PREDICTING MODULUS OF RUPTURE OF SOLID AND FINGER-JOINTED TROPICAL AFRICAN HARDWOODS USING LONGITUDINAL VIBRATION

JOSHUA AYARKWA
YOSHIHIKO HIRASHIMA
YASUTOSHI SASAKI

ABSTRACT

The longitudinal vibration technique was examined as a means of evaluating the modulus of elasticity (MOE) and predicting the modulus of rupture (MOR) of solid and finger-jointed lumber from three tropical African hardwoods, Obeche (*Triplochiton scleroxylon*), Makore (*Tieghemella heckelii*), and Moabi (*Baillonella toxisperma*). Dynamic MOE was well correlated to static bending MOE for solid and finger-jointed lumber from the three tropical African hardwoods. Correlation coefficients of 0.94 and 0.90 obtained for the regression of dynamic MOE on MOR for solid and finger-jointed lumber, respectively, were comparable to those of 0.95 and 0.91 between static MOE and MOR for solid and finger-jointed lumber, respectively. Regression models developed for the regression of dynamic MOE on MOR for both solid and finger-jointed lumber were statistically highly significant ($\alpha = 0.05$). The lower 5 percent exclusion limit lines derived seemed useful for predicting the MOR of solid and finger-jointed lumber from the three hardwoods. Although the static bending test is generally recognized as a more desirable method of determining MOR, the results indicated that the longitudinal vibration technique may also be useful as a nondestructive technique for predicting MOR of solid and finger-jointed tropical African hardwoods. The technique seems more applicable in situations where static bending testing is not feasible to undertake.

The shrinking tropical African forest resulting from shifting cultivation on a decreasingly shorter cycle, requirements for fuelwood, illegal logging, bush fires, and inefficient logging and timber processing calls for efficient utilization of timber resources (12,13,20). For example, Ghana's relatively large timber-processing industry generates large volumes of wood residue, most of which are reportedly suitable for the production of high value-added products such as finger-jointed lumber (23,24). An assessment of the availability of solid sawmill lumber off-cuts (residue) suitable for the production of finger-jointed lumber in Kumasi city alone, indicated the availability of over 70,000 m^3, which is presently not well utilized. Lumber processing mills in Ghana are currently being called upon to establish finger-jointing plants to utilize sawmill residues, in order to increase their profitability.

A finger-joint is a type of structural end joint used in glued laminated timber (glulam) to form long, continuous laminations out of individual pieces of lumber, and also in other engineered wood components such as trusses and I-joists (8). The strength of lumber is enhanced by finger-jointing (15). Structural finger-joints were developed to reduce the waste of high-quality lumber that resulted from machining of scarf joints, and they are reported to be one of the most economical ways of wood utilization (1,26,27). Low-grade wood can be used to produce high-quality finished products with improved strength and appearance because undesirable characteristics are removed (4,11).

The authors are, respectively, Graduate Student, Professor, and Associate Professor, Bio-material Engineering Lab., Graduate School of Bioagricultural Sciences, Nagoya Univ., Nagoya 464-8601, Japan. The authors wish to acknowledge the contributions of Aichi Timber Industries Limited and Iida Industrial Company Limited for helping in the preparation of the finger-joint specimens, and Oshika Shinko Company Limited for supplying glue for the study. This paper was received for publication in January 2000. Reprint No. 9078.

Forest Prod. J. 51(1):85-92.

The primary criterion for structural finger-joints is load-bearing strength. Strength requirements vary through a wide spectrum from studs on the low end to machine-stress-rated (MSR) lumber and glulam beams on the high end. The bending test is considered the most convenient and practical test for an extensive preliminary study of finger-joints, and can also be used for quality control after qualification (11). The Canadian National Lumber Grades Authority (NLGA) recommends a two-point loading test to evaluate solid and finger-jointed lumber (22). Although the classic static test is recognized as a more desirable method of determining wood properties, static testing may be difficult to carry out and may be time consuming. A fast, reliable, and easy-to-use method for predicting bending properties of solid and finger-jointed lumber would promote production and utilization of the product, and thereby encourage efficient timber utilization and conservation of tropical African forests.

Nondestructive wood testing permits strength and modulus of elasticity (MOE) values of individual lumber pieces determined destructively to be correlated with MOE measured nondestructively in order to assign property values without damage due to overloading, thereby improving the efficiency of timber utilization (6).

The main objective of this study was to evaluate the effectiveness of using the longitudinal vibration technique as a means of nondestructively predicting modulus of rupture (MOR) of solid and finger-jointed tropical African hardwoods of varying densities. If the technique is found effective, it may have value in stress grading of solid as well as finger-jointed tropical African hardwoods produced from sawmill lumber residues or off-cuts.

The dynamic MOE

Several methods for evaluating mechanical lumber properties exist. In addition to the classic static method of determining the elastic properties of wood, a method of dynamic evaluation, such as the longitudinal vibration based on measurement of natural frequency, has been used for many years (6,7,14,16,28). However, the number of studies reported in the literature involving both dynamic and static tests of lumber is limited, especially with respect to tropical African hardwoods.

The accuracy of the determination of MOE of wood by the vibration tests is said to be higher than that of static tests (6,16,19,28). The difference may be due to the rate of loading in static tests in which creep effects influence the measured static deflection (6) and also may be related to the viscoelastic nature of wood (19). According to Bodig and Jayne (6), MOE obtained by vibration tests proves to be 5 to 15 percent higher than that by static tests. Tsoumis (28) also reported that the difference ranges from 10 to 15 percent. Bucur (7) and Larsson et al. (19) reported that the value of MOE determined from dynamic tests is about 10 percent higher than by static tests for spruce and beech. Kollman and Krech (17) used the vibration method and obtained 19 and 14 percent higher MOE values than static test values for spruce and oak, respectively.

