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Ana Paula Duarte
Department of Paper Science and Technology
University of Beira Interior
Av. Marquês d'Ávila e Bolama
6200 Covilhã
Portugal

Danielle Robert
CERMAV/CNRS BP 53
38041 Grenoble cedex 9
France

Dominique Lachenal
EFPG/INPG
461 Rue de la Papeterie
38402 St Martin d'Hères
France

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# Monitoring Acoustic Emissions from Finger-Joints from Tropical African Hardwoods for Predicting Ultimate Tensile Strength

By J. Ayarkwa, Y. Hirashima, K. Ando and Y. Sasaki
Graduate School of Bioagricultural Sciences, Nagoya University, Japan

*Keywords*

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**Summary**

The patterns of acoustic emissions generated during tension test of finger-joints from three tropical African hardwoods, Obeche (*Triplochiton scleroxylon*), Makore (*Tieghemella heckelii*) and Moabi (*Baillonella toxisperma*) were evaluated to assess their potential usefulness for non-destructively predicting ultimate tensile strength. The acoustic emission patterns generated were observed to differ depending on the type of finger profile and the wood species. Regression coefficients from cumulative acoustic emission count versus applied stress squared functions also varied with the profile and species type. When ultimate tensile strength was correlated with these regression coefficients, for stresses applied up to 50 % of mean ultimate strength, the logarithmic regression model developed could predict finger-joint strength accurate to ±12 %, ±13 % and ±18 % for Obeche, Makore and Moabi, respectively. The model was also sensitive to the type of finger profile used for all three tropical African hardwoods.

The results indicate that this acoustic emission monitoring procedure could be useful for non-destructively predicting ultimate tensile strength of finger-joints from the three tropical African hardwoods.

## Introduction

### *Sawmill residues and finger jointing*

There have been significant changes in the utilization of forest product resources for engineering applications in recent years, particularly in the utilization of forest and sawmill residues for the production of various value-added products, such as finger-jointed timber. The need to set up finger jointing plants to utilize the enormous volume of trim ends and other sawmill residues has been a focal issue in Ghana recently (Prah 1994; Ofosu-Asiedu *et al.* 1996). The finger jointing technology is an opportunity for sawmills to upgrade waste, improve return on low-grade timber (Kohler 1981; Fisette and Rice 1988; Beaulieu *et al.* 1997), and is also an ideal method of improving the efficiency and profitability of sawmills (Strickler 1980; Ulasovets and Makerova 1988). It is also a means to promote the efficient utilization of tropical timber

A finger joint is a type of structural end joint used in glue laminated timber (glulam) to form long continuous laminations out of individual pieces of timber, and also in other engineered wood components such as trusses and I-joists (Burk and Bender 1989). The strength of a finger-joint has been found to depend on, among other factors, the strengths and qualities of the pieces being jointed, and since finger-joints may be produced from sawmill residues of varying qualities, there is the need to continually monitor the strength qualities of the finger-joints being produced. However, the classic static tests, which are considered as more desirable evaluation methods for the mechanical properties of structural timber, are often difficult to perform and are time consuming. Fast, reliable and easy-to-use non-destructive methods for predicting finger-joint properties may go a long way to promoting the development of the finger jointing technology in tropical African countries. Non-destructive wood testing permits wood properties of individual lumber pieces determined destructively to be correlated with other wood properties measured non-destructively in order to assign property values without damage due to overloading, thereby improving the efficiency of timber utilization (Bodig and Jayne 1982).

### *Acoustic emissions*

Timber, as well as all other materials, contains minute flaws randomly distributed throughout the volume of its substance. When subjected to stress, these flaws initiate microfractures. The term acoustic emission (AE) refers to the elastic waves produced by deformation and failure processes occurring in stressed materials. A flaw or a crack is generally regarded as the source of AE activity (Noguchi *et al.* 1986; Suzuki and Schniewind 1987; Rice and Skaar 1990; DeBaise *et al.* 1966). AE can give information regarding plastic deformation and failure of materials, and therefore has been a popular non-destructive material testing technique. According to DeBaise *et al.* (1966), the strain energy or stress waves released are, in most cases, caused by shifts in a local defect area, sometimes called micro-checks, and arise from local stress concentrations in non-homogenous materials. Other known reasons for the production of AE include material dislocations, phase changes or the growth of cracks (Rice and Skaar 1990). According to

**Table 1.** Selected finger profiles for the finger-joints

| Profile Type | Finger Length $L$ (mm) | Pitch $p$ (mm) | Tip Width $t$ (mm) | Slope of Fingers $\theta$ | Relative Joint Area ($2L/p$) | Cross Section Reduction ($t/p$) |
|---|---|---|---|---|---|---|
| F1 | 10 | 3.7 | 0.6 | 1 in 6 | 5.5 | 0.16 |
| F2 | 18 | 3.7 | 0.6 | 1 in 12 | 9.7 | 0.16 |
| F3 | 20 | 6.0 | 0.6 | 3 in 20 | 6.7 | 0.10 |

Refer to Figure 1

Porter *et al.* (1972) and Knuffel (1988), fractures develop in three distinct phases: initiation, growth and ultimate failure. Fracture growth in timber commences at very low stress levels, increases slowly at first and then at a certain point "takes off" rapidly, escalating in frequency and extent until catastrophic failure takes place (Knuffel 1988). As a material is stressed, the resulting AEs produced at the defect site propagate throughout the material, and are usually detected by a sensor coupled to the surface being monitored (Porter *et al.* 1972; Dedhia and Wood 1980; Honeycutt *et al.* 1985; Rice and Skaar 1990). The sensor converts the incoming signal to an electric impulse which is amplified and conditioned to remove extraneous noise. Many systems in current use allow the emissions to be filtered such that only signals (termed "counts" or "event-counts") above a certain threshold level are registered (Rice and Skaar 1990). The most common method of reporting AE activity is to describe the count rate or cumulative event-counts as a function of the stress applied to the material (Rice and Skaar 1990).

