations and IP settings obtained from the machine grading for each strength class and both species according to local modulus of elasticity and global modulus of elasticity are given in Tables 6 and 7, respectively.

Table 6. Characteristic Values and Machine Settings for $MOE_{\mathrm{d,vib\%12}}$ and $MOE_{\mathrm{d,ToF\%12}}$ (IP) – $E_{\mathrm{m,l\%12}}$ (GDP)

Characteristic Values (5-percentile)		f_{m}				MOE		Density			$MOE_{\mathrm{d,vib}}$ IP Setting (N/mm^2)	$MOE_{\mathrm{d,ToF}}$ IP Setting (N/mm^2)
		(N/mm^2)				(kN/mm^2)		(Kg/m^3)				
Species	Strength Grade	Mean	CoV (%)	P/NP	$f_{05,i}$	$E_{0,mean}$	V.K (%)	Mean	CoV (%)	$\rho_{05,i}$		
Scots Pine	C40	55.1	14.3	NP	43.3	15.7	9.3	533.1	10.0	460.1	13751	12968
	C30	46.8	16.2	NP	32.6	13.0	5.1	506.3	8.2	449.4	10958	10617
	C22	40.2	19.5	NP	25.7	11.1	7.7	494.6	8.8	425.0	8918	8899
	C16	33.9	18.9	NP	23.4	9.3	8.2	509.5	11.6	439.5	6877	7181
	Rej.	21.5	27.5	NP	13.1	7.4	9.7	488.4	10.4	431.6	-	-
Red Pine	C40	61.2	15.6	NP	46.3	15.9	13.6	581.7	12.2	499.1	13051	12176
	C30	48.5	19.5	NP	33.6	13.0	4.5	573.1	10.9	490.7	10514	9956
	C22	44.7	20.5	NP	27.0	11.2	6.2	533.4	9.5	453.9	8660	8333
	C16	35.3	24.6	NP	22.1	9.4	6.7	517.7	11.6	425.8	6807	6710
	Rej.	20.9	27.3	NP	15.3	9.0	13.9	487.4	7.5	450.9	-	-

Table 7. Characteristic Values And Machine Settings for $MOE_{\mathrm{d,vib\%12}}$ and $MOE_{\mathrm{d,ToF\%12}}$ (IP) – $E_{\mathrm{m,g\%12}}$ (GDP)

Characteristic Values (5-percentile)		MOR				MOE		Density			$\mathrm{MOE_{d,vib}}$ IP Setting (N/mm^2)	$\mathrm{MOE_{d,ToF}}$ IP Setting (N/mm^2)
		(N/mm^2)				(kN/mm^2)		(kg/m^3)				
Species	Strength Grade	Mean	CoV (%)	P/NP	$f_{05,i}$	$E_{0,mean}$	V.K (%)	Mean	CoV (%)	$\rho_{05,i}$		
Scots Pine	C40	57.1	14.0	NP	43.5	15.3	8.4	546.5	9.7	467.5	16112	14978
	C30	48.9	15.6	NP	34.1	13.0	5.3	512.2	7.8	461.7	12654	12053
	C22	42.3	18.3	NP	27.1	11.0	5.8	502.0	8.5	444.8	10128	9916
	C16	37.4	21.3	NP	25.7	9.1	5.3	493.1	10.8	426.7	7602	7779
	Rej.	27.2	28.9	NP	15.6	6.9	14.2	480.4	10.0	429.2	-	-
Red Pine	C40	63.8	17.0	NP	44.2	15.7	10.3	609.8	11.7	534.7	15340	14203
	C30	53.1	18.3	NP	37.8	12.9	4.5	577.0	11.5	493.1	12185	11422
	C22	47.3	19.1	NP	31.7	11.0	5.4	540.1	9.4	455.9	9879	9390
	C16	38.1	22.6	NP	25.6	9.1	6.1	530.7	10.4	452.7	7573	7358
	Rej.	28.3	24.0	NP	18.4	7.5	8.4	482.0	6.8	482.0	-	-

The machine grading results for all combinations obtained are shown for Scots and Red pine structural timbers in Fig. 6.

