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Structural and Design Values of Solid Timber Beams and Glued Laminated Timber Beams of *Dipteryx panamensis* and *Hieronyma alchorneoides* Wood from Fast-Growth Plantation

Strukturne i projektirane vrijednosti lameliranih greda i greda od cjelovitog drva *Dipteryx panamensis* i *Hieronyma alchorneoides* s brzorastućih plantaža

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ABSTRACT • *Dipteryx panamensis and Hieronyma alchorneoides are two species of high specific gravity used in reforestation programs in Costa Rica, but they lack products with structural value for commercialization. In order to introduce the wood of these two species in the market, the objective was established to study the behavior of solid timber beams and glued laminated timber beams of two cross sections (2 cm × 10 cm and 2 cm × 15 cm) and establish the design values in bending test. The results showed that the bending design values (f_b) ranged from 2 to 26 MPa in glued laminated timber beams, while in solid timber beams, fb ranged from 6 to 15 MPa. In the shear design values (f_v), the variation was from 0.29 to 0.67 MPa in glue laminated timber beams and from 1.80 to 2.58 MPa in solid timber beams. It was also found that the D. panamensis beams showed higher values than H. alchornoides beams. Finally, it was established that glued laminated timber beams showed better performance in bending parameters and higher design values, resulting in wider span values, than solid timber beams when used in floor and roof construction.*

KEYWORDS: *tropical species; bending; shear; mezzanine; glulam; mass timber*

SAŽETAK • *Dipteryx panamensis i Hieronyma alchorneoides dvije su vrste drva velike specifične gustoće koje su uvrštene u program pošumljavanja u Kostarici, ali se ne iskorištavaju za strukturne proizvode kako bi se komercijalizirale. Da bi se te dvije vrste drva plasirale na tržište, istraženo je ponašanje lameliranih greda i greda od cjelovitog drva s dva različita poprečna presjeka (2 cm × 10 cm i 2 cm × 15 cm) te su ispitivanjem savijanja*

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utvrđene projektirane vrijednosti. Rezultati su pokazali da su se projektirane vrijednosti savijanja (f_b) kretale u rasponu od 2 do 26 MPa za lamelirane grede te od 6 do 15 MPa za grede od cjelovitog drva. Projektirane vrijednosti smicanja varirale su od 0,29 do 0,67 MPa za lamelirane grede te od 1,8 do 2,58 MPa za grede od cjelovitog drva. Za grede od drva D. panamensis izmjerene su veće vrijednosti ispitivanih svojstava nego za grede od drva H. alchorneoides. Konačno, utvrđeno je da su lamelirane grede pokazale bolja svojstva savijanja i veće projektirane vrijednosti od greda od cjelovitog drva, što rezultira većim vrijednostima raspona kada se rabe na podu ili krovu.

KLJUČNE RIJEČI: *tropske vrste; savijanje; smicanje; mezanin; lamelirana greda; cjelovito drvo*

1 INTRODUCTION
1. UVOD

Costa Rica is a small Central American country currently characterized by the conservation of its natural resources, especially natural forests (Allen and Vásquez, 2017). However, the country has gone through several stages in the harvesting of natural forests, and the most critical point occurred in the 1980s, when forest cover decreased to critical levels (Stan and Sanchez-Azofeifa, 2019). The selective harvesting of natural forests resulted in the production of bigger logs (Johns, 1988), where large cross section lumber was obtained (Bello, 2020). In the market, lumber for furniture fabrication could be find with dimensions of 2.5 cm thickness, over 40 cm in width and length over 3.36 meters, while in the case of timber, the dimensions could be 10 cm in thickness, over 15 cm in width and length of up to 5.5 m. Thus, before the 1980s, buildings (houses and buildings) were characterized by the use of wood in all elements of high structural demand, such as beams and columns (Serrano-Montero and Moya, 2011).

After this critical period, the government encouraged reforestation programs through forestry incentives, with the aim to reduce the pressure on natural forests and to increase a source of sawlog supply for the country (Quesada-Mateo and Solis-Rivera, 1990). These programs were maintained for several years, resulting in the fact that commercial plantations currently supply 60 % of the volume of sawlogs consumed in Costa Rica (Ugalde, 2021). Throughout this process, about 20 forest species have shown adequate results in terms of growth and production. So, farmers have accepted many species to establish commercial plantations (Nichols and Vanclay, 2012). Fast-growing species, with rotation periods of less than 25 years, such as *Dipteryx panamensis*, *Terminalia amazonia*, *Vochysia guatemalensis, Cordia alliodora* and *Hieronyma alchorneoides* (native species) *and Tectona grandis, Cupressus lusitanica, Acacia mangium* and *Gmelina arborea* (exotic species), have been extensively studied (Petit and Montagnini, 2006) and have shown excellent results in forest plantations in Costa Rica (Petit and Montagnini, 2006; Nichols and Vanclay, 2012). However, it has been observed that most of the above species are concentrated in moderate density wood, used as lumber for furniture manufacturing (Moya *et al*., 2021).