The amount of strain energy or AE released is correlated with mechanical properties of timber or adhesive joints. Porter (1964) was the first to study the application of AE to wood by using it in a study of fracture mechanics in wood. There have been several attempts at using the technique to evaluate the strength of adhesive bonds. Pollock (1971) used the technique to predict failure of adhesive bonds stressed in tension, and found that specimens with poor adhesion had a higher emission rate than those with good adhesion which emitted at lower stress levels. Porter *et al.* (1972) and Dedhia and Wood (1980) used AE to non-destructively predict failure of 2" × 6" (i.e. 50 mm × 150 mm) Douglas fir finger-joints. These studies indicated that prediction of the ultimate bending strength depended on the load at which the prediction was made and the nature of the finger-joint. Porter *et al.* (1972) reported that a load level just beyond the proportional limit should permit estimates of failure load accurate to ±10%. Dedhia and Wood (1980) also concluded that the joint strength could be estimated from AE at 80% of failure load with an accuracy of 7%. Sato *et al.* (1983) investigated cumulative AE count versus tension stress to failure, and obtained a relationship quite similar to that reported on structural size tension specimens of *Pinus spp.* by Knuffel (1988). Sato *et al.* (1985), on the application of AE to mechanical testing of wood, reported on a useful regression of AE count versus load squared. According to Knuffel (1988), tension testing appeared to be the most appropriate mode in which AE phenomena in timber could be investigated.

The objective of this study was to determine whether any of the parameters of the acoustic emissions generated could be correlated with ultimate tensile strength (UTS) of finger-joints from three tropical African hardwoods with the aim of non-destructively predicting the UTS.

## Materials and Methods

### *Materials*

Finger-joints were prepared under factory conditions from three profile types (Table 1 and Fig. 1) using fairly straight-grained wood samples of Obeche (*Triplochiton scleroxylon*) of mean density of 351 kg/m$^3$, Makore (*Tieghemella heckelii*) of mean density of 677 kg/m$^3$, and Moabi (*Baillonella toxisperma*) of mean density of 819 kg/m$^3$. The wood samples, which were free of visible defects, were matched on the basis of their modulus of elasticity (MOE), determined by the longitudinal vibration technique, before jointing (Samson 1985; Fisette and Rice 1988). The mean moisture content of the kiln-dried wood samples at the time of finger jointing was 9%. The finger-joints were produced using resorcinol formaldehyde glue (DIANOL 33N) and end pressed using three different pressures (Table 2). The different finger profiles (F1, F2 and F3) and end pressures were studied in order to secure a wide range of failure stresses and to obtain different qualities of finger-joints for the analyses. The adhesive was double spread on the samples before pressing, and the specimens were cured under a temperature

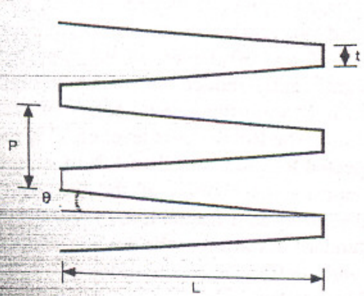


**Fig. 1.** Finger profile parameters.

**Table 2.** End pressures for the finger-jointing (MPa)

| End Pressure | 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 the three finger profiles studied of 30 °C for about 48 hours. The samples were planed, ripped and cross cut to tension test specimen dimensions of 15 × 70 × 700 mm for Makore and Moabi, and 15 × 58 × 700 mm for Obeche, due to insufficient supplied wood samples of Obeche. The specimens were conditioned to nominal 10 % moisture content, under controlled temperature of 20 ± 1°C and relative humidity of 55 ± 3 %, before the test.

*Static tension test*

The tension specimens were tested using a servo-controlled fatigue test machine (Shimadzu Servopulser EHF-ED 10/TD1) of static loading capacity of ±100 kN. A cross-head speed of 3 mm/min was used, and failure occurred within 5 to 10 minutes of test duration. Each replication of specimen was tested in accordance with ASTM D 198-84. Specimens were set up between the grips such that the finger-joint was at mid-span position of the 500 mm free span. Elongation was measured using two transducers set over a distance of 80 mm with the finger-joint positioned in the middle (Fig. 2). All the specimens were loaded to failure and ultimate tensile strength (UTS), modulus of elasticity (MOE) and mean proportional limit stress were determined. Ninety (90) specimens were tested for each species, and those that failed outside the joint were excluded from subsequent data analyses.

