FLEXURAL PROPERTIES OF WOOD I-BEAMS FLANGED WITH TROPICAL HARDWOODS

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CAMPOS MBS, DEL MENEZZI CHS & DE SOUZA MR. 2012. Flexural properties of wood I-beams flanged with tropical hardwoods. The paper is aimed at evaluating the flexural properties of wood I-beams flanged with two tropical hardwoods: castanha-de-macaco (*Cariniana micrantha*) and marupá (*Simarouba amara*). The flanges were nondestructively tested and used to assemble 16 MDF-webbed wood I-beams. Two adhesive types were used for bonding flange to web, namely, resorcinol-formaldehyde and castor-oil based polyurethane. Results showed that flexural properties of I-beams were highly affected by the flange stiffness and transversal vibration method showed models with the highest coefficient of determination. Castanha-de-macaco flanged I-beam presented flexural properties higher than marupá flanged I-beam. On the other hand, adhesive type affected only modulus of elasticity and resorcinol-formaldehyde yielded stiffer I-beam. All tested I-beams showed suitable flexural properties in comparison with data found in the literature. Although this was a preliminary study, the potential of tropical hardwoods as I-beam flange materials had been demonstrated and the research effort should be continued.

Keywords: Engineered wood products, nondestructive evaluation, tropical hardwood, flexural properties

CAMPOS MBS, DEL MENEZZI CHS & DE SOUZA MR. 2012. Ciri-ciri lentur rasuk-I kayu berbebibir kayu keras tropika. Kertas kerja ini menilai ciri lentur rasuk-I kayu berbebibir dua kayu keras tropika iaitu castanha-de-macaco (*Cariniana micrantha*) dan marupá (*Simarouba amara*). Bebibir diuji menggunakan teknik tak jahanam dan diguna untuk memasang 16 rasuk-I kayu web MDF. Dua jenis perekat digunakan untuk mencantumkan bebibir kepada web iaitu formaldehid resorsinol dan poliuretana berasaskan minyak jarak. Keputusan menunjukkan bahawa ciri-ciri lentur rasuk-I sangat dipengaruhi oleh kekakuan bebibir. Kaedah getaran lintang menunjukkan model yang mempunyai pekali penetuan paling tinggi. Rasuk yang berbebibir castanha-de-macaco menunjukkan ciri lentur yang lebih tinggi berbanding rasuk berbebibir marupá. Sebaliknya, jenis perekat hanya mempengaruhi modulus kekenyalan. Formaldehid resorsinol pula menghasilkan rasuk-I yang lebih keras. Semua rasuk-I yang diuji menunjukkan ciri lentur yang sesuai berbanding data yang telah diterbitkan sebelum ini. Walaupun ini merupakan kajian awal, potensi kayu keras tropika sebagai bahan bebibir rasuk-I telah terbukti dan penyelidikan lanjut harus dilaksanakan.

INTRODUCTION

The engineering concept of I-beams comprises two parts: the web and the flange. The web is the part responsible for resisting shear stresses and can be made from plywood, oriented strand board or fibreboard. Additionally, the web is very important because it is responsible for improving the moment of inertia of I-beam. The flanges, which are bonded to the web using water resistant and durable adhesives, are located on the top and bottom positions of the I-beam. The flanges are responsible for resisting the compression (top) and tension (bottom) stresses. During the utilisation of I-beam, the greatest stress levels are concentrated in these positions. Solid wood or structural composite lumber (SCL)—which have enough strength and stiffness to resist these high stress levels—are usually employed for these positions. Within SCL group, laminated veneer lumber (LVL) is most usually employed as I-beam flange, probably because it presents the highest production (1.1 mil m^3 which is 85% of USA and Canada's production) and suitable properties. According to UNECE (2010), 31.8% of the 2010 forecast LVL production would be used for

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assembling I-beams, with production reaching 169.2 million linear metres.

In the Brazilian Amazon region, during wood processing of tropical hardwood, a great amount of residue is produced. These residues (almost 60% of log volume) present a variety of geometry, from slivers up to larger pieces such as boards, studs and slabs. Most of these residues are composed of sound wood but they have been handled as non-valuable resource and, thus, burnt. It is very important to develop and propose technologies in order to add value to this material so that these residues can be utilised to assemble engineered wood product (EWP). However, properties of these materials should be accurately assessed prior to their utilisation. For instance, the utilisation of nondestructive methods for evaluating material stiffness has been widely used (e.g. Yang et al. 2008, Teles et al. 2010).

