# EFFECTS OF WOOD DENSITY AND INTERLOCKED GRAIN ON THE SHEAR STRENGTH OF THREE AMAZONIAN TROPICAL HARDWOODS

*Roger E. Hernández*†
Professor

and

*Giana Almeida*†
Graduate Student
Département des Sciences du Bois et de la Forêt
Université Laval
Québec, Canada, G1K 7P4

(Received March 2002)

ABSTRACT

Three tropical hardwoods, ishpingo (*Amburana cearensis* A.C. Smith), pumaquiro (*Aspidosperma macrocarpon* Mart.), and tulpay (*Clarisia racemosa* Ruiz and Pav.), were studied to determine the effects of wood density and interlocked grain on the shear strength parallel to grain. The maximum angular deviation (MAD) and the interlocked grain index (IG) were used to evaluate interlocked grain. The parameters were determined for interlocked grain samples and for ASTM D 143 shear blocks. There was a strong relationship between the interlocked grain parameters for the three species. MAD was simpler to evaluate compared to IG. The interlocked grain was highly variable within wood species. Failure of sheared blocks was irregular and in general followed the interlocked grain pattern. Hence, apparent shear strength was calculated using either a measured shear area (actual shear strength) or a fixed shear area of 2500 $mm^2$ (nominal shear strength). Wood density positively affected the apparent shear strength of the wood. The relationships were stronger for actual shear strength compared to nominal shear strength. For all species studied, the interlocked grain negatively affected actual shear strength. The relationships between nominal shear strength and interlocked grain parameters were positive for ishpingo and tulpay, but negative for pumaquiro. Finally, we concluded that the ASTM D 143 block shear test method should be adapted for woods with heavily interlocked grain.

*Keywords*: Interlocked grain, shear strength, tropical woods, *Amburana cearensis, Aspidosperma macrocarpon, Clarisia racemosa.*

## INTRODUCTION AND BACKGROUND

Several tropical trees exhibit an interlocked grain pattern in their wood. For example, Aróstegui (1982) found that 33 out of 60 Peruvian tropical hardwoods tested had this feature. An analysis of the anatomical properties of 258 tropical hardwoods indicates that about 75 percent could be classified as prone to interlocked grain (Kribs 1950). However, the influence of this feature on the physical and mechanical properties of wood is not well understood.

Interlocked grain is formed by the cells of successive growth layers alternately aligned in clockwise and anticlockwise spirals (Weddell 1961). This type of spiral grain occurs frequently in hardwood trees species and occasionally in conifer species (Northcott 1957; Rudinsky and Vité 1959). It is caused by repeated changes in both direction and angle of the spiral. Martley (1920) and Webb (1969) describe how these changes occur between growth increments as well as within a single growth increment. The interlocked grain pattern may be evolutionarily advantageous for certain species. Rudinski and Vité (1959) used

† Member of SWST.

dye to follow the water-conducting system of conifers and suggested that the interlocked grain pattern results in distribution of water over the entire upper crown, which enhances adaptability to changes in the environment.

Interlocked grain is sometimes considered as a wood defect since it can cause warp and cracks during drying (Weddell 1961). Problems such as twisting, grain-raising, and tearout during manufacture of veneer, plywood, and lumber can also occur (Webb 1969). In contrast, this grain pattern also shows up as a ribbon figure in quartersawn lumber and quarter-sliced veneer, which is particularly attractive for several end-uses of wood.

The influence of the interlocked grain on wood strength has long been recognized, but with the increasing use of tropical hardwoods for structural purposes more information is needed. Weddell (1961) reported that the modulus of rupture (MOR) and the modulus of elasticity (MOE) in bending were negatively affected by the presence of interlocked grain in utile and greenheart woods. This grain pattern also decreases the impact bending strength of white meranti wood (Marsoem and Kikata 1987).

Data are not available on the effect of interlocked grain on shear strength of wood. This strength is a measure of the ability of wood to resist forces that tend to cause material to slide or slip relative to adjacent material. The shear strength parallel to the grain is especially important since it is used to determine the dimensions of wood structures. A pure state of shear stress in wood is extremely difficult to produce experimentally (Bodig and Jayne 1982). This difficulty is amplified for woods with interlocked grain since this feature produces complex stress distributions within wood and an irregular sheared surface.

The objective of this study was to evaluate the effects of wood density and interlocked grain on the shear strength parallel to grain of three tropical hardwoods from Amazonian forests.

## MATERIALS AND METHODS

Three Peruvian tropical hardwood species, ishpingo (*Amburana cearensis* A.C. Smith), pumaquiro (*Aspidosperma macrocarpon* Mart.), and tulpay (*Clarisia racemosa* Ruiz and Pav.), were tested experimentally. These tree species are widely distributed throughout the Amazonian region and are known in Brazil as cerejeira, peroba rosa, and guariuba, respectively. They were selected as representative tropical hardwoods. The three species cover a wide range of density, interlocked grain level, and anatomical structure. The woods are also widely used in furniture, flooring, decorative panels, and construction.

Fifty-five green, defect-free samples 60 mm × 60 mm in the transverse direction and 90 cm long were taken randomly from three sawmills in Lima, Peru. The samples were protected with an antifungal solution, air-dried, and their ends were treated with paraffin to avoid checks and splits during shipping. Once at Laval University, the material was stored in a conditioning room at 20°C and 60% relative humidity (RH) for 12 months. At the end of this period, the average equilibrium moisture content (EMC) was 10.5%, 12.4%, and 10.9%, for ishpingo, pumaquiro, and tulpay, respectively. Variable concentrations of extractive substances among the three species would account for these differences. After conditioning, the pieces were jointed, planed, and trimmed to obtain sticks, 50 mm (R) by 50 mm (T) by 300 mm (L). Each stick was then cross-cut to yield sample pairs, one for the interlocked grain test (50 mm × 50 mm × 50 mm) and one for the shear strength test parallel to the grain (50 mm × 50 mm × 63 mm).