It seems clear that, although test procedures and dimensions of specimens may differ among studies found in the literature, the dynamically evaluated MOE is generally found to be somewhat higher than the static MOE. Thus, by using the vibration method to determine MOE, wood may be more efficiently utilized compared to the static test method. The dynamic method of determining MOE is also reported to have the advantage of comparatively shorter test duration (16).

Calculation of dynamic MOE

Bodig and Jayne (6) state that the velocity of propagation (C) of stress wave in the longitudinal direction of a rod supported at its midpoint is related to the MOE (E) and the mass density (ρ) as follows:

$$C = \sqrt{E/\rho} \qquad [1]$$

The general equation relating wavelength (λ) to length of the rod (L) and mode of vibration (n) is given by:

$$\lambda = 2L/n \qquad [2]$$

The wavelength is the ratio of wave velocity to the frequency of vibration (f_r), thus:

$$\lambda = C/f_r \qquad [3]$$

Combining Equations [1], [2], and [3] gives an expression for the frequency of vibration as follows:

$$f_r = n\sqrt{E/\rho}/2L \qquad [4]$$

Rearranging Equation [4] gives the following equation for calculating the dynamic MOE of lumber for the fundamental frequency (i.e., $n = 1$).

$$E = 4L^2\rho f_r^2 \qquad [5]$$

where E = MOE; ρ = mass density of lumber; L = length of lumber; f_r = fundamental resonant frequency.

Materials and methods

Preparation of specimens

Wood samples of Obeche (*Triplochiton scleroxylon*), Makore (*Tieghemella heckelii*), and Moabi (*Baillonella toxisperma*) were used for the study. The species were selected to represent the broad range of tropical African hardwoods commonly processed. Straight-grained heartwood samples without visible defects such as knots and spiral grain were randomly collected from three logs of each species. Kiln-dried samples of about 8 percent moisture content (MC) were planed and cross-cut to dimensions of 23 by 150 by 1000 mm. Samples were prepared such that no visible defects such as knots and spiral grains were present, and growth layers were at right angles to the width of each specimen. The 1000-mm-long samples were then matched in pairs on the basis of MOE (11,25) using the longitudinal vibration test method for finger-jointing.

Preparation of finger-jointed samples

The finger-jointing was done under factory conditions and in accordance with the NLGA and the German Standards (9,22). The finger profile used (**Fig. 1**) was the vertical profile type. For Makore and Moabi, the finger length (L) was 18 mm, tip width (t) was 0.6 mm

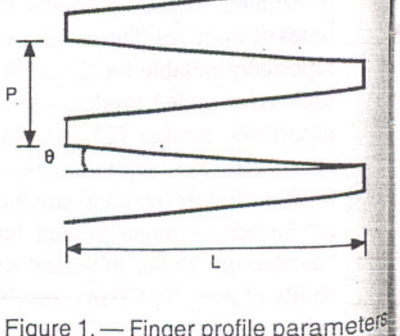


Figure 1. — Finger profile parameters.

pitch (p) was 3.7 mm, and slope (θ) was 1 in 12. For Obeche, however, L was 20 mm, t was 0.6 mm, p was 6.0 mm, and θ was 3 in 20. A finger-jointer equipped with woodworking, gluing, and pressing components was used. The woodworking machine used a clamping carriage that secured stacks of wood samples and guided them through a circular saw, a finger profile cutter, and suction. Another component aligned the wood during gluing and pressing.

The winter-type resorcinol formaldehyde glue (DIANOL 33N) was used. The glue was mixed in accordance with the supplier's instructions and according to the normal practice in the producing factory. Glue was applied by hand on both sides of the joint at a temperature of about 11°C. The joint was held open for about 60 seconds before mating and applying end pressure.

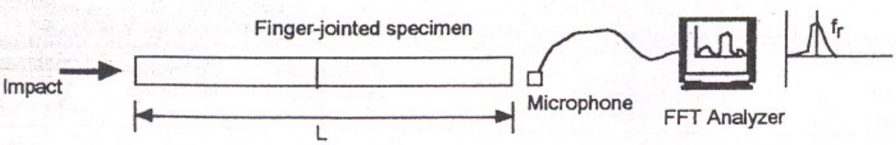
Three different end pressures used for pressing specimens of each species, selected under a broader study, are shown in **Table 1**. The finger-jointed specimens were cured in a chamber heated to over 30°C for more than 48 hours.

Processing of finger-jointed specimens after curing

The finger-jointed specimens were planed and the outer 5-mm edges along the length of each specimen were sawed off to remove inadequately bonded outer fingers, which could affect joint performance. Each specimen was then ripped in two, and both ends subsequently trimmed to final test specimen dimensions of 21 by 70 by 2000 mm for Makore and Moabi, and 21 by 58 by 2000 mm for Obeche. The test specimens were then conditioned to about 10 percent MC before testing. The middle 1000-mm portion that contained the finger-joint was tested as a finger-jointed specimen and the 860-mm lengths of the other sides, as well as additional similar-sized specimens, were tested as solid specimens. In all, 100 finger-jointed specimens and 276 solid specimens were tested.

TABLE 1. — End pressures for the study.

End pressure type	Moabi and Makore	Obeche
	(N/mm^2)	
P1	8	2
P2	12	3
P3	18	4



$$MOE = 4L^2 \rho f_r^2$$

Figure 2. — Schematic diagram of the longitudinal vibration test set-up.

