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STRENGTH GRADING OF TURKISH BLACK PINE STRUCTURAL TIMBER BY VISUAL EVALUATION AND NONDESTRUCTIVE TESTING

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ABSTRACT

We examined the compatibility between the visual strength grading and the mechanical properties determined by using nondestructive and destructive test methods in Turkish Black Pine structural timbers. Fifty three structural timber were graded with three different visual strength grading standards. Dynamic modulus of elasticity was determined by longitudinal vibration (MOEdv) and stress wave (MOEds) test methods. The static modulus of elasticity (MOEs) and the modulus of rupture (MOR) of the timbers were determined in structural size.

The average dynamic and static modulus of elasticity and modulus of rupture values of the timber sorted into best class of all standards were considerably higher than the lower classes. The differences in the modulus of elasticity values between the strength classes were found significant for British and German standards but insignificant for Turkish standard. However the decrease in modulus of rupture values with decreasing grading class was found significant for all standards. Best compliance between the visual grading class and the dynamic or static modulus of elasticity and modulus of rupture was observed. Strong correlations were found between the dynamic modulus of elasticity and static modulus of elasticity and modulus of rupture. Longitudinal vibration method showed better correlation with the static modulus of elasticity and modulus of rupture than stress wave method.

Keywords: Longitudinal vibration method, mechanical properties, *Pinus nigra,* stress wave method, visual strength grading.

INTRODUCTION

Regardless of species and size, lumber even if sawn from the same log, may show great variations in physical and mechanical properties due to its biological nature and the presence of irregularities. This is especially important for structural applications where the engineers are often confused with the performance variability found in structural members. Therefore, lumber used for structural applications must be graded and clearly marked to show it complies with the correct standards and strength requirements laid down by building codes and regulations. This grading process is helpful for building complex structures such as buildings, bridges, ships etc.

Strength grading of structural lumber is a process by which lumber is sorted by either visual inspection or mechanical strength grading into strength classes or strength grades. The hybrid systems that involve both of visual and mechanical grading have also been used commonly. In visual stress-grading, the lumber is sorted into groups based on the occurrences of strength-reducing features such as knots, slope of grain, splits etc. Mechanical strength grading is based on the measurements of modulus

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of elasticity (MOE) by non-destructive methods. Today, most commonly used form of mechanical stress-grading is machine strength grading. The system measures the MOE (flat) as the lumber passes longitudinally through a machine. This can be done either by measuring the deformation of lumber subjected to constant loads, or by measuring the loads required to keep the lumber at a constant deformation (Leicester 2004). The measurement of MOE by dynamic techniques (vibration technique, stress wave) is another common method for mechanical strength grading of lumber in sawmills.

Vibration methods to predict static properties have been investigated since 1950s (Kitazawa 1950, Bell *et al.* 1950, Fukada 1950, Jayne 1959, Matsumoto 1962). As a potential lumber grading method, the transverse vibration testing technique measures natural frequencies of the vibration in a very short time, which in turn provides the MOE of the test material since the natural frequencies of a member are governed by its MOE and other easily measured parameters of test specimens (Ross and Pellerin 1994). The use of vibration techniques in lumber grading has evolved considerably, especially in the past several years. Jayne (1959) designed and conducted one of the first studies that utilized transverse vibration techniques for evaluating the strength of wood. The relationship between dynamic MOE and static MOE was further validated and improved (Jayne 1959, James 1964, Pellerin 1965, Ross and Pellerin 1994, Divós and Tanaka 2005). In past decade, some researchers have focused on longitudinal vibration techniques and have achived successful results (Iniguez *et al.* 2008, Divós and Kiss 2010, Vega *et al.* 2011).

Another NDE method of attracting attention to grade structural lumber into strength classes is stress-wave technique which is based on the measurement of the velocity of propagation of a stress wave generated by a shock. This technique was developed in the USA at Washington State University for the determination of the dynamic elastic modulus of many wood products (Gerhards 1982, Bucur 2006, Wang 2008, Inés *et al.* 2011). The compliance between the visual strength grading and the mechanical properties has been also investigated by numerous researchers (Green and Shelley 1992, Baltrušaitis and Pranckevičienė 2003, Piazza and Riggio 2008, Wang *et al.* 2008, Casado *et al.* 2010).