We used a modification of the method described in Webb (1969) to measure interlocked grain. Samples were split along a radial plane with a wedge-shaped knife mounted on a universal machine (Fig. 1). The knife speed was fixed at 0.8 mm per min to reduce the propagation of splitting to other planes of failure (Debaise et al. 1966). Several interlocked patterns were produced in sample cross-sections

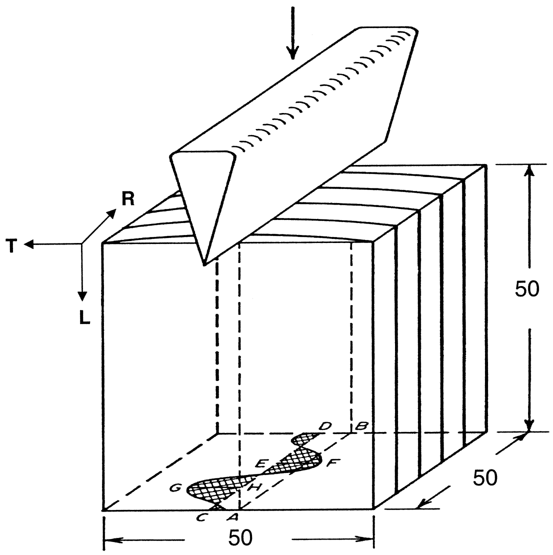


FIG. 1. Interlocked grain test. The shadow area shows the measure of interlocked grain parameters (dimensions in mm).

(Fig. 2). Micrographs of these cross-sections were taken with a Polaroid digital microscope camera attached to a computer. The interlocked patterns on the micrographs were then processed with Adobe Photoshop 4 software and Regent Instruments WinCell Pro 5.6d image analyzer at a magnification of about 5× (Fig. 2A). The projected line of the knife edge was traced as a straight radial line (AB). A second straight radial line (CD) parallel to AB was traced and served to divide the shadow area of the split into two equal parts (Fig. 1). The maximum angular deviation (MAD) was estimated as the addition of the maximum left spiral angle (angle obtained by the height of the specimen and the line GH) plus the maximum right spiral angle (angle from the specimen height and line EF), in degrees (Figs. 1 and 2B). In addition, the interlocked grain index (IG) was found by dividing the area between the median radial line CD and the tracing of the split (shadow area in Fig. 1), by the length of the line CD (Figs. 1 and 2B).

The shear strength parallel to grain test was carried out according to the ASTM D 143 standard (ASTM 1997a). Although this method has been criticized for not providing pure shear load to the sample, it is widely used. Several alternative methods have been recommended, but none has addressed the additional problems related to interlocked grain

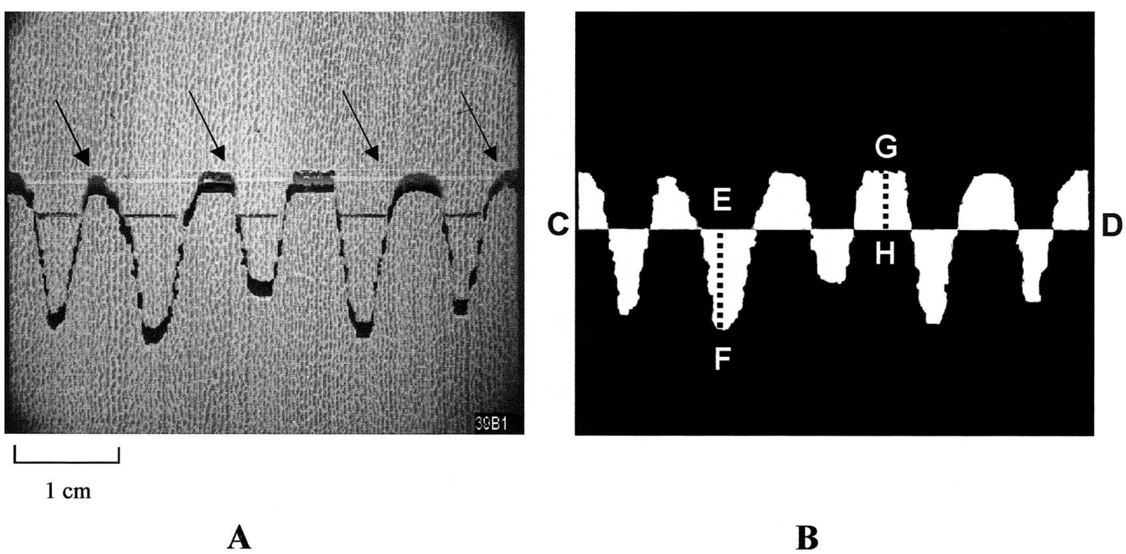


FIG. 2. Measure of interlocked grain parameters with the WinCell Pro image analyzer. (A) Micrograph of a cross-section taken by a digital camera. (B) Processed image using the Photoshop software. Arrows show where failure was restricted by the inner edge of the supporting surface of the ASTM D 143 shear tool.

patterns. The use of this standard allows comparison with results previously reported. The shear test was conducted on the radial shear plane using a universal testing machine with the load applied at a rate of 0.6 mm per min. Following the standard, there was an offset of 3.2 mm between the inner edge of the supporting surface and the specific plane along which the failure occurs. This adjustment ensures that shear failure occurs in the plane of least strength. Otherwise, compression failure parallel to grain may occur (Bodig and Jayne 1982). This offset was important in this study since failure in woods with interlocked grains did not occur in that specific plane.

The apparent shear strength ($\tau_{TL}$) is determined by dividing the load at failure by the shear area. Debaise et al. (1966) underlined the challenging problem concerning the proper definition of the area generated by fracture. Thus, for blocks having straight grain, this surface is estimated as approximately 2500 mm$^2$. However, the area of shear blocks with interlocked grain is extremely irregular. The area was estimated after testing by inserting a red metallized polypropylene film between the two sheared pieces. An image of this film was taken with the digital camera, and the shear area was then estimated with the Regent Instruments WinCell Pro 5.6d image analyzer. The apparent shear strength was then calculated for both a fixed shear area of 2500 mm$^2$ (nominal shear strength) and the measured shear area (actual shear strength). The measured shear area means and the standard deviations were 3383 mm$^2$ (305 mm$^2$), 3141 mm$^2$ (235 mm$^2$), and 2979 mm$^2$ (388 mm$^2$) for ishpingo, pumaquiro, and tulpay, respectively.

