Nondestructive Evaluation of Red Oak and White Oak Species

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Abstract

The objective of this article is to evaluate the relationship between the dynamic modulus of elasticity (MOE_d), which was obtained with acoustic-based nondestructive testing (NDT) methods, and static bending properties of two domestic hardwood oak species. The mechanical properties were conducted using static modulus of elasticity (MOE) and modulus of rupture (MOR) in radial and tangential directions. Mechanical tests were performed according to ASTM D143 on small clear, defect-free specimens from the two tree species: red oak (*Quercus rubra*) and white oak (*Quercus alba*). The MOE_d was determined by two NDT methods and three longitudinal vibration methods based on the fast Fourier transform. The destructive strength values obtained in this study were within the expected range for these species. The MOE was best predicted by NDT methods for both species but also had a strong capability to predict MOR.

Wood is a natural material with a diverse variability in its mechanical properties. In order to use a wood species for structural design, numerical simulations, or material selection, its quality control and material properties must be known. Reliable and repeatable information concerning the mechanical properties of wood is required to promote the introduction of species into a market for specific purpose.

Tree growth location, silvicultural treatments, genetics, weather, and soil conditions all influence growth characteristics and properties within and between species (Zobel and Van Buijtenen 1989). Several elements influence mechanical properties; some of these characteristics include knots, species, slope of grain, density, ratio of earlywood/latewood, fungal rot and other damage, processing, or loading history. Because wood is a natural material and exposed to different conditions and locations, it is impossible to replicate a sample or results exactly as previous studies (Forest Products Laboratory 2010).

The mechanical properties can be obtained by destructive and nondestructive methods. These properties are necessary to evaluate the quality of the wood and further compare with various other wood species. The destructive mechanical tests are typically performed according to the ASTM D143 standard test in small clear specimens to evaluate the strength and stiffness (ASTM International 2014).

The ASTM D143 standard demand for ''clear'' specimens, free of defects, is used to denote a specimen that does not contain any visible strength-reducing characteristics and has a limited slope of grain.

When performed, destructive tests increase the cost for companies, since after these tests the samples cannot be used. For these reasons, in the last decades the study of nondestructive test (NDT) techniques to assess the quality of wood has been increasing (Jayne 1959, Pellerin 1965, Kaiserlik and Pellerin 1977, Gerhards 1982, Falk et al. 1988, Ross et al. 1991, Ross 2015, Chauhan and Sethy 2016). Nondestructive tests reproduce a reliable and relatively quick result without affecting the wood properties, tree, log, or extracted lumber product, and hence the wood can be used in service thereafter (Wang 2013; Yang et al. 2015; França et al. 2018, 2019, 2020).

The use of longitudinal vibration waves in solid materials is crucial for several nondestructive techniques for material characterization. The use of longitudinal vibration waves has been a basic parameter, often used in materials such as

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Forest Prod. J. 70(3):370–377.
doi:10.13073/FPJ-D-20-00015

