Prediction of Bending Properties for Turkish Red Pine (*Pinus brutia* Ten.) Lumber using Stress Wave Method

Ergun Guntekin,* Zeynep Gozde Emiroglu, and Tugba Yilmaz

Bending properties of Turkish red pine (*Pinus brutia* Ten.) lumber pieces were predicted using the stress wave method. The lumber samples were taken from 30- to 80-year-old red pine trees harvested from a southwest site in Turkey. MTG timber grader was utilized to predict modulus of elasticity (MOE) and modulus of rupture (MOR) values of lumbers with 40 mm x 90 mm in cross section and 3 meters in length. Static MOE and MOR values of the lumber pieces were determined using a three-point bending test. The coefficient of determination between measured and predicted MOEs was 0.84 and that between dynamic MOE and bending strength was 0.69. However, the coefficient of determination between bending MOE and strength was only 0.45. It seems that dynamic MOE has better prediction capability for bending strength than static MOE. Effects of some variables such as log and visual grades on dynamic MOE values were also determined statistically. Natural frequency of the lumbers showed far more significant effects than other variables. It is apparent that the stress wave method has the potential to predict the bending properties of Turkish red pine lumber.

Keywords: Bending properties, Prediction; Stress wave; Turkish red pine

*Contact information: Department of Forest Products Engineering, Suleyman Demirel University, 32260 Isparta, TURKEY; * Corresponding author: ergunguntekin@sdu.edu.tr*

INTRODUCTION

Nondestructive evaluation (NDE) is the assessment of a material's properties without damaging its end use (Ross *et al.* 1998). The oldest nondestructive evaluation of wood was visual inspection, mostly used for classification of load-carrying members (Bucur 2006). Later, a machine stress rating system, which is one of the most used methods in lumber grading, was introduced and has been commercially used since the 1960's (Galligan and McDonald 2000). Developments in instrumentation have made it possible to use scientific nondestructive tools for the last two decades. Transverse vibration and ultrasonic wave velocity are particularly important in obtaining the modulus of elasticity. Ultrasonic wave velocity has more advantages over other techniques in practical terms (Esteban *et al.* 2009).

Stress-wave-based NDE methods have been investigated extensively during the past few decades and have proven useful for predicting the mechanical properties of wood materials. The ultrasonic wave propagation method has been applied on standing trees for detecting defects (Najafi *et al.* 2009). Several studies have investigated the relationship between the stress-wave-based modulus of elasticity of logs and the static MOE of lumber cut from log and have shown a correlation of 0.44 to 0.89 (Ross *et al.* 1997). A study by Wang *et al.* (2000) revealed that there can be a good correlation (R^2 = 0.63 to 0.91) between stress wave speed and dynamic modulus of elasticity of standing trees and clear wood specimens. Stress wave base methods have been also used and good correlations have been achieved in the case of wood-derived products such as laminated veneer lumber, glued-laminated wood, and particleboard. Investigations also have diagnosed components of timber structures (Esteban *et al*. 2009).

Ross and Pellerin (1994) summarized the results of different research reports related to the relationship between the modulus of elasticity in static and dynamic tests and stress wave methods. The coefficient of determination was scattered between 0.87 and 0.99. The authors concluded that the stress wave method could be a nondestructive method for wood. Divos and Tanaka (2005) also confirmed that the correlation between dynamic and static modulus of elasticity is high.

Turkish Red pine covers the largest area (3,096,064 ha) among conifers grown in Turkey, which corresponds to about 15.3 percent of the total forest area in Turkey. Red pine is a fast-growing tree; its wood is an important raw material for various fields including construction works (Bektas *et al.* 2003). The Turkish wood processing industry does not use any nondestructive-based grading methods to assess the lumber quality. It is believed that these methods are expensive. However, in Turkey the increase in lumber prices could make these methods suitable for the lumber industry. Additionally, consumers could benefit by using classified material, which would have higher quality and reliability than unclassified material. The purpose of this study was to predict bending properties of Turkish red pine lumber using stress wave method.