After the shear test, part of the specimen was used to determine EMC, humid density (weight and volume at time of testing), and basic density (oven-dry weight and green volume) according to ASTM standards D 4442—method B, D 2395—methods A and B, respectively (ASTM 1997b, c).

We expected that failures due to shear should follow a pattern influenced by the grain direction in the sample. The cross-section showing failure as a wavy line was hence used to estimate the interlocked grain parameters MAD and IG as explained earlier.

Data were analyzed using Statistical Analysis System (SAS) software (1988). Analyses of variance (GLM procedure) and Tukey tests (0.05 probability level) were performed to determine differences among species, between samples (interlocked grain and shear samples), and between interlocked grain parameters (MAD and IG) for each species. Multiple regression analyses were performed to determine the relationships between wood density and interlocked grain on shear strength. For this, the stepwise procedure of SAS was used and the selection or exclusion of the independent variables in the models was set at the 0.10 probability level. To evaluate the relative importance of each independent variable on shear strength variation, the regression coefficients were standardized by calculating the beta coefficients.

## RESULTS AND DISCUSSION

### *Wood properties*

The results of all properties for the three species studied are given in Table 1. Basic and humid densities of ishpingo were significantly lower than those of pumaquiro and tulpay. The mean basic density of ishpingo was similar to that reported by Chudnoff (1984) and Rijsdijk and Laming (1994), at 550 kg/m$^3$ and 530 kg/m$^3$, respectively. The mean basic density of pumaquiro was similar to that reported by Aróstegui (1982) and Chudnoff (1984), at 670 kg/m$^3$ and 650 kg/m$^3$, respectively. The reported basic density of tulpay is highly variable with values of 460 kg/m$^3$, 510 kg/m$^3$, and 620 kg/m$^3$ for trees from Colombia, Ecuador, and Bolivia, respectively (Keenan and Tejada 1984). The mean basic density of tulpay samples used here was comparable to that previously reported for trees from Bolivia.

The three species chosen for study had high mean values of interlocked grain. The interlocked grain of ishpingo and pumaquiro were

TABLE 1. *Means and coefficients of variation of the physical, interlocked grain, and shear strength properties of three tropical hardwoods.*

| Species | Number of specimens | Physical properties | | | Interlocked grain parameters: Interlocked grain samples | | Interlocked grain parameters: Shear samples | | Apparent shear strength parallel to grain | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | BD[1] (kg/m³) | HD (kg/m³) | EMC (%) | MAD (°) | IG (cm) | MAD (°) | IG (cm) | $\tau_{TL\ actual}$ (MPa) | $\tau_{TL\ nominal}$ (MPa) |
| Ishpingo | 62 | 552 A[2] | 633 A | 10.54 A | 16.4 A | 0.33 A | 16.2 A | 0.34 A | 8.3 A | 11.1 A |
| | | (7.3)[3] | (7.0) | (5.9) | (39) | (44) | (31) | (32) | (11.4) | (9.3) |
| Pumaquiro | 48 | 659 B | 781 B | 12.35 C | 16.0 A | 0.33 A | 15.4 A | 0.34 A | 10.8 B | 13.4 B |
| | | (3.4) | (4.1) | (3.0) | (33) | (42) | (29) | (36) | (10.8) | (7.9) |
| Tulpay | 44 | 664 B | 771 B | 10.90 B | 12.4 B | 0.28 A | 12.3 B | 0.28 B | 11.5 C | 13.6 B |
| | | (6.1) | (6.1) | (2.3) | (30) | (41) | (29) | (35) | (10.7) | (11.9) |

[1] BD = basic density; HD = humid density; EMC = equilibrium moisture content; MAD = maximum angular deviation; IG = interlocked grain index; $\tau_{TL\ actual}$ = actual shear strength; $\tau_{TL\ nominal}$ = nominal shear strength.
[2] Means within a column followed by the same letter are not significantly different at 0.05 probability level.
[3] Number in parentheses refers to the coefficient of variation (%).

similar, while tulpay had a lower value for both MAD and IG grain parameters. Limaye (1954) proposed a system for classifying the intensity of interlocked grains. Following this system, the interlocked grain for ishpingo and pumaquiro is very heavy and for tulpay is heavy.

There was high interlocked grain variation within species; the coefficient of variation (COV) of MAD and IG ranged from 30% to 44% for all species (Table 1). Large variation within species has been reported previously (Limaye 1954; Webb 1967, 1969; Détienne 1979; Marsoem and Kikata 1987).

The interlocked grain measured from shear blocks had a lower COV than that from interlocked grain specimens. The offset of the ASTM D 143 shear tool affected these results. In general, failures in shear blocks followed the wood grain. Thus, the cross-section in contact with the base of the shear tool showed an interlocked failure pattern similar to that obtained by splitting. However, the 3.2-mm offset partially affected one side of the wavy failure, especially in the heavily interlocked blocks (Fig. 2A). Fibers in interlocked grain woods are inclined to the vertical axis of a tree at opposite angles, reaching approximately equal maxima first to one side (left spiral) and then to the other (right spiral). In shear blocks, this inclination was more accentuated on one side due to the offset restriction. Propagation of the shearing to other planes of failure was also noticed in some samples as a result of the offset effect. Local failures in parallel compression were produced on the side affected by the offset in heavily interlocked shear blocks. However, given the high variation of the interlocked grain, only a slight decrease in MAD was measured from shear blocks compared to that from the interlocked grain (Table 1). This decrease was not statistically significant at the 0.05 probability level.

