PREDICTING TENSILE PROPERTIES OF FINGER-JOINTED TROPICAL AFRICAN HARDWOODS USING LONGITUDINAL VIBRATION METHOD

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ABSTRACT

*The longitudinal vibration technique was examined as a means of predicting ultimate tensile strength and tension modulus of elasticity of finger-jointed tropical African hardwoods using three different finger profiles. Modulus of elasticity measured using the longitudinal vibration technique (i.e. dynamic MOE) was significantly correlated to static tension modulus of elasticity (i.e. tension MOE) for 10, 18 and 20 mm long finger profiles studied for Obeche (*Triplochiton scleroxylon*), Makore (Tieghemella heckelii) and Moabi (*Baillonella toxisperma*). Dynamic MOE was also significantly correlated to tension MOE for the combined data for each species, and for the three species. High correlation coefficient of $r = 0.89$ was obtained for the regression of the combined data for the three species, and the regression model derived was also highly significant ($\alpha < 0.001$). Correlation between dynamic MOE and ultimate tensile strength was, generally, higher than that between tension MOE and ultimate tensile strength, for all the finger profiles studied for the three species. Correlation coefficient obtained for the combined data for the 18 mm finger profile of the three species ($r = 0.69$) was high, and the regression model derived highly significant ($\alpha < 0.001$). The lower 5 % exclusion limit line derived for the regressions of dynamic MOE as a function of tension MOE and tensile strength may be useful for predicting the static tensile properties of the three tropical hardwoods. Within the limits of the study, the longitudinal vibration technique, which is easier than the static test may be useful as a non-destructive method for accurately predicting tensile properties of finger-jointed tropical African hardwoods.*

Keywords: Finger-joint, Longitudinal vibration, Tropical hardwoods

INTRODUCTION

Finger-joints are a type of structural end joint used in glue 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 (Burk & Bender, 1989). The strength of timber is enhanced by finger-jointing (Kohler, 1981). Structural finger-joints were developed to reduce the waste of high quality lumber that resulted from machining of scarf joints, and it is one of the most economic ways of wood utilization (Strickler, 1980). Low-grade wood can be used to produce high quality finished products with improved strength and appearance, as undesirable characteristics are removed (Fisette & Rice, 1988; Beaulieu *et al.*, 1997).

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 (FAO, 1982; Ghana Forestry Department, 1994; Ministry of Lands and Forestry, Ghana, 1996). 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 timber (Prah, 1994; Ofosu-Asiedu, Nani Nutakor & Ayarkwa, 1996). An assessment of the availability of solid sawmill timber off-cuts (residue) suitable for the production of finger-jointed timber in

Kumasi city alone, indicated the availability of over 70 000 m^3, which is presently not well utilized. Timber processing mills in Ghana are presently being called upon to establish finger-jointing plants to utilize sawmill residues, in order to increase their profitability.

The primary structural importance of a finger-joint is its high load-bearing capacity. 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. Tensile strength and stiffness are of special interest in the use of glulam timber and are the most relevant strength properties, since failure frequently initiates in the tensile zone of a beam (Fisette & Rice, 1988; Burk & Bender, 1989; Aicher & Radovic, 1999).

Although the classic static test is recognized as a more desirable method of determining wood properties, evaluation of the tensile properties of structural finger-joints by static test may be difficult, and may require expensive test equipment which may be difficult to come by in many developing tropical African countries. Mechanical wood-testing machines available are old-fashioned and therefore unreliable. A fast, reliable and easy-to-use method for predicting tensile properties of finger-joints will promote production and utilization of the product, and thereby ensure efficient timber utilization and conservation of the tropical African forests.

Non-destructive wood-testing permits strength and modulus of elasticity (MOE) values of individual timber pieces determined destructively to be correlated with MOE measured non-destructively in order to assign properties, values without damage due to overloading, thereby improving the efficiency of timber utilization (Bodig & Jayne, 1982).

The main objective of the study was to evaluate the effectiveness of using the longitudinal vibration technique as a means of non-destructively predicting ultimate tensile strength and tension MOE of finger-jointed tropical African hardwoods of varying densities. If the technique is found effective, it may have value in stress grading finger-jointed tropical hardwoods produced from sawmill residues or off-cuts.

The Dynamic MOE

Several methods exist for evaluating the mechanical properties of timber. 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 (Hearmon, 1965; Kollman & Cote, 1968; Bodig & Jayne, 1982; Tsoumis, 1991; Bucur, 1995). However, the number of studies reported in the literature, involving both dynamic and static tests of timber is limited, especially with respect to tropical African hardwoods.

The accuracy of the determination of MOE of wood by the vibration tests is higher than that of static tests (Kollman & Cote, 1968; Bodig & Jayne, 1982; Tsoumis, 1991; Larsson *et al.*, 1998). The difference is due to the rate of loading in static test in which creep effects influence the measured static deflections (Bodig & Jayne, 1982); it is also related to the viscoelastic nature of wood (Larsson *et al.*, 1998). Kollman & Krech (1960) obtained from vibration test of Spruce and Oak, 19 and 14 % increase respectively over static test values, and these differences are small and negligible (Kollman & Cote, 1968). According to Bodig & Jayne (1982), MOE obtained by vibration tests proves to be 5 to 15 % higher than that by static tests. Tsoumis (1991) also reports that the difference ranges from 10 to 15 %. Bucur (1995) and Larsson *et al.* (1998) report that the value of MOE determined from dynamic tests is about 10 % higher than that by static tests for Spruce and Beech.