The Brazilian production of tropical sawnwood was 15.5 mil m^3 in 2009 with 14.5 mil m^3 destined for domestic consumption. This means that Brazil is the largest ITTO tropical sawnwood consumer (ITTO 2009). Although this huge production and consumption were mainly from the construction industry, utilisation of wood as main structural material for housing construction was not usual. The most important enduses of structural solid wood in housing are as trusses, roof frame and flooring. Large cross-section solid wood is still widely available on the market and it is preferred by final consumers, although the prices have been rising in the last five years. Therefore, the utilisation of EWP for housing virtually does not exist and Brazil does not have I-beam or LVL manufacturing plants. However, research at laboratory level regarding I-beam has been done, as can be seen in works e.g. by Pedrosa et al. (2005), Silva et al. (2008) and Santos et al. (2009). Most of these research efforts focused on utilisation of plantation tree species, mainly eucalypt and pinus, and only recently tropical hardwood species have been studied, as done by Abreu et al. (2010). At the international level, very little information about utilisation of tropical wood species for I-beams is available (Chu et al. 1993, Jamaludin et al. 2005).

In this context, the present paper aims at studying preliminarily the flexural properties of wood I-beams flanged with two well-known Amazonian tropical hardwoods. Specifically, the effect of nondestructive testing of flanges, comparison between species and the effect of adhesive type on these properties were investigated.

MATERIALS AND METHODS

Lumber species and wood-based material

Lumber from castanha-de-macaco (*Cariniana micrantha*) and marupá (*Simarouba amara*) was collected at trading companies and macroscopically identified by comparing with standard samples deposited at the Forest Products Laboratory Wood Anatomy Section (*Index Xilarium* FPBw), Brazilian Forest Service. The lumber was air dried for 60 days and subsequently stored in air-conditioned room (20 °C, 65% RH) for final moisture equalising. Flanges measuring 40 mm × 40 mm × 2750 mm (w × t × l) were cut from the lumber and then visually graded. Flanges with drying defects (bowing, twisting, crooking, etc.) or any evidence of biological deterioration (blue-stain, insect holes, etc.) were discarded. Finally, 36 flanges (10 from castanha-de-macaco and 26 from marupá) were selected to assemble the I-beams.

Following visual grading, selected flanges were nondestructively tested using three techniques, namely, stress wave, transverse vibration and static bending. Stress wave dynamic modulus of elasticity (E_{dsw}) and dynamic transverse modulus of elasticity (E_{dtv}) were assessed using commercial equipment (Teles et al. 2011). Static bending nondestructive testing (E_{sb}) was conducted by measuring the mid-span (1325 mm) flange deflection under 50 N weight.

Six boards of commercial medium density fibreboard (MDF) measuring 1500 mm × 9.5 mm × 2750 mm (w × t × l) were acquired and used as web material. They were ripped lengthwise to produce 150 mm-depth web material. According to the manufacturer, the MDF was made from *Pinus* sp. fibre, bonded with urea formaldehyde resin and had a density around 600 kg m^{-3}. Moisture contents of MDF was about 9.8% and wood, 11.9%.

Assembling I-beams

Initially, the flanges were machined to produce 15-mm depth routed grooves. Flange and square-edged MDF web were bonded using two kinds of adhesives applied at spread rate of 350 g m^{-2}: resorcinol–formaldehyde (RF, 61.5% of solid content, 2500 cP) and castor-oil based polyurethane adhesive (PUR, 100% of solid content, 2000 cP). These adhesives were chosen since they were commercially available to be employed in structural purposes. The RF adhesive was prepared by mixing five parts in weight of resorcinol and one part in weight of formaldehyde (5:1), whereas for PUR adhesive equal parts of polyol and prepolimer (1:1) were mixed. The mixed adhesive was directly applied into flange groove using a brush and then the web was spliced and the set was locked up for 24 hours.

Sixteen I-beams measuring 200 mm × 2750 mm were divided according to three groups: castanha-de-macaco flanged I-beam bonded with RF adhesive, and marupá flanged I-beam, bonded using RF and PUR adhesives separately. For the first group, four I-beams were assembled whereas for the other two groups, six I-beams each. The geometry of the beams is presented in Figure 1. After assembling, the I-beams were kept in air-conditioned room (20 ºC, 65% RH) for 15 days.