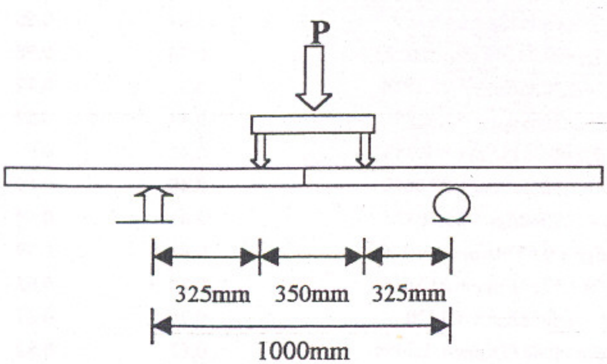


Figure 3. — Bending test set-up.

Test methods

Wood density and MC

The density of each finger-jointed specimen was determined in accordance with the American Society for Testing and Materials Standards (ASTM) (3). The MC of each specimen was measured using a resistance-type moisture meter calibrated with ovendried tests.

Test of dynamic MOE

Dynamic MOE was determined by the longitudinal vibration technique for both the solid and finger-jointed specimens. Dynamic MOEs of the solid specimens were tested before finger-jointing and the finger-jointed specimens were tested after jointing. The technique involved introducing vibration into the specimen by mechanical impact using a hammer. A microphone at the other end received the sound and transmitted it into a Frequency (FFT) Analyzer (**Fig. 2**), which measured the fundamental resonance frequency of each specimen. The MOE of the specimen was then calculated using Equation [**5**].

Static test

Both the solid and finger-jointed specimens were tested using an INSTRON TCM 10000 test machine with a static loading capacity of ±100 kN. The machine was set at a crosshead speed of 20 mm/min. (for Makore and Moabi) and 5 mm/min. (for Obeche), such that failure occurred within 3 to 5 minutes. **Figure 3** shows the static bending test set-up for the finger-jointed specimens. The finger-jointed specimen was positioned on the supports such that the finger-joint was at center of the 1000-mm span. The solid specimen was tested over a span of 860 mm. Each bending specimen replicate was tested under a four-point loading arrangement in accordance with ASTM standards (2). Deflection was measured within the shear-free zone (i.e., within the 350-mm distance between the two loading points), using two transducers positioned at each side of the finger-joint. Each specimen was tested to destruction to determine the MOR and MOE.

Model development

Mechanical properties of wood are linearly related (6,7,16,29). Least squares regression analyses are therefore usu-

TABLE 2. — *Summary of regression parameters for regression of density on MOR, static bending MOE, and dynamic MOE for the three hardwoods.*[a]

Species	Type of specimen	Regression model	Coefficient of determination r^2	Correlation coefficient r	Significance of model ($\alpha = 0.05$)
Obeche	Finger-joint	$f = 0.1170\rho + 0.0862$	0.59	0.77	0.000
(*Triplochiton scleroxylon*)	$n = 36$	$E_{ST} = 0.0513\rho + 1.3471$	0.33	0.57	0.000
		$E_{DYN} = 0.0207\rho + 0.5063$	0.50	0.71	0.000
	Solid	$f = 0.0822\rho + 19.5789$	0.18	0.42	0.000
	$n = 86$	$E_{ST} = 0.0064\rho + 4.3068$	0.07	0.26	0.017
		$E_{DYN} = 0.0106\rho + 3.4689$	0.20	0.45	0.000
Makore	Finger-joint	$f = 0.1622\rho - 16.6874$	0.42	0.65	0.000
(*Tieghemella heckelii*)	$n = 30$	$E_{ST} = 0.0353\rho - 10.1027$	0.85	0.92	0.000
		$E_{DYN} = 0.0376\rho - 10.2821$	0.85	0.92	0.000
	Solid	$f = 0.1884\rho - 23.6921$	0.42	0.65	0.000
	$n = 96$	$E_{ST} = 0.0320\rho - 7.5904$	0.40	0.63	0.000
		$E_{DYN} = 0.0304\rho - 6.1608$	0.77	0.88	0.000
Moabi	Finger-joint	$f = 0.0900\rho + 13.4885$	0.26	0.51	0.000
(*Baillonella toxisperma*)	$n = 29$	$E_{ST} = 0.0490\rho - 23.5584$	0.62	0.79	0.000
		$E_{DYN} = 0.0558\rho - 27.6523$	0.64	0.80	0.005
	Solid	$f = 0.1967\rho - 47.9994$	0.28	0.53	0.000
	$n = 94$	$E_{ST} = 0.0272\rho - 5.5013$	0.31	0.56	0.000
		$E_{DYN} = 0.0307\rho - 7.6760$	0.46	0.68	0.000
All species	Finger-joint	$f = 0.1121\rho + 4.9187$	0.83	0.91	0.000
	$n = 95$	$E_{ST} = 0.0227\rho - 1.2771$	0.94	0.97	0.000
		$E_{DYN} = 0.0241\rho - 0.7614$	0.96	0.98	0.000
	Solid	$f = 0.1453\rho - 0.7552$	0.85	0.92	0.000
	$n = 276$	$E_{ST} = 0.0223\rho - 1.2221$	0.90	0.95	0.000
		$E_{DYN} = 0.0223\rho - 0.6850$	0.96	0.98	0.000

[a] n = sample size; ρ = density (kg/m^3); E_{DYN} = dynamic MOE (GPa); E_{ST} = static bending MOE (GPa); f = MOR (N/mm^2).