D. panamensis (almendro) and *H. alchorneoides* (pilon) are two species used in reforestation programs due to their high specific gravity and therefore their high values in structural properties. However, three main problems have been identified in wood from forest plantations: (i) presence of warp during sawmilling process, (ii) high incidence of drying defects in the drying process and (iii) lack of product development for marketing. The first two have been recently addressed by Moya *et al*. (2021) and Moya and Tenorio (2021). The lack of products for the commercialization of these species is associated with two aspects: (i) they have a density greater than 0.5 g/cm^3, so they are classified as high-density timber, and consequently they cannot be used in the manufacture of furniture and pallets fabrication, which are the main markets for plantation sawlog, and (ii) the other most influential aspect is that the heartwood color of plantation timber has lighter color in relation to natural forest wood (Moya and Tenorio, 2021; Moya *et al*., 2021).

D. panamensis and *H. alchornoides* are classified as high wood density considering their characteristics of trees from natural forests in Costa Rica (Moya *et al*., 2021). The wood from these trees has an established market and is used for the construction of trusses, floors and columns to support walls, bridges, and truck, among others, that is, in uses where there is an important demand for structural strength (Moya and Tenorio, 2021). However, wood from trees growing in fast growth plantations showed a decreasing trend in specific gravity in relation to wood from natural forests (Senft *et al*., 1985). However, this decrease should not be a problem for plantation wood to be introduced in the same market sector established for wood from trees from natural forest (Moya *et al*., 2021).

One way to mitigate the limitations of these species is to develop new processing options and not only to minimize problems during the sawing or drying process (Moya *et al*., 2021, Moya and Tenorio, 2021 and 2022). It is also vital to develop highly engineered products that would enable wood from these species growing in fast growth plantation to competitively enter new markets (Zobel, 1981). A good example is the fabrication of glued laminated timber beams (Moody and Hernandez, 1997). This type of product is manufactured with laminates of limited thickness, with a certain degree of structural grading of its layers, and glued with structural adhesives (Kitek Kuzman *et al*., 2010), but may present some differences in structural values in relation to solid wood (Falk and Colling, 1995). For example, elements in compression are of higher strength, but in bending test show a higher modulus of elasticity and a lower shear strength than solid timber beams (Ndong Bidzo *et al*., 2021).

Although glued laminated timber beams and solid timber beams are produced from wood of relatively uniform quality, variations are always present (Moody and Hernandez, 1997), so they need to be standardized in order to establish different design values (Morin-Bernard *et al*., 2021). Thus, the present work aims to study the behavior of solid timber beams and glued laminated timber beams made of *D. panamensis* and *H. alchorneoides* wood from fast growth plantations in two cross sections (2 cm × 10 cm and 2 cm ×15 cm) and stablish the design values in bending test.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Site and characteristics of the plantation
2.1. Položaj i obilježja plantaže

Two fast-growth plantations were sampled: one of *H. alchorneoides* and another of *D. panamensis*. At the time of sampling, the *H. alchorneoides* plantation was 12 years old and had a density of 450 trees/ha, while the *D. panamensis* plantation was 16 years old and had a density of 550 trees/ha. More details on the characteristics of the plantations can be found in Moya and Tenorio (2021) and Moya *et al*. (2021).

2.2 Sampling and sawing trees
2.2. Uzorkovanje i piljenje stabala

Approximately 70 trees of each species were sampled, close to the average diameter of each plantation, 19.7 cm for *H. alchorneoides* and 17.9 cm for *D. panamensis*. Half of the logs were sawn using a typical cutting pattern for timber production in Costa Rica (Serrano-Montero and Moya, 2011), where a semi-log was obtained, which was sawn into 2.5 cm thick timber (Figure 1a). From the other half of the logs, a 6.2 cm thick central block was obtained across the width of the log (Figure 1b). Logs were sawn using a band saw and a single-cut resaw. The 2.5 cm and 6.2 cm timber were dried using a drying schedule proposed by Moya and Tenorio (2022).