I-beam bending testing

I-beams were tested in bending according to ASTM D198 (1999) using four-point schedule. The distance between load points (pure bending span) was 650 mm and between load and reaction points (shear span) was 1000 mm. Six lateral supports were positioned every 400 mm to reduce lateral instability of beam during loading. Load was applied using a Pavitest C-4070 hydraulic machine which was regulated for a speed of testing at 6.6 mm min^{-1}. Rupture of the I-beam happened within approximately 10 min, as required by the standard. Deflection of the beam neutral axis was measured between end reaction points (2650 mm) using a 50-mm linear variable differential transformer (LVDT) displacement. Load and deflection data were acquired through ADS0500 IP integrated system connected to AqDados 7.02 software. Figure 2 shows the testing schedule employed and load/deflection curves during testing.

The relation between shear span (1000 mm) and beam depth (200 mm) was 5:1. According to ASTM D198 (1999), this dimension is suitable to measure primarily the flexural properties of wood beams. Web shear modulus (G) was not computed in the calculation of the beam stiffness. Therefore, the apparent modulus of elasticity (E_M) and the modulus of rupture (f_M) were calculated according to equations 1, 2, 3 respectively. The rupture mode was analysed according to ASTM D5055 (2005).

$$E_M = \frac{P'a\,(3L^2 - 4a^2)}{48\,I\Delta'} \quad (1)$$

$$f_M = \frac{M_{max}\,y}{I} \quad (2)$$

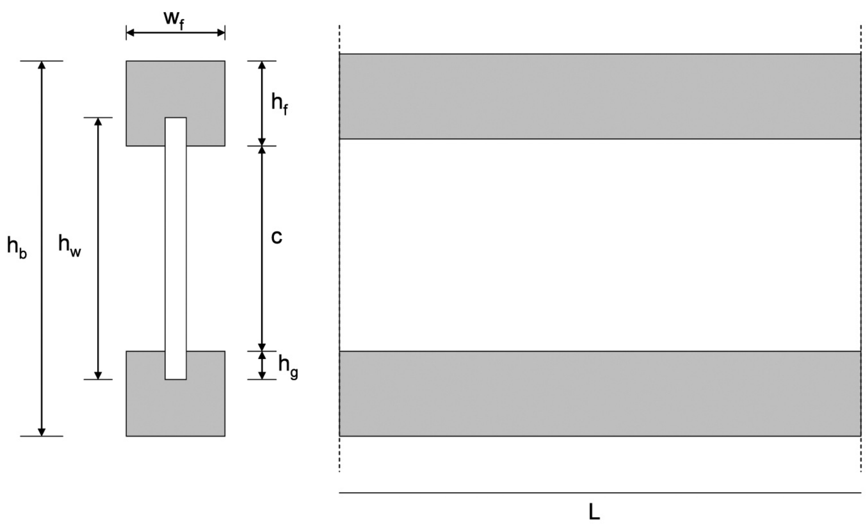

Figure 1 Cross-section and lateral view of the I-beam; L = beam length (2750 mm), h_b = beam depth (200 mm), h_w = web depth (150 mm), w_f, h_f = flange width and height (40 mm), c = apparent web height (120 mm) and h_g = groove height (15 mm)

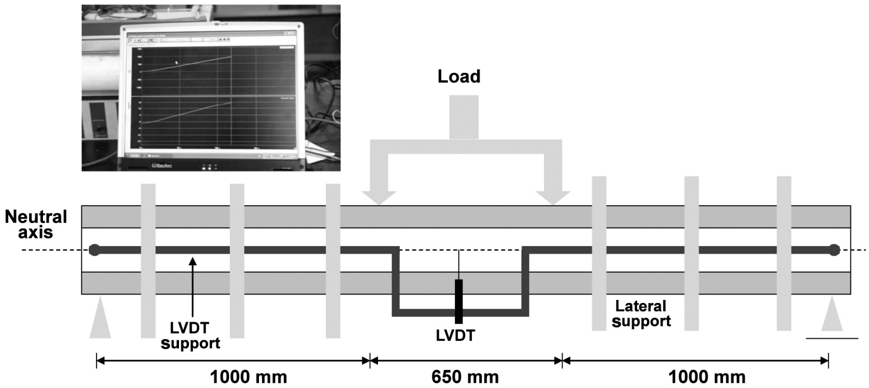

Figure 2 Four-point bending testing schedule and software interface showing load and deflection curves; LVDT = linear variable differential transformer

$$M_{max} = \frac{P_{rup}\ a}{2} \qquad (3)$$

where P' = load at 20–40% rupture load N, a = shear span (mm), L = total beam span (mm), P_{rup} = rupture load N, I = area moment of inertia (mm^4), Δ' = deflection at 20–40% rupture load (mm) and y = distance from neutral axis of beam to extreme outer fibre (mm).

