STRUCTURAL PERFORMANCE OF I-BEAM FABRICATED FROM A FAST-GROWING TREE, *GMELINA ARBOREA*

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MOYA R, TENORIO C, CARRANZA M, CAMACHO D & QUESADA-PINEDA H. 2013. Structural performance of I-beam fabricated from a fast-growing tree, *Gmelina arborea*. There is an increasing supply of fast-growing plantation species in Costa Rica. The main objective of this study was to assess the performance of I-beams fabricated from *Gmelina arborea* wood using lumber for the flanges and 12-mm plywood for the web. Three types of profiles were fabricated for static bending tests, i.e. 6.5 cm × 24.2 cm, 6.5 cm × 16.5 cm and 6.5 cm × 10 cm (width × depth) × 600 m (length). Modulus of rupture varied from 23 to 41 MPa while modulus of elasticity, 12 to 17 GPa. Static bending tests showed that it was necessary to classify the I-beams according to two qualities. Structural design values varied from 5.9 to 14.4 MPa in the bending test and from 4.0 to 8.9 MPa in the shear stress according to the Costa Rican structural standards.

Keywords: I-Joist, structural component, modulus of rupture, modulus of elasticity, tropical species

MOYA R, TENORIO C, CARRANZA M, CAMACHO D & QUESADA-PINEDA H. 2013. Prestasi struktur rasuk-I yang dihasilkan daripada kayu pokok cepat tumbuh, *Gmelina arborea*. Bekalan spesies ladang yang cepat tumbuh kian meningkat di Costa Rica. Objektif utama kajian ini adalah untuk menilai prestasi rasuk-I yang hasilkan menggunakan kayu *Gmelina arborea*. Bebibir rasuk-I diperbuat daripada kayu sementara webnya daripada papan lapis setebal 12 mm. Tiga jenis profil dihasilkan untuk ujian lentur statik iaitu 6.5 cm × 24.2 cm × 600 m, 6.5 cm × 16.5 cm × 600 m dan 6.5 cm × 10 cm × 600 m (lebar × dalam × panjang). Modulus kepecahan berjulat antara 23 MPa hingga 41 MPa sementara modulus kekenyalan antara 12 Gpa hingga 17 Gpa. Ujian lentur statik menunjukkan bahawa rasuk-I perlu dikelaskan kepada dua kategori kualiti. Reka bentuk struktur berjulat antara 5.9 MPa hingga 14.4 MPa dalam ujian lentur sementara dalam ujian tegasan ricih nilainya adalah antara 4.0 MPa hingga 8.9 MPa mengikut piawaian struktur Costa Rica.

INTRODUCTION

The growing demand for wood worldwide and the challenge faced by producers in meeting the demand for construction material have led to the development of composite materials based on wood such as plywood, laminated beams and I-beams (Aydin et al. 2004). These products provide commercial use for plantation logs, low quality logs and logs that would otherwise have little use because of their commercial value or structural properties (Lam 2001).

Composite products have better dimensional stability, greater mechanical resistance, lower processing costs and higher aesthetic values (Kamala et al. 1999). The physical and mechanical properties of composite products depend on wood properties of species used, the manufacturing process and the final use for the product. In north Europe and North America, I-beams have been used for over 40 years as construction material and studied for short- and long-term applications such as roofing and flooring systems. The web of the I-beam is made of structural plywood or laminated veneers lumber (LVL), while the flange is made using solid wood.

In tropical countries in America, several lesser-known species have been introduced for commercial reforestation. Among them are *Tectona grandis, Gmelina arborea* and a great variety of *Eucalyptus* species (Moya 2004, Erskinea et al. 2006). However, products made

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from these plantations species have been limited to products of little technological development such as wood for pallets, log or semiblock exports and dried or green lumber. In Costa Rica, studies have been conducted on the physical and mechanical properties of plywood and LVL boards manufactured from *G. arborea* veneers of fast-growing plantation species, glued with phenol formaldehyde resin (Tenorio et al. 2011). This present work builds on this and other researches and presents the developmental process for I-beams from *G. arborea* timber, a fast-growing forest plantation species for commercial use in the Costa Rican market. The resistance values, i.e. modulus of rupture (MOR) and modulus of elasticity (MOR), were determined as well as the allowable load and design values for I-beams joist fabricated from *G. arborea* wood. The methods used can be applied to ascertain the maximum allowable span for the use of this type of I-beam in flooring and roofing systems based on the Costa Rican standards.