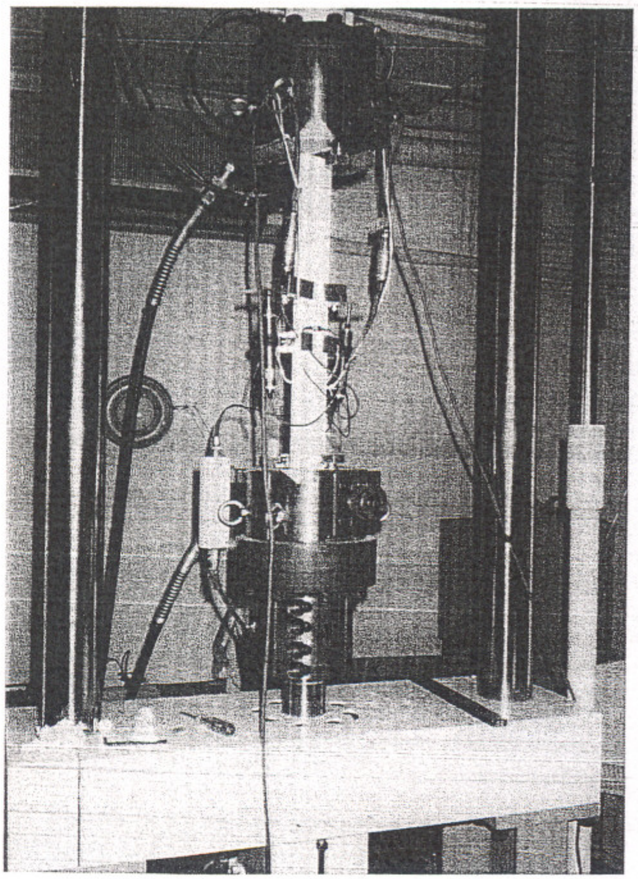

Fig. 2. Set-up of tension test for finger-jointed specimens.

*Recording of acoustic emissions*

One of the most critical factors in AE sensing is the coupling between the sensor face and the sensed material, in that air gaps greatly attenuate ultrasonic transmission (Beall and Wilcox 1987). Two AE sensors were coupled to each face of a test specimen 25 mm apart on each side of the finger-joint, with the aid of silicon grease and rubber bands (Figs. 2 and 3). Signals received by the AE sensors were pre-amplified to 40 dB and further amplified by a main-amplifier to 20 dB. Threshold level was 50 mV. This threshold was just above the noise level at the beginning of the test, and thus minimized the possibility of introducing emission signals arising from changing background noise level. An AE Analyzer, model SAE-1000A, equipped with band filters received, filtered and counted the amplified signals (Fig. 3). The filters were set between 100 kHz and 500 kHz. All signals outside this band were attenuated. Loads were also channeled through a strain amplifier to the AE Analyzer. The digital signals from the counter were converted to analog form and both loads and counts were sent to a personal computer for processing.

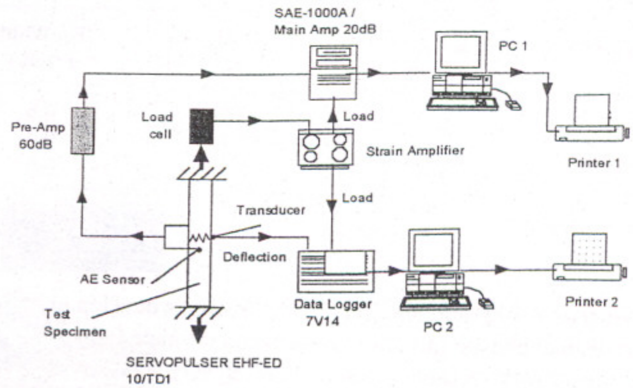


Fig. 3. Schematic diagram of the acoustic emission test set-up.

*Data analyses*

Analyses of variance of test data from different end pressures

Analyses of variance performed using the F-test (at $\alpha = 0.05$) showed that end pressure was not statistically significant with respect to UTS. Therefore the test data collected for the three different end pressures for each finger profile type were combined for each species in an attempt to increase sample size for the data analysis.

Selection of stress levels for predicting UTS

As non-destructive prediction method, low stress levels which would not cause incipient failure in the finger-joints and subsequently lead to failure in service, or stress levels which might break only an insignificant number of samples being tested were considered as best. The accuracy of predicting finger-joint strength, however, has been reported to decrease, the farther away from the ultimate stress the prediction was made (Porter *et al.* 1972; Dedhia and Wood 1980). Two stress levels, 50 % and 70 % of mean ultimate strength of each species, were selected for predicting the finger-joint UTS. The 70 % stress level was close to the proportional limit stress of Obeche finger-joints of 67 %, and it was also used for similar studies on modulus of rupture of specimens of the same species (to facilitate comparison). Strickler *et al.* (1970) reported that proof loads between 60 and 90 percent of the expected ultimate strength did not significantly reduce the tensile strength of end-jointed Douglas fir, indicating the general safety of predicting at 70 % of ultimate stress. The lower stress level of 50 % selected for prediction was expected to break less than 1 % of samples as calculated from the normal distribution of the test data (Fig. 4). Expressing the stress level as a fraction, $k$, of the mean ultimate strength, and the standard deviation as the product of the mean ultimate strength, $\mu$, and coefficient of variation, $CV$, the following equation (1) could be written.

$$k \cdot \mu = \mu - z \cdot \mu \cdot CV \qquad (1)$$

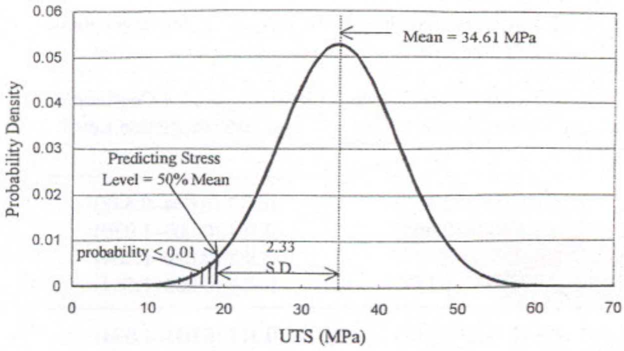


**Fig. 4.** Normal distribution of ultimate tensile strength (UTS) of finger-joints from Obeche.

From which $k = 1 - z \cdot CV$. For a standard normal variable $z = 2.33$ corresponding to 1% probability of failure, the equation was simplified as

$$k = 1 - 2.33 \cdot CV \tag{2}$$

The proportion of the ultimate strength used as the predicting stress level, $k$, calculated from equation (2) came to about 50 % for Obeche, 42 % for Makore and 31 % for Moabi. 50 % of ultimate stress level was used to ensure that a reasonable number of acoustic emissions could be collected for the case of Obeche specimens, where, generally, fewer AEs were emitted until 50 % of ultimate strength was reached. This explains the difference between the number of specimens tested and those analyzed for each species.