TABLE 3. — *Summary of regression parameters for relationships between MOR, dynamic MOE, and static bending MOE for the three hardwoods.*[a]

Species	Type of specimen	Regression model	Coefficient of determination r^2	Correlation coefficient r	Significance of model ($\alpha = 0.05$)
Obeche	Finger-joint	$f = 4.3260E_{ST} + 11.8067$	0.59	0.77	0.000
(*Triplochiton scleroxylon*)	$n = 36$	$E_{ST} = 0.7869E_{DYN} + 0.6048$	0.72	0.85	0.000
		$f = 3.9433E_{DYN} + 10.2969$	0.58	0.76	0.000
	Solid	$f = 5.1701E_{ST} + 14.7125$	0.44	0.66	0.000
	$n = 86$	$E_{ST} = 0.7794E_{DYN} + 0.9244$	0.56	0.75	0.000
		$f = 3.8251E_{DYN} + 20.9686$	0.22	0.47	0.000
Makore	Finger-joint	$f = 4.6464E_{ST} + 26.5723$	0.64	0.80	0.000
(*Tieghemella heckelii*)	$n = 30$	$E_{ST} = 0.9414E_{DYN} - 0.5223$	0.96	0.98	0.000
		$f = 4.3095E_{DYN} + 25.1834$	0.59	0.77	0.000
	Solid	$f = 3.3089E_{ST} + 57.7276$	0.33	0.57	0.000
	$n = 96$	$E_{ST} = 0.9519E_{DYN} + 0.3822$	0.42	0.65	0.000
		$f = 5.8025E_{DYN} + 20.3690$	0.48	0.69	0.000
Moabi	Finger-joint	$f = 1.9048E_{ST} + 55.7633$	0.46	0.68	0.000
(*Baillonella toxisperma*)	$n = 29$	$E_{ST} = 0.8934E_{DYN} + 0.3109$	0.98	0.99	0.000
		$f = 1.5734E_{DYN} + 58.8616$	0.38	0.62	0.000
	Solid	$f = 6.6868E_{ST} + 1.1420$	0.76	0.87	0.000
	$n = 94$	$E_{ST} = 0.8873E_{DYN} + 1.2496$	0.67	0.82	0.000
		$f = 6.0055E_{DYN} + 8.2155$	0.53	0.73	0.000

[a] n = sample size; ρ = density (kg/m^3); E_{DYN} = dynamic MOE (GPa); E_{ST} = static bending MOE (GPa); f = MOR (N/mm^2).

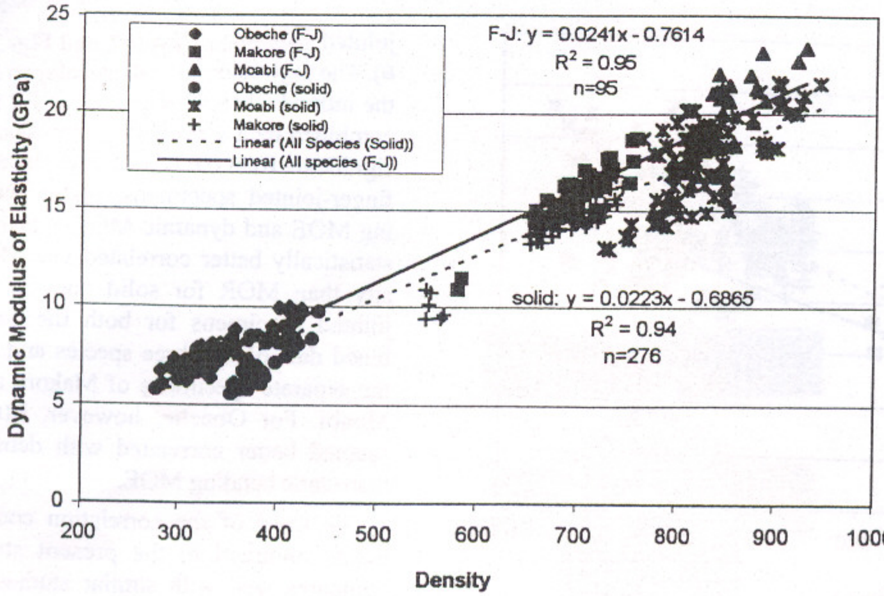


Figure 4. — Relationship between density and dynamic MOE for solid and finger-jointed lumber of Obeche, Makore, and Moabi.

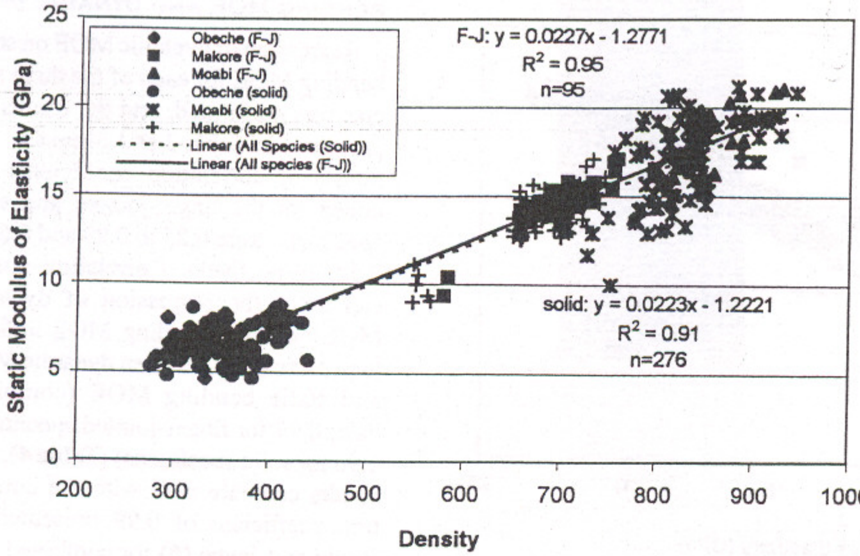


Figure 5. — Relationship between density and static MOE for solid and finger-jointed lumber of Obeche, Makore, and Moabi.

ally used in the study of wood properties (18).

