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BRIEF ORIGINAL

Shear strength parallel to grain with distinct ray orientation on four Brazilian wood species

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Abstract Ray orientation (perpendicular, parallel and diagonal) was compared with respect to shear strength parallel to grain and specific gravity in four Brazilian wood species. Higher absolute strengths occurred with ray oriented perpendicular to the shear plane, and lower ones for parallel orientation for almost all species. In particular, specimens with parallel ray orientation to shear plane did not differ statistically from shear values when compared to specimens having perpendicular and diagonal orientation to shear plane.

1 Introduction

Ray cells in the wood of Angiosperms are oriented perpendicularly with respect to the main stem axis; other cells, including fibers, vessel elements, and the axial parenchyma cells, are aligned to the stem axis. The biomechanical role of rays has been emphasized by Burgert et al. (1999) and Reiterer et al. (2002). When the stem is bent, for example, by wind action, rays prevent slippage of the growth rings onto each other, like the book pages when folded. Thus, rays prevent shear-caused sliding of the growth rings by blocking them and acting as a "bolt". In this context, it is clear that rays play a fundamental role in standing trees due to their influence. Therefore, in this study, the effect of ray orientation on shear parallel to the grain was evaluated. The effect of ray orientation on shear parallel to the grain was compared among four Brazilian native species.

2 Materials and methods

The studied species were *Balfourodendron riedelianum*, *Dipteryx alata*, *Myracrodruon urundeuva* and *Peltophorum dubium*, which were planted about 30 years ago in Pederneiras State Forest in the municipality of Pederneiras, São Paulo, Brazil (22°27′S, 48°44′W, elevation 500 m). The plantations were established at a spacing of 3 × 2 m and 3 × 3 m. Five trees of each species were harvested, and from each tree, three disks were sampled at base, 1.30 m from the ground (DBH—diameter at breast height) and 2 m from the ground. Specimens were taken with wood fiber parallel to the shear plane (inspected visually) and rays oriented perpendicularly (PE), parallel (PA) and diagonal (DI) to the shear plane, totaling 498 specimens. Specific gravity was determined according to Glass and Zelinka (2010) and shear strength parallel to the grain according to NBR 7190 (ABNT 1997), see Fig. 1. Anatomical analysis of rays was performed after mechanical tests with six specimens per species exhibiting rays perpendicular to the growth rings (PE) and sorted considering three levels of shear strength: low, medium and high (2 specimens per level). Specimens were prepared and softened in boiling water and glycerin (4:1), and longitudinal tangential sections 15–20-µm-thick were prepared on a sliding microtome. The sections were bleached with sodium hypochlorite (60%), washed in water, and stained with safranin 1%. Regarding statistical analysis, a parametric analysis of variance (one-way analysis of variance) was performed. When a significant difference was observed, the Tukey's test was used to identify pairs of significantly different means.

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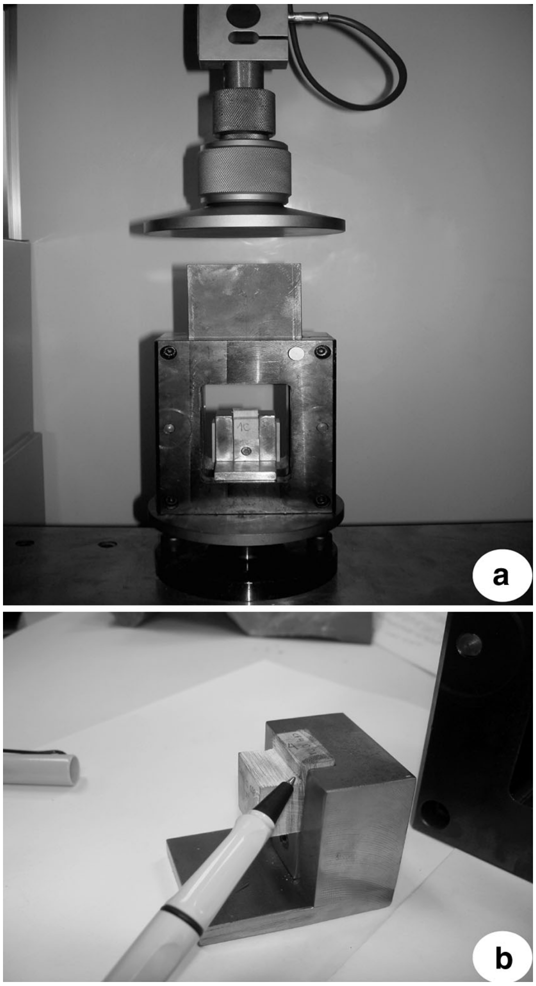

Fig. 1 **a** General view of the shear test setup; **b** details of the specimens in the test apparatus

3 Results and discussion

Dipteryx alata wood exhibits greater specific gravity (1002 kg m^{-3}) when compared to that of the other three species. *B. riedelianum* (868) and *M. urundeuva* (872) did not differ statistically, and lower specific gravity was noted in *P. dubium* (622) by Tukey's test ($P < 0.05$).

Considering the mean of the three sampling heights, shear strength parallel to the grain varied among species according to orientation. More specifically, in *B. riedelianum* and *P. dubium*, higher values occurred in specimens with perpendicular and diagonal ray orientation as a function of shear plane, although specimens having diagonal orientation did not differ in shear strength from specimens having parallel orientation. Higher values also occurred in specimens of *M. urundeuva* having perpendicular and parallel orientations, but without any differences in this species between parallel and diagonal orientations (Table 1).