Data analysis

Data from the nondestructive evaluation of the flanges (E_{sb}, E_{dsw} and E_{dvt}) were compared with those from flexural properties of I-beams (E_M, f_M and P_{rup}). Two-tailed Pearson correlation (r) was calculated and simple linear regression (y = a + bx) analysis was run using nondestructive values (x) as predictors of the flexural properties (y). One-way analysis of variation (ANOVA) at α = 0.05 level was run to study the effect of the flange wood species and the adhesive type on flexural properties of I-beams. In this analysis, two comparisons were made, namely, castanha-de-macaco vs. marupá flanged I-beams, both bonded with RF adhesive, and RF vs. PUR bonded I-beams, both flanged with marupá.

RESULTS AND DISCUSSION

Nondestructive testing of flanges

Table 1 presents the I-beam modulus of elasticity (E_M) and the nondestructive flange modulus of elasticity (E_{sb}, E_{dsw}, E_{dvt}). It could be observed that for marupá flanges, the mean values of dynamic nondestructive methods (E_{dsw}, E_{dvt}) were slightly higher than those obtained through nondestructive static method (E_{sb}). This trend was not observed for flanges from castanha-de-macaco since the three nondestructive values were almost the same, i.e. 15398, 15184 and 15285 N mm^{-2} for E_{sb}, E_{dsw} and E_{dvt} respectively. For tropical hardwoods, dynamic nondestructive methods usually gave higher values of modulus of elasticity in comparison with static values (Oliveira et al. 2002, Karlinasari et al. 2008, Del Menezzi et al. 2010b, Teles et al. 2010)

It is also clear that castanha-de-macaco flanges were stiffer than marupá flanges. Since the former (679 kg m^{-3}) had higher density than the latter (394 kg m^{-3}); this result was already expected. Castanha-de-macaco wood had E_M value of 12,800 N mm^{-2} and f_M of 110.4 N mm^{-2}, while E_M and f_M values for marupá wood were 7260 and 64 N mm^{-2} respectively (IBAMA 1997).

According to the engineering concept of I-beam, flanges are responsible for resisting compression and tension stresses during loading. Thus, it is vital to compare values of the flexural properties of I-beam and the respective modulus of elasticity values of flanges obtained nondestructively. The stiffness of flanges had a direct effect on all I-beam flexural properties (E_M, f_M and P_{rup}) (Table 2). Most of the Pearson r values were higher than 0.8, which meant that the variation of I-beam properties could be well explained by the three nondestructive variables (E_{sb}, E_{dsw}, E_{dvt}) tested. Within I-beam properties, E_M presented the highest correlations (> 0.91) with nondestructive methods followed by f_M (> 0.87) and P_{rup} (> 0.76). Between nondestructive methods, E_{dvt} showed the highest correlations with I-beam properties (> 0.84), followed by

Table 1 Values of the I-beams modulus of elasticity (E_M) and of the nondestructive modulus of elasticity of respective flange

Wood species/adhesive	Experimental and nondestructive E (N mm^{-2})			
	E_M	E_{sb}	E_{dsw}	E_{dvt}
Castanha-de-macaco/RF				
Maximum	12527	16349	15597	16038
Mean	11306	15398	15184	15285
Minimum	10811	14651	14720	14924
Marupá/RF				
Maximum	8500	9045	9381	9056
Mean	7300	8254	8597	8500
Minimum	6547	7785	7845	7014
Marupá/PUR				
Maximum	7200	7663	8408	9084
Mean	6409	7250	8075	7470
Minimum	5837	6737	7308	7184

RF = resorcinol-formaldehyde, PUR = castor-oil based polyurethane; E_M = static bending modulus of elasticity, E_{sb} = static bending nondestructive modulus of elasticity, E_{dsw} = stress wave dynamic modulus of elasticity, E_{dvt} = dynamic transverse modulus of elasticity

Table 2 Pearson correlation (r) between I-beam flexural and flange nondestructive properties

I-beam flexural property	Flange nondestructive property		
	E_{sb}	E_{dsw}	E_{dvt}
E_M	0.929**	0.950**	0.910**
f_M	0.872**	0.876**	0.920**
P_{rup}	0.828**	0.768**	0.845**

** = significant at α =0.01; E_{sb} = static bending nondestructive testing, E_{dsw} = stress wave dynamic modulus of elasticity, E_{dvt} = dynamic transverse modulus of elasticity, E_M = static bending modulus of elasticity, f_M = modulus of rupture, P_{rup} = rupture load N

E_{dsw} (> 0.82) and E_{sb} (> 0.76). E_{dvt} was found to be the most appropriate nondestructive technique for grading lumber to be used in glulam manufacturing (Teles et al. 2010).