Many studies have been conducted on regression of statically determined mechanical properties on dynamically determined properties. Regression of wood density on statically and dynamically determined properties has also been well documented (6,16,19,29,30). Larsson et al. (19) obtained the same correlation coefficient of 0.61 for the regression of static bending MOE on MOR and dynamic MOE on MOR for spruce solid specimens that measured 38 by 40 mm. For a 38- by 184-mm section, however, correlation coefficients of 0.56 and 0.58 were obtained for the regressions of static MOE on MOR and dynamic MOE on MOR, respectively. The authors concluded that the statistical correlation between statically and dynamically established moduli is very strong, and that the dynamic MOE was found to be as good a strength predictor as the static MOE. Studies on regression of finger-joint strength as a function of MOE are also well documented for temperate species (8,10,21).

Bender et al. (5) studied the effectiveness of using the longitudinal stress wave velocity by the impact method to predict static bending MOE and tensile strength for several grades and species groupings of solid and finger-jointed laminating lumber. The MOE calculated from stress wave velocity was significantly correlated to static bending MOE. The authors concluded that correlation coefficients between stress wave MOE and tensile strength, which ranged from 0.03 to 0.64 for finger-jointed specimens, and 0.33 to 0.44 for solid timber, were generally similar to those between static bending MOE and tensile strength. Thus, neither static bending MOE nor stress wave MOE dominated, in terms of predicting solid and finger-joint strength. The use of the stress wave velocity for predicting solid and finger-joint tensile strength as well as MOE was therefore recommended. Little information was obtained from the literature on regression studies involving finger-jointed tropical hardwood properties.

In the present study, the destructive parameters MOR and bending MOE were separately plotted as functions of the nondestructive parameter dynamic MOE. The regression of MOR as a function of static bending MOE was also assessed for comparison. Using least squares regression analysis, the best-fitting linear functions were determined. The regression models were of the following form:

$$E_{ST} = \beta_0 + \beta_1 E_{DYN} + \varepsilon_0$$

$$f = \beta_2 + \beta_3 E_{DYN} + \varepsilon_1$$

$$f = \beta_4 + \beta_5 E_{ST} + \varepsilon_2$$

where E_{DYN} = dynamic MOE of specimen (GPa); E_{ST} = static bending MOE of specimen (GPa); f = MOR of specimen (N/mm^2); β_0, β_1, β_2, β_3, β_4, and β_5 = regression coefficients; ε_0, ε_1, and ε_2 = residual errors.

Regressions of wood density on static and dynamic properties were also assessed in a similar manner.

RESULTS AND DISCUSSION

Analyses of variance (ANOVA) performed using the F-test, at a 5 percent significance level, indicated that end

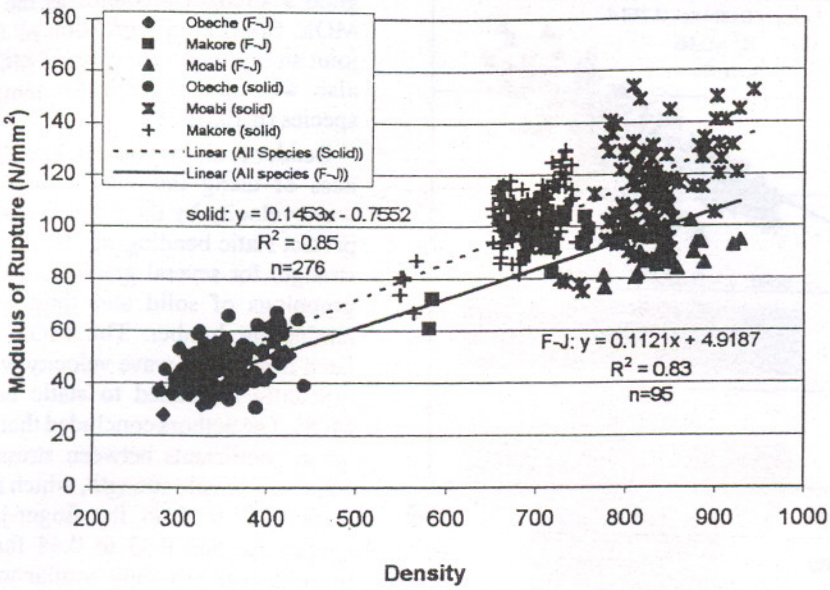


Figure 6.— Relationship between density and MOR for solid and finger-jointed lumber of Obeche, Makore, and Moabi.

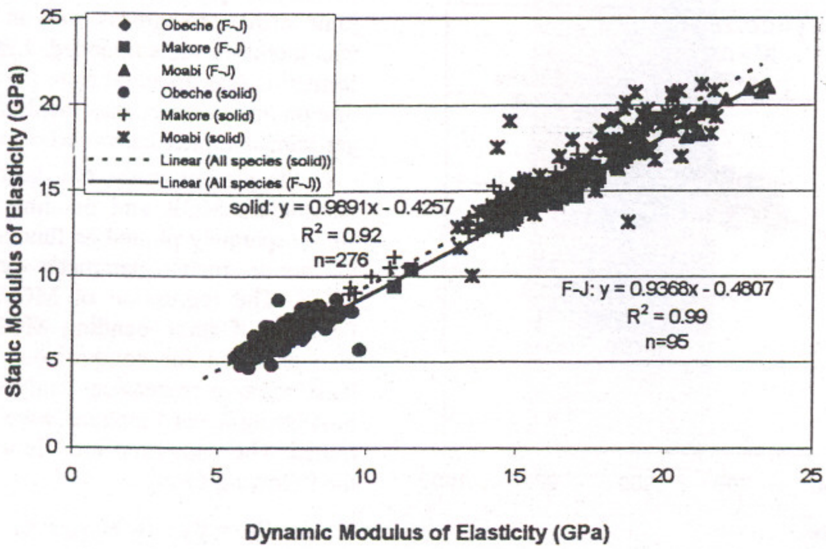


Figure 7.— Relationship between dynamic MOE and static MOE for solid and finger-jointed lumber of Obeche, Makore, and Moabi.

pressure was not statistically significant with respect to the finger-joint properties for each species. The data from the three end pressures for the finger-jointed specimens of each species were therefore combined, in an attempt to increase sample size, for the regression analyses.