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 one. The dynamic method of determining MOE also has the advantage of comparatively shorter test duration (Kollman & Cote, 1968).

Calculation of Dynamic MOE

Bodig & Jayne (1982) state that the velocity, C, of propagation of sinusoidal wave in the longitudinal direction of a rod supported at its midpoint is related to the modulus of elasticity, E, and the mass density, ρ, as follows:

$$C = \sqrt{(E/\rho)} \quad (1)$$

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

$$\lambda = 2L / n \quad (2)$$

The wavelength is the ratio of wave velocity to the frequency of vibration (f_r).

Thus, $$\lambda = C / f_r \quad (3)$$

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

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

Rearranging Equation 4 gives the following equation for calculating the dynamic modulus of elasticity of timber for the fundamental frequency (i.e. $n = 1$).

$$E = (4 L^2 \rho \, f_r^{\,2}) \quad (5)$$

where

E = modulus of elasticity
ρ = mass density of timber
L = length of timber
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 studied. Radial-sawn, straight-grained heartwood samples were randomly collected from three logs of each species (Fig. 1). Kiln-dried samples of about 8 % moisture content were planed and cross cut to dimensions of 23 mm × 150 mm × 500 mm. Samples were prepared such that no visible defects such as knots and spiral grain were present, and growth layers were at right angle to the width of each specimen. The 500 mm long samples were then matched in pairs on the basis of modulus of elasticity (Samson, 1985; Fisette & Rice, 1988) using the longitudinal vibration test method, for finger-jointing.

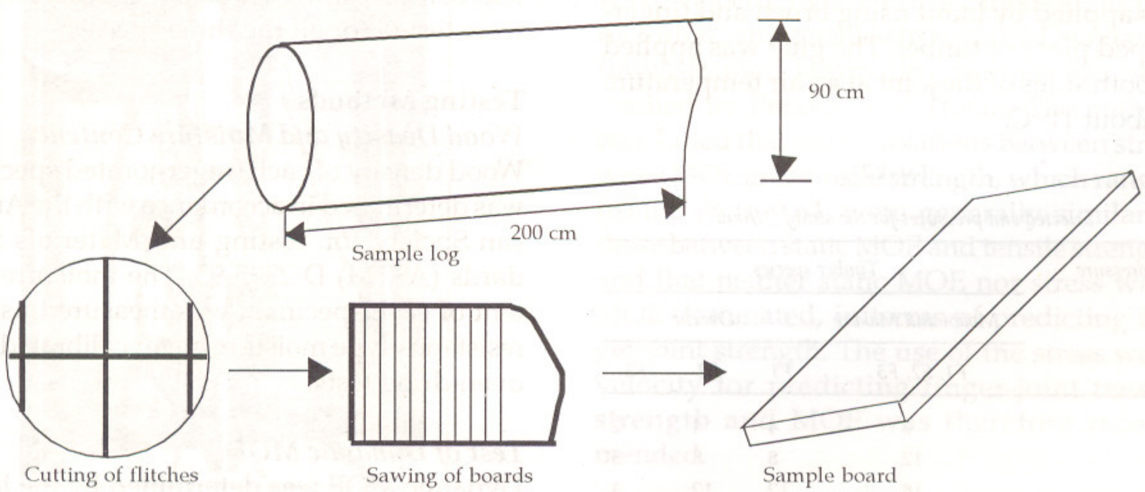

Fig. 1. Samples of cutting pattern.

Preparation of Finger-jointed Samples

The finger-jointing was done according to the normal production processes in two finger-jointing companies, and also in accordance with the Canadian National Lumber Grades Authority (NLGA) Special Products Standard for Finger-joined Structural Lumber SPS 1 and the German Standard DIN 68140. Three different finger profiles (Table 1 and Fig. 2) were studied. A finger-jointer equipped with woodworking and gluing and pressing components was used. The woodworking machine used a clamping carriage which secured stacks of the wood samples and guided them through a circular saw, finger profile cutter and suction. The other component aligned the wood during gluing and pressing. Only the vertical finger orientation was studied.

TABLE 1

Selected finger profile geometry for the study

Type of joint	*Length L (mm)*	*Pitch P (mm)*	*Tip width t (mm)*	*Slope of fingers θ (deg.)*	*Relative joint area (2 L/p)*	*% cross section reduction (100 t/p)*
F1	10	3.7	0.6	9.50	5.5	16.2
F2	18	3.7	0.6	4.80	9.7	16.2
F3	20	6.0	0.6	8.50	6.7	10.0

Refer to Fig. 2.

The winter-type resorcinol formaldehyde glue (DIANOL 33N) was used. Mixing of the glue was done in accordance with the supplier's instructions and according to the normal practice in the two finger-jointing companies. Glue was applied by hand using brush and finger-shaped piece of timber. The glue was applied on both sides of the joint at an air temperature of about 11 °C.