MATERIALS AND METHODS

Red Pine lumber pieces were sawn from logs that came from the southwestern region of Turkey. The ages of trees were approximately between 30 to 80 years. Logs were approximately 23 to 57 cm in diameter, and they consisted of three visual grades (I, II, and III). Grading of the logs according to TS EN 1927-2 was made by the state forest service. The butt end of each log was painted with a specific color as coding label. The logs were transferred to a private mill and sawn to approximately 40 x 90 x 3000 mm lumber. After the lumber had been delivered to the laboratory, the boards were visually graded according to the Turkish standard TS 1265. In the Turkish standard the lumber is graded into three classes I, II, and III. These grades consider defects such as knots, checks, and bows occurring in the lumber. Then, they were stored in a room for air drying. During the drying process, experimental procedures were performed. The average annual ring width of the lumbers was measured with a digital caliper. The moisture content (MC) of the lumbers was measured with a pinned moisture meter. The apparent density of the lumbers was calculated using their weighs and dimensions.

After the measurements, nondestructive testing was applied to the lumber. The stress wave timer used in this study is called Timber Grader MTG, which is a handheld grading device for sawn wood developed by Brookhuis Micro-Electronics and TNO (Rozema 2007). Timber grader MTG works on the principle of sound waves emission. It measures natural frequency and dynamic modulus of elasticity (MOE) of the lumbers when density, MC, and dimensions are entered. Following stress wave measurement, all lumber samples were tested in flatwise bending to obtain static MOE. The static bending tests were conducted on each specimen within elastic limit using center-point loading (ASTM 2003). Only 150 samples were destructively tested in order to calculate bending strength or modulus of rupture (MOR).

Analysis of variance (ANOVA), using the general linear model procedure, was run with SAS statistical analysis software to interpret the effects of measured physical properties on the dynamic MOE of the lumber pieces. Linear models for prediction of MOE and MOR based on dynamic MOE were developed.

RESULTS AND DISCUSSION

Average static and dynamic MOE and some physical parameters of the lumber samples are presented in Table 1. The moisture content of the lumber pieces ranged from 12% to 50% with an average of 27% and coefficient of variation of 11%. Density of the lumber specimens varied from 0.38 to 0.90 g/cm^3 with an average of 0.57 g/cm^3 and coefficient of variation of 13%. Natural frequency values had an average of 1228 Hz with a coefficient of variation of 24%.

The ANOVA results indicated that log grades, log diameter, visual grades of lumbers, annual ring width, and natural frequency had significant effects ($p<0.0001$) on dynamic MOE (Table 2). Log grades, lumber visual grades, and annual ring widths were treated as class variables. Among the significant variables, natural frequency followed by lumber visual grades and log grades were able to explain most of the variability in dynamic MOE. It can be concluded that natural frequency may be a good predictor of the MOE of the lumber for Turkish red pine because it has the highest F-value among the variables tested.

Linear regression analysis procedure was performed to establish relationships between dynamic MOE and bending properties. The relationship between static and dynamic MOE is shown in Fig. 1. Generally, the values obtained through stress wave method were higher than static values. Several studies have reported that values of dynamic modulus of elasticity are often higher than those obtained using static bending tests (Teles *et al.* 2011; Passialis and Adamopoulos 2002; Barrett *et al.* 2008). The lower static MOE values were expected because static measurement includes shear deflection, whereas MTG results are essentially shear free MOE values (Barrett *et al*. 2008).

The mean values of the variables that are significant were compared using Duncan’s test. A total of 790 pieces of lumber were visually graded, of which 232 of them were grade I, 336 of them were grade II, and 220 of them grade III. The results indicated that all visual grades yield significantly different dynamic MOE values. Also, the higher the visual grading, the higher were the values of the dynamic modulus of elasticity. Average mean values of dynamic MOE caused by lumber visual grades are compared in Table 3 using Duncan’s Test. According to Duncan’s test, higher log grades corresponded to higher dynamic MOE values. The relationship between dynamic MOE and log grades is compared in Table 4. No meaningful relationship between log diameter and dynamic MOE of lumbers, and annual ring width and dynamic MOE was found.

The coefficient of determination between dynamic MOE and bending strength is presented in Fig. 2. The coefficient of determination between static MOE and bending strength is much lower than the coefficient between dynamic MOE and bending strength as shown in Fig. 3. This means that dynamic MOE is a better predictor of bending strength than static MOE.