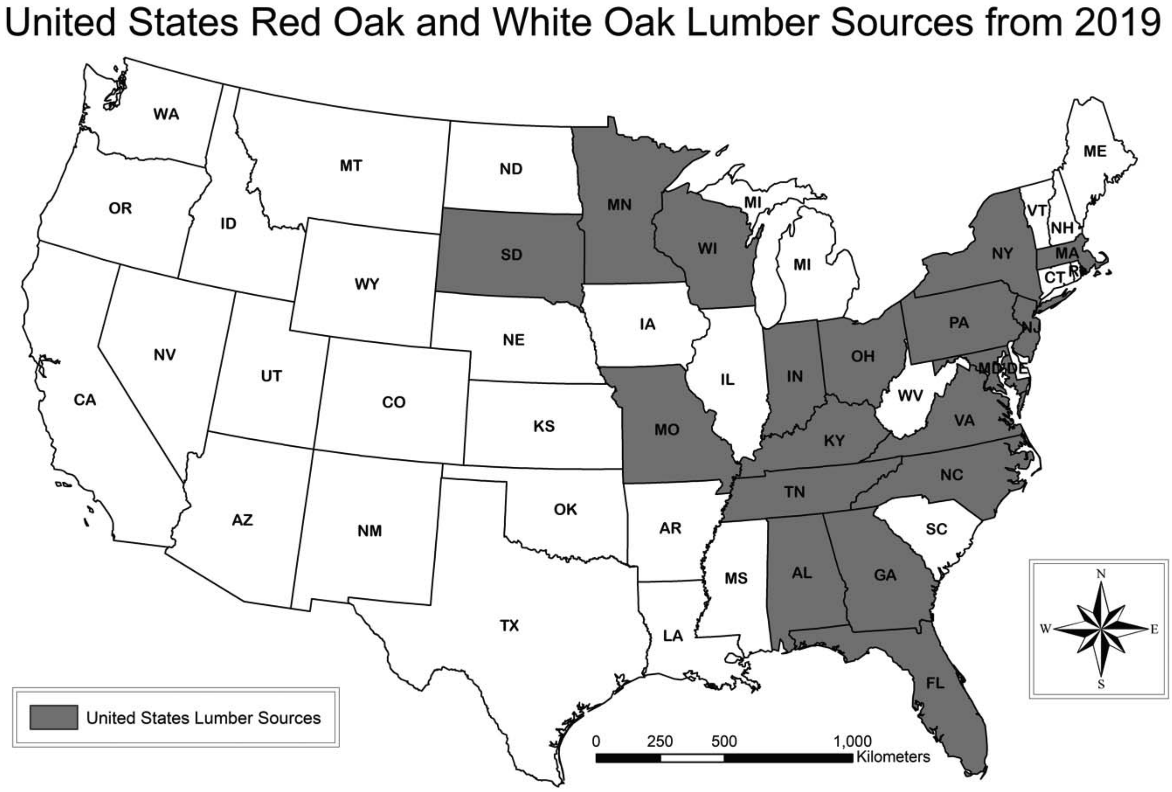

Figure 1.—Origin source of the raw material samples acquired in this study, highlighted in gray.

wood, stones, and refractory products, which can be used to determine the static modulus of elasticity (MOE) and to predict its modulus of rupture (MOR; Rosell and Cantalapiedra 2011). The advantage of using the longitudinal vibration waves as a tool to determine the MOE is the simplicity of its determination, inexpensiveness, and suitability across applications. This technique provides an estimation of the materials' parameters without the destructive rupture of the material, leading to fiscal savings (Ross 2015).

The standard ASTM E1876 (ASTM International 2015) describes the method based on measuring the resonant frequencies of the test specimen after being physically impacted. The sample specimen and vibration analysis are to obtain the natural frequency. The longitudinal frequency is analyzed based on the fast Fourier transform (FFT) that converts the time domain signal into frequency domain signal. The dynamic modulus of elasticity (MOE_d) is calculated based on the natural frequency from the FFT.

The MOE_d is used to predict the static MOE of the material and indirectly the MOR, given the positive correlation between static MOE and MOR. The range for this correlation goes from 0.18 to 0.72 (Diebold et al. 2000; Hanhijärvi et al. 2005; Shmulsky et al. 2006; Iniguez et al. 2007; Divós and Sismándy-Kiss 2010; Nocetti et al. 2010; França et al. 2018, 2019). Despite what is known regarding NDT and its relationship with mechanical properties, there is still limited information about its ability to predict mechanical properties of small clear samples from hardwood species. This study focuses on acoustic-based methods, such as longitudinal wave vibrations, to predict the MOE and MOR. Specifically, the objective of this study was to assess the relationship between MOE_d measured by three NDT techniques and compare the mechanical properties of small clear specimens of two domestic oak (*Quercus* spp.) hardwood species.

Material and Methods

Material

For this study, 48 red oak (*Quercus rubra*) and 44 white oak (*Quercus alba*) boards were used (donated from the Stairbuilders and Manufacturers Association members). The supplied wood samples represent the material used in staircase industry production. Figure 1 shows the origin sources of the raw material acquired in this study during 2019. Because the staircase manufacturer location was known, it was possible to trace back the origin of the boards to a particular sawmill. In addition, sampling was randomized, where boards used were sent from different locations. The boards used were under staircase production specifications, which included defect-free boards kiln-dried at 12 percent moisture content (MC) and straight grain. The material was considered high-quality hardwood boards with no presence of visual defects. Each board sent by the manufacturers had the following dimensions: 3.1 by 11.4 by 91.0 cm. The original dimensions of the boards were used to conduct NDT, and then small clear specimens were manufactured from the boards.

Boards were placed in an environmental-conditioned room (21°C and 65% relative humidity) for 90 days to equilibrate the wood MC to around 12 percent. Tests were performed in the same environment where the boards were conditioned. The MC of each board was measured using a capacitance type moisture meter (Wagner MMC220; Wagner Meters, Rogue River, Oregon).

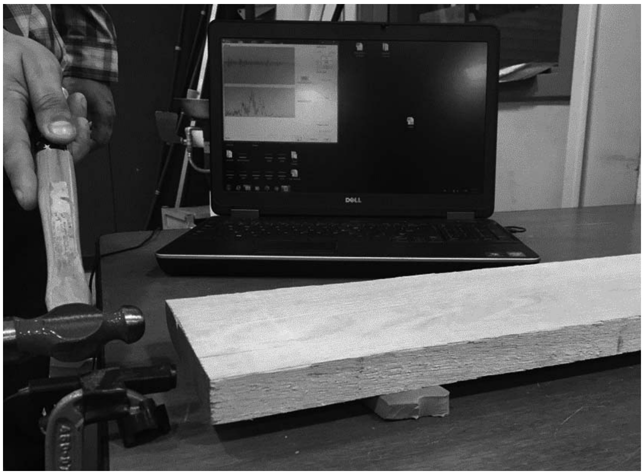

Figure 2.—Test setup for nondestructive testing procedure.

