Relationship between Timber Grade and Local, Global, and Dynamic Modulus of Elasticity in Red Oak and Red Maple Structural Lumber

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The modulus of elasticity (MOE) of structurally graded one-inch-thick red oak (*Quercus rubra*) and red maple (*Acer rubrum*) lumber was measured in this work. The center-point, third-point static loading tests, and the stress wave timer methods were used. The objective was to determine if there are statistical differences between three structural lumber grades based on their MOE values. The study considered both the within separated grades and the across combined grades. For red oak and red maple, significant differences in MOE values from center-point static loading tests were observed solely between Select Structural and Below-grade lumber. With the dynamic method, no significant differences were found between any visual grades, including Below-grade lumber. Regardless of the MOE determination method used, the MOE value was not useful for distinguishing the structural, No. 2, and No. 3 visual grades. The strongest correlation existed between the global MOE and the dynamic MOE, which was even higher when the analyses were conducted on separated visual grades. In the case of red maple, stronger correlations between the dynamic MOE, local MOE, and global MOE were observed when separated by visual classes, compared to the analysis conducted on the combined grades. The global MOE was found to be a better predictor of the local MOE than the dynamic MOE.

DOI: 10.15376/biores.20.2.2609-2627

Keywords: Hardwood; Machine strength grading; Nondestructive method; Stiffness; Stress wave time; Visual strength grading

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INTRODUCTION

Currently, softwood species represent the majority of wood used in the construction industries across the US. Lumber for a variety of uses is readily available in both wholesale and retail markets with standardization of lumber grades, surface conditions, moisture conditions, sizes, and species. Because hardwood sawmills specialize in supplying wood for appearance graded applications (*e.g.*, furniture, cabinets, millwork, flooring, *etc.*), the visual grading system developed by the National Hardwood Lumber Association (NHLA) was initiated in 1898 and has continued to evolve to this day (NHLA 2023).

The utilization of hardwood species (especially red maple and red oak) for construction is not new, as we can find numerous examples like the construction of wooden bridges (highway and railroad bridges), temporary bridges for off-road applications, mats, glulam, *etc*. The possibility of wider utilization of structural hardwood lumber may now be possible with the appearance of CLT (Cross-laminated Timber) (Ritter *et al.* 1998; Hassler *et al*. 2022). The possibilities of using hardwoods for construction purposes have highlighted the need for mechanical classification of hardwoods (DeBonis and Bendtsen 1988; Green and McDonald 1993a,b; Kretschmann and Green 1999; Ross and Erickson 2020).

Structural lumber grading can be implemented using two approaches, the widely used visual grading and machine-used mechanical grading (Galligan and McDonald 2000). A variety of equipment is available to conduct mechanical grading (often referred to as machine stress rating (MSR) or Machine Evaluated Lumber (MEL)). The American Lumber Standards Committee (ALSC) provides certification of MSR and MEL equipment, which measures/estimates the lumber's real MOE (Modulus of Elasticity) values with several nondestructive methods. The MOE is one of the key properties of lumber and is most commonly used to assign individual timber elements to strength classes. An accurate measurement of the modulus of elasticity is therefore crucial for the proper utilization of timber.

The traditional static test methods determine the static modulus of elasticity (MOE_{stat}) by bending. The European standard EN 408 (2010) specifies the use of two-point loading (4-point bending) to determine the static bending MOE. In contrast, the North American standard ASTM D198 (2015) distinguishes between two-point loading (4-point bending), third-point loading (also 4-point bending), and center-point loading (3-point bending) methods. The primary difference between two-point and third-point loading lies in the position of the applied loads on the span. Both 4-point bending methods are used to determine the static modulus of elasticity in bending, defined as the local (MOE_l) and global (MOE_g) modulus. However, the 3-point bending method enables only the measurement of the global modulus (MOE_g). The MOE_l is based on deformation measurements within the constant bending moment zone in a 4-point bending arrangement, specifically the mid-span deflection relative to the loading points. In contrast, the MOE_g is determined by measuring the mid-span deflection relative to the supports, where the total deformation includes both bending and shear effects. Regardless of the loading method, increasing the span-to-depth ratio reduces the contribution of shear deformation when measuring the global MOE. The terminology for static MOEs differs between standards. The European standard EN 408 (2010) uses the terms “local MOE” and “global MOE,” whereas the ASTM D198 (2015) standard refers to “shear-free” or “true” for local MOE and “apparent” for global MOE, despite relying on the same mechanical principles. The local modulus (MOE_l) is more prone to measurement errors due to factors such as reference point positioning, initial specimen twisting, and small deflection sizes. Consequently, the global modulus (MOE_g) is often preferred, despite incorporating shear deformation into the experimental data (Boström *et al.* 1999; Solli 2000). To address this, the European standard EN 384 (2016) provides the following equation for calculating MOE_l from MOE_g for structural softwood lumbers:

$$MOE_{local} = 1.3 * MOE_{global} - 2690 \tag{1}$$

While Eq. 1 was determined based on European softwood species (spruce, pine, Douglas-fir, and larch), only marginal differences were observed in the linear correlation equation for Norway spruce (Holmqvist and Boström 2000; Solli 2000), as well as for fir (*Abies alba*) and the tropical hardwood species *Manilkara* spp., as reported by Ravenshorst and Van de Kuilen (2009).

Initially, in the United States, the 3-point MSR devices were adopted by various softwood lumber associations and continue to be used today to classify lumber in which the apparent modulus of elasticity (MOE_{app}) value was measured on a 4-ft (1.22m) span basis (Galligan and McDonald 2000)

More recently, non-interference methods have been used. These devices calculate dynamic modulus of elasticity (MOE_d) values based on density and the material's vibration properties, wave propagation, acoustical emission, or X-ray transmission (Kalliopi and Aligizaki 2003; Brashaw *et al.* 2009). Regardless of the method used, a visual override must also be carried out in all cases. Visual override is necessary so that quality-affecting edge characteristics or limitations such as warp or wane, which are not sensed by the machine, can be considered during the lumber grading process. The term "visual quality level" (VQL) was introduced for this purpose (Kretschmann *et al.* 1999).