Keenan and Tejada (1984) reported a shear strength of 13.1 MPa at 12% EMC for pumaquiro coming from Peru. This value agrees with the mean nominal shear strength in this study for this wood (13.4 MPa). Shear strength values reported previously for tulpay at 12% EMC were 9.7 MPa, 10.0 MPa, 11.7 MPa, and 12.4 MPa, for trees coming from Colombia, Ecuador, Brazil, and Bolivia, respectively (Keenan and Tejada 1984; IBDF 1988). The differences among the literature values and this study (13.6 MPa) could be due to density and EMC variations.

### *Relationships between the interlocked grain parameters*

For all species, there was a high linear correlation between MAD and IG parameters measured from interlocked grain samples (Fig. 3). A similar relationship was found when these parameters were determined from shear samples ($IG = -0.003 + 0.02\ MAD$; $R^2 =$

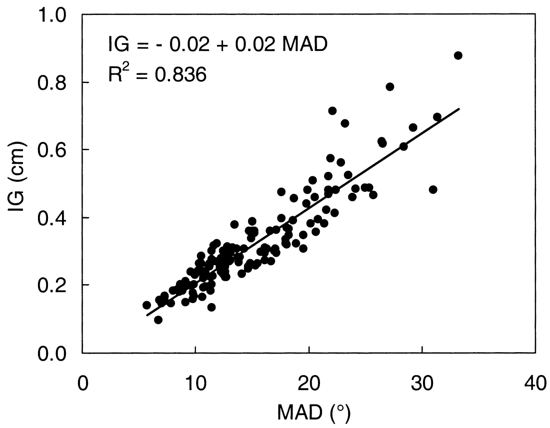


FIG. 3. Relationship between the interlocked grain parameters (MAD and IG) from interlocked grain samples for the three species combined.

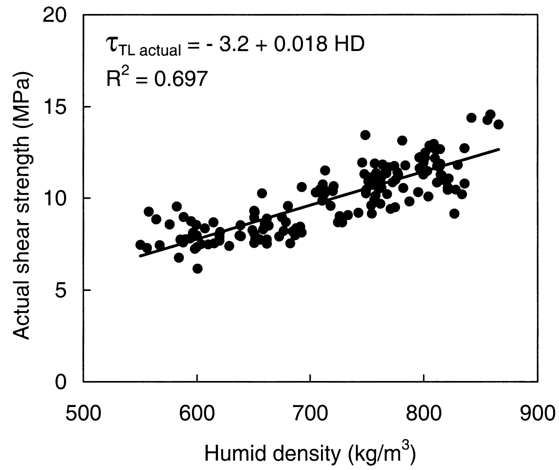


FIG. 4. Relationship between actual shear strength ($\tau_{TL\ actual}$) and humid density (HD) (weight and volume at test) for the three species combined. The relationship with basic density (BD) was similar ($\tau_{TL\ actual} = -4.2 + 0.023$ BD; $R^2 = 0.677$).

0.853). A comparable relationship ($R^2 = 0.70$) between the two interlocked grain parameters was previously reported (Webb 1969). Given that MAD is easier to determine than IG, MAD was selected as the independent variable for multiple regression analyses that follow. Results with IG in place of MAD as an independent variable were similar.

### *Relationships among shear strength, wood density, and interlocked grain*

Simple correlation analyses among all variables for each wood species were separately run (not shown), to detect global trends in the data, identify relationships between variables, and select the independent variables included in the multiple regression analyses. Highly significant correlations between humid density (HD) and EMC as well as between basic density (BD) and EMC were found. As a result, these three variables were not included as independent variables in a same regression.

The multiple regressions were performed using either the actual shear strength (calculated from the measured shear area) or the nominal shear strength (calculated from the fixed shear area of 2500 $mm^2$) as dependent variables. The independent variables chosen were wood density (HD or BD) and MAD measured from the interlocked grain specimen ($MAD_{int}$) or from the shear blocks ($MAD_{shear}$). A total of four models for each dependent variable were evaluated ($MAD_{shear}$ and HD; $MAD_{shear}$ and BD; $MAD_{int}$ and HD; and $MAD_{int}$ and BD).

*Actual shear strength.*—It was not possible to obtain single and multiple regression equations for shear strength with data from the three species taken together. This was due to the statistically different intercept and regression coefficient (slope) values for ishpingo compared to the other species. However, a simple linear regression of pooled values between actual shear strength and humid density highlights the global tendency (Fig. 4). There was an important positive relationship of shear strength with humid density and basic density, with similar correlations between these two wood densities and shear strength. The coefficients of determination ($R^2$) between basic density and actual shear strength for each species were 0.15 for ishpingo, 0.09 for pumaquiro, and 0.65 for tulpay. In all cases, the regression equations were statistically significant at the 0.05 probability level.

The multiple linear regression equations and the beta coefficients of actual shear strength

TABLE 2. *Regression equations of the actual shear strength as a function of wood density and maximum angular deviation (MAD)*[1].

| Wood species | Equations | $R^2$ | COV |
|---|---|---|---|
| Ishpingo | $\tau_{TL\ actual} = 2 + 0.012\ HD - 0.08\ MAD_{shear}$ (0.55) (−0.45) | 0.370 | 9.2 |
| | $\tau_{TL\ actual} = 3 + 0.012\ BD - 0.09\ MAD_{shear}$ (0.53) (−0.46) | 0.341 | 9.4 |
| Pumaquiro | $\tau_{TL\ actual} = -6 + 0.025\ HD - 0.17\ MAD_{shear}$ (0.70) (−0.65) | 0.554 | 7.4 |
| | $\tau_{TL\ actual} = -6 - 0.17\ MAD_{shear} + 0.030\ BD$ (−0.63) (0.58) | 0.415 | 8.5 |
| | $\tau_{TL\ actual} = -5 + 0.022\ HD - 0.09\ MAD_{int}$ (0.60) (−0.43) | 0.356 | 8.9 |
| | $\tau_{TL\ actual} = -5 + 0.025\ BD - 0.09\ MAD_{int}$ (0.49) (−0.42) | 0.236 | 9.7 |
| Tulpay | $\tau_{TL\ actual} = -4 + 0.021\ HD - 0.08\ MAD_{shear}$ (0.81) (−0.23) | 0.704 | 5.9 |
| | $\tau_{TL\ actual} = -4 + 0.024\ BD - 0.07\ MAD_{shear}$ (0.81) (−0.21) | 0.696 | 6.0 |
| | $\tau_{TL\ actual} = -5 + 0.022\ HD - 0.08\ MAD_{int}$ (0.85) (−0.25) | 0.710 | 5.9 |
| | $\tau_{TL\ actual} = -5 + 0.025\ BD - 0.07\ MAD_{int}$ (0.84) (−0.21) | 0.699 | 6.0 |