Table 1. Average Static and Dynamic MOE Values of the Lumbers Tested

Log class	Log Diameter (cm)	Number of samples	Density g/cm^3	moisture content (%)	Static MOE (N/mm^2)	Dynamic MOE (N/mm^2)
1	20-30	48	0,53	27	10369	11036
1	30-40	51	0,58	28	10760	11377
1	40-50	48	0,50	26	10265	11267
1	>50	46	0,55	27	9696	10787
2	20-30	49	0,52	26	9766	10750
2	30-40	55	0,58	33	9236	9983
2	40-50	82	0,56	33	9310	9728
2	>50	93	0,58	30	9531	9856
3	20-30	40	0,56	18	8910	9764
3	30-40	94	0,54	36	7299	7169
3	40-50	69	0,62	19	10221	10515
3	>50	113	0,58	19	9487	9905

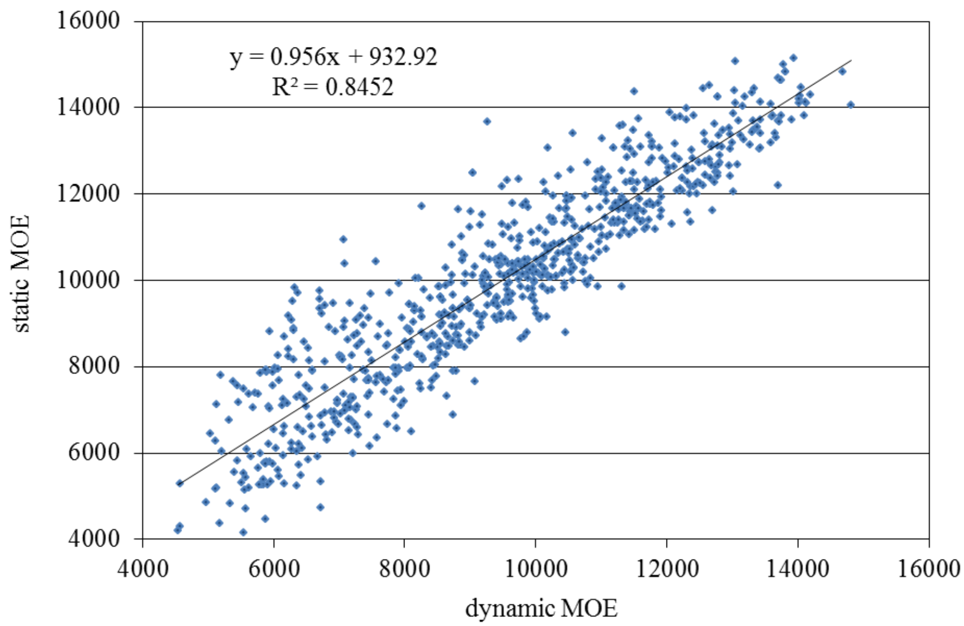

Fig. 1. Relationship between static and dynamic MOE (N/mm^2) of lumber pieces

Table 2. Effects of Variables on dynamic MOE Values

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	35	3541314337	101180410	79.45	<.0001
Log grades	2	486522386	243261193	191.02	<.0001
Log diameter	21	342311926	16300568	12.80	<.0001
Lumber Visual Grades	2	897245115	448622558	352.29	<.0001
Annual ring width	9	179577682	19953076	15.67	<.0001
Natural Frequency	1	1635657229	1635657229	1284.42	<.0001
Error	754	960192364	1273465		
Corrected Total	789	4501506702			
R-Square	Coeff Var	Root MSE	MOEdyn Mean		
0.786695	11.29758	1128.479	9988.681		

Table 3. Effects of Lumber Visual Grades on Dynamic MOE Values

Duncan Grouping	Mean (N/mm^2)	Sample size	Lumber Grades
A	11555	232	1
B	9974	336	2
C	8372	222	3

Table 4. Effects of Log Grades on Dynamic MOE Values

Duncan Grouping	Mean (N/mm^2)	Sample size	Log Grades
A	11156	215	1
B	9973	259	2
C	9206	316	3