Each board was given an identification label that included letters representing each species and a board number within that species. For example, RO 001 indicated red oak and board number 001 within that species. A structured query language database record was created to store the data collected and to minimize typing errors. The common and scientific name for each species, percentage of latewood, and number of rings per inch are shown in Table 1.

Nondestructive evaluation

Boards were tested using longitudinal wave vibration procedures. To reduce any interference of sawhorse vibration, foam was placed at each end between the sawhorse and specimen. To generate the vibration frequency, a ball peen hammer was used to stress each board. The vibration signal was collected by acoustic microphones. The following NDT tools were used to collect the vibrational signals: (1) computer-based Fakopp Microsecond Timer (Fakopp Enterprise Bt. 2005); (2) computer-based Falcon A-grader (Falcon Engineering 2006); and (3) phone-based NDT application (SmartThumper 2018).

The natural frequencies, shown in Figure 2, obtained by this study were in accordance with standard ASTM E1876 (ASTM International 2015). The MOE_d of each board was calculated using the natural frequency collected by all three NDT tools according to Equation 1.

$$MOE_d = \rho(2 \cdot L \cdot f)^2 \tag{1}$$

Table 1.—Species name, percentage of latewood, and number of rings per inch. Coefficients of variation (%) in parentheses.

Common names	Botanical names	Percentage of latewood	No. rings per in.
Red oak	*Quercus rubra*	70.5 (45.3)	8.1 (17.0)
White oak	*Quercus alba*	68.0 (42.6)	10.7 (19.0)

where MOE_d = dynamic modulus of elasticity (MPa), ρ = density (kg m^{-3}), L = length of the board (m), and f = longitudinal wave vibration natural frequency (Hz).

After vibrational tests were performed, the boards were moved to a woodshop for further processing. As shown in Figure 3, boards were cut into small clear specimens following ASTM D143 (ASTM International 2014). The specimens were labeled so that each specimen could be traced to its respective original board and subsequently returned to the conditioning room. Bending specimens labeled as A were tested in the radial orientation, while the bending specimens labeled as B were tested in the tangential orientation.

Static bending destructive tests

The samples were cut to 2.54 by 2.54 by 40.64 cm (1 by 1 by 16 in.) in accordance with Section 8.1 of the ASTM D143 Standard (ASTM International 2014) for secondary specimens. The samples were cut according to the tangential and radial axis (Fig. 4). All static bending specimens were destructively tested via a three-point loading using an Instron Satec (2,250 lbf.) Model 5566 Universal Testing Machine located in the Department of Sustainable Bioproducts Mechanical Testing Laboratory at Mississippi State University. The loading rate was 0.127 cm/min (0.05 in./min) with a load span of 36 cm (14 in.; Fig. 5). Density was determined according to ASTM D2395 (ASTM International 2017). Samples for specific gravity use in determining compression and hardness were also extracted.

Statistical analyses

All statistical analyses of static bending (MOE and MOR) and MOE_d values obtained from longitudinal wave vibration tests were conducted using SAS 9.4 (SAS Institute Inc. 2013). Single variable linear regression analyses ($\alpha = 0.05$) were used for each species to quantify the relationship between the NDT measured and the bending MOE and MOR values. The linear regressions were conducted given

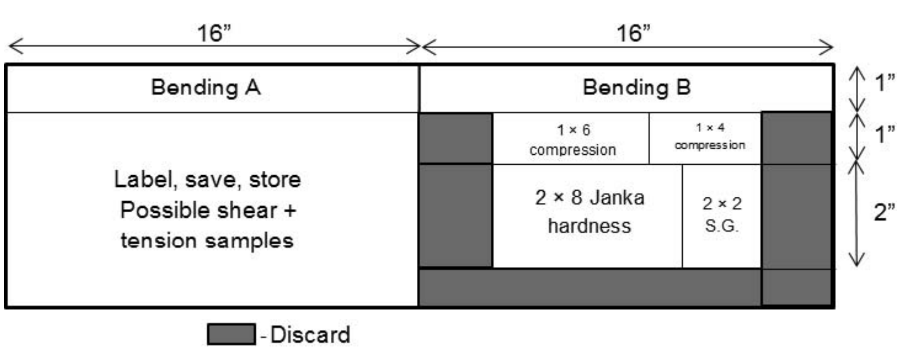

Figure 3.—Cut-up process of small clear specimens from each board.

Table 2. —Overall results for red oak and white oak species. Coefficients of variation (%) in parentheses.