The objective of this study is to determine the compatibility between the visual strength grading and the mechanical properties determined by using nondestructive and destructive test methods in Turkish Black Pine (*Pinus nigra*) structural timbers. The specific objectives are (1) to examine the relationships between visual strength grading and dynamic MOE determined by longitudinal vibration (MOEdv) and stress wave (MOEds) test methods (2) to examine the relationships between visual strength grading and static MOE (MOEs) and modulus of rupture (MOR), (3) to compare the different visual strength grading standards in terms of their strength grading success with destructive values (MOEs and MOR) and (4) to determine the relationships between MOEdv, MOEds and MOEs, MOR values.

MATERIALS AND METHODS

Materials

In this study, 53 structural lumbers of Turkish Black Pine (*Pinus nigra* var *pallasiana* Arnold.) in air-dry condition with the dimension of 6 cm width, 8-10 cm depth and 2-m-length were used. The moisture content of the lumbers was measured using electrical resistance equipment by following the procedure defined in the EN 13183-2 standard. The average moisture content of the lumbers was determined as 15,4%.

Visual grading

First lumbers were graded in accordance with the specifications for three visual grading standards; TS 1265 (Turkish), DIN 4074 (German), and BS 4978 (English). Table 1 shows the grading classes of these standards.

As seen on Table 1, BS 4978 standard has two grading classes while the other standards have three classes. The timber, which were not graded into any quality class, were marked as “out of grade”.

Table 1. Visual grading classes of standards.

Standards	Classes (Best		Worst)	
TS 1265	I.	II.	III.	Out of grade
DIN 4074	S13	S10	S17	Out of grade
BS 4978	SS	GS	-	Out of grade

Longitudinal Vibration Method

Following the visual examination, dynamic MOE (MOEdv) was determined by using of longitudinal vibration non-destructive test method. This method is based on measuring the resonance frequency of longitudinal vibration produced by the impact at one end of the piece, which crosses in its entirely. The test setup is represented in Figure 1.

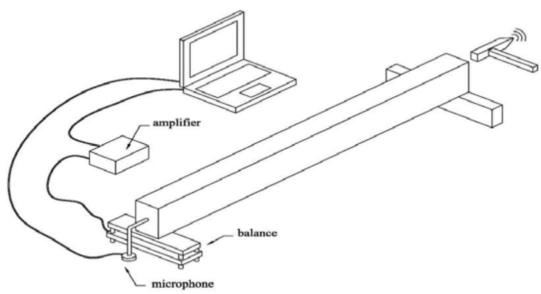

Figure 1. Longitudinal vibration method setup for portable lumber grader (PLG) developed by FAKOPP.

In the test procedure the specimens are placed on two supports with soft polyurethane pillows to ensure test pieces are free of vibration. One of these is simultaneously supported and balanced, recording the half mass of each piece. The end of a specimen is hit by a hammer 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. The fundamental vibration frequency of the sound is analysed by fast Fourier transform sound analyser.

Using the specimen's mass (m, in kg), width (w, in m), length (l, in m), height (h in m), and the longitudinal vibration frequency (f, in Hz), MOEdv (in N/mm^2) is calculated with the following equation (Equation 1):

$$MOEdv = \frac{\left(\frac{m}{lwh}\right)(2fl)^2}{1000} \quad (1)$$

Stress Wave Method

As a second NDT technique, stress wave method was used to measure the dynamic MOE (MOEds) of lumbers. The method was carried out using a Fakopp Microsecond Timer (23kHz). This is a portable microsecond stress-wave timer with two piezoelectric-type transducers equipped with 60 mm long spikes. The spike probe fixes the transducer into the wood and also functions as a wave guide. The stress wave is induced by a simple hammer impact and the output displayed on the meter is the time-of-flight (ToF) in microseconds (Figure 2).