[1] $\tau_{TL\ actual}$ = actual shear strength (MPa); HD = humid density ($kg/m^3$) (weight and volume at test); BD = basic density ($kg/m^3$); $MAD_{int}$ = maximum angular deviation for interlocked grain samples (°); $MAD_{shear}$ = maximum angular deviation for shear samples (°). $R^2$ = coefficient of determination; COV = coefficient of variation (%).
The terms in parentheses are the beta coefficients of the regression.

for the three woods are given in Table 2. The retained models explained from 24% to 71% of the total variation in actual shear strength. The low coefficients of variation (from 6% to 10%) suggest that these equations may be used for predictive purposes. For all species, the regression equations where HD was a variable gave slightly higher $R^2$ values than those including BD. This may be because HD could partially include the effect of EMC on shear strength of samples.

The results show that the actual shear strength decreased as wood density decreased and interlocked grain increased. However, the relative influence of these variables on shear strength was dependent on the wood species. Previous work indicates that interlocked grain causes similar negative effects on other mechanical properties of wood (Limaye 1954; Weddell 1961).

As a result of the offset effect on the shear failure, the interlocked grain parameters measured directly from the shear blocks produced better correlations than those from the interlocked grain samples (Table 2).

There was a slight but statistically significant relationship between actual shear strength, wood density, and interlocked grain in ishpingo. The retained models explained 34% and 37% of the total variation in actual shear strength. For this wood, equations implicating the interlocked grain parameters measured from the interlocked grain samples were not statistically significant. However, this species showed the highest interlocked grain variation among the species studied (Table 1). At a higher degree, another independent variable could affect the shear strength of this wood. The large proportion of confluent paratracheal parenchyma in ishpingo could play an important role in its shear behavior.

On contrast, there was a better relationship between actual shear strength, wood density, and interlocked grain for pumaquiro compared to ishpingo. The retained regression models explained from 24% to 55% of the total var-

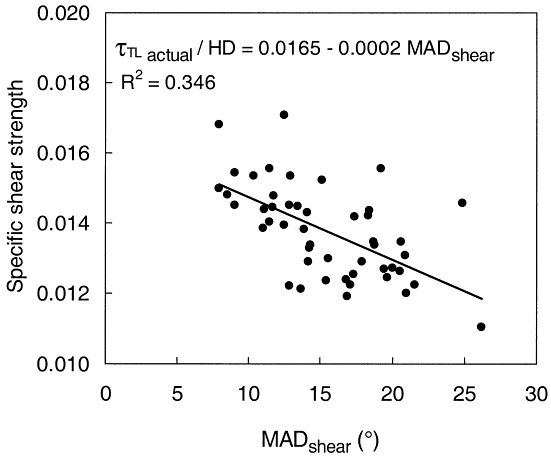


FIG. 5. Relationship between specific actual shear strength and interlocked grain parameter for pumaquiro wood.

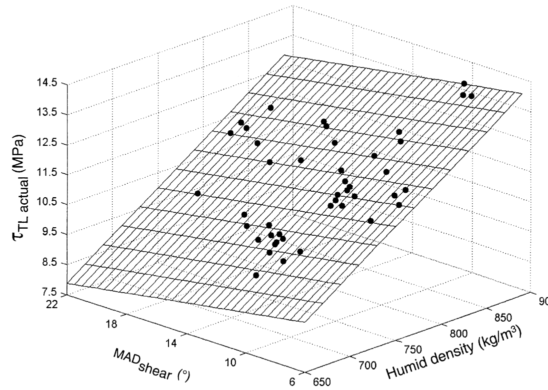


FIG. 6. Response surface of the actual shear strength ($\tau_{TL\ actual}$) as a function of humid density (HD) (weight and volume at test) and interlocked grain ($MAD_{shear}$) for tulpay wood ($\tau_{TL\ actual} = -4 + 0.021$ HD $- 0.08MAD_{shear}$, $R^2 = 0.70$). Dots on surface represent x-y location of test data on surface.

iation in actual shear strength. The effects of wood density and interlocked grain on shear strength were similar, and the beta coefficients of these variables accounted for about 53% and 47% of the actual shear strength variation explained by the regression equations (all regressions pooled). Thus, the actual shear strength of pumaquiro increased as wood density increased and as interlocked grain decreased. The pumaquiro regression coefficients corresponding to MAD in the equations were the highest among the three species studied. This means that shear strength in pumaquiro was the most sensitive to changes in interlocked grain. This behavior could be explained by the homogeneous anatomical structure of this species compared to the others. The effect of the interlocked grain is also evident in specific shear strength, which is the ratio of the actual shear strength to humid density. The relationship between the specific actual shear strength and $MAD_{shear}$ for pumaquiro is given in Fig. 5.

Tulpay showed the highest $R^2$ among the three species studied (Table 2). The retained regression equations explained from 70% to 71% of the total variation in actual shear strength. The low coefficients of variation (6%) also indicate that these equations can be used for prediction. In contrast with pumaquiro, wood density was the most significant variable affecting the actual shear strength of tulpay. The beta coefficients showed that density variation accounted for more than 80% of the variation explained by the multiple regressions (all regressions pooled). The influence of the interlocked grain on shear strength of tulpay was lower than for the other two species. The large proportions of confluent paratracheal parenchyma and ray tissues in tulpay could play an important role on the development of fracture during shearing. The effect of wood density and interlocked grain are illustrated in Fig. 6, which shows the response surface obtained by one of the multiple linear regressions in Table 2. In this case, the positive effect of wood density and the negative effect of the interlocked grain on actual shear strength are shown.