Variable[a]	Red oak			White oak		
	Mean	Min	Max	Mean	Min	Max
Moisture content (%)	8.53 (15.67)	5.10	11.40	10.38 (16.44)	6.70	13.90
Density (kg m^3)	682 (6.22)	594	762	758 (10.21)	607	934
MOE_d Falcon (MPa)	12,811 (16.26)	7,515	15,677	12,322 (21.43)	6,740	21,643
MOE_d SmartThumper (MPa)	14,045 (21.26)	8,653	19,126	12,790 (24.30)	6,775	21,445
MOE_d Fakopp (MPa)	13,496 (21.36)	7,158	17,766	12,422 (24.12)	6,429	20,503
MOE radial (MPa)	11,148 (16.32)	5,683	14,384	10,538 (19.60)	6,420	14,815
MOE tangential (MPa)	11,475 (17.74)	5,934	15,270	10,524 (21.10)	6,436	14,620
MOR radial (MPa)	112.68 (14.35)	64.32	148.14	112.60 (19.20)	53.04	153.01
MOR tangential (MPa)	113.87 (15.37)	65.22	149.19	116.27 (19.25)	59.62	153.27

[a] MOE = modulus of elasticity; MOR = modulus of rupture.

the independent variables (x, which is represented by the MOE_d) and the dependent variable (y, which is represented by MOE and MOR).

Two-sample t tests were performed to determine if there were significant mean differences in density, MOE, and MOR between species. The t tests were performed to compare the radial and tangential orientations, and average values of density, MOE, and MOR for each species.

Results and Discussion

The overall results are listed in Table 2. Red oak had lower MC and density when compared with the average values of white oak. The MOE_d values obtained with NDT tools were higher than static MOE values. This occurred due to the difference between the length/width ratio of the tested boards and small clear specimens (8 and 14, respectively). The smaller the length/width ratio, the higher the obtained values for MOE_d. This is explained in more detail by Newlin and Trayer (1956).

Red oak MOE was higher in the tangential direction. Red oak showed slightly higher MOR values in the tangential direction. The average values for MOE in white oak obtained in radial and tangential orientations were similar. White oak MOR was higher in the tangential direction.

Two-sample t tests for density, static MOE, and MOR of small clear samples for red oak and white oak are shown in Table 3. A two-sample t test revealed significant differences at the α level of 0.05 for density and overall MOE between red oak and white oak samples. No significant differences ($P > 0.40$) were found between radial and tangential orientations for MOE and MOR for both species.

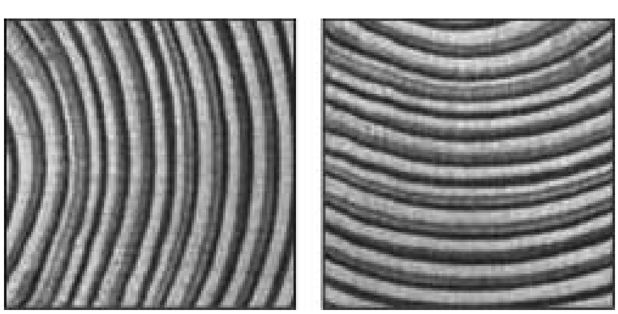

Figure 4.—Small clear specimens: radial and tangential cross sections.

Linear regressions for red and white oak are shown in Figures 6 and 7, respectively. This was done to evaluate the ability of NDT tools to better predict the static bending MOE and MOR values. Two-sample t tests for density, MOE, and MOR of red oak small clear samples are shown in Table 4.

Density had a higher prediction of red oak in the radial orientation of MOE and MOR when compared with tangential direction. The SmartThumper and Fakopp NDT tools were better predictors of red oak MOE and MOR when compared with the Falcon tool and density as a single predictor. The prediction of radial MOE was higher when compared with tangential MOE for all three tools. All three NDT tools were highly capable with tangential samples in predicting MOR. Two-sample t tests for density, MOE, and MOR of white oak small clear samples are shown in Table 5.

Density had a higher prediction of white oak tangential MOE when compared with the radial directions, and for radial MOR when compared with tangential orientation. The SmartThumper and Fakopp NDT tools were better predictors of white oak MOE and MOR values. The prediction of MOE was similar for radial and tangential directions. All

Table 3.—Two-sample t test for density, modulus of elasticity (MOE), and modulus of rupture (MOR) of small clear samples for red oak and white oak.[a]

Property	Species/direction	n	Mean	t test	P
Density	Red oak	48	682	5.88	<0.001
	White oak	44	758		
MOE	Red oak (R + T)	96	12,322	4.99	<0.001
	White oak (R + T)	88	10,531		
MOE	Red oak radial	48	11,148	−0.83	0.41 ns
	Red oak tangential	48	11,475		
MOE	White oak radial	44	10,538	0.03	0.97 ns
	White oak tangential	44	10,524		
MOR	Red oak (R + T)	96	113.3	−0.40	0.69 ns
	White oak (R + T)	88	114.4		
MOR	Red oak radial	48	112.7	−0.35	0.73 ns
	Red oak tangential	48	113.9		
MOR	White oak radial	44	112.6	−0.78	0.44 ns
	White oak tangential	44	116.3		

[a] ns = not significant (α = 0.05); R + T is the combination of radial and tangential samples.