The two most used dynamic test methods are the transverse vibration of a supported beam and the longitudinal stress wave timing. In the case of the transverse vibration method, the MOE_d value is calculated from the oscillation frequency, which is due to the specimens mid-span deflection. The MOE_d calculation from the longitudinal stress wave method is conducted by determination of the transmission time of the stress wave between a start and a stop transducer.

The exploration of various wood species and testing methods has shed light on the intricate relationship between mechanical properties and factors such as moisture content, loading methods, and anatomical characteristics. From the investigation into the comprehensive studies, this section presents a panorama of findings that contribute to an understanding of the (MOE) determination and its contextual dependencies.

Liu *et al.* (2014) used three different methods - longitudinal stress wave (LSW), free–free beam vibration (FBV), and three-point static bending (TSB) - to determine the MOE of yellow birch and sugar maple. The MOE values of Yellow Birch were 11% higher than those of sugar maple, regardless of the method and lumber width. Furthermore, the MOE_{stat} results obtained with the TSB method were generally 5 to 10% higher than the MOE_d results obtained with the LSW and FBV methods.

Ponneth *et al.* (2014) tested seven hardwood species for their modulus of elasticity using 3-point static bending and the longitudinal stress wave (LSW) method. Contrary to Liu's results, the MOE_d values determined by the Treesonic Microsecond Timer (TMT) method were found to be significantly higher (12%) than the MOE_{stat} values and a much stronger correlation (r^2=0.76) was measured between them. Using the same stress wave and static bending method, several studies confirm the trend and the strong correlation between the MOE_{stat} and MOE_d values (Passialis and Adamopoulos 2002; Horvath *et al.* 2010; Guntekin *et al.* 2013; Yang *et al.* 2015).

A comparative non-destructive test (NDT) of white oak and red oak revealed that the MOE_{stat} values based on 3-point static bending on small, defect-free specimens were 19% lower than the average MOE_d values of the Treesonic Microsecond Timer (TMT) (Turkot *et al*. 2020).

In the case of Beech lumber, MOE_d measured with the MTG Timber Grader,- which also works on the stress wave propagation principle,- was 6.5% higher on average than the MOE_{stat} determined by 3-point bending test, but the r^2 value was 0.86 suggesting a strong correlation between the two methods (Guntekin *et al.* 2014).

During the mechanical examination of *Eucalyptus nitens*, Ettelaei *et al*. (2022) found a close correlation (r^2= 0.88) between MOE_d and MOE_{stat}. Using the 4-point edgewise bending MSR device (Calibre STFE10), the measured average MOE_{stat} value was

14% lower than the MOE_d measured with a stress wave timer (Director HM200TM).

In another study, during mechanical testing of full-sized 50.8 x152.4 mm by 3.05 m-long red maple boards, the closest correlation (r^2=0.85) was observed between the static MOE_g from center-point bending and the dynamic MOE determined using the transverse vibration method (Metriguard E-computer). The correlation between the static MOE and the dynamic MOE determined using the stress wave timing method (Metriguard Model 239A) was r^2=0.69. In addition, the transverse vibration modulus was approximately 22% higher than the mean of the MOE_g from proof loading (Wolcott 1998).

Comparing the accuracy of the transversal vibration and ultrasonic stress wave NDT methods in predicting the static MOE of poplar, beech, oak, Paulownia, and Scots pine in structural sizes, Acuña *et al.* (2023) reported an r^2 value of 0.73 between static MOE and MOE_d (stress wave) and an r^2 value of 0.76 for the transversal vibration method in Oak species. Similarly, as Wolcott (1998) reported across all species, the transversal vibration method yielded a stronger correlation than the ultrasonic stress wave NDT method.

Based on the analysis of the MOE data from a large number (40000) of bending tests, Brancheriau *et al.* (2002) concluded that in the case of the 3- and 4-point bending, the relative difference between the two MOE values depends on the density of the homogeneous clear wood specimens, if the indentation of the crosshead is considered. The difference between the MOE_{stat} values based on 3- and 4-point bending can be as much as 11% if the shear and the indentation effects of the bending head are neglected.

Johansson *et al.* (1992) showed that there are significant differences between the MOE_{stat} results measured by the differing types of MSR equipment used in the industry. Further, differences in MSR readings can be caused by the anatomical characteristics of the wood, as well as weak zones resulting from growth or processing. Weak zones can cause global MOE to exceed the local MOE values (Nocetti *et al*. 2013; Ravenshorst *et al* 2014).

Regardless of the wood species and the mechanical bending test method, the thickness of the specimens above 4 to 6 mm has no significant effect on the MOE_{stat} values (Gaff *et al.* 2017; Schlotzhauer *et al.* 2017). When applying the NDE (Non-destructive Evaluation) method, changes in the width of the boards affect the measured MOE_d value. However, this is not relevant in the case of parallel edging structural lumber (Divos *et al.* 2005).

Babiak *et al.* (2018) carried out 3- and 4-point bending tests of spruce and oak species with different moisture contents. They found that both the static measurement method and the moisture content of the wood have a significant effect on the MOE_{stat} results. In the case of both loading methods, the moisture content increase caused a lower MOE_{stat} value of both species. With 3-point bending, a significant decline (38%) in MOE_{stat} was observed when the moisture content increased from 8%MC to 16%MC of the spruce specimens. In case of the 4-point bending between the 8%MC and FSP (Fiber Saturation Point) were significant differences observed (19%). In the case of oak, during the 4-point bending, increasing moisture content showed a significant difference only when raised from 16% to the fiber saturation point, resulting in a 25% decrease in MOE value. During three-point bending, there was a significant difference between 8% and FSP, resulting in a 22% decrease in MOE value. Regardless of the method, increasing the moisture from 0% to 8% had no significant effect on the MOE for both species.

The moisture content and temperature of wood influences its acoustic properties. These effects must be considered when comparing the data from NDT methods. To obtain comparable data, empirically corrected models must be developed and used for the species being tested (Sandoz 1993; Unterwieser and Schickhofer 2011).