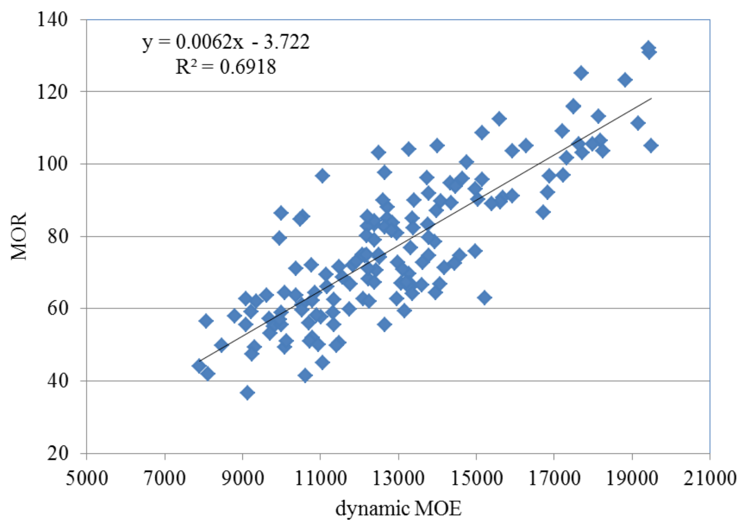

Fig. 2. Relationship between dynamic MOE and MOR (N/mm^2) of lumber pieces

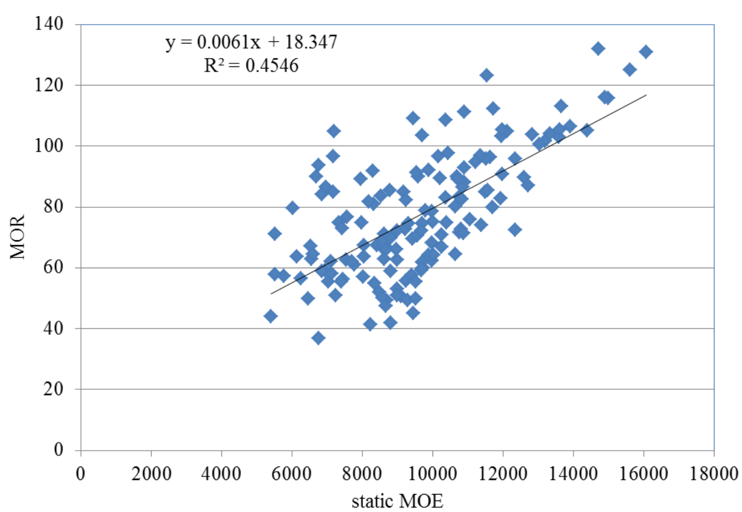

Fig. 3. Relationship between static MOE and MOR (N/mm^2) of lumber pieces

The coefficient of determination values for predicting bending properties were high, indicating that stress wave can be used in prediction of red pine lumber's bending properties. In non-destructive evaluation of wood, R^2 values are usually dependent on the methods, species used, moisture content, type of samples tested, *etc*. Results of nondestructive testing on wood were summarized by Ross and Pellerin (1994). They have stated that the R^2 value can be as high as 0.98 and 0.88 for clear wood species and dimension lumber, respectively. Divos and Tanaka (2005) reported that R^2 values between static and dynamic MOE values can be between 0.9 and 0.96, and dynamic MOE values are usually 10% higher than the static MOE values. Biechele *et al.* (2010) have reached the coefficient of determination values of 0.80 and 0.97 for spruce timber using stress wave and transverse vibration methods, respectively, while Teles *et al.* (2011) have reported the coefficient of determination values of 0.84 and 0.94 for tropical hardwood species using same methods. Ravenshorst and van de Kuilen (2006) evaluated bending properties of 30 different hardwood species using both destructive and non-destructive testing. They have reached a coefficient of determination of 0.62 and 0.85 for bending strength and bending elasticity, respectively. Krzosek *et al.* (2008) tested Polish grown structural pine lumber employing several nondestructive methods including MTG. They have reported a coefficient of determination of 0.84 for bending stiffness.

CONCLUSION

A total of 790 pieces of lumber were evaluated using the stress wave method in order to determine bending properties. Linear statistical modeling was utilized to interpret the relationship between dynamic MOE and bending properties of the lumber specimens. The coefficient of determination between dynamic modulus and three-point bending modulus was 0.84. The coefficient of determination between dynamic MOE and bending strength of Turkish red pine sawn lumber was 0.69. Dynamic MOE seemed a better predictor for bending strength than static MOE, which yielded a coefficient of determination of 0.45 for bending strength. According to the ANOVA results obtained, log and lumber visual grades significantly affect dynamic MOE of the lumbers. It can be concluded that the stress wave method can be used for predicting bending properties of Turkish red pine lumber. Timber Grader MTG provides fast elasticity measurements.

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