TABLE 2

Selected end pressures for the study (N/mm²)

End pressure type	*Timber species*			
	Moabi and Makore	*Obeche*		
	F1, F2, F3	*F1*	*F2*	*F3*
P1	8	4	4	2
P2	12	8	8	3
P3	18	12	12	4

F1, F2 and F3 represent finger profile types (Table 1).

Three different end pressures (Table 2) were studied for each finger profile type. The finger-jointed specimens were cured in a chamber heated to over 30 °C for more than 48 h.

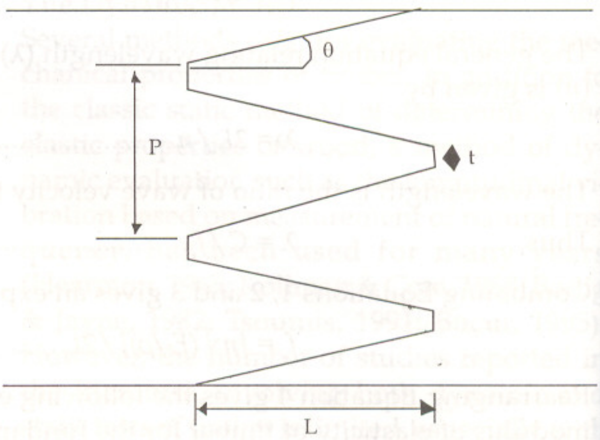

Fig. 2. Finger-joint profile parameters.

Processing of Finger-jointed Specimens after Curing

The finger-jointed specimens were planed, and the outer 5 mm edges of each specimen containing an outer finger were then sawed off. Each specimen was then ripped into two, and both ends subsequently trimmed to final test specimen dimensions of 15 mm × 70 mm × 700 mm for Makore and Moabi, and 15 mm × 58 mm × 700 mm for Obeche. The test specimens were then conditioned to about 10 % moisture content before testing. Three hundred specimens were tested for all the three species.

Testing Methods

Wood Density and Moisture Content

Wood density of each finger-jointed specimen was determined in accordance with the American Society for Testing and Materials Standards (ASTM) D 2395-93. The moisture content of each specimen was measured using a resistance-type moisture meter calibrated with oven-dried tests.

Test of Dynamic MOE

Dynamic MOE was determined by the longitudinal vibration technique. This involved introducing vibration into the test 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. 3) which measured the fundamental resonance frequency. The modulus of elasticity of the specimen was then calculated using Equation 5.

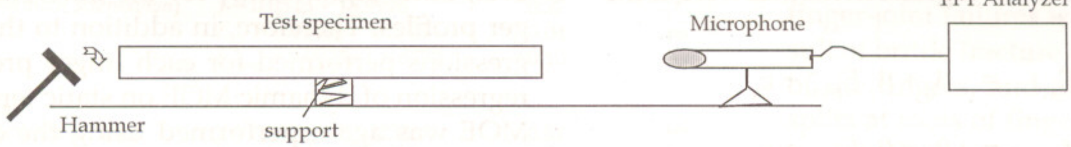

Fig. 3. Schematic diagram of longitudinal vibration test set-up.

Static Test
The tension specimens were tested using a servo-controlled fatigue testing machine (SHIMADZU SERVOPULSER EHF-ED10/TD1) of static loading capacity of ± 100 kN (10 ton f), set to a constant cross head speed of 3 mm/min, to achieve specimen failure within about 5 to10 min of test duration. Fig. 4 shows the set-up of the tension test. Each replication of tension specimen was tested in accordance with the ASTM D 198-84 test procedure. Elongation was measured at the finger-joint positioned at the center of the 65 cm free span between the grips. Each specimen was tested to determine the ultimate tensile strength parallel to the grain and the tension MOE. Specimens that did not fail at the finger-joint were excluded from subsequent data analysis.

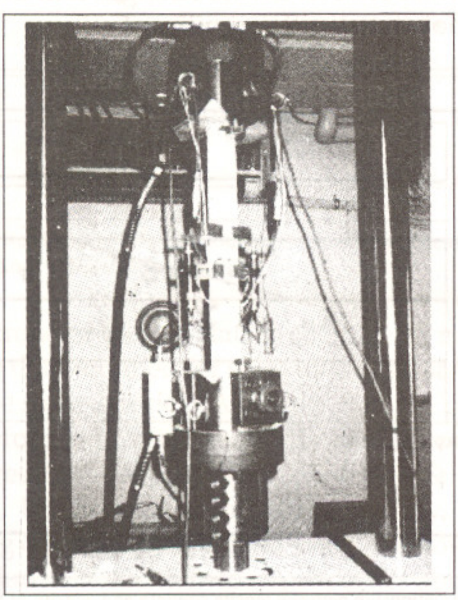
Fig. 4. Tension test set-up.

Model Development
Little information was obtained in the literature on regression studies involving finger-jointed tropical hardwood properties. However, regression of finger-joint tensile strength as a function of MOE is well documented on temperate species (Moody, 1970; Ehlbeck, Colling & Gorlacher 1985; Burk & Bender, 1989). Mechanical properties of wood are linearly related (Kollman & Cote, 1968; US Forest Products Laboratory, 1987; Bodig & Jayne, 1982; Bucur, 1995). Least squares regression analyses are therefore usually used.