MATERIALS AND METHODS

Materials

I-beams used in this study were made by Maderas Cultivadas in Costa Rica. The beams were fabricated using timber from mature *G. arborea* plantations in the northern and southern regions of Costa Rica. The wood was from third thinning (8 to 10 years old) and final harvest trees. Lumber were extracted from kiln-dried boards with 12% moisture content.

Design

I-beams were built with the following dimensions: 6.5 cm width and depths of 10 cm (profile 1), 16.5 cm (profile 2) and 24.2 cm (profile 3) (Figure 1a). For stability during use, thickness values of flanges were 2.8 cm for profiles 1 and 2, and 3.8 cm for profile 3. The web of the I-beam was built using plywood of 1.2 cm in thickness (Tenorio et al. 2011).

Manufacturing process

Briefly, two panels of 178 cm were used for the ends while a 244-cm panel was used in the middle section (Figure 1d) that was attached through finger joints (box combing) (Figure 1c) to avoid joints in the centre of the I-beam. Dried lumber used for the flanges were from 3.2- and 4.2-cm boards, which were dried to 12% moisture content. These boards were cut into widths of 7 cm. Wood with encased knots, knots greater than 2.5 cm in diameter, cracks or having traces of insect or fungi was eliminated. The small pieces were cut in minimum lengths of 50 cm. Using urea formaldehyde adhesive, the ends were joined using structural finger joint (Figure 1b) up to 600 cm in length (González et al. 2004). The pieces were dimensioned, planed and molded to form grooves that joined the web (Figure 1a). Finally, flanges were glued to the web using phenol formaldehyde at 138 KPa for 8 hours at room temperature. The I-beams were then visually classified according to two qualities (A and B) taking into account the amount of joints and their locations in the flanges, the quantity and size of knots in the flanges as well as in the web, the location of joints in the web, and the presence of spiral grain in the flanges (Table 1).

Mechanical testing

I-beams were tested for static bending with a universal testing machine. The conditions of spacement between supports, load velocity and deflection were determined according to EN 408 (European Standard 2003). MOE and MOR were determined using equations 1 and 2 respectively.

$$\text{MOE (GPa)} = \frac{0.852 \times F_{LP} \times L^2}{24 \times I \times y} \times 0.09807 \quad (1)$$

$$\text{MOR (MPa)} = \frac{\text{Fmax} \times L \times \frac{H}{2}}{6 \times I} \times 98.07 \quad (2)$$