RELATIONSHIP BETWEEN DENSITY AND THE MECHANICAL PROPERTIES

Relationships between wood density and dynamic MOE, static bending MOE, and MOR were analyzed for each species, and the regression parameters are presented in **Table 2**. It is evident from the results that correlation was generally high for the regressions, for both solid and finger-jointed specimens. Correlation generally seemed slightly better for the finger-jointed specimens compared to the solid specimens for each of the three species. For the combined data of the three species, however, similar correlation coefficients were obtained for the solid and the finger-jointed specimens (**Table 2 and Figs. 4-6**). The regression models developed for the individual species as well as for the combined data were highly statistically significant ($\alpha = 0.05$) for both solid and finger-jointed specimens. Static bending MOE and dynamic MOE appeared statistically better correlated with density than MOR for solid and finger-jointed specimens for both the combined data of the three species and for the separate specimens of Makore and Moabi. For Obeche, however, MOR seemed better correlated with density than static bending MOE.

The trend of the correlation coefficients obtained in the present study compares well with similar studies in the literature (6,16,19,30). The results also followed the general linear relationship between density and mechanical properties (6,7,16 29).

RELATIONSHIP BETWEEN STATIC BENDING MOE AND DYNAMIC MOE

Regression of dynamic MOE on static bending MOE for each of the three species was performed, and the results are presented in **Table 3** and **Figure 7**. The ranges of correlation coefficients obtained for the finger-jointed and solid specimens were 0.85 to 0.99 and 0.65 to 0.82, respectively. Correlation coefficients for the regression of dynamic MOE on static bending MOE indicate high correlation between dynamic MOE and static bending MOE (combined data; 0.99 for finger-jointed specimens; 0.96 for solid specimens) **(Table 4)**. The results compare well with the correlation coefficient of 0.99 presented by Bodig and Jayne (6) for combined data from tests of solid timber of West Coast hemlock, coastal Douglas-fir, and inland Douglas-fir. The comparatively lower correlation coefficients for the individual species (**Table 3**) might be due to the small sample sizes. The regression models developed for the combined data for the three species were highly significant ($\alpha = 0.05$), thus confirming the linearity of the relationship between the two properties. The regression results seem to indicate that the correlation between statically and dynamically established moduli is very strong and that the dynamic MOE may be as good a strength predictor as the static MOE, in agreement with Larsson et al. (19)

PREDICTING MOR OF SOLID AND FINGER-JOINTED LUMBER

Dynamic MOE and static bending MOE were each separately correlated to MOR for each of the three species, and the results are presented in **Tables 3** and **4**. The regression results show that, generally, there was high correlation between MOE and MOR for both solid and finger-jointed specimens of each of the three species. The results for the individual species show that the correlation between static bending MOE and MOR was only slightly higher than that between dynamic MOE and MOR for both solid and finger-jointed specimens, except for the case of solid specimens of Makore. For the combined data (**Table 4**), almost the same correlation coefficients of 0.91 and 0.90 were obtained between static bending MOE and MOR, and between dynamic MOE and MOR, respectively, for the finger-jointed specimens. For the solid specimens also, the correlation coefficient of 0.95 obtained for the regression of static bending MOE on MOR was almost the same as the 0.94 obtained between dynamic MOE and MOR. The regression models developed for the relationship between dynamic MOE and MOR as well as between static bending MOE and MOR were all highly statistically significant ($\alpha = 0.05$). The statistically high correlation coefficients and the highly significant regression models developed for the combined data for the three species (**Table 4**) seemingly indicate that both static bending MOE and dynamic MOE may be good indicators of the MOR of solid and finger-jointed tropical African hardwoods. The regression lines of dynamic MOE as well as static bending MOE on MOR are graphically presented for solid and finger-jointed specimens, for the combined data for all the species, in **Figures 8** and **9**. The lower 5 percent exclusion limit line developed for the regression of dynamic MOE on MOR for solid and finger-jointed specimens for the combined data is shown in **Table 4** and graphically in **Figure 9**. This lower 5 percent exclusion limit may be used to predict the MOR of solid and finger-jointed timber from the three tropical hardwoods using their dynamic MOE.