*Nominal shear strength.*—Linear regression analysis between the nominal shear strength and humid density was performed with pooled data of the three species (Fig. 7). The nominal shear strength varied positively with wood density. The determination coefficients ($R^2$) were 0.58 for humid density and 0.57 for basic density. These coefficients were lower than those between wood density and actual shear

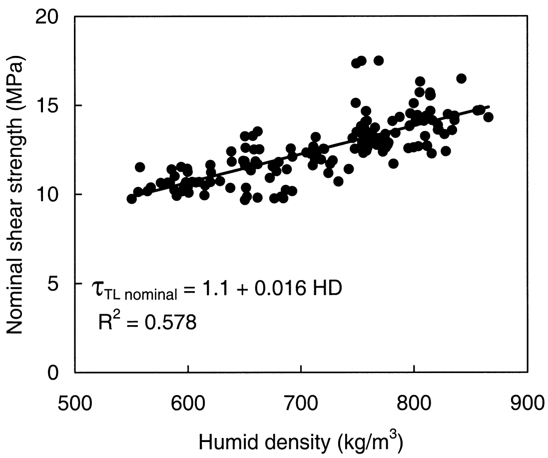


FIG. 7. Relationship between nominal shear strength ($\tau_{TL\ nominal}$) and humid density (HD) (weight and volume at test) for the three species combined. The relationship with basic density (BD) was similar ($\tau_{TL\ nominal}$ = 0.2 + 0.020 BD; $R^2$ = 0.568).

strength. However, for all cases, the regression models were statistically significant at the 0.01 probability level. The coefficients of determination for each species were 0.16 for ishpingo, 0.27 for pumaquiro, and 0.21 for tulpay. These low $R^2$ values highlight the problem when shear strength is evaluated using a fixed shear area. Previous workers have reported a positive effect of wood density on the nominal shear strength parallel to grain, with $R^2$ of 0.51 for Queensland maple (Kloot 1948) and 0.46 for Douglas-fir (Riyanto and Gupta 1996).

The multiple linear regressions and the beta coefficients for nominal shear strength are given in Table 3. The retained models explained from 25% to 58% of the total variation in the nominal shear strength. For all three species, the values for the coefficients of determination ($R^2$) were lower for regressions using nominal shear strength compared to those incorporating actual shear strength. This confirmed that correction of the sheared area for calculation of shear strength in interlocked grain woods was

TABLE 3. *Regression equations of the nominal shear strength as a function of wood density and maximum angular deviation (MAD)*[1].

| Wood species | Equations | $R^2$ | COV |
|---|---|---|---|
| Ishpingo | $\tau_{TL\ nominal} = 7 + \underset{(0.34)}{0.05\ MAD_{int}} + \underset{(0.24)}{0.006\ HD}$ | 0.253 | 8.1 |
| | $\tau_{TL\ nominal} = 7 + \underset{(0.34)}{0.06\ MAD_{int}} + \underset{(0.23)}{0.006\ BD}$ | 0.249 | 8.2 |
| Pumaquiro | $\tau_{TL\ nominal} = -2 + \underset{(0.64)}{0.021\ HD} - \underset{(-0.29)}{0.07\ MAD_{shear}}$ | 0.351 | 6.5 |
| | $\tau_{TL\ nominal} = -6 + \underset{(0.67)}{0.032\ BD} - \underset{(-0.34)}{0.08\ MAD_{shear}}$ | 0.363 | 6.4 |
| | $\tau_{TL\ nominal} = -2 + \underset{(0.62)}{0.021\ HD} - \underset{(-0.27)}{0.05\ MAD_{int}}$ | 0.339 | 6.6 |
| | $\tau_{TL\ nominal} = -6 + \underset{(0.67)}{0.031\ BD} - \underset{(-0.33)}{0.07\ MAD_{int}}$ | 0.358 | 6.5 |
| Tulpay | $\tau_{TL\ nominal} = -1 + \underset{(0.58)}{0.27\ MAD_{shear}} + \underset{(0.45)}{0.015\ HD}$ | 0.554 | 8.1 |
| | $\tau_{TL\ nominal} = -2 + \underset{(0.60)}{0.27\ MAD_{shear}} + \underset{(0.47)}{0.019\ BD}$ | 0.578 | 7.9 |
| | $\tau_{TL\ nominal} = 1 + \underset{(0.40)}{0.014\ HD} + \underset{(0.35)}{0.15\ MAD_{int}}$ | 0.335 | 9.9 |
| | $\tau_{TL\ nominal} = 0.6 + \underset{(0.42)}{0.017\ BD} + \underset{(0.36)}{0.16\ MAD_{int}}$ | 0.353 | 9.8 |

[1] $\tau_{TL\ nominal}$ = nominal shear strength (MPa); HD = humid density (kg/m$^3$) (weight and volume at test); BD = basic density (kg/m$^3$); $MAD_{int}$ = maximum angular deviation for interlocked grain samples (°); $MAD_{shear}$ = maximum angular deviation for shear samples (°). $R^2$ = coefficient of determination; COV = coefficient of variation (%).

The terms in parentheses are the beta coefficients of the equations.

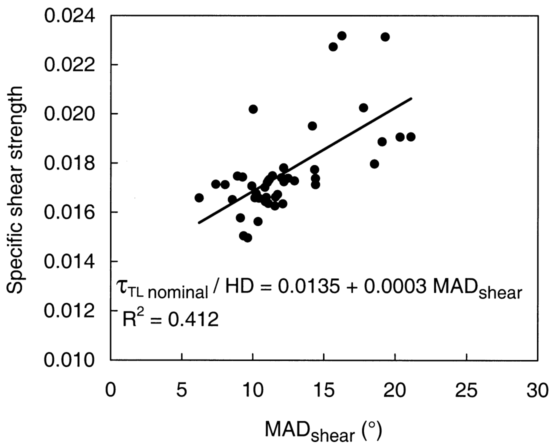


FIG. 8. Relationship between specific nominal shear strength and interlocked grain parameter for tulpay wood.