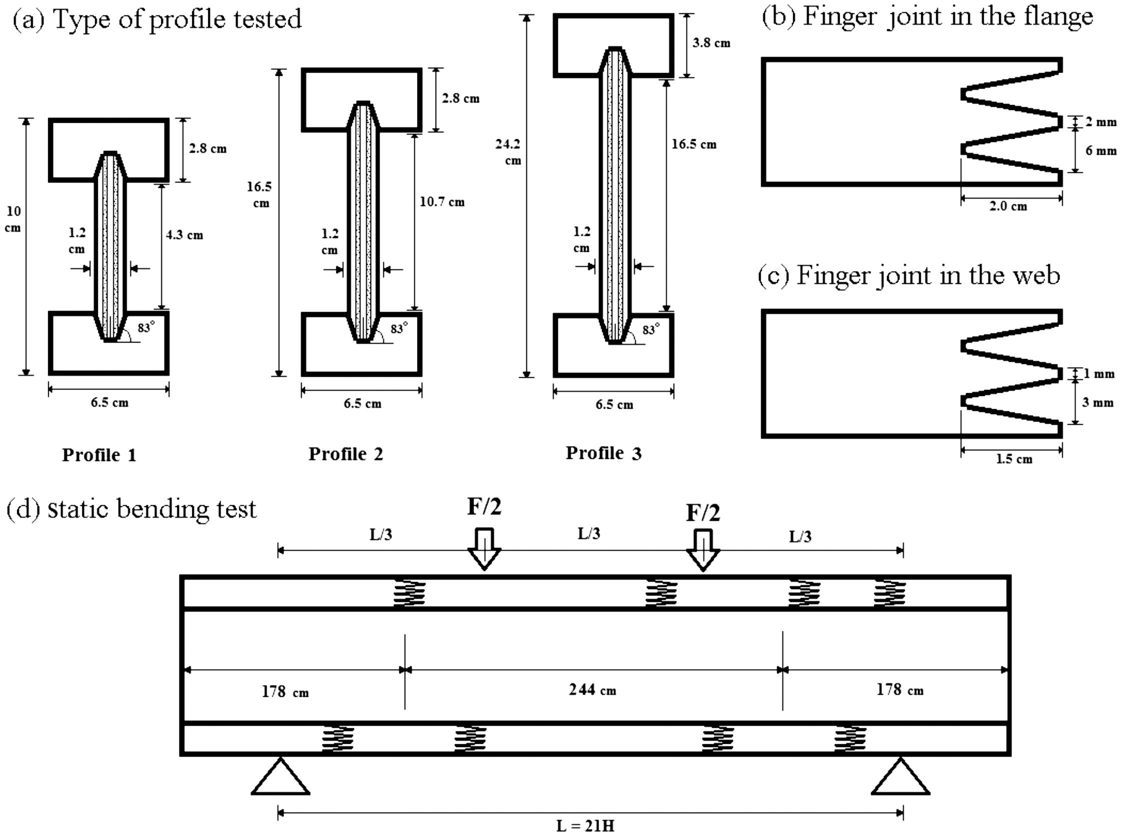

Figure 1 Design of I-beam joist tested: (a) profile dimensions, (b) finger joint used in flange, (c) finger joint used in the web and (d) static bending condition test

where F_{LP} = load at proportional limit (kg), Fmax = rupture load (kgf), L = span (cm), I = moment of inertia (cm^4), y = deflection (cm) and H = depth of the I-beam (cm), 0.09807 = conversion unit from kgf cm^{-2} to GPa and 98.07 = conversion unit from kgf cm^{-2} to MPa.

Determination of I-beam weight and density

Following bending tests, a 5-cm cross-section was extracted from the I-beam and weighed. Its volume was determined to calculate the density (kg m^{-3}). This value was later used to calculate total weight of the I-beam.

Design properties

Design properties were established for I-beam profiles (1, 2 and 3) and qualities (A and B). Design value adjustment of the I-beam was structurally analysed from its bending capacity, shear capacity and deflection in the span. For bending capacity, maximum load that the length of I-beam (6 m) with various depths could withstand was determined, taking into account only maximum stress of the transverse section. To determine shear capacity, maximum shear values in supports produced by maximum load distributed over the length of I-beam was ascertained. Finally, maximum deflection produced by maximum load distributed over the length of I-beam was the span deflection. To derive design properties, equations 3–5 were used (CFIA 2002):

$$\text{Mpp (kgf cm)} = \frac{\text{Weight} \times \text{L}}{8} \qquad (3)$$

$$\text{Mrup (kgf cm)} = \frac{\text{Fmax}}{2} \times \frac{\text{L}}{3} + \text{Mpp} \qquad (4)$$

$$\text{MORc (MPa)} = \frac{\text{Mrup} \times (\text{H}/2)}{\text{I}} \times 98.07 \qquad (5)$$

Table 1 Factors considered in the classification of the fabricated *Gmelina arborea* I-beams

Factor	A quality	B quality
Quantity of finger joint in the flange	Four to five finger joints in 6 m in length	Not limited
Localisation of finger joint in the flange	Not allowed in the middle of length (3 m) (at least 84 cm from the center of the beam)	Allowed anywhere on the flange
Localisation of the knots in the web	Knots small, healthy and strong; not allowed in the center of the I-beam (at least 84 cm from the center of the I-beam)	Medium and large, healthy and strong; allowed anywhere on the length of the I-beam
Localisation of the knots in the flange	Knots small, healthy and strong; not allowed in the center of the beam (at least 84 cm from the center of the I-beam)	Medium and large, healthy and strong; allowed anywhere on the length of the I-beam
Localisation of the finger joint in the web	Not allowed in the center of the I-beam (at least 84 cm from the center of the I-beam)	Allowed anywhere on the I-beam length
Wood grain	Allowed anywhere on the flange with an inclination of 8% at maximum	Allowed in any part of the flange with an inclination of 8 at 20% at maximum
Decay presence	Not allowed	Not allowed

where Mpp = weight moment due to beam dead load, Mrup = moment of rupture in flexure, MORc = modulus of rupture in shear and 98.07 = conversion unit from kgf cm^{-2} to MPa.

Using MORc values, a frequency distribution was carried out. The fifth percentile was selected as the bending value which was used for bending and shear capacities. With average values of MOE and bending capacity and a temporary load duration factor (0.8) (AITIM 2003), bending value was taken parallel to the fibre design (Fd) and, with this value, the MOR bending design was calculated.

Shear value was calculated using shear capacity and a 0.5 correction factor (AITIM 2003) to yield the final shear value. Finally, for the deflection in span, average MOE of each I-beam profile and quality of I-beam, A or B, as well as the inertia were used to calculate stiffness to bending (American Wood Council 2005).