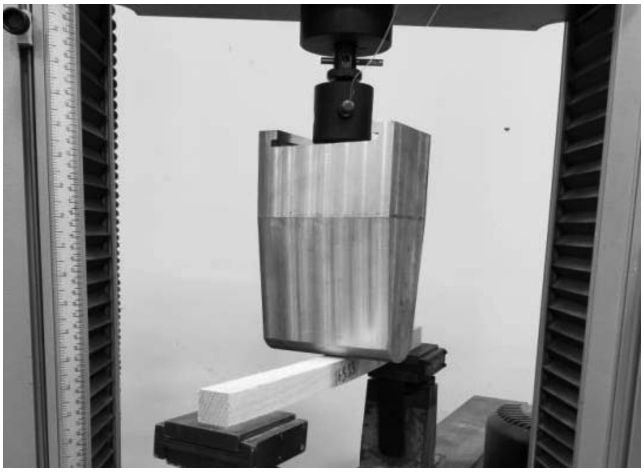

Figure 5.—Three-point loading static bending destructive test setup.

three NDT tools had strong capability with tangential samples in predicting MOR.

For static MOE, the standard error of estimates for density as independent variable was lower for white oak in both orientations tested. When analyzing static MOR, red oak had better results. SmartThumper and Fakopp tools showed lower standard error of estimates for static MOE and MOR for both species. Based on standard error analysis, these two tools are more reliable for small dimension boards.

Conclusions

Based on the results obtained in this study, it was possible to obtain more information on mechanical properties of the two oak species commercially sold in the staircase market. The results of this research can be used not only by staircase manufacturers to develop design values, but also in the sawmill to implement grading for the hardwood species studied that is up to date with the building codes and

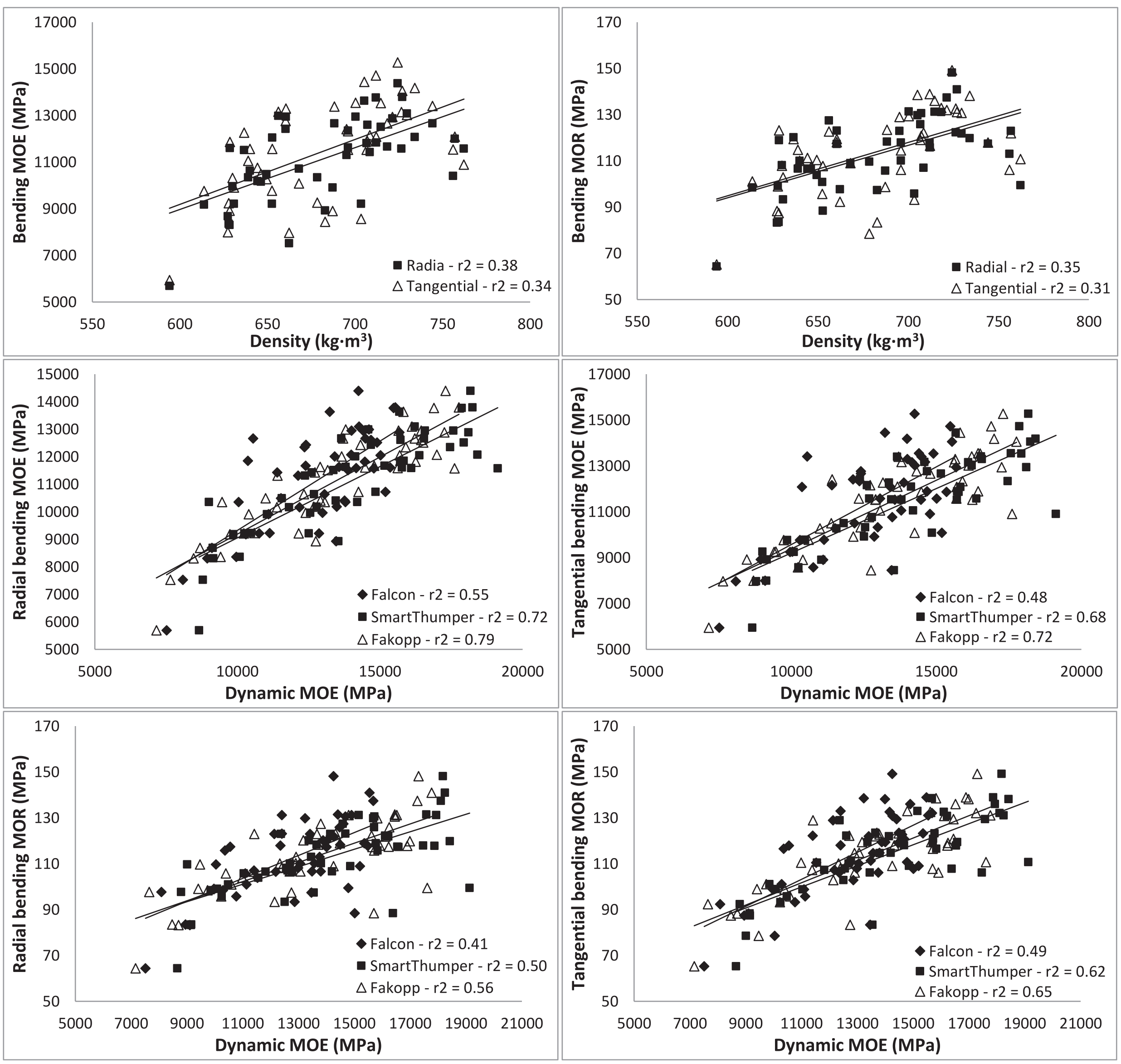

Figure 6.—Linear regressions between the independent variables and static modulus of elasticity (MOE) and modulus of rupture (MOR) for red oak.