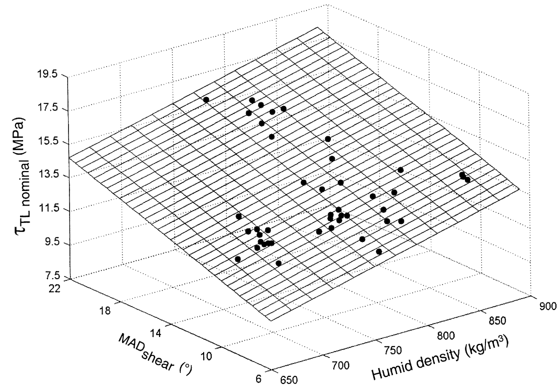


FIG. 9. Response surface of the nominal shear strength ($\tau_{TL\ nominal}$) as a function of humid density (HD) (weight and volume at test) and interlocked grain (MAD$_{shear}$) for tulpay wood ($\tau_{TL\ nominal}$ = −1 + 0.27 MAD$_{shear}$ + 0.015HD, $R^2$ = 0.55). Dots on surface represent x-y location of test data on surface.

appropriate. The influence of the wood density and the interlocked grain on nominal shear strength depended on the wood species similar to results of actual shear strength.

The relationships between nominal shear strength and interlocked grain parameters were positive for ishpingo and tulpay. This occurred because an increase in the interlocked grain produced an increase in the shear area. When using the nominal value of the shear area, the effect of the interlocked grain on shear strength was masked. Similar to actual shear strength, ishpingo had the lowest relationship between nominal shear strength, wood density, and interlocked grain. While the models were statistically significant, they explained only 25% of the total variation in nominal shear strength.

The relationship between specific nominal shear strength and interlocked grain for tulpay is shown in Fig. 8. The specific nominal shear strength is the ratio between the nominal shear strength and the humid density. There was a positive influence due to interlocked grain when the fixed shear area was used to calculate shear strength. Among the woods studied, tulpay had the best fit using multiple regressions (Table 3). The retained models explained from 33% to 58% of the total variation in nominal shear strength. The response surface for tulpay for one of the multiple linear regressions is given in Fig. 9, which shows the positive effect of the wood density and interlocked grain on nominal shear strength.

For pumaquiro, the negative effect of interlocked grain on the nominal shear strength was evident even when nominal sheared area was used (Table 3). The change of sign from negative (Table 2) to positive (Table 3) did not occur given the higher shear sensitivity of this species to changes in interlocked grain. Thus, when using the nominal shear area, the effect of the interlocked grain on shear was only partially masked. The effects of the interlocked grain and wood density on the nominal shear strength were significant, and the retained models explained from 34% to 36% of the total variation in nominal shear strength. Compared to actual shear strength, the influence of interlocked grain in the regressions was reduced to about 35% and that associated with wood density accounted for about 65% of the variation explained by the regressions (all regressions pooled).

## *General discussion*

The bending and shear strengths of wood must be considered in the design of timber beams. Shear strength is sometimes more important in a design than bending strength (Bodig and Jayne 1982; Soltis and Rammer 1997). Shear strength for nonsplit, nonchecked, solid-sawn beams decreases as beam size increases. An empirical formula to estimate beam shear strength from ASTM shear blocks strength can be applied (U.S. Forest Products Laboratory 1999). This formula defines the shear area as beam width multiplied by the length of beam subjected to shear force. In beams with interlocked grain, the effective shear area is unknown and the nominal area is used. The results of this study show that the effect of interlocked grain on the nominal shear strength will depend on the wood species; for ishpingo and tulpay this was positive and for pumaquiro negative.

Although we found that the presence of offset caused little problem in determining the interlocked grain parameters in shear blocks, offset can prevent free development of failure that causes a combination of shear and compression stresses (Fig. 2A). Bodig and Jayne (1982) found that if the offset is not sufficient to produce free development of the fracture, the state of stress causing block failure is not pure shear but a complex combination of shear and normal stresses. This problem will be more severe for interlocked grain woods because of their mode of failure.

The standard ASTM shear test has been criticized for not providing pure shear load on samples. For this reason, a number of researchers have proposed alternative testing methods to estimate the shear strength (Liu 1984; Lang 1997; Liu et al. 1999; Yoshihara et al. 1999; Lang et al. 2000). However, none of the proposed methods considers the interlocked grain pattern. A measure of pure shear strength in interlocked grain woods will be difficult to obtain, since the shear surface in these species is irregular and follows grain orientation. Other researchers who found irregularities in the failure mode concluded that the shear strength depends on the initiation of failure and not on the direction of fracture propagation (Liu and Floeter 1984; Lang et al. 2000). Consequently, their results were reported as apparent shear strength, and all measured values were reported, even when the specimen failed in a plane that was outside of that theoretically expected. The Arcan test (Arcan et al. 1978) may be adapted to determine the shear strength in interlocked grain woods, because fracture development is not prevented using this method. The Arcan test can induce a pure shear state in the critical section of a butterfly-shaped specimen. However, if simultaneous determination of shear strength and interlocked grain is required, the thickness of the sample should be increased to cover the entire cycle of interlocked grain patterns.

In summary, the ASTM shear test needs to be improved if it is to be useful for determining the shear strength in wood samples containing interlocked grain. Further investigation is needed to account for the influence of interlocked grain patterns on shear and other mechanical wood properties.

## CONCLUSIONS

The effects of wood density and interlocked grain on shear strength parallel to grain were investigated in three tropical hardwoods. The maximum angular deviation (MAD) and the interlocked grain index (IG) were evaluated. The failure observed in shear tests (shear area) was irregular and in general followed the interlocked pattern. Two apparent shear strengths were calculated, one using the measured shear area (actual shear strength) and another using a fixed shear area of 2500 mm$^2$ (nominal shear strength). The main conclusions of this work may be summarized as follows:

1. Strong relationships were found between the interlocked grain parameters (MAD and IG) for the three species studied. The MAD was easier to evaluate than IG.
2. There was high within-species variation in interlocked grain parameters (COV about 40%).
3. Wood density positively affected the apparent shear strength. The relationships

were stronger for actual shear strength compared to nominal shear strength.