Ehlbeck *et al.* (1985) performed a logarithmic transformed regression model for Spruce finger-jointed tensile strength as a function of bending MOE, and obtained a coefficient of determination, r^2, of 0.27. Moody (1970) performed a simple linear regression of finger-joint tensile strength as a function of MOE for southern pine 50 mm × 150 mm lumber, and obtained r^2 value of 0.25. Burk & Bender (1989) obtained correlation coefficients ranging from 0.39 to 0.66 for regression of finger-joint tensile strength on MOE for different grades of Douglas fir 50 mm × 150 mm lumber. The effectiveness of using the longitudinal stress wave velocity by the impact method, to predict MOE and tensile strength of Douglas fir finger-jointed laminating lumber has been studied by Bender *et al.* (1990). The authors concluded that the correlations between stress wave MOE and tensile strength, which ranged from 0.03 to 0.64, were generally similar to those between static MOE and tensile strength, and that neither static MOE nor stress wave MOE dominated, in terms of predicting finger-joint strength. The use of the stress wave velocity for predicting finger-joint tensile strength and MOE was therefore recommended.

Under the present study, the destructive parameters ultimate tensile strength and tension MOE were separately plotted as a function of the non-destructive parameter dynamic MOE. The regression of ultimate tensile strength as a function of tension MOE was also assessed for comparison. Using least squares regression analysis, the best fitting linear functions were determined. The regression models were of the 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 tension MOE of specimen (GPa)

f = ultimate tensile strength of specimen (N/mm²)

β_0, β_1, β_2, β_3, β_4 and β_5 = regression coefficients

ε_0, ε_1 and ε_2 = residual errors

RESULTS

Analyses of variance (ANOVA) of the test results for the three finger profiles and end pressures were performed using the F-test, at 5 % level of significance [results presented in a separate paper]. The first set of ANOVA tests was performed to determine if there was statistically significant difference between properties of the specimens pressed with the different end pressures, for each finger profile. The ANOVA indicated that end pressure was not statistically significant with respect to tensile strength of the specimens for the three finger profiles of Makore, for profiles F1 (i.e. 10 mm long) and F3 (i.e. 20 mm) of Obeche, and for F3 of Moabi. In an attempt to increase sample size, all the statistically similar results were combined for each finger profile of each species. For finger profile F2 (i.e. 18 mm long) of Obeche, and profiles F1 and F2 of Moabi, however, data from end pressure P3 significantly differed in tensile strength from the others, and therefore excluded from the analysis.

A second set of ANOVA tests was performed to ascertain whether significant difference existed between the properties of the specimens of the different finger profiles. The results indicated that for all the three species studied, ultimate tensile strength significantly differed for each of the three finger profiles. The results were therefore analyzed separately for each finger profile of each species. Dynamic MOE and static tension MOE did not, however, differ significantly for the different finger profiles. Therefore, in addition to the regressions performed for each finger profile, regression of dynamic MOE on static tension MOE was again performed using the combined data of the three profiles, for each species.

Relationship Between Density and the Other Wood Properties

The relationships between wood density and dynamic MOE, static tension MOE as well as ultimate tensile strength were analyzed for each species and the regression parameters are presented in Table 3. It is evident from the results that correlation was generally low for the regressions. However, the correlation for Makore seems significantly better and the regression models statistically highly significant ($\alpha < 0.001$) than for Moabi and Obeche, for all the wood properties (Table 3 and Fig. 5 and 6). The regressions between static tension MOE and density as well as between dynamic MOE and density for Obeche were not statistically significant ($\alpha < 0.05$). For Moabi also, the regression between tensile strength and density was not statistically significant.

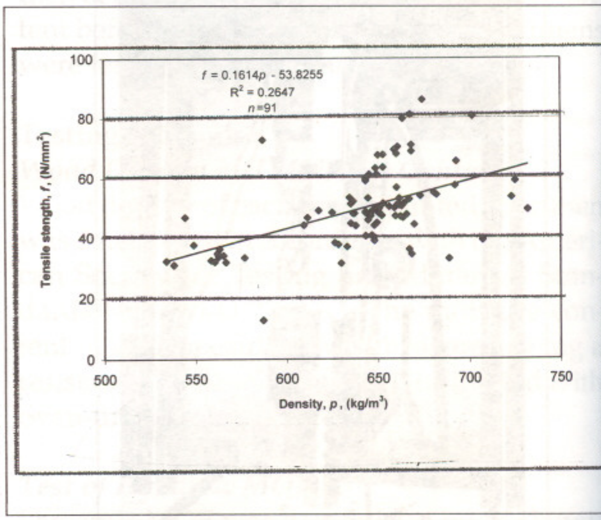

Fig. 5. Relationship between tensile strength and density of Makore (*Tieghemella heckelii*).