Shear strength parallel to the grain was also evaluated based on both orientation and sampling height. For perpendicular orientation, *B. riedelianum* and *M. urundeuva* showed higher shear strength values; however, *M. urundeuva* did not differ from *D. alata*, which, in turn, did not differ from *P. dubium*. In parallel orientation, *P. dubium* showed lower shear strength, while *B. riedelianum*, *D. alata* and *M. urundeuva* values were higher and did not differ significantly. In diagonal orientation, higher shear strength values occurred in *B. riedelianum* and *D. alata*, while shear strength values were lower in *M. urundeuva* and *P. dubium* (Table 1).

Burgert et al. (1999) investigated the importance of rays for strength of living trees and observed that rays are mechanically functional. Bader et al. (2015) studied shear stiffness and its relationship to the microstructure of 10 European and tropical hardwood species and found that rays provide reinforcement in the radial-tangential plane. These studies and others cited previously, Burgert et al. (1999) and Reiterer et al. (2002) emphasize the biomechanical role of rays. However, based on the present data, the influence of ray orientation on shear strength was not statistically confirmed, even using small and defect free specimens with straight grain (oriented parallel to the shear plane). It was found that the specimens with parallel ray orientation to shear plane did not differ statistically with respect to shear values when compared to specimens having perpendicular and diagonal orientation to shear plane (Table 1). It is expected that for structural size members (lumber) this association would be hardly found.

When analyzing the dimensions and frequency of the rays with respect to shear strength, no consistent pattern was seen. Higher rays occurred when the shear strength was medium and high in *B. riedelianum, D. alata* and *M. urundeuva*. Wider rays were associated with low strength in *D. alata*, but the same result was not observed for the other species. For example, in *M. urundeuva*, wider rays occurred at both low and high strength, whereas for the two other species, the values did not differ. High frequency of rays was associated with low and medium strength in *B. riedelianum* and *P. dubium*, while in *D. alata*, high frequency of rays was associated with high and medium strength, and in *M. urundeuva*, no variation was seen (Table 1). Based on the longitudinal tangential sections of the four species, no differences are evident between shear strength and either ray dimensions or frequency. Only the storied structure in *D. alata* is noted, a feature that does not occur in the other three species.

De Borst et al. (2011) described how ray cells affect wood macroscopic stiffness by their content, arrangement and shape. While the authors agree with this, other cells, especially fibers, likely play a more effective role in shear strength because fibers with thicker walls may provide

Table 1 Shear parallel to the grain and ray features in four Brazilian wood species

Part 1	*B. riedelianum*				*D. alata*				*M. urundeuva*				*P. dubium*			
	Base	DBH	2 m	Mean	Base	0.5 m	DBH	Mean	Base	DBH	2 m	Mean	Base	DBH	2 m	Mean
PE	27.4	23.1	23.6	24.9Aa	19.3	18.9	22.7	20.3BCa	23.0	19.7	20.5	22.1ABa	18.4	16.1	13.0	16.4Ca
PA	21.6	19.5	19.6	20.7Ab	19.3	18.0	21.9	20.0Aa	19.1	20.0	15.9	18.8Aab	14.3	13.7	11.7	13.6Bb
DI	22.9	21.6	21.8	22.2Aab	22.5	21.8	20.3	21.6Aa	17.4	18.5	16.7	17.6Bb	14.6	13.7	15.8	15.5Bab

Part 2	*B. riedelianum*			*D. alata*			*M. urundeuva*			*P. dubium*		
SS	RH	RW	RF	RH	RW	RF	RH	RW	RF	RH	RW	RF
H	238a	25a	7.1b	201ab	13b	12.0a	232ab	25a	8.7a	216a	20a	8.2b
M	228ab	24a	7.4ab	205a	11b	12.3a	248a	19b	8.7a	219a	18a	9.2a
L	216b	26a	7.9a	192b	16a	10.2b	223b	23a	8.9a	209a	18a	10.0a

First part—Shear parallel to the grain (MPa), regarding ray orientation as a function of shear plane: *PE* perpendicular, *PA* parallel and *DI* diagonal. Distinct letters in line (comparison among species, uppercase letters) and column (comparison among ray orientation in same species, lowercase letters) differ statistically ($P < 0.05$) by Tukey's test. Second part—Height, width (mm) and frequency (n° mm^{-1}) of rays categorized according to three levels of strength to shear parallel to the grain (MPa) (high, medium, andlow). *SS* Shear strength. *H* High (29.55-39.24 MPa), *M* Medium (16.84-25.44 MPa), *L* Low (7.35-11.80 MPa). *RH* Ray height, *RW* Ray width and *RF* Ray frequency. Distinct letters in column differ statistically ($P < 0.05$) by Tukey's test

higher resistance. It is also possible that the contact distance between fibers in the longitudinal direction and extent of adhesion area between fibers could influence mechanical requirements. Therefore, although such analyses are complex, the development of a protocol to measure the extent of adhesion area between fibers could clarify some doubts about wood quality and its uses.

4 Conclusion

Dipteryx alata wood has greater specific gravity when compared to that of the other three species. For the four species, although the higher absolute shear strength occurred with rays oriented perpendicular, statistically these results did not differ from those obtained in distinct orientations, for example, diagonal, and the results were inconclusive in relating higher strength to a specific ray orientation to the shear plane. Despite higher rays occurring in specimens with high and medium levels of shear strength, other ray dimensions and its frequency did not show any evidence pattern when related to shear strength.

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