RESULTS AND DISCUSSION

MOE and MOR

The average strength values for each I-beam profile and quality are presented in Table 2. It was found that profile 1 of A quality (1A) I-beam yielded the highest MOR values (40.87 MPa), followed by 2A (34.06 MPa) and 3A (32.44 MPa). It was observed that 1B, 3B and 2B I-beams had the lowest MOR values, i.e. 24.46, 24.34 and 23.75 MPa respectively. Analysis of variance (ANOVA) showed that all MOR values of A quality I-beams were statistically different from those of B quality. Within A quality I-beams profile 1 was found to be greater than profiles 2 and 3 (no significant difference was found in these two). For B quality I-beams, there was no statistical difference within the three profiles (Table 2).

Table 2 Average strength values obtained for I-beams of *Gmelina arborea*

Profile	Quality	Density (kg m^{-3})	MOR (MPa)	MOE (GPa)
1	A	491.63	40.87 (16.04) a	13.97 (55.64) a
	B	491.91	24.46 (25.07) b	14.57 (31.13) a
2	A	493.53	34.06 (12.59) c	17.38 (20.33) b
	B	492.30	23.75 (15.99) b	14.75 (22.05) a
3	A	494.57	32.44 (9.09) c	12.54 (5.15) a
	B	495.16	24.34 (11.02) b	12.13 (4.20) a

Values in parentheses present coefficients of variation; different lowercase letters in the same column indicate that the values are statistically different at confidence level of 95%

The highest MOE value was obtained in 2A I-beam. No statistical differences were found in the rest of the profiles (both qualities). The MOE value for IB was higher than IA although they were not statistically different (Table 2). Another important point related to coefficient of variation was found in profiles 1 and 2. These values were higher than 20%, especially in 1A where the coefficient of variation was 55.64%. Design values derived for MOR of profiles 1 and 2 in both qualities were considered as high coefficients of safety.

Gmelina arborea timber has lower MOR and higher MOE values than other species. For instance, *Pinus taeda* and *Eucalyptus dunnii* I-beams presented higher MOR values than those found in this study, with values varying from 91 to 102 MPa but lower MOE values than 13 GPa (Pedrosa et al. 2005). The difference between *G. arborea* and *P. taeda* or *E. dunnii* I- beams can be attributed to the conformation of web and flanges. I-beams used by Pedrosa et al. (2005) had oriented-strand board (OSB) webs and LVL flanges. This type of I-beam is known to be stiffer than solid lumber and plywood. In this study, flanges were fabricated with solid lumber and the webs were made of plywood.

We also compared the MOR and MOE values obtained in this study with different profiles and qualities of I-beams made using solid wood from *G. arborea* (Moya 2004). It was observed that solid wood had higher (39 to 77 MPa) MOR values and lower (6 to 10 GPa) MOE values than those reported in Table 2. This difference can be explained by the shape of the beam. Specifically, Moya (2004) reported the values from a quadratic section (5 cm × 5 cm) while in this study, the values were derived from the I-beam profile and this shape was stiffer than a quadratic section.

The load versus deflection curve produced in each I-beam profile and quality is shown in Figure 2. I-beams 1A and 2A were similar, whereas 3A showed more deflection. I-beams 1B and 3B also had similar deflection while I-beam 2B had slightly higher values. It was observed that in profiles 1 and 2, deflection produced by the application of a load was lower for A quality I-beams compared with B. On the other hand, for profile 3, B quality beams had slightly lower deflection than A quality beams. It was concluded that A quality I-beams were able to withstand loads heavier than 500 kg in any profile. However, B quality I-beams could only withstand loads lighter than 500 kg, with maximum load of 360 kg for profile 1.

I-beams made from *Pinus* sp. and fabricated with OSB in the web and LVL in the flanges had deflection values up to 1.5 cm for 470 kg loads (Santos et al. 2009) which were lower than those obtained for this study for the same load; the deflection for profile 3 I-beams in this study was approximately 3 cm for 470 kg load (Figure 2). Differences in MOR, MOE and deflection values between *G. arborea* and *Pinus* sp. can be attributed to the fact that LVL offers greater resistance than I-beam (Sheldon & Walker 2006). The density for *Pinus* sp. is 0.55–0.62 g cm^{-3} (Pedrosa et al. 2005) whereas for *G. arborea*, 0.48 g cm^{-3}. OSB offers greater resistance than plywood (Sheldon & Walker 2006). Length of span used may also influence resistance. The span in *Pinus* sp. used by