TABLE 3

Regression models for density on ultimate tensile strength, static tensile MOE and dynamic MOE

Species	*Regression model*	*Correlation coefficient*	*Level of significance of model*
Obeche (*Triplochiton scleroxylon*)	$f = 0.054\rho + 15.9996$	0.27	*
	$E_{ST} = 0.0010\rho + 4.1343$	0.04	ns
	$E_{DYN} = 0.0025\rho + 6.6722$	0.10	ns
Makore (*Tieghemella heckelii*)	$f = 0.1614\rho - 53.8255$	0.51	***
	$E_{ST} = 0.0441\rho - 15.7508$	0.58	***
	$E_{DYN} = 0.0351\rho - 5.6225$	0.79	***
Moabi (*Baillonella toxisperma*)	$f = 0.0409\rho + 5.0424$	0.16	ns
	$E_{ST} = 0.0245\rho - 5.6559$	0.33	**
	$E_{DYN} = 0.0221\rho + 2.3693$	0.47	***

ρ = density in kg/m^3
E_{DYN}, E_{ST} = modulus of elasticity in GPa
f = ultimate tensile strength in N/mm^2
Levels of significance of the models are indicated as follows:
*** denotes significance at $\alpha \leq 0.001$
** denotes significance at $0.001 < \alpha \leq 0.01$
* denotes significance at $0.01 < \alpha \leq 0.05$
ns denotes not significant at $\alpha \leq 0.05$

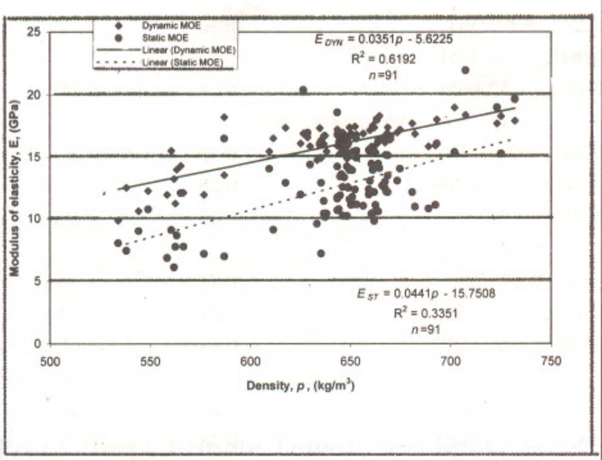

Fig. 6. Relationship between modulus of elasticity and density of Makore (*Tieghemella heckelii*).

The trend of the correlation coefficients is similar to that obtained for solid unjointed samples of the same species (Ayarkwa *et al.*, in press), and follows the general linear relationship between wood properties (Kollman & Cote, 1968; US Forest Products Laboratory, 1987; Bodig & Jayne, 1982; Bucur, 1995). The low correlation between the wood properties obtained for the relatively low density Obeche wood may be attributed to the brittleness of the wood and the difficulty of identifying wood grain direction during processing, due to the pale white color of the wood. Severe cross-grain could have caused premature finger-joint failure in high-density specimens. Many finger-joint failures were the result of brittle fracture at the base of the fingers, and also due to splits at roots of fingers extending into the whole specimen. The comparatively very straight-grain and fine texture of the wood of Makore may be responsible for the good strength. The low correlation obtained for the Moabi wood may be due to its comparatively very high density, which might have resulted in poor glue-bonding and, consequently, low finger-joint strength.

Predicting Static Tension MOE

Regressions of dynamic MOE on tension MOE for the different finger profiles of each species were performed, and the results are presented in Table 4. The regression lines of dynamic MOE on tension MOE for the combined data for each species are also graphically presented in Fig. 7. The regression line for the combined data for the three species as well as the lower 5 % exclusion limit line (at 95 % confidence interval), representing the boundary above which 95 % of the data points are expected to fall, are plotted in Fig. 8. The regression results, generally, indicate good correlation between dynamic MOE and tension MOE, for each finger profile and for the combined data (Table 4 and Fig. 7 and 8). The regression models derived for the combined data for all finger profiles of Obeche, Makore and Moabi were all statistically highly significant ($\alpha < 0.001$). The model developed for the combined data for all the three species was also statistically highly significant ($\alpha < 0.001$), thus indicating a linear relationship between the two properties.

The ranges of correlation coefficients obtained for Obeche, Makore and Moabi of 0.55 to 0.72, 0.50 to 0.74, and 0.38 to 0.71 respectively, fall

TABLE 4

Summary of regression parameters for relationships between ultimate tensile strength, dynamic MOE and static tension MOE for all finger profiles and wood species