### Theoretical considerations on AEs

According to Hartbower *et al.* (1972), Ono (1973) and Suzuki and Schniewind (1987), the release rate of fracture energy, $G$, in the plane stress of isotropic materials is related to the stress intensity factor, $K$, by

$$G = K^2 / E \tag{3}$$

where $E$ is Young's modulus.

Onogami *et al.* (1979) reported that cumulative AE count, $N$, is proportional to the stress intensity factor, $K$, as

$$N \propto K^2 \tag{4}$$

The stress intensity factor, $K$, is also proportional to the applied stress, $P$, as follows

$$K \propto P \tag{5}$$

This indicated that cumulative AE count was related to the applied stress as $N \propto P^2$
implying that,

$$N = aP^2 \tag{6}$$

where $a$ = constant.

Sato *et al.* (1985) showed that the cumulative AE count, $N$, and the applied load, $Q$, could be similarly related as shown in equation (7).

$$N = aQ^2 + b \tag{7}$$

where $a$ = regression coefficient of the cumulative AE count vs. applied load curve, and
$b$ = coefficient relating to the Kaiser effect (Kaiser 1953)

The importance of the relationship between applied stress and cumulative AE count lies in the possibility of estimating ultimate tensile strength non-destructively using AEs. The regression of $N$ on applied stress, $P$, for the finger-jointed specimens under the present study (Fig. 5) followed Sato's *et al.* (1985) regression function expressed by equation (7).

### AE generation from the different profiles and lumber species

The cumulative AE count versus applied stress curves (Fig. 5) showed that AE activity started earlier in specimens of profiles F1 and F3 than those of profile F2 for all the three species studied (Table 3). For profile F2, AE began at stress levels of 48 %, 19 % and 25 % of mean UTS for Obeche, Makore and Moabi, respectively (Table 3). Shortly after start, AE generation from profiles F1 and F3 seemed to have increased rapidly (Fig. 5) until failure occurred at comparatively lower stress levels than for profile F2. For specimens from profile F2, however, AE generation seemed to have proceeded less rapidly than specimens from profiles F1 and

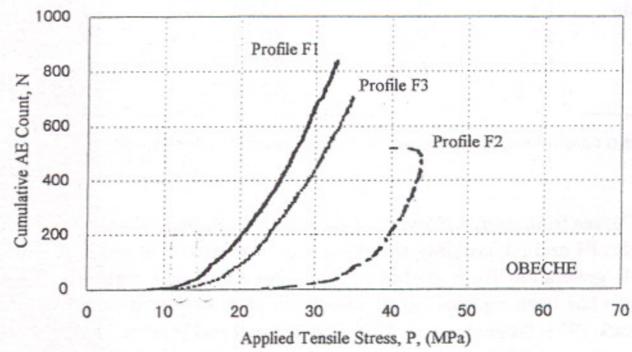


**Fig. 5a.** Relationship between cumulative AE count and applied tensile stress for Obeche finger-joints of three profile types.

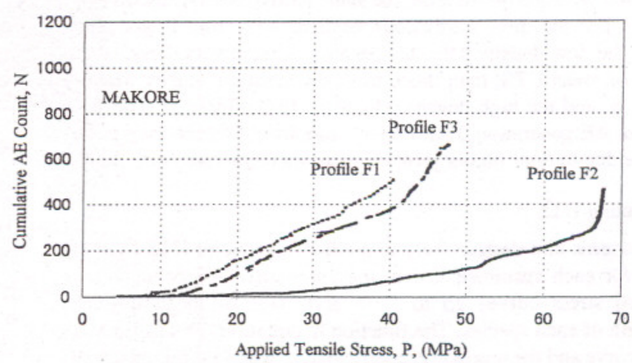


**Fig. 5b.** Relationship between cumulative AE count and applied tensile stress for Makore finger-joints of three profile types.

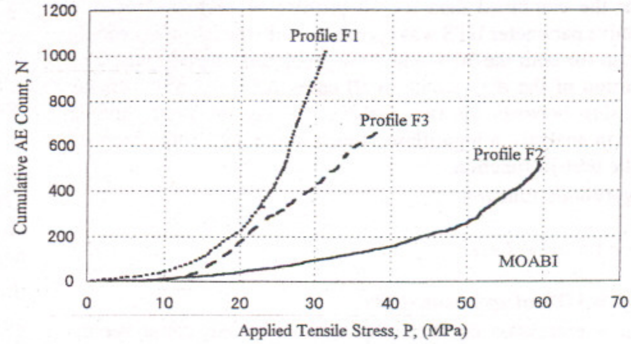


**Fig. 5c.** Relationship between cumulative AE count and applied tensile stress for Moabi finger-joints of three profile types.