Utilisation of E_{dvt} values as predictor explained more than 84 and 70% of the variation in f_M and P_{rup} respectively (Figure 3). On the other hand, stress wave values (E_{dsw}) explained more than 90% of the I-beam modulus of elasticity (E_M). Two groups can be identified in Figure 3, namely, those lower values (E_{dsw}, E_{dvt} < 9500 N mm^{-2}) representing marupá and higher values (E_{dsw}, E_{dvt} > 14000 N mm^{-2}) representing castanha-de-macaco flanges. There is a region, between 9500–14000 N mm^{-2}, virtually without points. As previously mentioned and observed in Table 1, the species presented quite different wood properties which implied two different groups. Therefore, future studies should evaluate wood with densities and mechanical properties between these two tested species. Nonetheless, the trend of the results observed in this study showed that stiffer flange had higher I-beam flexural properties. This meant that the nondestructive methods employed were suitable for the purposes stated in the present paper.

When the regression analysis was run separately for each kind of I-beam, four relationships were significant. The E_{dvt} values appeared in three relationships (r^2 = 0.636, 0.507, 0.355) and E_{dsw} values only in one (0.418) (results not shown). For castanha-de-macaco flanged I-beam only f_M could be explained (0.355) by the nondestructive values of flanges, while for marupá both E_M (0.636,

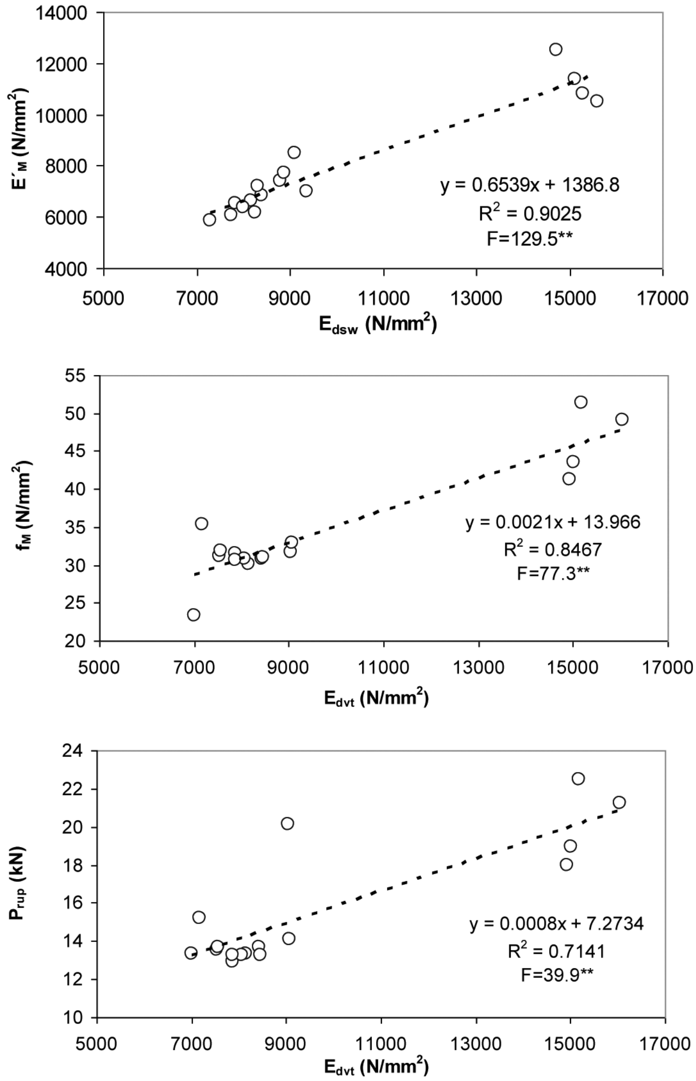

Figure 3 Linear regression models to predict I-beam flexural properties as function of nondestructive modulus of elasticity of the flanges; ** = significant at α = 0.01 level; E_M = apparent modulus of elasticity, f_M = modulus of rupture, P_{rup} = rupture load

0.418) and f_M (0.507) could be explained. The above mentioned r^2 values were comparatively low in relation to those in Table 2 because variation between the three kinds of I-beams was higher than variation within them. Similar results were obtained in a nondestructive study of six tropical hardwoods (Del Menezzi et al. 2010b). With stress wave nondestructive values as predictors of flexural properties (E_M, f_M and P_{rup}) of these wood species, the authors found models which presented r^2 values higher than 0.86 when the analysis was run between the six study species (N = 120). On the other hand, when the analysis was done for each species separately (N = 20), significant r^2 values ranged only from 0.205 to 0.614.