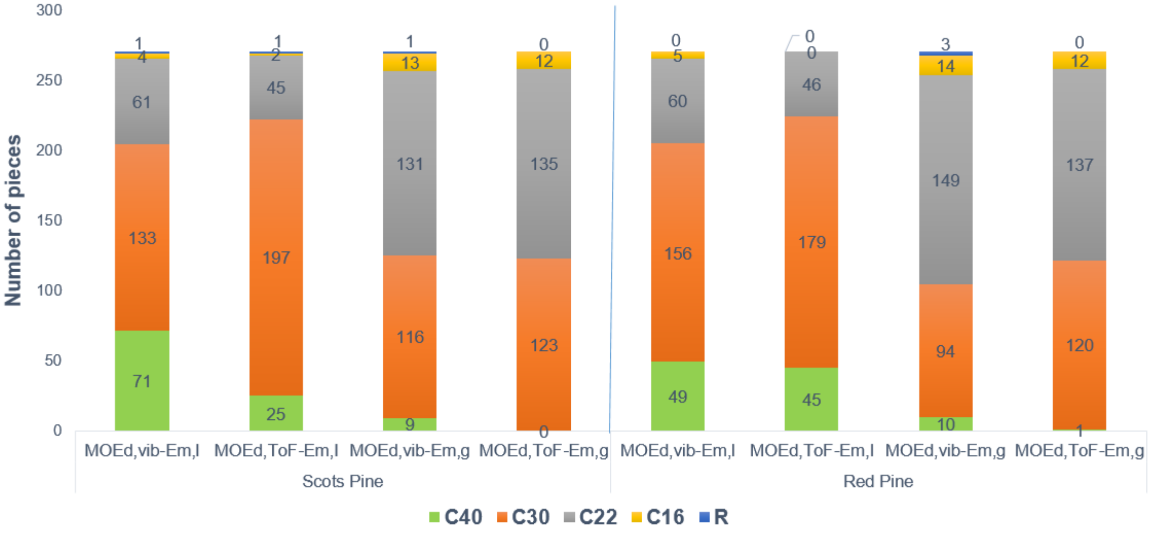

Fig. 6. Results of machine grading for all combinations in Scots and Red pine structural timbers

According to the machine grading results, the vibration method (IP) - local modulus of elasticity (GDP) setting gave the best yield for both species, while the ToF method (IP) - global modulus of elasticity (GDP) gave the lowest yield. Moreover, when machine strength grading was compared with visual strength grading, it is apparent that the efficiency of machine strength grading was much higher. For this reason, machine strength grading is judged to be more advantageous than visual strength grading. Many European companies are working on this subject and developing new machines (Nocetti *et al*. 2010; Ridley-Ellis *et al*. 2016; Burawska-Kupniewska *et al*. 2020; Krzosek *et al*. 2020; Krzosek and Burawska 2022). In Türkiye, studies continue to produce devices that can be used for this purpose.

CONCLUSIONS

1. According to the non-destructive test results, it was determined that the MOE_d obtained by the vibration method was 12.3% lower in Scots pine and 15.4% lower in Red pine than the MOE_d obtained by the ToF method, respectively. It was determined that there was a very high, positive, and significant relationship between the vibration method and the ToF method for both species (r = 0.86). Generally, it has been determined that the vibration method gives higher correlations with destructive tests than the ToF method. For this reason, it was more successful in timber grading.
2. Due to the destructive tests, the ratios between local and global modulus of elasticity were determined as 1.14/1.00 for Scots pine and 1.15/1.00 for Red pine, respectively. As an alternative to the conversion formula in the EN 384 (2018) standard, the formula "$E_{m,l} = E_{m,g} \times 1.22 - 834.2$ ($R^2 = 0.78$)" was derived. It was demonstrated that using the global modulus of elasticity may cause changes in strength classes. In the current system, using the local modulus of elasticity is more advantageous than the global modulus of elasticity. Additionally, approximately 7% higher values were obtained in bending strength in Red pine than in Scots pine.

3. Characteristic values were calculated for each visual class. For local and global modulus of elasticity in Scots pine, class 1, class 2, and class 3 structural timbers are assigned to C35-C27-C22 strength classes, respectively. Red pine is assigned to strength classes C40-C27-C24 for local modulus of elasticity and C35-C24-C22 for global modulus of elasticity. Accordingly, it has been determined that as the visual class degrades, the strength class also degrades. According to the results, the TS 1265 (2012) standard is suitable for structural timber classification.
4. In the machine strength grading, separate machine settings were made for local and global modulus of elasticity using both vibration and ToF methods for the C40-C30-C22-C16-R strength combination. Accordingly, the best efficiency in machine strength grading was obtained in the vibration method (IP)-local modulus of elasticity (GDP) combination. Higher efficiency was achieved in machine strength grading compared to visual strength grading. Thus, it has been demonstrated that the strength classes of structural timbers can be evaluated more efficiently with non-destructive methods.

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Author Contributions

All authors contributed to the conceptualization and methodology of the study. Material preparation, data collection, and analysis were performed by FK. The first draft of the manuscript was written by FK and NA commented on subsequent versions of the manuscript. All authors read and approved the final manuscript.

Availability of Data and Material

Data used for this work are available from the corresponding author upon reasonable request.

Orcid

Fatih Kurul: https://orcid.org/0000-0002-4473-4159
Nusret As: https://orcid.org/ 0000-0002-5269-1574

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