**Table 3.** Mean stresses, ratios of stresses at start to stresses at completion of AE, and mean regression coefficients, *a*, for finger-joints from Obeche, Makore and Moabi

| Species | Profile Type | Mean Stress at 1st AE Count (MPa) | Mean UTS (MPa) | *Ratio of Stress at 1st AE to UTS (%) | Mean Regression Coefficient, *a*, at 50 % Prediction Level | Mean Regression Coefficient, *a*, at 70 % Prediction Level |
|---|---|---|---|---|---|---|
| Obeche | F1 | 9.52 | 35.39 | 28 | 0.291 (0.007–2.457) | 0.217 (0.004–0.537) |
| | F2 | 16.74 | 40.40 | 48 | 0.151 (0.008–0.665) | 0.164 (0.003–1.030) |
| | F3 | 10.19 | 29.77 | 29 | 0.526 (0.028–3.177) | 0.388 (0.020–1.564) |
| | ALL F | 11.77 | 34.61 | 34 | 0.347 (0.007–3.177) | 0.265 (0.003–1.564) |
| Makore | F1 | 5.92 | 48.38 | 12 | 0.358 (0.042–1.515) | 0.313 (0.035–1.084) |
| | F2 | 9.17 | 57.10 | 19 | 0.162 (0.003–2.759) | 0.125 (0.003–0.630) |
| | F3 | 5.82 | 44.44 | 12 | 0.335 (0.015–0.789) | 0.342 (0.022–0.752) |
| | ALL F | 6.88 | 49.36 | 14 | 0.286 (0.003–2.759) | 0.268 (0.003–1.084) |
| Moabi | F1 | 4.01 | 30.79 | 10 | 0.586 (0.010–1.436) | 0.497 (0.013–1.353) |
| | F2 | 9.43 | 52.10 | 25 | 0.151 (0.004–0.854) | 0.147 (0.001–0.974) |
| | F3 | 6.48 | 33.38 | 17 | 0.288 (0.010–1.285) | 0.321 (0.009–1.026) |
| | ALL F | 6.39 | 38.50 | 17 | 0.339 (0.004–1.436) | 0.322 (0.001–1.353) |

* Ratio calculated using mean UTS of all profiles of each species (i.e. ALL F). Values in parenthesis are ranges of regression coefficients, *a*.

F3. Curves from profile F2 were of lower curvature than those from profiles F1 and F3, possibly stemming from the less rapid increase in AE generation from profile F2. A more rapid and early AE activity has been reported to be indicative of a weaker specimen (Pollock 1971; Noguchi *et al.* 1986, 1992; Beall and Wilcox 1987). The pattern of AE activities from the three finger profiles of each species seemed to be indicative of the fact that finger-joints from profile F2 were stronger (Table 3) and more efficient than those from profiles F1 and F3. This result agreed with earlier results reported on finger-joints from the same hardwoods (Ayarkwa *et al.* 2000). For the three hardwoods studied, AEs from finger-joints from the low-density Obeche began comparatively later, about 34 % of mean UTS, than those from the medium-density Makore of 14 %, and the high-density Moabi of 17 % (Table 3). The later start of AE generation from finger-joints from Obeche may possibly be due to their higher joint efficiencies (Ayarkwa *et al.* 2000).

Predicting UTS

AE patterns non-destructively to predict finger-joint UTS by plotting, for each specimen tested, the cumulative AE count versus applied stress curves up to 50 % and 70 % of mean ultimate strength of each species. The function in equation (7) was fitted to each curve and the regression coefficient, *a*, was determined. Mean values of the regression coefficients, *a*, summarized in Table 3, indicated that the lower the regression coefficient, the stronger the finger-joint for all finger profiles studied for each species.

For the specimens tested for each finger profile of each species, and for the combined data for all profiles of each species, the destructive parameter UTS was correlated with the regression coefficient, *a*, for both the 50 % and 70 % prediction stress levels. The distribution of the data points in all cases indicated a non-linear relationship between the two variables. Using the least squares regression analysis, a logarithmic function (eq. (8)) was observed to be the best-fit function.

Logarithmic function:

$$f = c \operatorname{Ln}(a) + d + \varepsilon \tag{8}$$

where $f$ = UTS of specimen (MPa)
$a$ = regression coefficient of cumulative AE count versus applied stress curve
$c$, d = regression coefficients for logarithmic function
$\varepsilon$ = residual error

Absolute percentage error

The scatter of the points on the plots of UTS against the regression coefficient, *a*, was assumed to stem primarily from errors in predicting the UTS. Therefore, absolute percentage error for each prediction made using the developed regression models was calculated using the relationship

$$\text{Absolute percentage error (\%)} = \frac{|\text{predicted UTS} - \text{actual UTS}|}{\text{Actual UTS}} \times 100 \tag{9}$$

Mean absolute percentage errors were calculated for each finger profile of each species, and for the combined data for all profiles of each species.

## Results and Discussion

The summary of the results of the study are presented in Tables 3, 4 and 5 for the mean stresses, correlation coefficients and mean absolute percentage errors for the predictions of UTS for the different finger profiles and the combined data for each species. Table 5 also presenteds the regression parameters and the significance of the regression models developed for the combined data for each species (at $\alpha = 0.01$), for both the 50 % and 70 % predicting stress levels. Regression diagrams for the combined data from the three profile types of each species are presented for the two predicting stress levels in Figures 6 to 8. The regression diagram of UTS on static tension MOE for the same finger-jointed specimens are also presented in Figure 9 for comparison.