4. The actual shear strength was negatively affected by the interlocked grain for the three species. In contrast, the relationships were different when the nominal shear strength was considered. For ishpingo and tulpay, the nominal shear strength varied positively with interlocked grain parameters. For pumaquiro, the effect of interlocked grain was negative.
5. The ASTM block shear standard is not suitable for measuring shear strength in heavily interlocked grain woods, given that it does not allow the free development of failure.

## ACKNOWLEDGMENTS

The authors gratefully acknowledge the Natural Sciences and Engineering Research Council of Canada and the International Tropical Timber Organization (ITTO) for financial support. Special acknowledgment is also addressed to Professors Alain Cloutier and Yves Fortin for useful suggestions and help.

## REFERENCES

American Society for Testing and Materials (ASTM). 1997a. ASTM D 143. Standard method of testing for shearing parallel to grain. Philadelphia, PA.

———. 1997b. ASTM D 2395. Standard test methods for specific gravity of wood and wood-base materials. Philadelphia, PA.

———. 1997c. ASTM D 4442. Standard test methods for direct moisture content measurement of wood and wood-base materials. Philadelphia, PA.

Arcan, M., Z. Hashin, and A. Voloshin. 1978. A method to produce uniform plane-stress states with applications to fiber-reinforced materials. Exp. Mech. 18(4):141–146.

Aróstegui, A. 1982. Recopilación y análisis de estudios tecnológicos de maderas peruanas. Proyecto PNUD/FAO/PER/81/002. Doc. de trabajo N° 2. Lima, Perú. 52 pp.

Bodig, J., and B. Jayne. 1982. Mechanics of wood and wood composites. Van Nostrand Reinhold, New York, NY. 712 pp.

Chudnoff, M. 1984. Tropical timbers of the world. USDA, Forest Service. 466 pp.

Debaise, G. R., A. W. Porter, and R. E. Pentoney. 1966. Morphology and mechanics of wood fracture. Mat. Res. Stand. 6(10):493–499.

Détienne, P. 1979. Contrefil à rythme annuel dans les faro, *Daniellia sp.pl.* Bois et forêts des tropiques 183: 67–71.

Instituto Brasileiro de Desenvolvimento Florestal (IBDF). 1988. Madeiras da Amazônia, características e utilização. Estação experimental de Curuá-Una. V.2, Brasília, Brazil. 236 pp.

Keenan, F. J., and M. Tejada. 1984. Tropical timber for building materials in the Andean Group countries of South America. IDRC-TS49e, Ottawa. 151 pp.

Kloot, N. H. 1948. Mechanical tests on small clear specimens of Queensland maple. Australian Division Forest Products, Reprint N° 107. J. Council Scient. Ind. Res. 21(4):279–297.

Kribs, D. A. 1950. Commercial foreign woods on the American market, a manual to their structure, identification, uses and distribution. Tropical Wood Laboratory, State College, PA. 241 pp.

Lang, E. M. 1997. An alternative method for shear strength assessment. Forest Prod. J. 47(11/12):81–84.

———, L. Bejo, J. Szalai, and Z. Kovacs. 2000. Orthotropic strength and elasticity of hardwoods in relation to composite manufacture. Part I. Orthotropy of shear strength. Wood Fiber Sci. 32(4):502–519.

Limaye, V. D. 1954. Interlocking of grain in Indian timbers. Indian Forester 80(1):6–9.

Liu, J. Y. 1984. New shear strength test for solid wood. Wood Fiber Sci. 16(4):567–574.

———, and L. H. Floeter. 1984. Shear strength in principal plane of wood. J. Eng. Mech. 110(6):930–936.

———, D. D. Flach, R. J. Ross, and G. J. Lichtenberg. 1999. An improved shear test fixture using the Iosipescu specimen. Mechanics of Cellulosic Materials. ASME. AMD-Vol. 231/MD-Vol. 85:139–147.

Marsoem, N., and Y. Kikata. 1987. The effect of interlocked grain on the mechanical properties of *white meranti.* Bull. Nagoya Univ. For. N° 9:51–77.

Martley, J. F. 1920. Double cross-grain. Ann. Apl. Bio. 7:224–268.

Northcott, P. L. 1957. Is spiral grain the normal growth pattern? Forestry Chronicle 33:335–352.

Rijsdijk, J. F., and P. B. Laming. 1994. Physical and related properties of 145 timbers: Information for practice. Kluwer Academic Publishers, London, UK. 380 pp.

Riyanto, D. S., and R. Gupta. 1996. Effect of ring angle on shear strength parallel to the grain of wood. Forest Prod. J. 46(7/8):87–92.

Rudinsky, J. A., and J. P. Vité. 1959. Certain ecological and phylogenetic aspects of the pattern of water conduction in conifers. Forest Sci. (5):259–266.

SAS Institute. 1988. SAS/Stat Users Guide, Release 6.03 Ed. SAS Institute, Inc., Cary, NC.

Soltis, L. A., and D. R. Rammer. 1997. Bending to shear ratio approach for beam design. Forest Prod. J. 47(1): 104–108.

U.S. Forest Products Laboratory. 1999. Wood Handbook: Wood as an engineering material. General Technical Report FPL-GTR-113. USDA, Forest Serv., Forest Prod. Lab., Madison, WI.

WEBB, C. D. 1967. Interlocked grain in *Liquidambar styraciflua* L. XIV IUFRO Congr. München, Vol. XIV, IX, section 41+WG 22/41:398–412.

———. 1969. Variation of interlocked grain in Sweetgum. Forest Prod. J. 19(8):45–48.

WEDDELL, E. 1961. Influence of interlocked grain on the bending strength of timber, with particular reference to utile and greenheart. J. Inst. Wood Sci. 7:56–72.

YOSHIHARA, H., O. HISASHI, Y. KUBOJIMA, AND M. OHTA. 1999. Applicability of the Iosipescu shear test on the measurement of the shear properties of wood. J. Wood Sci. 45:24–29.