Species	*Profile type*	*Mean species density (kg/m³)*	*Regression model*	*Correlation coefficient*	*Level of significance of model*
Obeche	F1		$f = 4.4756E_{ST} + 14.7380$	0.50	**
(*Triplochiton scleroxylon*)	(n =28)	354	$E_{ST} = 0.7226E_{DYN} - 0.185$	0.72	***
			$f = 5.0845E_{DYN} + 1.5279$	0.56	**
	F2		$f = 0.8724E_{ST} + 35.0676$	0.14	ns
	(n =19)	345	$E_{ST} = 0.8583E_{DYN} - 1.7366$	0.61	**
			$f = 4.4671E_{DYN} + 8.5447$	0.50	*
	F3		$f = 2.6951E_{ST} + 17.9075$	0.46	**
	(n =40)	349	$E_{ST} = 0.7109E_{DYN} + 0.0160$	0.55	**
			$f = 4.6961E_{DYN} + 0.0418$	0.63	***
Makore	F1		$f = 0.7268E_{ST} + 39.2836$	0.27	ns
(*Tieghemella heckelii*)	(n =27)	644	$E_{ST} = 1.2717E_{DYN} - 5.8393$	0.67	***
			$f = 2.4454E_{DYN} + 12.5988$	0.48	*
	F2		$f = 4.8864E_{ST} - 0.3709$	0.84	***
	(n =27)	646	$E_{ST} = 1.0570E_{DYN} - 4.1331$	0.74	***
			$f = 6.1511E_{DYN} - 35.6164$	0.74	***
	F3		$f = 1.1222E_{ST} + 30.2363$	0.36	*
	(n =37)	638	$E_{ST} = 1.3184E_{DYN} - 7.3051$	0.50	**
			$f = 5.0806E_{DYN} - 32.4809$	0.61	***
Moabi	F1		$f = 0.1001E_{ST} + 26.4133$	0.11	ns
(*Baillonella toxisperma*)	(n =17)	765	$E_{ST} = 0.8446E_{DYN} - 1.0466$	0.55	*
			$f = 0.3376E_{DYN} + 21.9948$	0.24	ns
	F2		$f = 1.1956E_{ST} + 37.9529$	0.70	**
	(n =18)	804	$E_{ST} = 1.0365E_{DYN} - 5.0470$	0.71	**
			$f = 1.4588E_{DYN} + 27.9538$	0.59	*
	F3		$f = 0.5466E_{ST} + 26.1546$	0.26	ns
	(n =35)	809	$E_{ST} = 0.8825E_{DYN} - 1.5881$	0.38	*
			$f = 3.1122E_{DYN} - 21.8723$	0.63	***

n = no. of specimens
E_{DYN}, E_{ST} = modulus of elasticity in GPa
f = ultimate tensile strength in N/mm²

Levels of significance of the models are indicated as follows:
*** denotes significance at $\alpha \leq 0.001$
** denotes significance at $0.001 < \alpha \leq 0.01$
* denotes significance at $0.01 < \alpha \leq 0.05$
ns denotes not significant at $\alpha \leq 0.05$

within range of data available in the literature (Bender *et al.*, 990). Correlation coefficient of 0.89 was obtained for the combined data for the three species (Fig. 8). This was in agreement with the correlation coefficient of 0.99 obtained for solid timber of West Coast Hemlock, West Coast Douglas fir and Inland Douglas fir (Bodig & Jayne, 1982). The lack of significant differences for some of the data for the finger profiles might be due to the small sample size. The regression results seem to suggest that tension MOE of the tropical hardwood species may be predicted from the dynamic MOE determined by the longitudinal

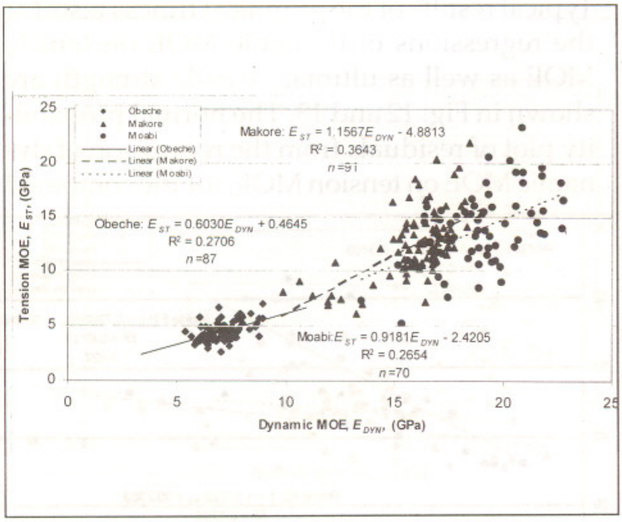

Fig. 7. Relationship between tension MOE and dynamic MOE for Obeche (*Triplochiton scleroxylon*), Makore (*Tieghemella heckelii*) and Moabi (*Baillonella toxisperma*).

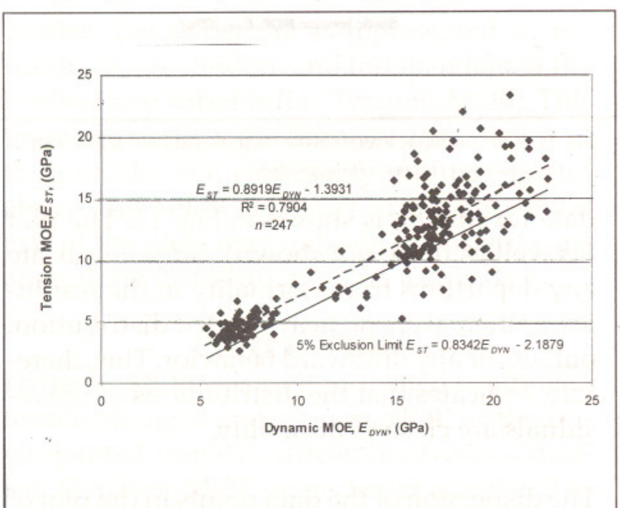

Fig. 8. Relationship between tension MOE and dynamic MOE for combined data for Obeche (*Triplochiton scleroxylon*), Makore (*Tieghemella heckelii*) and Moabi (*Baillonella toxisperma*).

vibration technique with reasonable statistical justification.