The results showed negative correlation between UTS and the regression coefficient, *a*, for all the regressions (Table 5 and Figs. 6 to 8). This indicated that as the regression coefficient, *a*, increased, UTS decreased, and *vice versa*. For the individual finger profiles (Table 4), the trend in the differences in correlation coefficients between the 50 % and the 70 % predicting stress levels was not consistently clear. However, correlation coefficients obtained for the 70 % stress level seemed slightly higher than those for the 50 % stress level for Makore and Moabi. For the combined

**Table 4.** Summary of parameters for the regression of UTS on regression coefficient, $a$, of cumulative AE count versus applied stress squared for three finger profiles of Obeche, Makore and Moabi

| Species | Profile Type | Correlation Coefficients from Prediction at 50 % | 70 % | #Mean Absolute Percentage Errors from Prediction at 50 % | 70 % |
|---|---|---|---|---|---|
| Obeche | F1 | 0.49 (n = 24) | 0.43 (n = 19) | 10.84 [10.69] | 9.35 [7.38] |
| | F2 | 0.58 (n = 14) | 0.44 (n = 22) | 10.64 [7.91] | 11.37 [8.00] |
| | F3 | 0.30 (n = 22) | 0.57 (n = 23) | 12.02 [9.71] | 7.94 [5.10] |
| Makore | F1 | 0.42 (n = 21) | 0.41 (n = 21) | 13.29 [12.60] | 13.02 [12.21] |
| | F2 | 0.68 (n = 26) | 0.72 (n = 26) | 12.70 [7.48] | 12.20 [9.13] |
| | F3 | 0.18 (n = 36) | 0.18 (n = 31) | 12.84 [11.23] | 12.81 [11.35] |
| Moabi | F1 | 0.19 (n = 20) | 0.29 (n = 21) | 21.22 [23.64] | 14.31 [12.36] |
| | F2 | 0.62 (n = 22) | 0.63 (n = 22) | 10.89 [10.49] | 10.53 [10.25] |
| | F3 | 0.41 (n = 23) | 0.45 (n = 23) | 21.34 [8.94] | 15.08 [9.82] |

n = sample size analyzed. Values in square brackets are standard deviations.
# Denotes absolute percentage error calculated from equation (9).

**Table 5.** Summary parameters for the regression of UTS on regression coefficient, $a$, of cumulative AE count versus applied stress squared for combined data from three profiles of Obeche, Makore and Moabi

| Species | Prediction Level | No of Specimens Analyzed | Linear Regression Model | Correlation Coefficient | Significance of Model at 1% | #Mean Absolute % Error |
|---|---|---|---|---|---|---|
| Obeche | 50 % | 60 | $f = -2.493\mathrm{Ln}(a) + 28.978$ | 0.55 | * | 12.41 (8.46) |
| | 70 % | 64 | $f = -2.555\mathrm{Ln}(a) + 31.376$ | 0.56 | * | 11.54 (6.86) |
| Makore | 50 % | 78 | $f = -5.308\mathrm{Ln}(a) + 40.872$ | 0.62 | * | 12.92 (9.50) |
| | 70 % | 78 | $f = -6.002\mathrm{Ln}(a) + 40.652$ | 0.63 | * | 12.70 (8.50) |
| Moabi | 50 % | 65 | $f = -4.704\mathrm{Ln}(a) + 31.143$ | 0.66 | * | 17.99 (11.19) |
| | 70 % | 66 | $f = -5.114\mathrm{Ln}(a) + 30.870$ | 0.67 | * | 17.55 (9.38) |

$f$ = MOR; $a$ = regression coefficient of cumulative AE count versus applied stress squared. Values in parenthesis are standard deviations.
* Denotes statistically significant at 1% level. # Denotes absolute percentage error calculated from equation (9).

data for each species (Table 5), there seemed to be no significant differences between the correlation coefficients obtained for the two predicting stress levels. Among the three finger profiles studied for each species (Table 4), profile F2 seemed to have resulted in higher correlation coefficients than profiles F1 and F3, for both the 50% and the 70% predicting stress levels. This trend might be related to the higher joint efficiency reported on finger-joints produced from finger profile F2 than those from profiles F1 and F2 (Ayarkwa *et al.* 2000). Although the correlation coefficients, which ranged between 0.18 and 0.72 for the individual finger profiles (Table 4) and between 0.55 and 0.67 for the combined data for each species (Table 5), were not very high, the test of significance (at $\alpha = 0.01$) indicated that the regressions were statistically highly significant. Thus the data obtained gave reason to conclude that logarithmic relationship existed between the UTS and the regression coefficient, $a$.

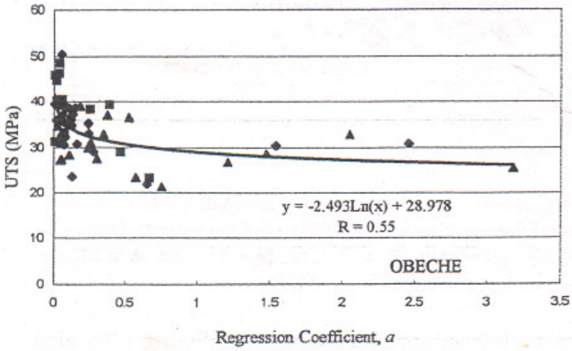


**Fig. 6a.** Regression of ultimate tensile strength (UTS) of Obeche finger-joints on regression coefficient ($a$) of cumulative AE versus applied stress squared up to 50% of ultimate stress. ◆ = Obeche, ■ = Makore, ▲ = Moabi.