Table 4.—Two-sample t *test for density, modulus of elasticity (MOE), and modulus of rupture (MOR) of red oak small clear samples.*

Variable	Slope (m)	Intercept (b)	Coefficient of determination (r^2)	Standard error of estimate	P
Red oak MOE radial					
Density	26.50	−6,930	0.38	4.98	<0.001
MOE_d Falcon	0.65	2,835	0.55	0.09	<0.001
MOE_d SmartThumper	0.52	3,873	0.72	0.05	<0.001
MOE_d Fakopp	0.56	3,586	0.79	0.04	<0.001
Red oak MOE tangential					
Density	27.84	−7,514	0.34	5.77	<0.001
MOE_d Falcon	0.68	2,799	0.48	0.10	<0.001
MOE_d SmartThumper	0.56	3,582	0.68	0.06	<0.001
MOE_d Fakopp	0.60	3,405	0.72	0.06	<0.001
Red oak MOR radial					
Density	0.23	−42.20	0.35	0.05	<0.001
MOE_d Falcon	0.005	48.67	0.41	0.001	<0.001
MOE_d SmartThumper	0.003	59.13	0.50	0.001	<0.001
MOE_d Fakopp	0.004	56.14	0.56	0.001	<0.001
Red oak MOR tangential					
Density	0.23	−43.62	0.31	0.05	<0.001
MOE_d Falcon	0.005	38.33	0.49	0.001	<0.001
MOE_d SmartThumper	0.005	49.26	0.62	0.001	<0.001
MOE_d Fakopp	0.005	48.01	0.65	0.001	<0.001

regulations. In addition, the results showed that NDT tools are capable of predicting MOE and MOR.

Acknowledgments

The authors wish to acknowledge the support of US Department of Agriculture (USDA), Research, Education, and Economics (REE), Agriculture Research Service (ARS), Administrative and Financial Management (AFM), Financial Management and Accounting Division (FMAD), Grants and Agreements Management Branch (GAMB), under Agreement No. 58-0204-6-001. The authors acknowledge the support from USDA Forest Service Forest Products Laboratory in Madison, Wisconsin, as a major contributor of technical assistance, advice, and guidance to this research. The authors would like to recognize the following individual for their input and continued support in this ongoing research: Dr. Robert J. Ross (USDA Forest Service, Forest Products Laboratory). The authors also thank the Stairbuilders and Manufacturers Association members for donating the material for this research. This publication is a contribution of the Forest and Wildlife Research Center at Mississippi State University. This article was approved as

Table 5.—Two-sample t *test for density, modulus of elasticity (MOE), and modulus of rupture (MOR) of white oak small clear samples.*

Variable	Slope (m)	Intercept (b)	Coefficient of determination (r^2)	Standard error of estimate	P
White oak MOE radial					
Density	10.43	2,633	0.15	3.79	0.009
MOE_d Falcon	0.49	4,484	0.39	0.09	<0.001
MOE_d SmartThumper	0.57	3,230	0.74	0.05	<0.001
MOE_d Fakopp	0.59	3,109	0.75	0.05	<0.001
White oak MOE tangential					
Density	12.20	1,282	0.18	4.01	0.004
MOE_d Falcon	0.54	3,916	0.41	0.10	<0.001
MOE_d SmartThumper	0.61	2,701	0.73	0.06	<0.001
MOE_d Fakopp	0.64	2,544	0.75	0.06	<0.001
White oak MOR radial					
Density	0.16	−12.28	0.35	0.03	<0.001
MOE_d Falcon	0.003	68.68	0.19	0.001	0.003
MOE_d SmartThumper	0.004	63.51	0.30	0.001	<0.001
MOE_d Fakopp	0.004	61.84	0.32	0.001	<0.001
White oak MOR tangential					
Density	0.16	−4.87	0.31	0.04	<0.001
MOE_d Falcon	0.004	64.54	0.25	0.001	<0.001
MOE_d SmartThumper	0.004	59.11	0.39	0.001	<0.001
MOE_d Fakopp	0.005	56.78	0.41	0.001	<0.001