In a study involving double I-beam from balsam fir (*Abies balsamea*) flanges and waferboard webs, maximum load in flexure correlated linearly (r^2= 0.51) to the average stiffness of the tension flange (Samson 1983). However, very low and non-significant r^2 values between beam E_M/f_M and flange E_{dsw} were obtained with I-beam from *Pinus kesyia*–LVL flanges and oriented strand board (OSB)/plywood web which were nondestructively tested using stress wave method (E_{dsw}) (Del Menezzi et al. 2010a).

Effects of wood species and adhesive type

The standard deviation in flexural properties of study I-beams was very low (Figure 4). Thus,

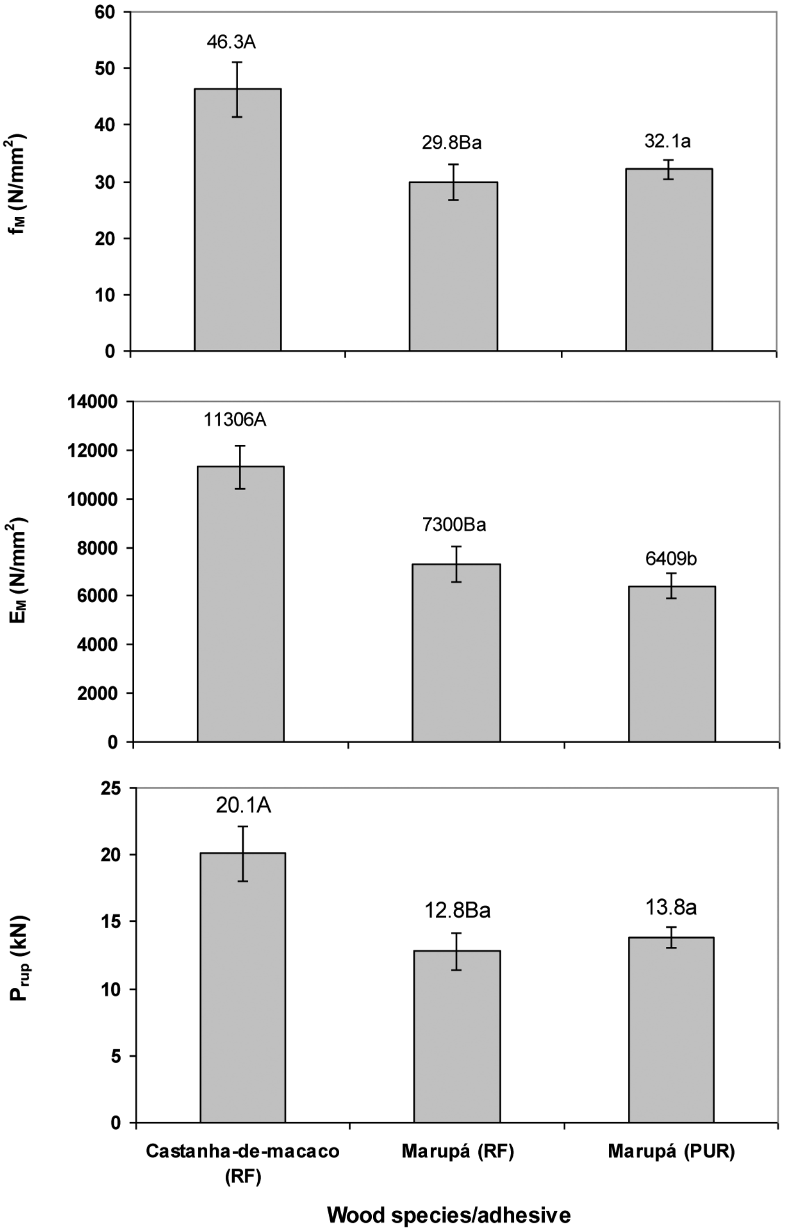

Figure 4 Mean and standard deviation of flexural properties for the three types of I-beam tested; upper-case letters compare statistically means between RF adhesives, whereas lower-case letters compare values between marupá beams; RF = resorcinol–formaldehyde adhesive, PUR = castor-oil based polyurethane adhesive; f_M = modulus of rupture, E_M = apparent modulus of elasticity, P_{rup} = rupture load