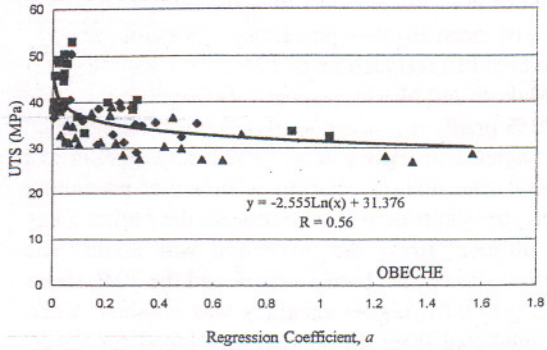


**Fig. 6b.** Regression of ultimate tensile strength (UTS) of Obeche finger-joints on regression coefficient ($a$) of cumulative AE versus applied stress squared up to 70% of ultimate stress. ◆ = Obeche, ■ = Makore, ▲ = Moabi.

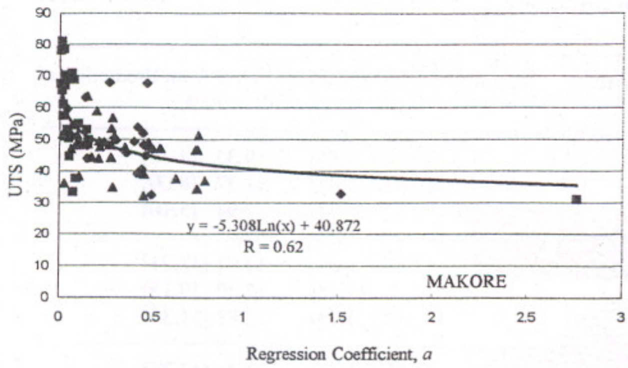


Fig. 7a. Regression of ultimate tensile strength (UTS) of Makore finger-joints on regression coefficient (*a*) of cumulative AE versus applied stress squared up to 50 % of ultimate stress. ◆ = Obeche, ■ = Makore, ▲ = Moabi.

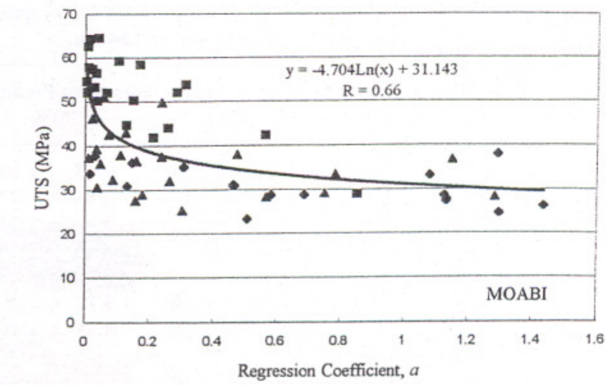


Fig. 8a. Regression of modulus of rupture (MOR) of Moabi finger-joints on regression coefficient (*a*) of cumulative AE versus applied stress squared up to 50 % of ultimate stress. ◆ = Obeche, ■ = Makore, ▲ = Moabi.

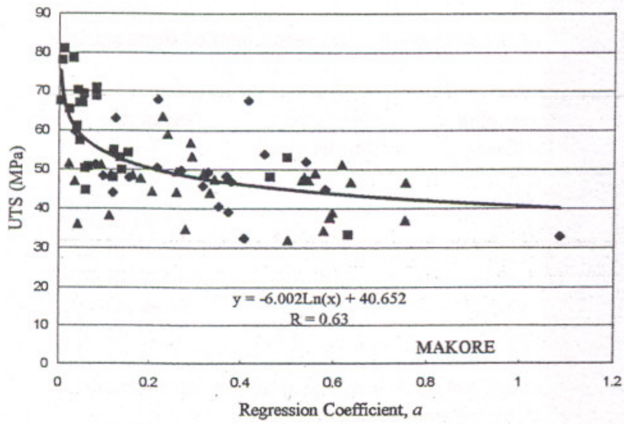


Fig. 7b. Regression of ultimate tensile strength (UTS) of Makore finger-joints on regression coefficient (*a*) of cumulative AE versus applied stress squared up to 70 % of ultimate stress. ◆ = Obeche, ■ = Makore, ▲ = Moabi.

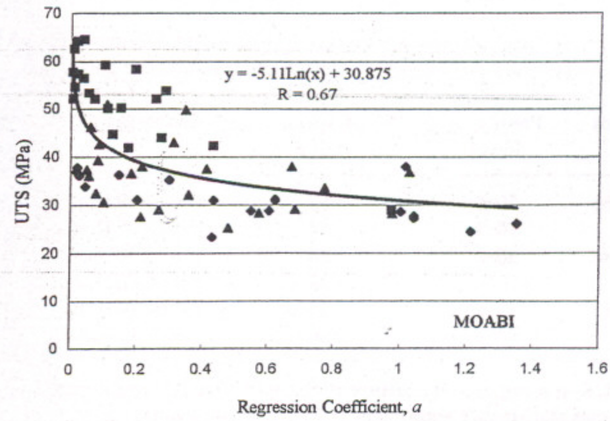


Fig. 8b. Regression of ultimate tensile strength (UTS) of Moabi finger-joints on regression coefficient (*a*) of cumulative AE versus applied stress squared up to 70 % of ultimate stress. ◆ = Obeche, ■ = Makore, ▲ = Moabi.