Predicting Ultimate Tensile Strength

Dynamic MOE and static tension MOE were each correlated to ultimate tensile strength for all the three species, and the results are presented in Table 4. The regression results indicate that, generally, correlation between dynamic MOE and ultimate tensile strength was significantly better than that between static tension MOE and ultimate tensile strength, for all the three species; except for profile F2 of Makore and Moabi, in which case correlation between static tension MOE and ultimate tensile strength was better. The regression lines of dynamic MOE as well as tension MOE on ultimate tensile strength are graphically presented, separately, for each of the three finger profiles for Makore in Fig. 9 and 11. It is evident from each plot that there is better correlation for the finger profile F2 than for profiles F1 and F3. A similar result was obtained for Moabi (Table 4). In the case of Obeche, the correlation for profile F1 seems the best (Table 4).

The regression models developed for the regression of tension MOE on ultimate tensile strength for finger profiles F1 and F3 for Moabi, F1 for Makore and F2 for Obeche were not statistically significant ($\alpha > 0.05$). The mod-

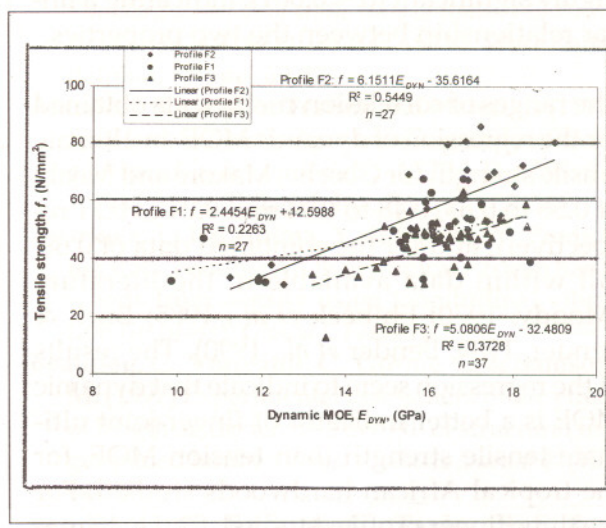

Fig. 9. Relationship between tensile strength and dynamic MOE for Makore (*Tieghemella heckelii*).

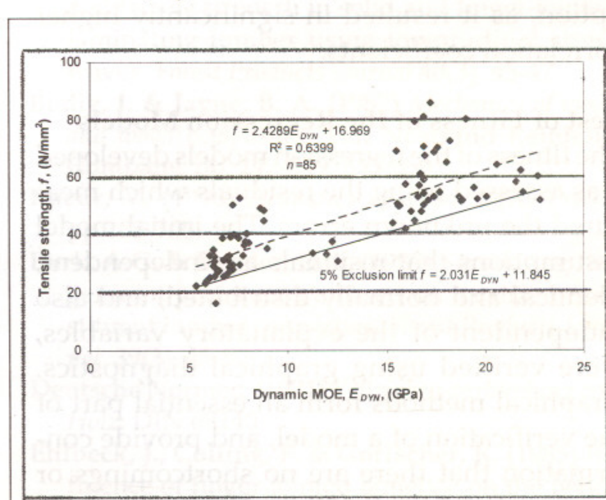

Fig. 10. Relationship between tensile strength and dynamic MOE for combined data for finger profile F2 of Makore (*Tieghemella heckelii*) and Moabi (*Baillonella toxisperma*), and profile F3 of Obeche (*Triplochiton scleroxylon*).

els developed for the regression of dynamic MOE on tensile strength were all statistically significant ($\alpha < 0.05$) except for profile F1 of Moabi ($\alpha > 0.05$). Regression models derived for profile F2 were statistically more significant compared with profiles F1 and F3, except for the case of Obeche. Since the three finger profiles were significantly different with regard to ultimate tensile strength, only the data for the best finger profile F2 of each species were combined to assess the regression of dynamic MOE on ultimate tensile strength. The same was done for the lower 5 % exclusion limit line for the three species (Fig. 10). There was a high correlation coefficient of 0.69 for this regression. The regression model was also highly significant ($\alpha < 0.001$), indicating a linear relationship between the two properties.

The ranges of correlation coefficients obtained for the regression of dynamic MOE on ultimate tensile strength for Obeche, Makore and Moabi of 0.56 to 0.63, 0.48 to 0.74 and 0.24 to 0.71 respectively, and for the combined data of 0.69, fall within data available in the literature (Moody, 1970; Ehlbeck *et al.*, 1985; Burk & Bender, 1989; Bender *et al.*, 1990). The results of the regression seem to indicate that dynamic MOE is a better indicator of finger-joint ultimate tensile strength than tension MOE, for the tropical African hardwoods studied. For the three finger profiles studied, F2 (i.e. 18 mm long fingers) seems to be the most efficient option, as it resulted in significantly higher correlation coefficients.

Test of Fitness of the Regression Models

The fitness of the regression models developed was assessed using the residuals which measured the unknown errors. The initial model assumptions that residuals are independent, identical and normally distributed, and also independent of the explanatory variables, were verified using graphical diagnostics. Graphical methods form an essential part of the verification of a model, and provide confirmation that there are no shortcomings or systematic defects in the model (Kottegoda & Rosso, 1998). Only the statistically significant regression models with high correlation coefficient were tested.