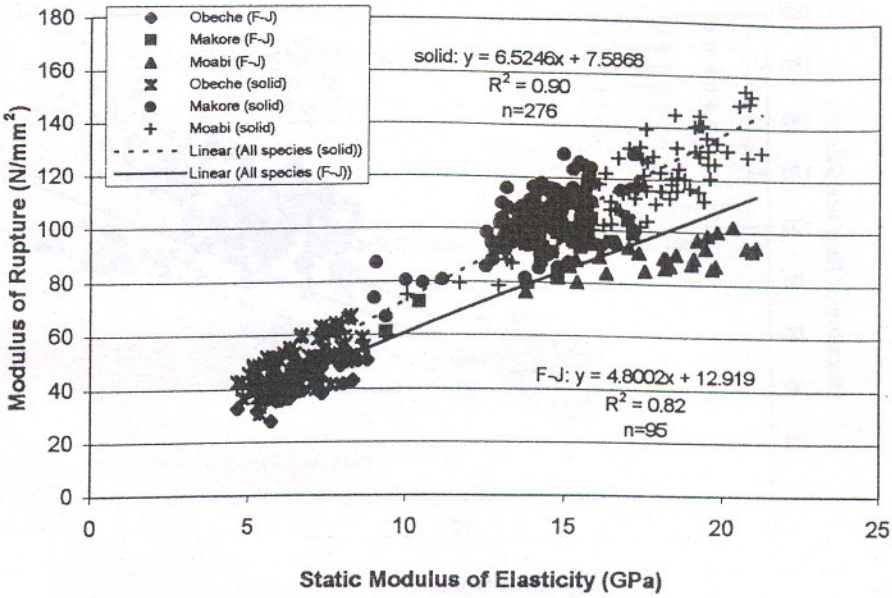


Figure 8. — Relationship between static MOE and MOR for solid and finger-jointed lumber of Obeche, Makore, and Moabi.

TABLE 4. — Regression parameters for relationships between MOR, dynamic MOE, and static bending MOE for combined data for all species for finger-jointed and solid specimens.[a]

Specimen type	Regression model	Coefficient of determination r^2	Correlation coefficient r	Significance of model ($\alpha = 0.05$)
Finger-joint	$f = 4.8002E_{ST} + 12.919$	0.83	0.91	0.000
$n = 95$	$E_{ST} = 0.9410E_{DYN} - 0.5471$	0.98	0.99	0.000
	$f = 4.4893E_{DYN} + 10.7286$	0.81	0.90	0.000
	5% Exclusion limit line			
	$f = 4.0401E_{DYN} + 4.0125$			
Solid	$f = 6.5246E_{ST} + 7.5868$	0.90	0.95	0.000
$n = 276$	$E_{ST} = 0.9891E_{DYN} - 0.4257$	0.92	0.96	0.000
	$f = 6.4261E_{DYN} + 4.8830$	0.88	0.94	0.000
	5% Exclusion limit line			
	$f = 6.1460E_{DYN} + 0.9347$			

[a] n = sample size; ρ = density (kg/m^3); E_{DYN} = dynamic MOE (GPa); E_{ST} = static bending MOE (GPa); f = MOR (N/mm^2).

CONCLUSIONS

Dynamic MOE was well correlated to static bending MOE for solid and finger-jointed tropical African hardwoods. The correlation between dynamic MOE and static bending MOE was only slightly lower for solid specimens compared to finger-jointed specimens.

Correlation between dynamic MOE and MOR for the combined data for the three species was comparable to that between static bending MOE and MOR for both solid and finger-jointed lumber. Therefore, dynamic MOE may be as good a strength predictor as static bending MOE. Regression models developed were highly statistically significant. The lower 5 percent exclusion limits derived seem useful for predicting MOR of solid and finger-jointed lumber. Although the static bending test is generally recognized as a more desirable method of determining MOR, these results have indicated that the longitudinal vibration technique may also be useful as a nondestructive method for predicting the MOR of solid and finger-jointed tropical African hardwoods. The technique is suitable, especially in situations where the static bending test is not feasible to undertake. This nondestructive testing method may encourage efficient timber utilization and the conservation of tropical African forests.

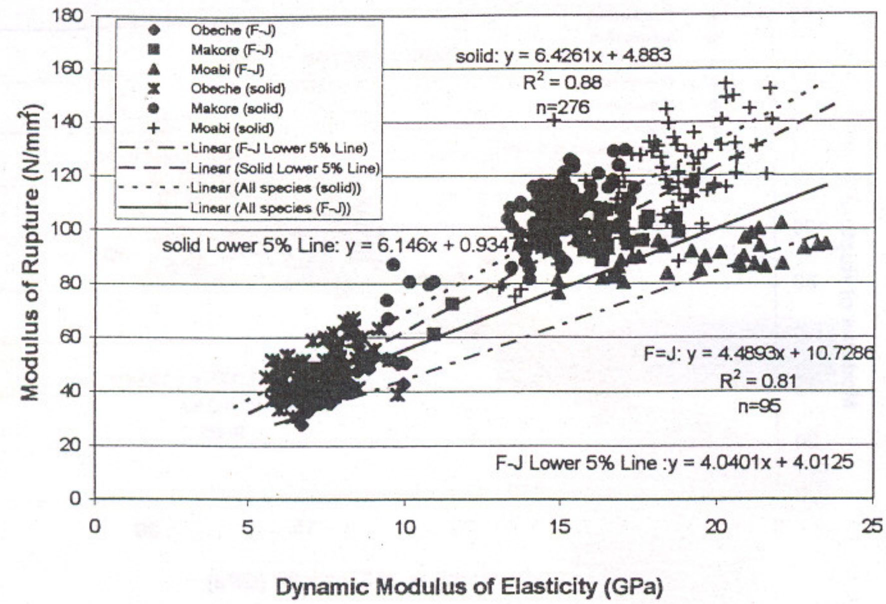


Figure 9. — Relationship between dynamic MOE and MOR for solid and finger-jointed lumber of Obeche, Makore, and Moabi.