Mean absolute percentage errors calculated from the regression models, did not show significant differences between the 50 % and the 70 % predicting stress levels for the combined data for each species (Table 5), although the 70 % stress level appeared to have resulted in slightly lower mean errors. For the different finger profiles of each species, the results showed that the 70 % predicting stress level resulted in lower mean percentage errors than the 50 % stress level (Table 4). The mean absolute percentage errors for the combined data could be rounded up to 12 %, 13 % and 18 % for Obeche, Makore and Moabi, respectively, for both the 50 % and the 70 % predicting stress levels. The results obtained seemed to agree with Porter *et al.* (1972) and Dedhia and Wood (1980) who reported that the accuracy of predicting finger-joint strength from was AE reduced, the farther away from the ultimate stress the prediction was made. The results further showed for both the 50 % and the 70 % stress levels that, generally, higher accuracy was obtained when UTS was predicted from the models developed for specimens from profile F2 than those from profiles F1 and F3 (Table 4). Finger profile F2 has been reported to be the most efficient profile among the three profiles studied (Ayarkwa *et al.* 2000), seemingly indicating that as the quality of the

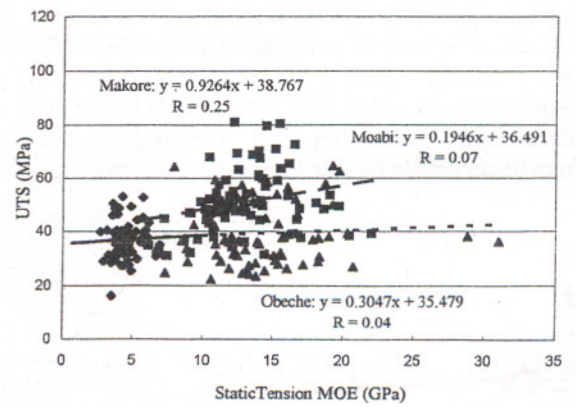


Fig. 9. Regression of ultimate tensile strength (UTS) on static tension modulus of elasticity (MOE) of finger-joints from Obeche, Makore and Moabi. ◆ = Obeche, ■ = Makore, ▲ = Moabi, —— Obeche, – – – Makore, ········ Moabi.

finger-joints dedined, the accuracy of predicting UTS also reduced. This also agreed with Porter *et al.* (1972) and Dedhia and Wood (1980) who indicated that the accuracy of predicting finger-joint strength from AE depended on the nature of the joint. The decreased accuracy for the less efficient finger profiles F1 and F3 may be partly attributable to spurious acoustic signals generated by the poor-quality joints loosening up. This might have led to an underestimation of the true UTS of the specimens. Among the three species studied, prediction accuracy for the combined data appeared to decrease with wood density, decreasing from the low-density Obeche of 12 %, through the medium-density Makore of 13 % to the high-density Moabi of 18 %, for both the 50 % and the 70 % predicting stress levels. This might be due to the increase in variability of UTS of finger-joints with increase in wood density already reported on finger-joints from the three species (Ayarkwa *et al.* 2000). The greatest variability in finger-joint UTS reported on the high-density Moabi were attributed to poor gluability, possibly stemming from low porosity, poor wettability and the likely presence of extractives in excess amount in the wood. The decreased accuracy may also have resulted from spurious acoustic signals generated by the poorly jointed fingers of the finger-joints from Moabi sliding over each other, which might also have led to an underestimation of the true UTS of the specimens. It may be inferred from the mean percentage errors (Tables 4 and 5) that predicting UTS at 70 % of mean ultimate strength seemed a slightly better option. However, the 70 % stress level could break an unrealistically high proportion of specimens of each of the three species during stress application. Consequently, the 50 % predicting stress level, which could break a small proportion of specimens of the three species (less than 5 %) under proof testing, may therefore be recommended as the most economic option. For Obeche, however, to ensure that reasonably adequate number of AEs would be generated for subsequent analysis, around 60 % of ultimate stress level, which might break only about 3 % of specimens may be recommended.

Machine stress grading is based on the establishment of a statistical correlation between the stiffness of lumber (MOE) and its UTS. The correlation coefficients of 0.04, 0.25 and 0.07 obtained from the regression of UTS on MOE for the finger-joints from Obeche, Makore and Moabi, respectively (Fig. 9), indicated that the UTS-MOE correlation would be of little use for the finger-joints used in this study. Therefore, the AE monitoring appeared to hold greater prospects for non-destructively predicting UTS of finger-joints from the three tropical African hardwoods.

## Conclusions

The results of the study suggested that the regression coefficient, $a$, of the cumulative acoustic emissions counts versus applied stress squared function is a sensitive indicator of ultimate tensile strength of finger-joints from the three tropical hardwoods. Although correlation coefficients obtained for the regressions were low, the regression models developed were statistically highly significant ($\alpha = 0.01$), indicating their suitability for predicting ultimate tensile strength. Mean absolute percentage errors obtained were reasonably good, indicating that measuring AE up to 50 % of ultimate strength of finger-joints from Makore and Moabi, and up to 60 % for Obeche seem the best options. The developed models also seemed sensitive to the quality of the finger-joint, as the accuracy of predicting ultimate tensile strength reduced with the strength of the finger-joint.

The results of the study have given an indication that this acoustic emission monitoring procedure could be useful for non-destructively predicting UTS of finger-joints from the three tropical African hardwoods.


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Joshua Ayarkwa
Prof. Yoshihiko Hirashima
Kosei Ando
Assoc. Prof. Yasutoshi Sasaki
Bio-material Engineering Laboratory
Graduate School of Bioagricultural Sciences
Nagoya University
Furo-cho
Chikusaku
Nagoya 464-8601
Japan
Tel: +81-52-789-4146; Fax: +81-52-789-4147
E-mail: ayark@gol.com