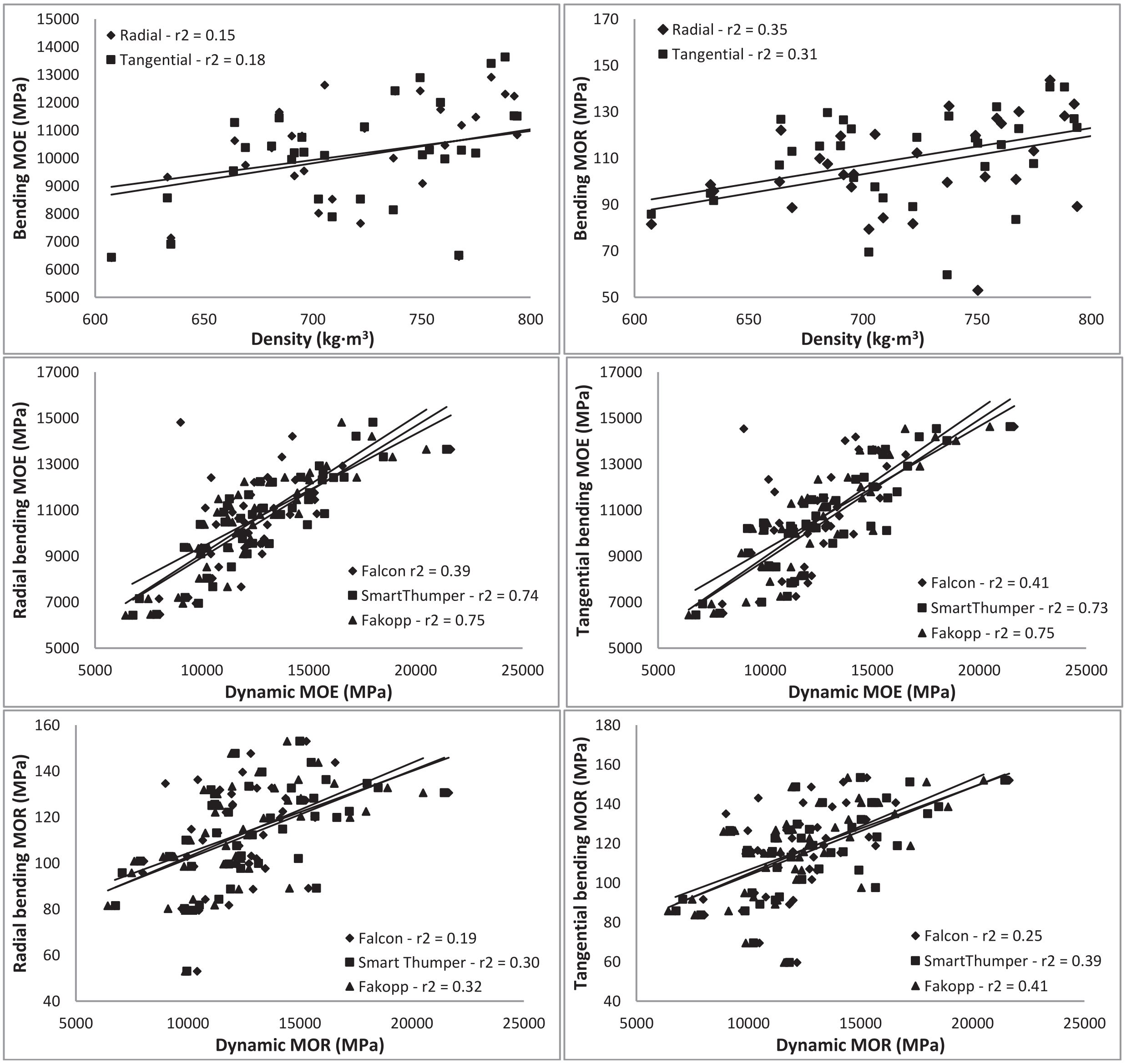

Figure 7.—Linear regressions between the independent variables and static modulus of elasticity (MOE) and modulus of rupture (MOR) for white oak.

journal article SB 980 of the Forest & Wildlife Research Center, Mississippi State University.

Literature Cited

ASTM International. 2014. Standard test methods for small clear specimens of timber. ASTM D143. ASTM International, West Conshohocken, Pennsylvania.

ASTM International. 2015. Standard test method for dynamic young's modulus, shear modulus, and Poisson's ratio by impulse excitation of vibration. ASTM E1876. ASTM International, West Conshohocken, Pennsylvania.

ASTM International. 2017. Standard test methods for density and specific gravity (relative density) of wood and wood-based materials. ASTM D2395. ASTM International, West Conshohocken, Pennsylvania.

Chauhan, S. and A. Sethy. 2016. Differences in dynamic modulus of elasticity determined by three vibration methods and their relationship with static modulus of elasticity. *Madera Cien*. *Tecnol*. 18(2):373–382.

Diebold, R., A. Schleifer, and P. Glos. 2000. Machine grading of structural sawn timber from various softwood and hardwood species. *In:* Proceedings of the 12th International Symposium on Nondestructive Testing of Wood, September 13–15, 2000, Sopron, Hungary; University of Western Hungary, Sopron. pp. 139–146.

Divós, F. and F. Sismándy-Kiss. 2010. Strength grading of structural lumber by portable lumber grading—Effect of knots. *In:* Proceedings of the Future of Quality Control for Wood and Wood Products, May 4–7, 2010, Edinburgh; Forest Products Research Institute / Centre for Timber Engineering, Edinburgh Napier University. The final conference of COST Action E53. 7 pp.