2.3 Timber dimension and beam fabrication
2.3. Dimenzije drvene građe i izrada greda

The timber was dried using the drying schedule proposed by Moya and Tenorio (2022) with a target moisture content of 12 %. Extensive details of the drying process for the two species can be found in Moya and Tenorio (2022). After drying, timber of 2.5 cm in thickness was planed to 2 cm × 6.5 cm × 270 cm, while timber of 6.2 cm was planed to 5.0 cm. Two type of timber beams (solid and glued laminated) were prepared with length of 270 cm of two different cross dimensions: (i) 5 cm × 10 cm and (ii) 5 cm × 15 cm. For solid timber beams, the dried timber with 5 cm in thickness was cut to the width of 10 cm and 15 cm. From each cross-section, 15 solid timber beams were prepared. Meanwhile, glued laminated timber beams were fabricated in two cross sections and a length of 270 cm: (i) 5 cm × 10 cm

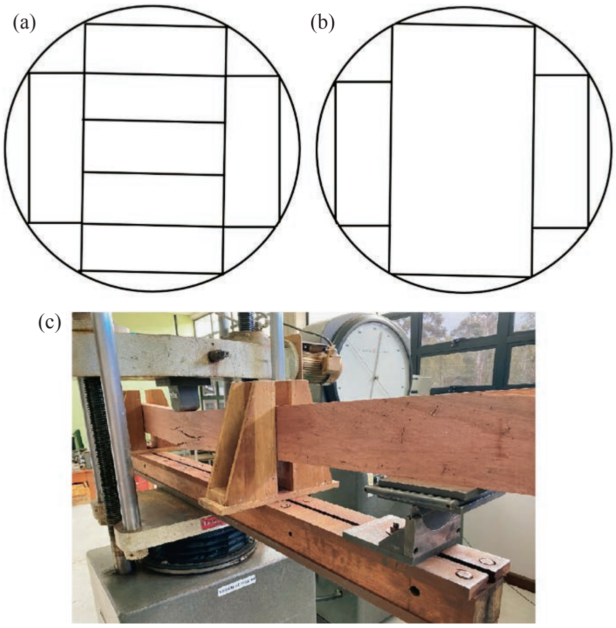

Figure 1 Sawing pattern used for obtaining 2.5 cm thickness for fabricating glued laminated timber beams (a), sawing patter used for obtaining 6.2 cm thick solid timber beams (b) and three-point bending test (c)
Slika 1. Način piljenja za dobivanje 2,5 cm debelih elemenata za izradu lameliranih greda (a), način piljenja za dobivanje 6,2 cm debelih elemenata za izradu greda od cjelovitog drva (b) i ispitivanje savijanja u tri točke (c)

with 6 lamellas of 20 cm in thickness and (ii) 5 cm × 15 cm with 8 lamellas of 20 mm in thickness. A total of 15 glued laminated timber beams were constructed for each cross section, for a total of 60 beams (2 different types of beams × 2 cross-sections × 15 beams). Advantage EP-950A® isocyanate polymer emulsion (EPI)+catalyst 200 Franklin® (isocyanate polymer) adhesive system (Franklin Adhesives and Polymers, OHIO, USA) was used. The adhesive was applied at a weight of 200 g/m^2 on one side of lamellas. The lamella was placed on a balance and the required amount of adhesive was applied with micropore rollers. The pressing was performed with an ITALPRESSE PL/9/SCF/8 hydraulic press (Italpresse S.A., Bergamo, Italy), at a pressure of 8.0 MPa for 3600 s.

2.4 Bending test
2.4. Ispitivanje savijanja

The solid and glued laminated timber beams were tested by three-point static bending test over a span of 2.10 m as shown in Figure 1c. Testing was conducted with a Tinus Olsen Super L universal testing machine, with the capacity of 60 tons. The test conditions, load speed and deflection determination were compliant with ASTM D198-21a (ASTM, 2021a). A displacement sensor (LVDT) was placed at the center of the beam under the king post, to measure the vertical displacement at the time of load application, then load and displacement were measured each 30 µs. From the results of these tests, the modulus of elasticity (*MOE*) and modulus of rupture (*MOR*) were determined using Eq. 1 and 2, respectively. The shear stress (τ) in bending was determined according to Eq. 3.

$$MOE = \frac{0.852 \cdot F_{LP} \cdot L^3}{48 \cdot I \cdot y}\ (\text{GPa}) \qquad (1)$$

$$MOR = \frac{F_{max} \cdot L \cdot \frac{H}{2}}{6 \cdot I} \cdot 0.0981\ (\text{MPa}) \qquad (2)$$

$$\tau(\text{MPa}) = \frac{3 \cdot F_{max}}{4 \cdot b \cdot H} \cdot 0.0981 \qquad (3)$$

Where: F_{LP} – load at proportional limit (kgf), F_{max} = rupture load (kgf), L – span (cm), I – moment of inertia (cm^4) for rectangular form, y – deflection (cm), b – beam width, H – beam depth (cm), 0.0000981 conversion units from kgf/cm^2 to GPa and 0.0981 – conversion units from kgf/cm^2 to MPa, and 0.852 is derived from general equation for *MOE* for one load (Eq. 3).