Wolcott *et al.* (1993) examined the mechanical properties of beech, hickory, and yellow poplar on 50.8x152.4x2438mm (TxWxL) full-size test samples using non-destructive and destructive methods. For all of the wood species, there were no significant differences between the MOE_{stat} values and SS, No.1, No.2 NELMA visual grades. The MOE_d determined by the transverse vibration method was approximately 20% higher than the MOE_{stat} value obtained from the three-point bending test.

During the literature review, the authors did not encounter any studies that investigated the stiffness of one-inch thick hardwood lumber using both static bending and dynamic methods. Additionally, in the available literature, no separate correlation analyses for MOE were conducted for visual grades; all analyses were only performed for combined grades. Therefore, it is unclear how quality affects the correlation between different MOE values and visual grades. Adopting a new approach, this study increased the support span for three-point bending tests from the commonly used 1219 mm to 2895 mm in order to examine the full board's elastic properties.

The main objective of the investigation was to determine if statistical differences existed for the three structural lumber grades based on their MOE values. Additionally, the study examined the correlations between MOE values measured using three methods and for both within separated classes and across combined grades. The measurements were conducted on red oak (*Quercus rubra*) and red maple (*Acer rubrum*) Select Structural, No. 2, No. 3, and Below grade dimensional size lumber (25.4 mm thick and less) with 7% moisture content. The No 1. grade lumber was not included in the research due to insufficient sample size.

EXPERIMENTAL

Materials

In this study, 166 red oak (*Quercus rubra*) and 118 red maple (*Acer rubrum*) kiln-dried to 7% MC, 4-side surfaced boards from different structural grades were tested. The boards were sourced from the Appalachian region in the USA.

Table 1. Frequency Distributions of the Red Oak and Soft Maple Boards Included in the Analysis, by Grade

Wood species	Visual grade	Sample size	Sample size (in % of total)
Red oak	Select structural (SS)	32	19
	No.2	50	30
	No.3	14	9
	Below Grade (BG)	70	42
	Total	166	
Red maple	Select structural (SS)	32	27
	No.2	37	32
	No.3	18	15
	Below Grade (BG)	31	26
	Total	118	

After machining, the lumber was graded by licensed graders in accordance with the Northeastern Lumber Manufacturers Association (NeLMA). In the case of the No. 2, No. 3, and Below Grade (BG) boards, knots were the predominant wood defects, and their sizes and locations determined the actual grade according to the NeLMA rules. Some boards, besides having knots, also contained shake, but the size of these defects was negligible. Boards that contained wane, split, check, or other defect types were not included in analysis. Table 1 contains the number of boards, by grade.

The average cross-sectional dimensions of the boards were 24.17x158.75 mm for red oak and 24.23x157.28 mm for red maple and the length was 3048 mm. Before testing, the boards were conditioned in the laboratory (average 40% RH, 22°C) to an average moisture content of 7%. A DELMHORST RDM-2S -type moisture meter was used to determine moisture content.

Nondestructive Evaluation

The full-span dynamic modulus of elasticity (MOE_d,) was obtained on each piece using a Treesonic Microsecond Timer (TMT) (FAKOPP, FAKOPP Enterprise Bt. HUNGARY). Transducers were inserted into the lumber's wide face at a 45-degree angle (Fig. 1c). The start transducer was impacted with a hammer and the travel time of the sound wave was obtained by the timer. The dynamic MOE (MOE_d) was determined from the density of the wood and the sound propagation speed, using the following equation,

$$MOE_d = \rho * V^2 \quad (1)$$

where MOE_d is the dynamic modulus of elasticity (Pa), ρ is the density of specimens at the given moisture content (kg /m^3), and V is the sound propagation velocity (m/s). An average value from three replications was used as the MOE_d value.

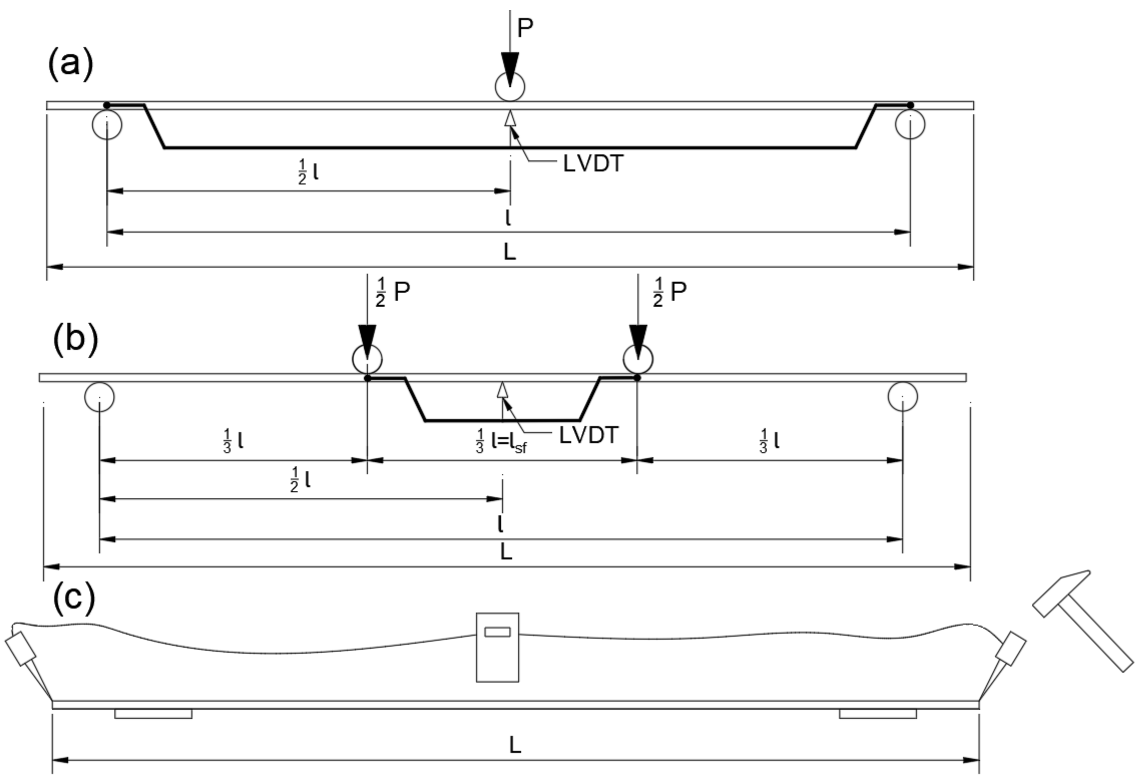

Fig. 1. Schematics for each type of MOE testing. (a) Center-point loading (3-point bending), (b) Third-point loading (4-point bending), (c) Longitudinal stress wave timing NDT