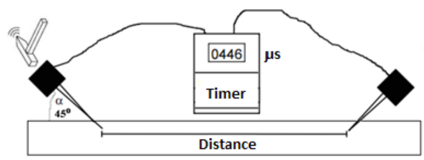

Fig ner.

Stress wave velocity (V, in m/s) was calculated using distance between the transducers (L, in m) and the ToF of the pulse from the transmitting transducer to the receiving transducer (t, in µs) by the following Equation 2:

$$V = \frac{L}{t} x1000000 \quad (2)$$

Later, dynamic elasticity of modulus (MOEds, in MPa) was calculated using the specimen's density (d, in g/cm^3), by the following Equation 3:

$$MOEds = \frac{V^2 d}{1000} \quad (3)$$

Destructive tests

Following the nondestructive tests, static modulus of elasticity (MOEs) and modulus of rupture (MOR) were determined on the timbers in structural size in accordance with EN 408 (Figure 3).

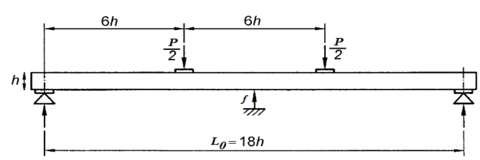

Figure 3. Static Four Point Bending Test Arrangement According to EN 408.

Tests were carried out with the universal testing machine, which was equipped with load cell of 100 kN. Global static modulus of elasticity (MOEs) was calculated as follows Equation 4 :

$$MOEs = \frac{(L_0)^3 (\mathrm{P}_2 - \mathrm{P}_1)}{bh^3 (f_2 - f_1)} \left[\left(\frac{3a}{4L_o} \right) - \left(\frac{a}{L_o} \right)^3 \right] \quad (4)$$

Where; MOEs is the static modulus of elasticity (N/mm^2), L_0 is the effective span distance (mm), P_2-P_1 is the load difference between 10% and 40% of maximum load (N), f_2-f_1 is the deflection difference at 10% and 40% of maximum load (mm), b is the width (mm), h is the height (mm) and a is the distance between loading point and nearest support point (6h) (mm).

Modulus of rupture (MOR) was calculated as follows Equation 5:

$$MOR = \frac{3P_{\max} a}{bh^2} \quad (5)$$

Where; MOR is the static modulus of rupture (N/mm^2) and P_{max} is the maximum load (N).

In order to analyze the obtained data, first the percentages of the lumber sorted into each strength class according to different visual grading standards were compared each other. Than the relationships between the following parameters were examined, (1) visual strength classes vs. MOEd (ANOVA), (2) visual strength classes vs. MOEs and MOR (ANOVA), (3) MOEd (stress wave, vibration) vs. MOEs and MOR (regression analysis). The strength grading success of different visual grading standards was evaluated in consideration of the grading class-strength and stiffness relationships.

RESULTS AND DISCUSSION

The results of the visual strength grading of the lumbers according to three standards are shown in Table 2. The lumbers graded according to TS 1265 took place mostly in high strength class while the lumber graded according to DIN 4074 and BS 4978 took place in a high proportion of medium strength class. The highest frequency of below-grade-lumber was found in grading according to BS 4978 while the lowest frequency was found for TS 1265.

Table 2. Results of the visual strength grading of the lumbers.

Standard	Class	Frequency	Percentage (%)
TS 1265	I	20	37,8
	II	15	28,3
	III	14	26,4
	Below Grade	4	7,5
DIN 4074	S13	4	7,5
	S10	23	43,4
	S7	16	30,2
	Below Grade	10	18,9
BS 4978	SS	15	28,3
	GS	24	45,3
	Below Grade	14	26,4

Table 3. Non-destructive and destructive tests results.