Typical results of the graphical fitness tests for the regressions of dynamic MOE on tensile MOE as well as ultimate tensile strength are shown in Fig. 12 and 13. The normal probability plot of residuals from the regression of dynamic MOE on tension MOE, for the combined

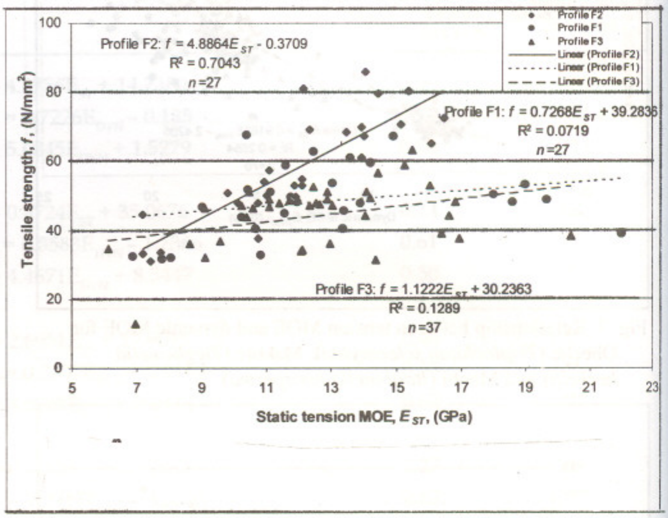

Fig. 11. Relationship between tensile strength and static tension MOE for Makore (*Tieghemella heckelii*).

data for Moabi, is shown in Fig. 12. The plot (as well as those not shown) did not indicate any departures from normality in the residuals, as there were no heavy-tailed distribution, outliers or any untoward behavior. This, therefore, indicates that the distributions of the residuals are close to normality.

The dispersion of the data points in the plot of residuals against dynamic MOE (Fig. 13) in-

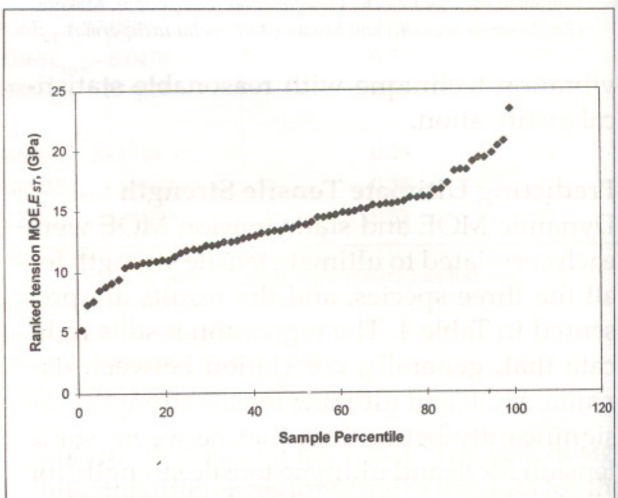

Fig.12. Normal probability plot of residuals from regression of dynamic MOE on tension MOE for Moabi (*Baillonella toxisperma*).

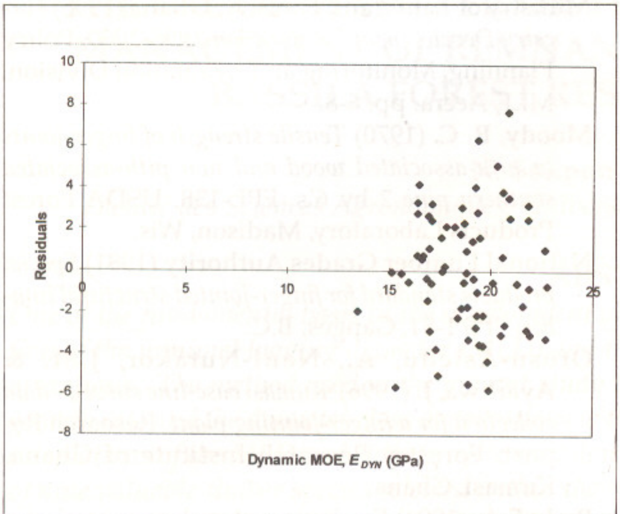

Fig. 13. Plot of residuals against dynamic MOE for combined data for Moabi (*Baillonella toxisperma*).

dicates that the errors as represented by the residuals, are random and independent of the explanatory variable (i.e. dynamic MOE). This therefore verifies the linearity assumption of the models. The reasonably uniform spread above and below any part of the horizontal axis of the plots may indicate a constant variance of the distribution of the residuals.

CONCLUSION

Dynamic MOE was well correlated to ultimate tensile strength and tension MOE of the finger-jointed tropical African hardwoods studied. Dynamic MOE seems better correlated to ultimate tensile strength than tension MOE. Regression models developed were, generally, statistically significant, and correlation coefficients obtained agreed well with the data reported in the literature. The lower 5 % exclusion limit lines derived under the study seem useful for predicting ultimate tensile strength and tension MOE of finger-joints with reasonable statistical justification. The longitudinal vibration technique may be useful as a non-destructive method for predicting the ultimate tensile strength and tension MOE of finger-jointed tropical African hardwoods, especially, in situations where static tension test is not feasible to undertake. The use of the vibration technique, which is a fast non-destructive testing method, may lend support to the production and utilization of finger-jointed timber from sawmill lumber residues. This will not only ensure efficient timber utilization, but also the conservation of the tropical African forests.

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