Static Bending

Center- and third-point loading (3- and 4-point bending) were used to determine the global and the local modulus of elasticity values according to ASTM D198 (2015). The load direction for each method was flatwise. The bending test set up is shown in Fig. 1. The span was altered from the traditional MSR grading 1219 mm to the maximum allowable span (l), *i.e.*, to 2895 mm, in order to examine the elastic properties of the entire board. In both cases, the span-to-depth (l/d) ratio was 116. The global modulus of elasticity (MOE_g) values were obtained from the center-point loading method (Fig. 1a), and the local modulus of elasticity (MOE_l) values came from the third-point loading (Fig. 1b) setup. The main difference between MOE_g and MOE_l lies in how the deflection is determined when the board is loaded. The global modulus of elasticity is related to the rigidity of the entire board since the deflection is determined on the full board, while the local modulus of elasticity represents the shear-free ("true") rigidity of the middle third of the board, where shear forces are not present. The two modulus of elasticity values capture different aspects of the lumbers' mechanical behavior and were obtained through distinct testing methods.

The bending tests were conducted until a 75 mm displacement of the machine crosshead was achieved. The deflection was measured with Linear Variable Differential Transformer (LVDT). The load was applied to the face nearest to the pith, and due to the extended span, the 75 mm deflection did not cause any damage, as the lumber's deflection remained within the elastic range. The two types of static modulus of elasticity values were calculated using the equations below (ASTM D198 2015),

$$MOE_g = \frac{Pl^3}{4bd^3\Delta} \quad (2)$$

$$MOE_l = \frac{Pll_{sf}^2}{4bd^3\Delta_{sf}} \quad (3)$$

where MOE_g is the global (apparent) modulus of elasticity, (MPa) (from center-point loading method), MOE_l is the local (shear-free) modulus of elasticity, (MPa) (from third-point loading method), P is the increment of the applied load on flexure (N), l is the span of flexure, (mm), b is the specimen width, (mm), d is the specimen depth or thickness, (mm), l_{sf} is the the shear-free span, (mm), Δ is the deflection increment of the specimen's neutral axis measured at midspan over distance l and corresponding load P, (mm), and Δ_{sf} is the deflection increment of the specimen's neutral axis measured at midspan over distance l_{sf} and corresponding load P, (mm).

Statistical Analyses

All statistical analyses were conducted using the TIBCO® Data Science / Statistica 13 software. The correlations between the distinct MOE values and quality grades were established by linear regressions. For the two static MOE's (global and local) the effect of density on elasticity was additionally considered. The Nonparametric Kruskal-Wallis and Dunn-Bonferroni Multiple Comparison test was used to determine if statistically significant differences existed between the MOE values of the lumber with distinct grades (SS, No.2, No.3, BG). In both species, one-way ANOVA was used to determine if significant differences existed between the three different types of MOE. For both statistical analyses the significance level was set at α=0.05.

RESULTS AND DISCUSSION

The overall results of the measurements are presented in Table 2, and plotted in Fig. 2, along with results for each structural grade analyzed.

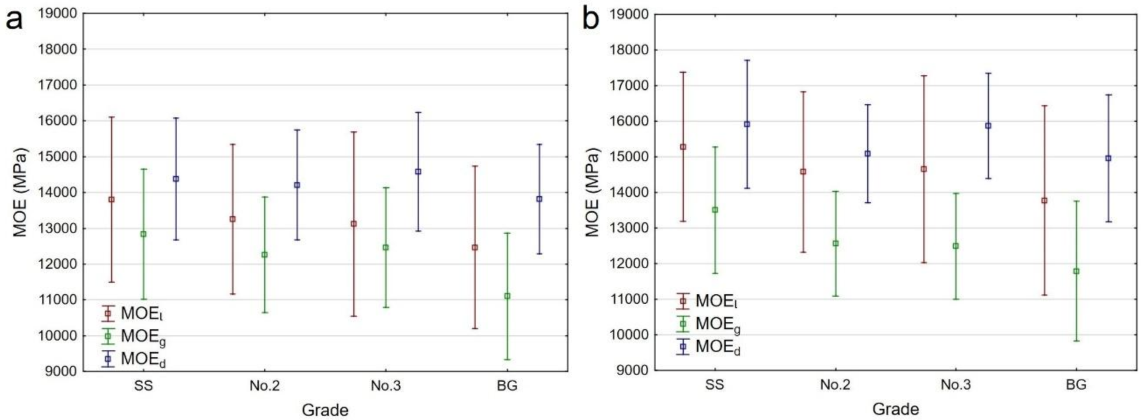

Fig. 2. Mean plot of MOE comparison by grade for (a) red maple and (b) red oak. Whiskers represent the standard deviation

As the quality/grade of the lumber deteriorated, a slight decrease in both static MOE average values could be observed while the dynamic MOE appeared less sensitive to changes in grade. The average dynamic MOE was the highest, while the global MOE was the lowest, regardless of species and grade. For red maple, the global MOE in grades SS, No. 2, and No. 3 showed strong agreement with the global MOE values reported for 50.8x101.6mm red maple of the same grades by Green and McDonald (1993b). The reported MOE_g values were slightly higher in grades SS and No. 2, with differences of 1.5% in SS and 0.1% in No. 2, while in grade No. 3, the reported value was lower by 5.3%.