Standard	Class	MOEds (GPa)	MOEdv (GPa)	MOEs (GPa)	MOR (MPa)
TS 1265	I	15,468 (2,98)^{a}	12,940 (2,97)^{f}	13,258 (3,02)^{k}	76,62 (14,17)^{p}
	II	14,202 (2,51)^{a}	11,480 (2,46)^{f}	12,031 (2,76)^{k}	64,76 (18,92)^{pq}
	III	15,038 (2,14)^{a}	11,585 (1,56)^{f}	12,706 (2,01)^{k}	55,63 (17,27)^{q}
	Below Grade	15,509 (2,54)^{a}	11,525 (2,57)^{f}	10,961 (2,70)^{k}	57,31 (20,29)^{q}
DIN 4074	S13	16,953 (2,09)^{b}	14,325 (3,15)^{g}	14,579 (3,19)^{l}	87,00 (6,99)^{r}
	S10	14,878 (2,78)^{bc}	11,934 (2,42)^{gh}	12,570 (2,75)^{lm}	68,65 (14,09)^{s}
	S7	15,401 (2,45)^{bc}	12,306 (2,35)^{gh}	12,968 (2,25)^{lm}	62,45 (21,39)^{s}
	Below Grade	13,853 (2,27)^{c}	11,060 (2,80)^{h}	11,244 (2,80)^{m}	58,56 (21,00)^{s}
BS 4978	SS	16,462 (2,32)^{d}	14,187 (2,18)^{i}	14,667 (2,12)^{n}	82,91 (10,34)^{t}
	GS	14,960 (2,19)^{de}	11,713 (1,81)^{j}	12,217 (2,17)^{o}	65,90 (13,12)^{u}
	Below Grade	13,318 (2,74)^{e}	10,386 (2,66)^{j}	11,010 (2,85)^{o}	49,03 (18,08)^{v}

*The numbers in pharantesis are standard deviations, the same letter on the numbers showes homogeneity groups ($p<0,05$).

Table 3 summarizes the average values of dynamic MOE determined by longitudinal vibration (MOEdv) and stress wave (MOEds) nondestructive tests and static MOE and MOR obtained from static bending tests for grading classes of the standards. ANOVA was applied for investigating the compatibility between the mechanical properties and the grading classes of the standards. The same letter on the numbers showed homogeneity groups at the 95% confidence level for each standard. It was noted that the ANOVA was applied separately for each standard.

When considering the dynamic MOE determined by both stress wave and longitudinal vibration methods, the average values of best classes of all standards were considerably higher than the other classes (Table 3). The differences between the visual strength classes were found significant ($p<0,05$) for British and German standards but nonsignificant for Turkish standard. Best compliance between the visual grading class and the dynamic MOE was observed for British standard where the dynamic MOE decreased as the visual grading class decreased. It has been noted that the British standard has two strength classes while the Turkish and German standards have three strength classes.

Another point to note in terms of dynamic MOE in Table 3 is that the average values determined by stress wave method (MOEds) were higher than the longitudinal vibration method (MOEdv). Stress wave method is based on the measurement of the time for the stress wave travel from the transmit probe to the receiver probe (ToF).

As the ToF is measured in a path between the two probes as shortest as possible, ToF is less affected by the material's characteristics. However, the longitudinal vibration method is based on the observation of hundreds of acoustic pulses resonating longitudinally in a timber and provides a weighted average acoustic velocity (Wang and Carter 2015). Therefore, the acoustic velocity measured by longitudinal vibration highly depends on the material's characteristics.

The average static MOE values showed a similar trend with the dynamic MOE (Table 3). The highest MOEs values were obtained from the timber sorted into the best class of the standards.

These were found significant ($p<0,05$) for British and German standards but insignificant for Turkish standard. Again, the visual strength grading according to BS 4978 displayed best match with the static MOE.

Especially for MOR values in Table 3, significant ($p<0,05$) differences were found between the timber sorted into the best class and the lower classes for all standards used in this research. In general, the lower visual grading class resulted in the lower average of MOR values. The MOR values displayed the best match with the visual grading classes for all standards when comparing to dynamic and static MOE. This was expecting because the visual strength grading is based on the strength reducing features of the material such as knots, splits, slope of grain etc. and the MOR is more sensitive to these defects than the MOE. As in static and dynamic modulus of elasticity, BS 4978 showed the best match with the average MOR values where the higher visual grading class resulted in significantly higher MOR ($p<0,05$). It is well known that knots are the most important strength-reducing feature in a timber.

Table 4. Comparison of the best and the worst class of the standards.