In addition, the type of failure that occurred in the two types of beams was determined. For glued laminated timber beams, the type of failure was first categorized according to the location of the failure in the lamina number, with L1 being the lamina where the load is applied and Ln being the lamina farthest away from the load; it was L6 for the 10 cm high beams and L8 for the 15 cm high beams (Figure 2a-b). Second, it was determined if the failure was due to delamination (Figure 2c), which refers to the separation of the glue-line between two lamellae, or if any lamellae that make up the beam failed; this type of failure can be of two types: tension and shear (Figure 2d-e). Meanwhile, for solid timber beams, 5 types of failure were established according to ASTM D-143 standards (ASTM, 2021b): simple tension (Figure 2f), cross-grain tension (Figure 2g), splintering tension (Figure 2h), brash tension (Figure 2i) and horizontal sheer (Figure 2j).

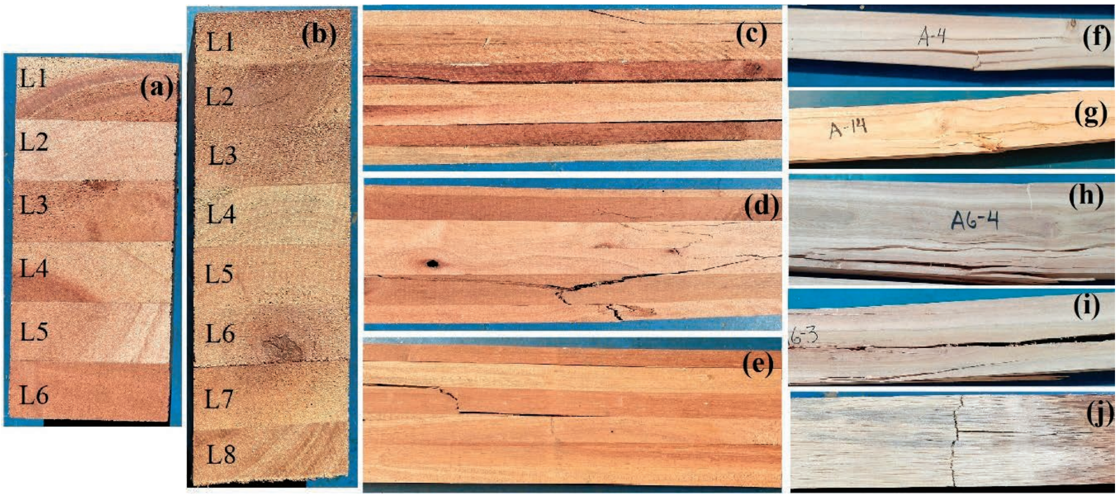

Figure 2 Number of laminates in glued laminated timber beams of 5 cm × 10 cm (a) and 5 cm × 15 cm (b), types of failures in glued laminated timber beams: delamination of glued line (c) and failure in lamina by tension (d) or shear (e), and failure in solid timber beams: simple tension (f), cross-grain tension (g), splintering tension (h), brash tension (i), and horizontal sheer (j) in static bending

Slika 2. Broj lamela u lameliranim gredama presjeka 5 cm × 10 cm (a) i 5 cm × 15 cm (b). Vrste lomova u lameliranim gredama: lom po ljepilu (c) i lom po lameli zbog napetosti (d) ili smicanja (e); vrsta loma u gredama od cjelovitog drva: jednostavna napetost (f), napetost u poprečnom presjeku (g), cijepanje (h), trzajna napetost (i) i horizontalni pomak pri statičkom savijanju (j).

2.5 Density, moisture content and stress in shear parallel to grain
2.5. Gustoća, sadržaj vode i smično naprezanje u smjeru vlakanaca drva

Following bending tests, a 5-cm cross-section was extracted from each beam. Its volume and weight were measured, and density (kg/m^3) was calculated. Then, the sample was oven-dried at 103 °C for 24 hours, and moisture content was determined. Density value was later used to calculate the total weight of the beam. Glue line test was used for determining stress in shear parallel to the grain in glued laminated timber beam and shear resistance of solid timber beam. A sample of approximately 20 cm length was taken from each beam, from a section away from the failure area. From this, two samples of 6.5 cm in length were extracted (60 samples in total) and tested according to ASTM D905 (ASTM, 2021c) for glued laminated timber beam (30 samples) and ASTM D143 (2021b) for solid timber beam (30 samples).