Fakopp Enterprise Bt. 2005. Fast Fourier Vibration analyzer User's Guide. Fakopp Enterprise Publication, Ágfalva, Hungary.

Falcon Engineering. 2006. A-Grader. Falcon Engineering, Inglewood, New Zealand.

Falk, R. H., M. Patton-Mallory, and K. A. McDonald. 1988. Nondestructive testing of wood products research and structures: State-of-the-art and research needs. *In:* Proceedings of Conference on the Nondestructive Testing Evaluation for Manufacturing and Construction, Champaign, Illinois; Hemisphere Publishing Corp., New York. pp. 137–147.

Forest Products Laboratory. 2010. Wood handbook—Wood as an engineering material. General Technical Report FPL-GTR-190.

Centennial Edition. USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin. 508 pp.
França, F. J. N., R. D. Seale, R. Shmulsky, and T. S. F. A. França. 2018. Modeling mechanical properties of 2 by 4 and 2 by 6 southern pine lumber using longitudinal vibration and visual characteristics. *Forest Prod. J.* 68(3):286–294.
França, F. J. N., R. D. Seale, R. Shmulsky, and T. S. F. A. França. 2019. Assessing southern pine 2 × 4 and 2 × 6 lumber quality: Longitudinal and transverse vibration. *Wood Fiber Sci*. 51(1):1–14.
França, T. S. F. A., F. J. N. França, R. D. Seale, and R. Shmulsky. 2020. Nondestructive evaluation of 2 by 8 and 2 by 10 southern pine dimensional lumber. *Forest Prod. J.* 70(1):79–87.
Gerhards, C. C. 1982. Longitudinal stress waves for lumbers stress grading: Factors affecting applications: State of art. *Forest Prod. J.* 32(20):20–25.
Hanhijärvi, A., A. Ranta-Maunus, and G. Turk. 2005. Potential of strength grading of timber with combined measurement techniques. Report of the Combigrade-project phase 1. VTT Publications 568. VTT, Espoo, Finland.
Iniguez, G., M. Esteban, J. D. Barrett, and F. Arriaga. 2007. Visual grading of large structural coniferous sawn timber according to Spanish standard UNE 56544. *Forest Prod. J.* 57(10):45–50.
Jayne, B. A. 1959. Vibrational properties of wood as indices of quality. *Forest Prod. J.* 9(11):413–416.
Kaiserlik, J. H. and R. F. Pellerin. 1977. Stress wave attenuation as an indicator of lumber strength. *Forest Prod. J.* 27(6):39–43.
Newlin, J. A. and G. W. Trayer. 1956. Deflection of beams with special reference to shear deformations: The influence of the form of a wooden beam on its stiffness and strength-I. FPL Report 1309. USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin. 19 pp.
Nocetti, M., M. Bacher, M. Brunetti, A. Crivellaro, and J. W. van de Kuilen. 2010. Machine grading of Italian structural timber: Preliminary results on different wood species. *In:* Proceedings of the 11th World Conference on Timber Engineering, June 20–24, 2010, Riva del Garda, Italy; Trees and Timber Institute, National Research Council, Trentino, Italy.
Pellerin, R. F. 1965. A vibrational approach to nondestructive testing of structural lumber. *Forest Prod. J.* 15(3):93–101.
Rosell, J. R. and I. R. Cantalapiedra. 2011. Simple method of dynamic Young's modulus determination in lime and cement mortars. *Mater Construc*. 61(301):39–48.
Ross, R. J. 2015. Nondestructive evaluation of wood. 2nd ed. General Technical Report FPL-GTR-238. USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin. 169 pp.
Ross, R. J., E. A. Geske, G. L. Larson, and J. F. Murphy. 1991. Transverse vibration nondestructive testing using a personal computer. Research Paper FPL-RP-502. USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin.
SAS Institute. 2013. SAS® software, version 9.4. The SAS Institute Inc., Cary, North Carolina.
Shmulsky, R., R. D. Seale, and R. D. Snow. 2006. Analysis of acoustic velocity as a predictor of stiffness and strength in 5-in-diameter pine dowels. *Forest Prod. J.* 56(9):52–55.
SmartThumper. 2018. Department of Sustainable Bioproducts, College of Forest Resources, Mississippi State University, Starkville.
Wang, X. 2013. Stress wave e-rating of structural timber—Size and moisture content effects. *In:* Proceedings of the 18th International Nondestructive Testing and Evaluation of Wood Symposium, R. J. Ross and X. Wang (Eds.), September 24–27, 2013, Madison, Wisconsin; Forest Products Society, Madison, Wisconsin. pp. 38–46.
Yang, B. Z., R. D. Seale, R. Shmulsky, J. Dahlen, and X. Wang. 2015. Comparison of nondestructive testing methods for evaluating No. 2 southern pine lumber: Part A, modulus of plasticity. *Wood Fiber Sci*. 47(4):375–384.
Zobel, B. J. and J. P. Van Buijtenen. 1989. Wood Variation: Its Causes and Control. Berlin, Springer-Verlag. 418 pp.