Class	Standard	MOEds (GPa)	MOEdv (GPa)	MOEs (GPa)	MOR (MPa)
Best	TS 1265	15467 (2,98)^{a}	12940 (2,97)^{c}	13258 (3,02)^{e}	76,62 (14,18)^{g}
	DIN 4074	16953 (1,04)^{a}	14187 (3,15)^{c}	14579 (3,19)^{e}	87,00 (6,99)^{g}
	BS 4978	16463 (5,99)^{a}	14325 (2,18)^{c}	14667 (2,12)^{e}	82,91 (10,34)^{g}
Worst (Below grade)	TS 1265	15510 (2,54)^{b}	11525 (3,41)^{d}	10961 (2,79)^{f}	57,31 (20,29)^{h}
	DIN 4074	13853 (2,27)^{b}	11060 (2,80)^{d}	11244 (2,80)^{f}	58,56 (21,00)^{h}
	BS 4978	13318 (2,74)^{b}	10386 (2,66)^{d}	11010 (2,85)^{f}	49,03 (18,08)^{h}

* The numbers in pharantesis are standard deviations, the same letter on the numbers showed homogeneity groups ($p<0,05$).

For determining the strength class of the timber, unlike TS 1265 and DIN 4074, BS 4978 takes into consideration the knots not only their presence and size but also locations. Another point is that British standard evaluates the knots as three dimensional while TS 1265 and DIN 4074 take into account them only appearance on the surface. We thought that, these are the reasons of the better compliance of BS 4978 with the mechanical properties of timber than the other standards. This result indicates that, a more detailed assessment considering the size, the location, and the extension of the strength reducing features of timbers is required for improving the succsess of visual strength grading.

In order to compare the mechanical properties of timber sorted into same class according to different standards, ANOVA was applied to the best and the worst (below grade) grading class. Table 4 gives the results of the ANOVA test. No significant differences were found between the grading standards in terms of the best and the worst grading class ($p<0,05$). This result reveals that there is no considerable difference between the same visual classes of the standards.

Figure 4 and Figure 5 shows the linear regression analysis performed between non-destructive and destructive test results for all timber.

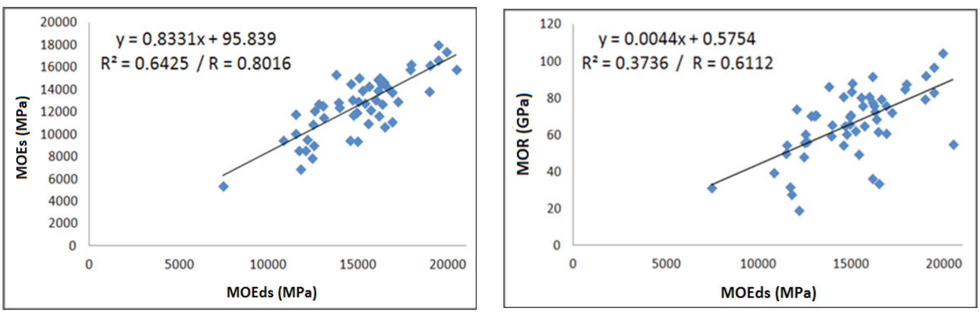

Figure 4. The relationships between the dynamic MOE determined by stress wave test and static MOE and MOR.

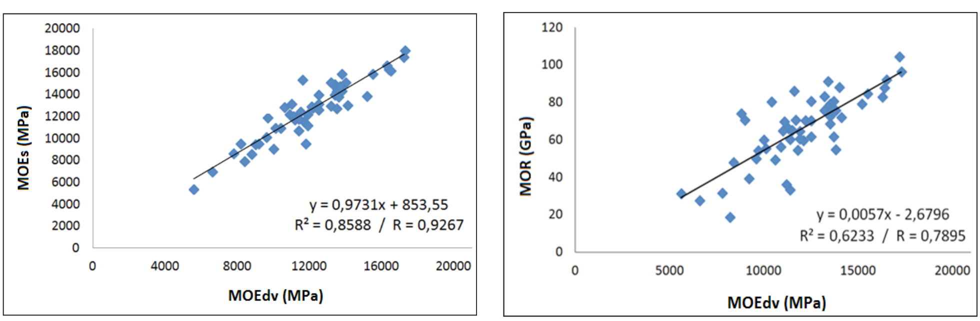

Figure 5. The relationships between the dynamic MOE determined by longitudinal vibration test and static MOE and MOR.