In contrast, for red oak, the reported MOE_g values were considerably lower across all grades (Green and McDonald 1993b). The differences were 7.3% in grade SS, 15.4% in grade No.2, and 22.4% in grade No.3. The noticeable differences between the previously published results for the two species can presumably be attributed to species-specific influence of stiffness properties to moisture content. The reported results were measured at an average MC of 11.5%, which was higher than the 7% MC of the tested lumber in this study. Comparing MOE values at "green" and 12% MC for the two species, it can be observed that red oak exhibited a much greater change in MOE with varying moisture content than red maple (Senalik and Farber 2021). Similarly, Babiak *et al.* (2018) reported differences in the influence of moisture content on stiffness between spruce and White oak species. This suggests that the stiffness of red maple is less sensitive to changes in moisture content compared to red oak. However, this does not fully explain the variability in grade-related differences for red oak.

The relative difference between the global MOE and the dynamic MOE was strongly influenced by visual grades. This difference was lowest in the Select Structural grade, at 18% for red oak and 12% for red maple, and the highest in the Below-grade quality, at 27% and 24%, respectively. The average difference across the combined grades and species was 20%, which closely aligns with the stiffness measurement results reported by Wolcott (1993) for various hardwood species and by Turkot *et al.* (2020) for clear small specimens of oak species. In contrast, the differences between the average dynamic and static MOE for softwood vary, with 6.5% reported by Franca *et al.* (2018), 5.1% reported by As *et al.* (2020), and 12.2% reported by Yang *et al.* (2015).

The ratio between the local and global MOE (MOE_l/MOE_g) ranged from 1.05 to 1.12 across the grades for red maple and from 1.13 to 1.17 for red oak. According to Ravenshorst and Van de Kuilen (2009), tests conducted on softwoods, temperate hardwoods, and tropical hardwoods revealed that ratio was approximately 1.15 across all species.

Within each grade, the global MOE for red oak showed strong agreement with the values reported by Ogunruku *et al.* (2024).

The average global MOE for red maple was higher than the reported value of 11,300 MPa by Senalik and Farber (2021). However, this difference can be attributed to variations in moisture content (MC) and specimen dimensions. Both static MOE values are almost identical for grades No. 2 and No. 3 in both species. A similar result was reported by Ogunruku *et al.* (2024), who observed the same global MOE values for No. 2 and No. 3 grade red oak lumber. The Coefficient of Variation (COV) varied depending on the grade and the type of MOE. Generally, the COV was lowest in the Select Structural grade (except red oak dynamic MOE) and highest in the Below-grade quality, showing a gradual increase as the quality grade decreased. Among the different MOE measurement methods, the dynamic method showed the lowest COV, followed by the center-point loading method, while the third-point loading method resulted in the highest COV.

Based on the complete dataset, the one-way ANOVA analysis confirmed a significant difference between the MOE values obtained using the three different techniques (Fig. 3).

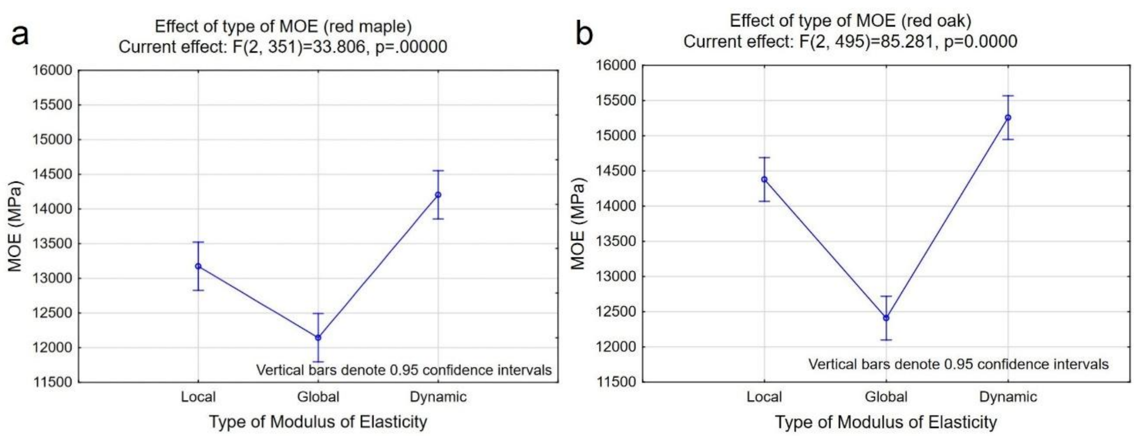

Fig. 3. Comparing the effect of the different methods of determining MOEs. (a) red maple; (b) red oak

Table 2. MOE Results by Species and Visual Grade

Wood species	Visual grade	Local MOE (MPa)			COV%	Global MOE (MPa)			COV%	Dynamic MOE (MPa)			COV%
		Mean	Median	Min.		Mean	Median	Min.		Mean	Median	Min.	
Red oak	SS	15,280	14,793	11,292	13.7	13,503	13,329	9,942	11.1	15,914	15,832	12,229	11.3
	No.2	14,576	14,598	8,680	15.5	12,560	12,447	8,734	11.7	15,091	15,188	11,352	9.1
	No.3	14,657	14,149	11,260	17.9	12,490	12,647	10,210	11.9	15,870	15,695	13,229	9.3
	BG	13,773	13,784	8,365	19.3	11,790	11,995	6,462	16.6	14,957	14,985	10,461	11.9
	TOTAL*	14,379	14,409	8,364	17.3	12,411	12,425	6,461	14.9	15,259	15,284	10,461	11.0
Red maple	SS	13,802	13,682	9,752	15.7	12,837	12,796	9,741	12.2	14,372	14,202	11,441	10.5
	No.2	13,256	13,078	9,406	16.6	12,264	12,286	8,625	13.2	14,209	14,258	9,867	10.8
	No.3	13,117	13,304	8,871	17.9	12,458	12,087	9,765	13.4	14,577	14,722	11,744	11.4
	BG	12,467	12,471	7,199	19.6	11,098	10,962	7,288	15.9	13,817	14,103	10,242	12.9
	TOTAL*	13,176	13,089	7,199	17.4	12,143	12,081	7,288	14.9	14,206	14,263	9,867	11.3

**TOTAL represents the combined grades. BG- Below Grade, SS-Select Structural*

The average density values for both species, categorized by grade, are presented in Table 3. Red oak showed a higher density than red maple across all grades, with an average density of 703 kg/m³ and a COV of 6.8%. For red maple, the overall average density was 611 kg/m³, also with a COV of 6.8%. According to the Multiple Comparison of Means test, neither species exhibited a significant difference in density across the different grades.