Literature Cited

1. Aicher, S. and B. Radovic. 1999. Investigations on the influence of finger-joint geometry on tension strength of finger-jointed glulam lamellas. Holz als Roh-und Werkstoff 57:1-11. (in German).
2. American Society for Testing and Materials. 1994. Standard methods of static tests of timbers in structural sizes. ASTM D 198-84. ASTM, West Conshohocken, Pa.
3. __________. 1994. Standard test method for specific gravity of wood and wood-base materials. ASTM D 2395-93. ASTM, West Conshohocken, Pa.
4. Beaulieu, C., C. Verreault, C. Gosme, and M. Samson. 1997. Experimental assessment of the effect of length on the tensile strength of structural finger-joined lumber. Forest Prod. J. 47(10):94-100.
5. Bender, D.A., A.G. Burk, S.E. Taylor, and J.A. Hooper. 1990. Predicting localized MOE and tensile strength in solid and finger-jointed laminating lumber using longitudinal stress waves. Forest Prod. J. 40(3): 45-47.
6. Bodig, J. and B.A. Jayne. 1982. Mechanics of Wood and Wood Composites. Van Nostrand Reinhold company, New York. pp. 247-269, 645-650.
7. Bucur, V. 1995. Acoustics of Wood. CRC Press, Boca Raton, Fla.. pp. 105-106.
8. Burk, A.G. and D.A. Bender. 1989. Simulating finger-joint performance based on localized constituent lumber properties. Forest Prod. J. 39(3):45-50.
9. German Standards. 1971. Finger-jointing of wood. DIN 68140. German Institution for Standards, Berlin, Germany. (in German).
10. Ehlbeck, J., F. Colling, and R. Gorlacher. 1985. Influence of finger-jointed lamellae on the bending strength of glulam beams: Input data for the computer model. Holz als Roh-und Werkstoff 43(9):369-373.
11. Fisette, P.R. and W.W. Rice. 1988. An analysis of structural finger-joints made from two northeastern species. Forest Prod. J. 38(9):40-44.
12. Food and Agriculture Organization of the United Nations. 1982. Tropical Hardwood Resources. *In*: Tropical Hardwood Utilization: Practice and Prospects. R.A.A. Oldeman, ed. Forestry Sciences. Martinus/Nijhoff/Dr. W. Junk Publishers, The Hague, Boston, London. pp. 27-31.
13. Ghana Forestry Department. 1994. Timber species classification and the assessment of exploitation patterns. *In*: Proc. of the Ghana Forest Inventory and Management Project (FIMP) Seminar. Ghana Forestry Dept., Planning Branch, Kumasi, Ghana. pp. 1-8.
14. Hearmon, R.F.S. 1965. The assessment of wood properties by vibrations and high frequency acoustic waves. *In*: Proc. of the 2nd Symp. on Nondestructive Testing of Wood. Washington State Univ., Olympia, Wash. pp. 49-66.
15. Kohler, G. 1981. Finger-jointing of unseasoned sawn timber for pallet manufacture. Holz-Zentralblatt 107(130):2015-2016.
16. Kollman, P. and W.A. Cote. 1968. Principles of Wood Science and Technology. 1. Solid Wood. Springler Verlag, Berlin, Germany. pp. 301-302.
17. __________and H. Krech. 1960. Dynamic measurement of the elastic and damping properties of wood. Holz als Roh-und Werkstoff 2:41-51.
18. Kottegoda, N.A. and R. Rosso. 1998. Statistics, Probability, and Reliability for Civil and Environmental Engineers. McGraw-Hill Inter. Ed. pp. 349-351.
19. Larsson, S., S. Ohlsson, M. Perstorper, and J. Brundin. 1998. Mechanical properties of sawn timber from Norway spruce. Holz als Roh-und Werkstoff 56:331-338.
20. Ministry of Lands and Forestry. 1996. Forestry development master plan 1996-2000. Policy Planning, Monitoring and Evaluation Div., MLF, Accra, Ghana. pp. 6-8.
21. Moody, R.C. 1970. Tensile strength of finger-joints in pith-associated wood and non-pith-associated southern pine 2 by 6's. FPL-138. USDA Forest Serv., Forest Prod. Lab., Madison, Wis.
22. National Lumber Grades Authority. 1981. Special products standard for finger-joined structural lumber. SPS 1-81. NLGA, Ganges, B.C.
23. Ofosu-Asiedu, A., J.M. Nani-Nutakor, and J. Ayarkwa. 1996. Kumasi base-line survey - data collection for a finger-jointing plant. Res. Rept. Forestry Res. Inst. of Ghana, Kumasi, Ghana.
24. Prah, E.A. 1994. Environment and recovery in industrial processing of timber. *In*: Proc. of a Seminar on the Environment and the Utilization of Wood Waste. Assoc. of Ghana Industries, Kumasi, Ghana. pp. 17-19.
25. Samson, M. 1985. Potential of finger-joined lumber for machine stress-rated lumber grades. Forest Prod. J. 35(7/8):20-24.
26. Strickler, M.D.1980. Finger-jointed dimensioned lumber - past, present and future. Forest Prod. J. 30(9):51-56.
27. __________ and R.F. Pellerin. 1971. Tension proof-loading of finger-joints for laminated beams. Forest Prod. J. 21(6):19-24.
28. Tsoumis, G. 1991. Science and Technology of Wood. Structure, Properties, Utilization. Van Nostrand Reinhold, New York. pp. 327-361.
29. U.S. Forest Products Laboratory. 1987. Wood Handbook: Wood as an Engineering Material. Agri. Handb. 72. USDA Forest Serv., Forest Prod. Lab., Madison, Wis. pp. 4-5, 2-27.
30. Wang, S.-Y. and C.-Y. Ko. 1998. Dynamic modulus of elasticity and bending properties of large beams of Taiwan-grown Japanese cedar from different plantation spacing sites. J. of Wood Sci. 44:62-68.