Strong correlations were found between the MOEdv and MOEs (R= 0,93) MOEdv and MOR (R=0,79) comparisons as seen in Figure 5. It was also found strong correlation between the MOEds and MOEs (R= 0,80) but the correlation between the MOEds and MOR was relatively weak (R=0,61) (Figure 4). These results showed that the dynamic MOE determined by longitudinal vibration test displayed better correlations with the static MOE and MOR than the dynamic MOE determined by stress wave test. As mentioned before, ToF measured by stress wave test is result of a single wave path as shortest as possible and less affected by the material's characteristics. However, the longitudinal vibration method is based on the observation of hundreds of acoustic pulses resonating longitudinally in a timber and provides a weighted average acoustic velocity. In contrast to ToF approach, the resonance method provides a very accurate and repeatable velocity measurement (Wang and Carter 2015), resulting in a better correlation with the static strength and elasticity of the material. Baar *et al.* (2015) showed similar results in their studies that the weakest prediction of the MOR was found in the case of the ultrasound method (ToF) where the correlation coefficients were between 0,22 and 0,57 in five tropical hardwood species. Also they found higher correlations between dynamic MOE and MOR when they used resonance (vibrational) method as in this study.

For better explanation, the basic relationship, MOEs and MOR were compared (Figure 6).

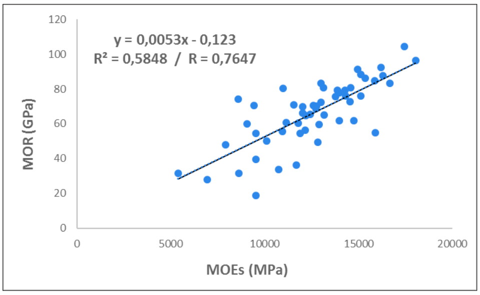

Figure 6. The relationships between the static MOEs and MOR.

As seen in in Figure 6, a good correlation was found between the MOEs and MOR (R=0,76) as expected. It is well-known from many researchs that there is a good correlation between the static MOE and MOR (Kaynak). As mentioned before, we also found a good correlation between the MOEdv and MOR with a R value of 0,79 which is very close to R value found between MOEs and MOR. This is an expected situation due to strong correlation between the MOEdv and MOEs with a R value of 0,93 (Figure 5).

CONCLUSIONS

In the light of the results obtained in this study, we can highlight the following conclussions:

The average dynamic and static MOE values of the timber sorted into best class of each standard used in this research were considerably higher than the other classes. The differences in the MOE values between the visual strength classes were found significant for British and German standards but insignificant for Turkish standard ($p<0,05$).

When considering the MOR values, significant differences were found between the timber sorted into the best class and the lower classes for all standards used in this research ($p<0,05$). In general, the lower visual grading class resulted in the lower MOR value. The MOR displayed the best match with the visual grading classes for all standards when comparing to dynamic and static MOE.

Best compliance between the visual grading class and the dynamic or static MOE and MOR was observed when the timber graded according to BS 4978.

No significant differences were found between the grading standards used in this study in terms of the mechanical properties of best and the worst grading class ($p<0,05$).

For improving the succsess of visual strength grading, more detailed assessment is required considering not only the presence and size but also the location and extension of the strength reducing features of timbers.

The average dynamic MOE determined by stress wave method (MOEds) were higher than the longitudinal vibration method (MOEdv).

In general, strong correlations were found between the dynamic MOE determined by both stress wave and longitudinal vibration methods and static MOE and MOR. Longitudinal vibration method gave better correlation with the static MOE and MOR than stress wave method.

Longitudinal vibration technique can be used reliably for estimating the bending properties and strength grading of structural timber. Best results can be achieved with combining the visual evaluation and vibration test techniques.

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