Table 3. Density Results by Species and Lumber Grades

Wood species	Visual grade	Density (kg/m^3)				COV (%)
		Mean	Median	Minimum	Maximum	
Red oak	SS	695	702	588	820	8.4
	No.2	698	693	632	784	5.6
	No.3	725	728	636	804	6.4
	BG	706	710	606	824	6.9
	TOTAL*	703	703	588	824	6.8
Red maple	SS	603	604	530	685	6.0
	No.2	605	603	543	689	5.8
	No.3	629	636	559	692	5.6
	BG	616	609	511	712	8.6
	TOTAL*	611	607	511	712	6.8

*Combined the four grades *BG- Below Grade, SS-Select Structural*

Table 4 shows the effect of grades on MOE values using the Multiple Comparison of Means test for the two species. The Shapiro-Wilk and Kolmogorov-Smirnov normality tests revealed the normal distribution of each MOE data set. However, the data grouped by individual grades showed non-normal distributions. Hence, the nonparametric Dunn-Bonferroni Multiple Comparison test was used.

Table 4. Comparison of Grade Effects on MOE Values with the p-Values of Dunn-Bonferroni Multiple Comparison Test for the Two Wood Species

	RED MAPLE						**RED OAK**			
	GRADE	SS	No.2	No.3			GRADE	SS	No.2	No.3
MOE_l	No.2	1.000				MOE_l	No.2	1.000		
	No.3	1.000	1.000				No.3	1.000	1.000	
	BG	0.223	1.000	1.000			BG	**0.038**	0.777	1.000
MOE_g	No.2	1.000				MOE_g	No.2	0.298		
	No.3	1.000	1.000				No.3	0.653	1.000	
	BG	**0.003**	0.108	0.117			BG	**0.001**	0.258	1.000
MOE_d	No.2	0.183				MOE_d	No.2	0.237		
	No.3	0.690	0.861				No.3	1.000	0.578	
	BG	0.991	0.845	1.529			BG	0.105	1.000	0.379

The bold values indicate significant differences when $p \leq 0.05$

For red maple, the analysis revealed only one significant difference in MOE values. Specifically, the (MOE_g) values were significantly different between Select Structural and Below-grade lumber. The third-point and center-point loading tests indicated significant differences in MOE values between Select Structural and Below-grade for red oak lumber. However, no significant differences in dynamic MOE values were observed between Select Structural, No. 2, No. 3, and Below-Grade lumber for either species. Ogunruku *et al.* (2024) measured the global MOE using third-point loading and found no significant differences in MOE_g values across grades SS, No. 1, No. 2, and No. 3 for red oak and yellow poplar specimens. Consistent with this study, only the No. 4 grade (referred to as BG in the current study) exhibited MOE_g values that significantly differed from those of the other grades.

Linear Regressions Analysis

Linear regressions between the different types of MOE for both species, separated by grades, are depicted in Fig. 4, while Fig. 5 illustrates the regressions for the combined grades. Table 6 presents the equations of regression lines for the MOE values based on Figs. 4 and 5. In all cases of the local MOE correlation, based on the standard EN 384 conversion equation was plotted with a dashed line.