it is imparted that the coefficient of variation ranged from 5.6 to 10.9%. Such low variability in properties is fundamental for engineering purposes. There is very little research about flexural properties of I-beam flanged with tropical hardwood, but values obtained in this study were within the range found in the literature (Chu et al. 1993, Jamaludin et al. 2005, Jahromi et al. 2006, Santos et al. 2009, Abreu et al. 2010). Abreu et al. (2010) evaluated short span (1800 mm) I-beams flanged with the tropical hardwood louro-vermelho (*Sextonia rubra*). OSB was employed as web material and the effect of OSB strength axis orientation (parallel or perpendicular to flanges) was studied. Ten I-beams were tested and the mean value (both axes computed) of E_M was 18,222 N mm^{-2} while f_M was 22.5 N mm^{-2}.

The comparison between species revealed that castanha-de-marupá flanged I-beam bonded with RF presented significantly higher f_M (46.3 N mm^{-2}) and E_M (11306 N mm^{-2}) values than beams made from marupá bonded with the same adhesive (29.8 and 7300 N mm^{-2} respectively), as can be seen in Figure 4. On the other hand, the comparison between adhesives showed that marupá I-beam bonded with RF had slightly higher (7300 N mm^{-2}) E_M values than beams bonded with PUR (6409 N mm^{-2}) while no significant difference was observed for f_M values (29.8 N mm^{-2} and 32.1 N mm^{-2} respectively).

Failure mode analysis

A total of fifteen I-beams presented failures as expected in long-span bending moment test including flange failure in tension (FT), compression (FC) and buckling (FCB) (Table 3). Only one I-beam had mode of failure associated with short-span beams, i.e. web crushing at end reaction (WC). The most common failure mode was compression (8 of 16 beams) followed by buckling (5).

The castanha-de-macaco flanged I-beams failed mainly because of rupture of the top flange under compression and web crushing (Figures 5a and b). Of the 12 marupá flanged I-beams, 10 had failures due to compression. Inadequate lateral support caused flange buckling in five I-beams (Figures 5d and e), in spite of having lateral supports every 400 mm. Flange failure in tension occurred in two marupá flanged I-beams (Figures 5c and f). The beam shown in Figure 5f had a gallery made by a boring insect (beetle

Table 3 Beam failure mode classified according to ASTM D5055 (2005)

Wood species/adhesive	Failure mode/number of beams			
	WC	FT	FC	FCB
Castanha-de-macaco/RF	1		3	
Marupá/RF		1	2	3
Marupá/PUR		1	3	2

RF = Resorcinol-formaldehyde adhesive; PUR = castor-oil based polyurethane adhesive; WC = web crushing, FT = flange failure in tension, FC = flange failure in compression, FCB = flange failure in buckling

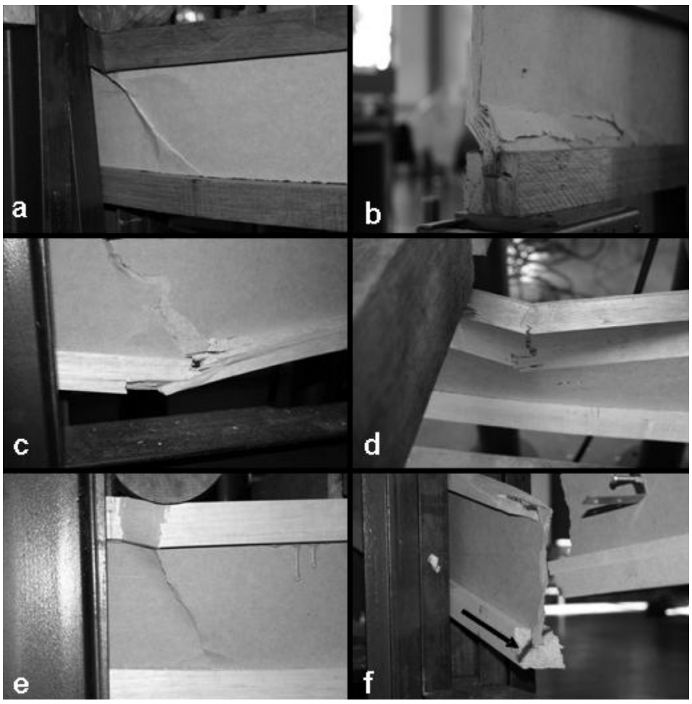

Figure 5 I-beam failure pattern—(a) castanha-de-macaco: failure in compression and web crushing, (b) castanha-de-macaco: web crushing at end reaction, (c) marupá: failure in tension, (d) marupá: top flange buckling, (e) marupá: failure in compression and (f) marupá: failure in tension caused by insect damage

species which grows fungi in the gallery) and, being in the failure region, was undoubtedly the cause of the failure.