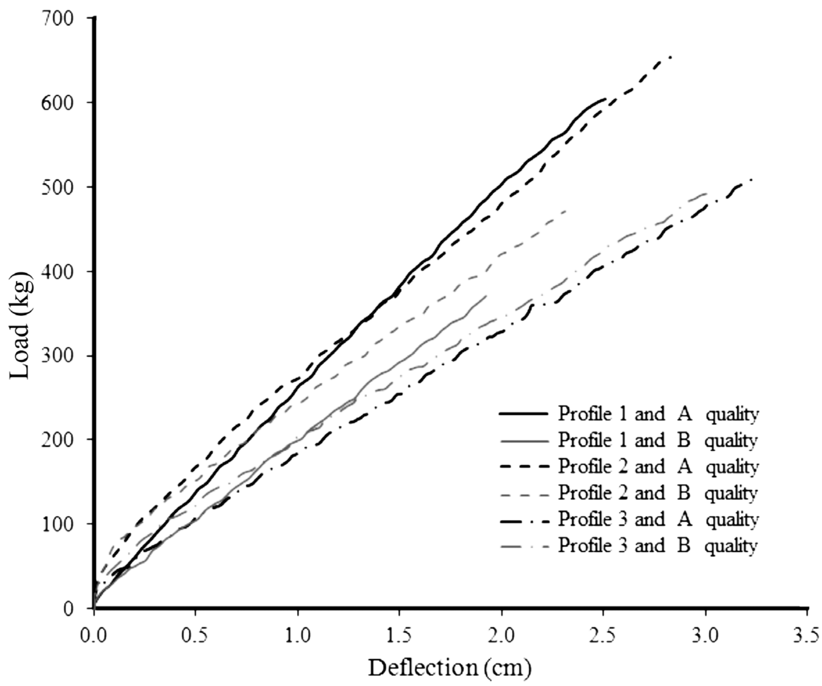

Figure 2 Relation between load and deflection for the different *Gmelina arborea* I-beams

Pedrosa et al. (2005) was 176 cm while that used in *G. arborea* for the current study was 600 cm.

Design properties

Design values obtained for each I-beam profile and quality are shown in Table 3. Bending and shear values were determined for each I-beam profile and quality, while the stiffness in static bending was only determined for each profile, considering average values of qualities A and B. Results obtained showed that 1A I-beams had higher bending and shear values (14.46 and 9.04 MPa), followed by 3A and 2A beams. B quality I-beams had lower design values compared with A; 3B I-beam was the highest between them with 7.92 MPa for bending and 4.95 MPa for shear, followed by 1B and 2B. For bending stiffness, profile 3 I-beams had the highest value with 302,787,437 kg cm^2, followed by profiles 2 and 1 with 126,099,373 and 35,892,503 kg cm^2 respectively.

According to the classification proposed for timbers from South American countries, I-beam of *G. arborea* (basic density of 0.45 g cm^{-3}) can be classified into group C, i.e. species with the lowest resistance and stiffness (Keenan & Tejada 1987). Admissible design value for this group of South American country should be higher than 7.25 MPa in bending stress, which is lower than the values obtained for A quality I-beams in all profiles in this study (Table 3). However, B quality I-beams did not reach the minimum value (7.25 MPa). In this study, shear values obtained in B quality for all profiles (3.69 to 4.95 MPa) are lower than the permissible values specified in group C of South American countries (Keenan & Tejada 1987).

CONCLUSIONS

Results show that it is possible to build I-beams with fast-growing *G. arborea* from timber plantations for the studied heights (10, 16.5 and 24.2 cm) because these profiles allow adequate resistance. Classification of I-beams according to quality, which considers the presence of defects such as amount of joints in the flanges and web, amount of encased knots in those parts of the I-beam and the inclination of the grain in the flange, show an acceptable performance when these defects

Table 3 Design values obtained for I-beams of *Gmelina arborea* of three profiles and two qualities

Profile	Quality	Mpp (kg cm)	Mrup (kg cm)	MORc (MPa)	Fd (MPa)	Fv (MPa)	I × MOE (kg cm^2)
1	A	126.0	20674.9	20.6	14.46	9.04	35,892,503
	B	125.8	12480.6	12.4	6.62	4.14	
2	A	411.5	39084.5	17.2	11.63	7.27	126,099,373
	B	409.2	27322.1	12.1	5.89	3.69	
3	A	1243.9	78783.2	16.5	11.78	7.36	302,787,437
	B	1228.9	59253.6	12.4	7.92	4.95	

Mpp = moment of I-beam weight, Mrup = moment of rupture, MORc = modulus of rupture corrected, Fd = bending stress, Fv = shear stress, MOE × I = bending stiffness, I = moment of inertia, MOE = module of elasticity

decrease, leading to greater MOR and MOE values. Therefore, A and B quality I-beams can be used in civil construction as far as wood mechanical resistance is concerned.

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