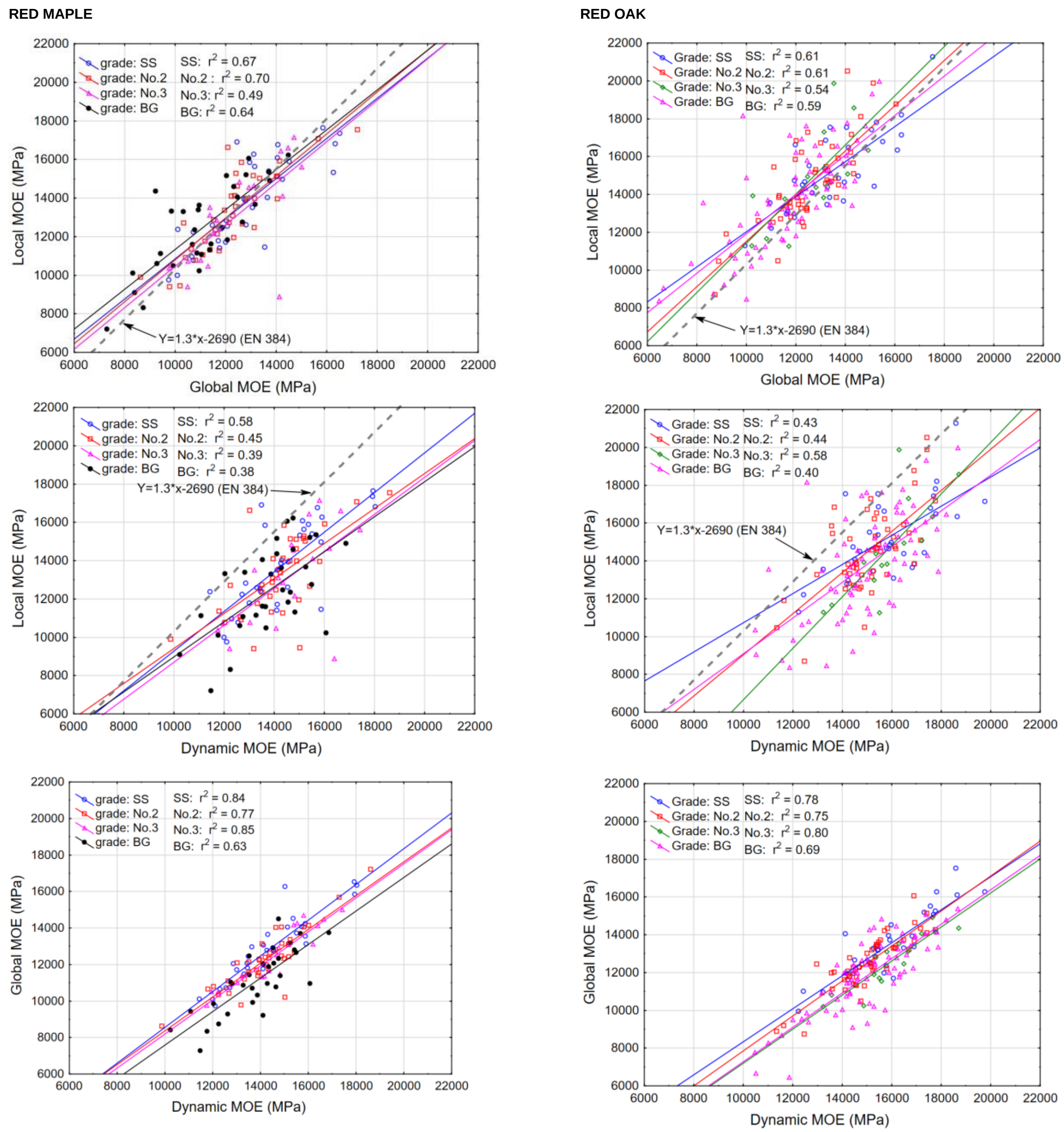

Fig. 4. Linear regressions between 3 types of modulus of elasticity (MOE) separated by grades

Table 6. Regression Equations Connecting MOE Values and the Coefficient of Determination

Relationship		RED MAPLE		RED OAK	
	GRADE	EQUATION	r^2	EQUATION	r^2
MOE_t (Y) – MOE_g (x)	SS	Y= 1.04*x+440	0.67	Y= 0.93*x+2765	0.61
	No.2	Y= 1.09*x-72	0.70	Y= 1.96*x-438	0.61
	No.3	Y= 1.08*x-276	0.49	Y= 1.30*x-1594	0.54
	BG	Y= 1.03*x+1000	0.64	Y= 1.04*x+1486	0.59
	TOTAL*	Y=1.01*x+899	0.64	Y=1.05*x+1383	0.61
MOE_t (Y) – MOE_d(x)	SS	Y= 1.03*x-1060	0.58	Y= 0.77*x+3022	0.43
	No.2	Y= 0.94*x+268	0.45	Y= 1.08*x-1806	0.44
	No.3	Y= 0.96*x-945	0.39	Y = 1.36*x-6935	0.58
	BG	Y= 0.92*x-183	0.38	Y= 0.94*x-335	0.40
	TOTAL*	Y= 0.97*x-634	0.46	Y= 0.975*x-500	0.44
MOE_g (Y)- MOE_d(x)	SS	Y= 0.98*x-1251	0.84	Y= 0.87*x-403	0.78
	No.2	Y= 0.93*x-890	0.77	Y= 0.92*x-1393	0.75
	No.3	Y= 0.93*x-1126	0.85	Y=0.90 *x-1806	0.80
	BG	Y= 0.92*x-1581	0.63	Y= *0.91x-1850	0.69
	TOTAL*	Y= 0.98*x-1747	0.74	Y= 0.93*x-1769	0.72

*TOTAL represents the entire sample size regardless of the grade. BG- below grade, SS-select structural