The rupture mode identified for castanha-de-macaco flanged I-beam was in accordance with the wood property. This species presents high values of modulus of rupture in bending (f_M = 110.4 N mm^{-2}), while compression strength parallel to grain is not so high ($f_{c,0}$ = 51.2 N mm^{-2}) (IBAMA 1997). Since there was no data about tension strength parallel to grain ($f_{t,0}$) for Brazilian tropical hardwoods, it could be assumed that $f_{t,0}$ was equal to wood f_M. Therefore, during testing of I-beams the bottom flanges which were under tension stress could bear twice the stress level as top flanges. This way, when the top flanges reached bending stress near $f_{c,0}$ value, they failed, causing I-beam rupture. The same explanation could be given for marupá wood. The marupá wood has $f_{c,0}$ = 33 N mm^{-2} (IBAMA 1997) which means that both wood species have $f_{c,0}$ values close to I-beam f_M values, i.e. 51.2 N mm^{-2} (IBAMA 1997) vs. 46.3 N mm^{-2} (this study) for castanha-de-macaco, and 33 N mm^{-2} (IBAMA 1997) vs. 30.9 N mm^{-2} (this study) for marupá. Failure in buckling of top marupá flanges could indicate that its slenderness ratio was probably high, and with relatively low modulus of elasticity, this led to flange instability. Therefore, it might be important that marupá flange should be wider, thus improving the radius of gyration, reducing slenderness ratio and eventually improving the stability of the I-beam flange.

One of the clearest advantages of using I-beam instead of cross-section solid wood beam is material economy. In I-beams, the larger volume of material is positioned in the regions where stress levels are higher. The cross-section dimensions required for a beam made entirely from tested woods are given in Table 4. Although solid wood beam (120 mm) had shallower cross-section compared with I-beam (200 mm), the volume of wood required to manufacture one beam for the former was higher (133 × 10^{-6} vs. 88 × 10^{-6} m^3 respectively). This meant that to assemble an I-beam, one-third less wood was required in comparison with a solid wood beam. Thus, a substantial amount of natural resources could be saved.

Additionally, from Table 4, it can be inferred that I-beams flanged with castanha-de-macaco had higher load capacity than solid wood beams (+ 6.4%). However, the opposite was observed for marupá wood (– 5.7%). Castanha-de-macaco wood was slightly denser (+ 13.1%) than MDF web. Therefore, when part of the solid beam cross-section was replaced by MDF, the beam weight was reduced and the load capacity improved. Contrarily, since MDF web material was denser than marupá wood (+ 52.3%), that replacement caused an improvement in the I-beam weight and consequently, beam load capacity was reduced.

CONCLUSIONS

The flexural properties of I-beams were highly affected by flange stiffness. The transversal vibration nondestructive method showed models with the highest coefficient of determination. As expected, I-beam flanged with denser wood showed higher flexural properties. Since I-beam ruptures were more associated with top flange failure in compression, wood compression strength parallel to grain was an important parameter for choosing species. No I-beam failed

Table 4 Comparative dimensions and load capacity for hypothetical beams made entirely from solid wood to bear the same rupture load of the tested I-beam

Dimension/capacity	Hypothetical solid wood beam		Tested I-beam	
	Castanha-de-macaco	Marupá	Castanha-de-macaco	Marupá
Beam depth (mm)	117	124	200	200
Beam width (mm)	40	40	40	40
Moment of inertia (10^3 mm^4)	5319	6413	21650	21650
Beam wood volume (10^{-6} m^3)	129	137	88	88
Beam weight (kg m^{-1})	3.17	1.96	2.98	2.07
Relative beam load capacity (N kg^{-1} of beam)	2303	2449	2450	2318

because of inadequate bonding between flange and web. However, the adhesive type affected the modulus of elasticity and RF yielded stiffer I-beam. In comparison to data found in the literature, all tested I-beams showed suitable flexural properties with low variability. Although this was a preliminary study, the potential of tropical hardwoods as I-beam flange material had been demonstrated and the research effort should be continued.

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