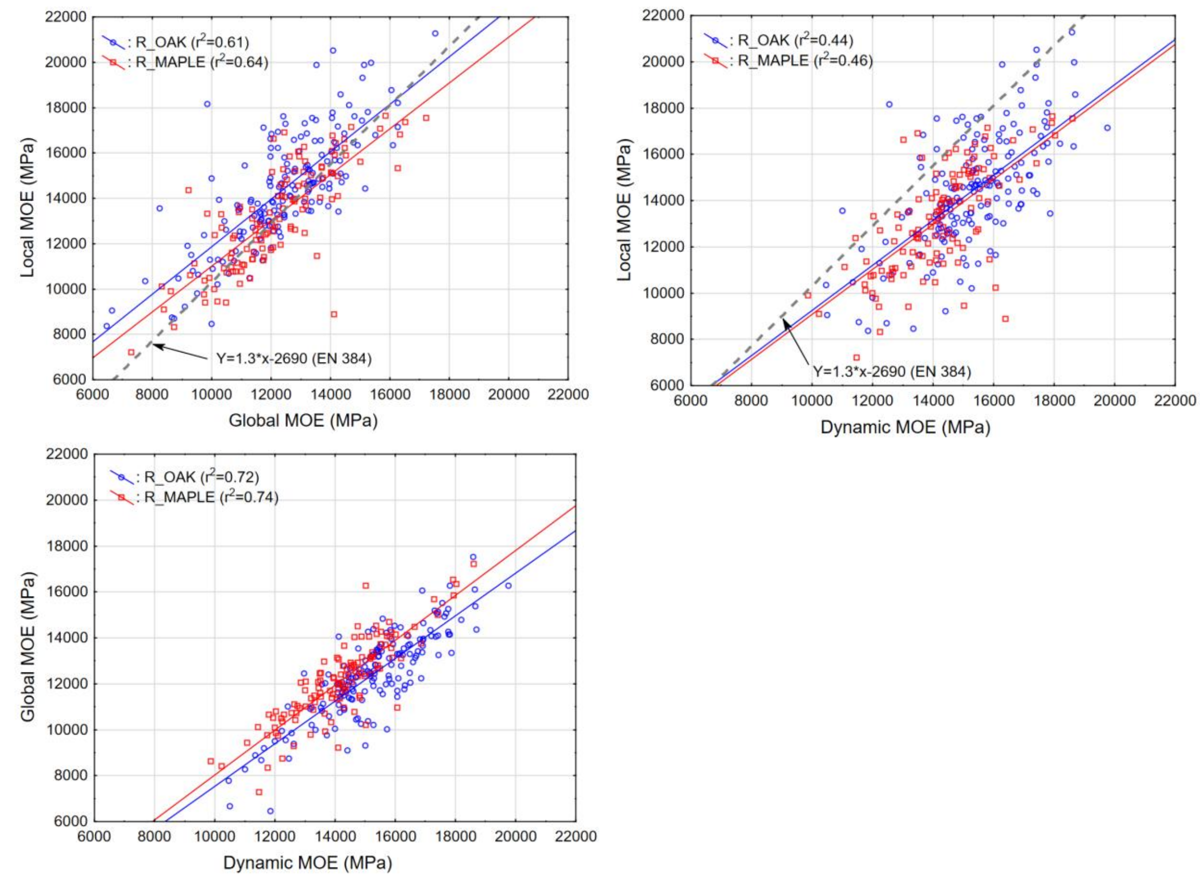

Fig. 5. Linear regressions between the three types of modulus of elasticity (MOE) for two wood species using the total (combined grades) dataset from each method

The strongest correlations were found between MOE_d and MOE_g, regardless of whether the grades were combined or separated. For both species, grade separation increased the correlation coefficient in grades SS, No. 2, and No. 3. In contrast, the separated grade BG resulted in lower r^2 values than the combined grades for both species. The highest correlations were observed in grade No. 3, with r^2 values of 0.85 for red maple and 0.80 for red oak. The r^2 values of 0.74 for red oak and 0.72 for red maple in the combined grades align with previously reported values for hardwood species. Specifically, r^2 values of 0.76, 0.72, 0.69, 0.73 were reported by Ponneth *et al.* (2014), Turkot *et al.* (2020), Wolcott (1998), and Acuña *et al.* (2023), respectively. Nevertheless, the higher r^2 values obtained in grade No. 3 and SS for both species align more closely with the published r^2 values reported for softwood species. The relationship between longitudinal vibration MOE_d and static bending MOE_g for Southern pine species was reported as 0.87 by Gerhards (1982), 0.81 by Shmulsky *et al.* (2006), 0.86 by França *et al.* (2019) and for Douglas fir 0.80 by Wang *et al.* (2008).

In contrast to the strong correlation between dynamic and global MOE, the weakest correlations were observed between dynamic and local MOE. Additionally, the regressions within each grade did not yield better correlations, except for grade SS in red maple and grade No. 3 in red oak. Notably higher r^2 values of 0.58 were obtained for grades SS and No. 3, compared to the r^2 values of 0.46 for red maple and 0.44 for red oak in the combined grades. When comparing the regression models to the equation from the standard EN 384 (Eq. 1), it is evident that the equation consistently overestimated the local MOE within the measurement ranges, regardless of grades or wood species. As no previous study investigating the correlation between dynamic and local MOE was found, comparing the accuracy of obtained models is impossible.

The separation by grades did not yield a stronger linear regression between the local and global MOE for red oak lumber, and only a slight increase was observed in grades SS and No. 2 for red maple. The r^2 values for the combined grades was 0.61 for red oak, and 0.64 for red maple. Both correlations were noticeably lower than those reported for softwood species (spruce: $r^2 = 0.95$, pine: $r^2 = 0.97$, Douglas-fir: $r^2 = 0.97$) by Denzler *et al.* (2008). Slightly lower values were reported by Nocetti *et al.* (2013) for Douglas-fir ($r^2 = 0.89$) and Corsican pine ($r^2 = 0.89$). For hardwoods, chestnut showed an r^2 of 0.81, which was the only hardwood analyzed in their study. To compare the accuracy of the regression models from the combined dataset and the standard EN 384 (2016) equation in predicting the local MOE from the global MOE, the Mean Absolute Percentage Error (MAPE) was calculated. The MAPE values indicated that the regression model provided a slightly more accurate prediction of the local MOE than the EN 384 (2016) equation for red oak, with MAPE values of 8.5% and 9.4%, respectively. For red maple, both methods showed identical accuracy, with a MAPE of 8.2%. These results suggest that the regression model has a minor advantage over the EN 384 (2016) equation for red oak, while the two methods perform equally well for red maple.

CONCLUSIONS

1. For both red oak and red maple wood species, significant differences in MOE values from center-point static loading tests were observed solely between Select Structural and Below-grade lumber.
2. With the stress wave timer method, no significant differences were found between any visual grades, including Below-grade lumber.
3. Regardless of the MOE determination method used, the MOE value of the analyzed one-inch-thick hardwood lumber is incapable of reliably distinguishing among the examined Select Structural, No. 2, and No. 3 visual grades.
4. In the case of red maple, it proved advantageous to conduct the correlation analysis of MOE values obtained by different measurement methods separated by visual classes. This approach resulted in higher coefficient of determination (r^2) values for both Select Structural and No. 2 classes compared to the analysis performed on the combined grades.
5. The strongest linear correlation was found between the global MOE and the dynamic MOE, which is even higher when the analyses are conducted separately by visual classes (Select Structural, No.2, No. 3) compared to the combined grades.
6. The global MOE was a better predictor of the local MOE than the dynamic MOE. The accuracy of the regression model did not differ from the standard conversion equation for red maple, while it differed only slightly for red oak.

ACKNOWLEDGMENTS

The research on which this article is based was partially supported by grants provided by the USDA Forest Service Wood Innovation Program (# 22-DG-11083150-104), the Appalachian Regional Commission (ARC), and the WVU Hardwood Research Trust (HRT) Program. The authors also gratefully acknowledge Allegheny Wood Products Company for donations of material, services, and time.

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Article submitted: November 18, 2024; Peer review completed: January 10, 2025; Revised version received and accepted: January 29, 2025; Published: February 12, 2025.
DOI: 10.15376/biores.20.2.2609-2627