2.6 Derivation of design values
2.6. Deriviranje projektiranih vrijednosti

Design values were derived from *MOE* and *MOR* values of glued laminated timber and solid timber beams tested in bending test, and its applicability will be shown as beam in flexion applications. In the derivation of design values, the beam was structurally analyzed in two different ways: (i) bending capacity, and (ii) deflection in the span. For bending capacity, the superimposed load in different spans was determined, considering only maximum stress of the transverse section.

For the derivation of the design values, a normal distribution of the *MOR* and *MOE* obtained for each type of beam was assumed. Then using the t-student statistical distribution function, the basic stress LRFD is obtained according to Eq. 4 and transformed into ASD stress by applying Eq. 5. This step was not performed for the *MOE* because it was not necessary. Next, the nominal bending strength (ΦMn), nominal shear strength (ΦVn) and bending stiffness (*EI*) were calculated, considering Eqs. 6, 7 and 8, respectively.

$$F_{\mathrm{LRFD}} = \overline{X} \cdot \left(1 - t_{\mathrm{f}} \cdot \frac{CV}{100}\right) \tag{4}$$

$$F_{\mathrm{ASD}} = \frac{F_{\mathrm{LRFD}}}{K_F \cdot \phi} \tag{5}$$

$$\Phi Mn = f_{\mathrm{b}} \cdot S \cdot K_{\mathrm{F}} \cdot \phi \tag{6}$$

$$\Phi Vn = \frac{2}{3} \cdot f_{\mathrm{v}} \cdot A \cdot K_{\mathrm{F}} \cdot \phi \tag{7}$$

$$EI = MOE \quad I \tag{8}$$

Where: $\overline{X}$ – average value of data, CV – coefficient of variation of data (percentage), t_f – *t*-Student factor for a 95 % exclusion level according to sample size, K_{F} – format conversion factor, according to NDS 2018 (American Wood Council, 2018), 2.54 for flexure and 2.88 for shear, Φ - strength reduction factor, according to Seismic Code of Costa Rica 2010 revision 2014 (CIFA, 2011; INTECO, 2011), which in this case was 0.85 for bending and 0.75 for shear, f_b – bending design values, S – elastic section modulus, f_v – shear design values, A – cross-sectional area, E – *MOE* determined in Eq. 1, I – moment of inertia and EI – bending stiffness.

Subsequently, the maximum capacity in terms of overload (distributed load per unit area, w) in supported flexure was calculated, varying span length (L) and the separation between beams (sep) using Eqs. 9, 10 and 11. From these three calculated values, the lowest one was selected by safety factor, which is the one that determines the design values.

$$w = \frac{8 \cdot \Phi Mn}{sep \cdot L^2} \tag{9}$$

$$w = \frac{384 \cdot Y \cdot EI}{5 \cdot sep \cdot L^4} \tag{10}$$

$$w = \frac{2 \cdot \Phi Vn}{sep \cdot L} \tag{11}$$

Where: ΦMn – nominal bending strength, Y – maximum allowable deflection (L/240), EI – product of modulus of elasticity and the second moment of area and ΦVn – nominal shear strength.

2.7 Statistical analysis
2.7. Statistička analiza

One-way ANOVA was applied to mechanical parameters in flexure test (load and deflection at proportional limit, maximum load, *MOR* and *MOE*) and maximum stress in shear test - the physical parameters (density, *MC* and *WA*). The Tukey test was used to test the mean difference at a level of significance of $p<0.01$ per species and each type of beams. The SAS 8.1 statistics program for Windows (SAS Institute Inc., Cary, N.C., USA) was used to carry out the analyses.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Density and moisture content
3.1. Gustoća i sadržaj vode

Figure 3 presents the *MC* and density values obtained for the two species by cross section and type of beam. The *MC* was higher in the glued laminated timber beams for both species and cross section of beams, except for the 5 cm × 10 cm cross section of *D. panamensis* (Figure 3a). Wood density of the solid beams of both species presented the highest values, except for 5 cm × 10 cm cross section of *D. panamensis*, which showed no differences between the two types of beams. In addition, the beams manufactured with *D. panamensis* timber (solid and laminated) had higher wood density in relation to the beams of *H. alchorneoides* (Figure 3b).

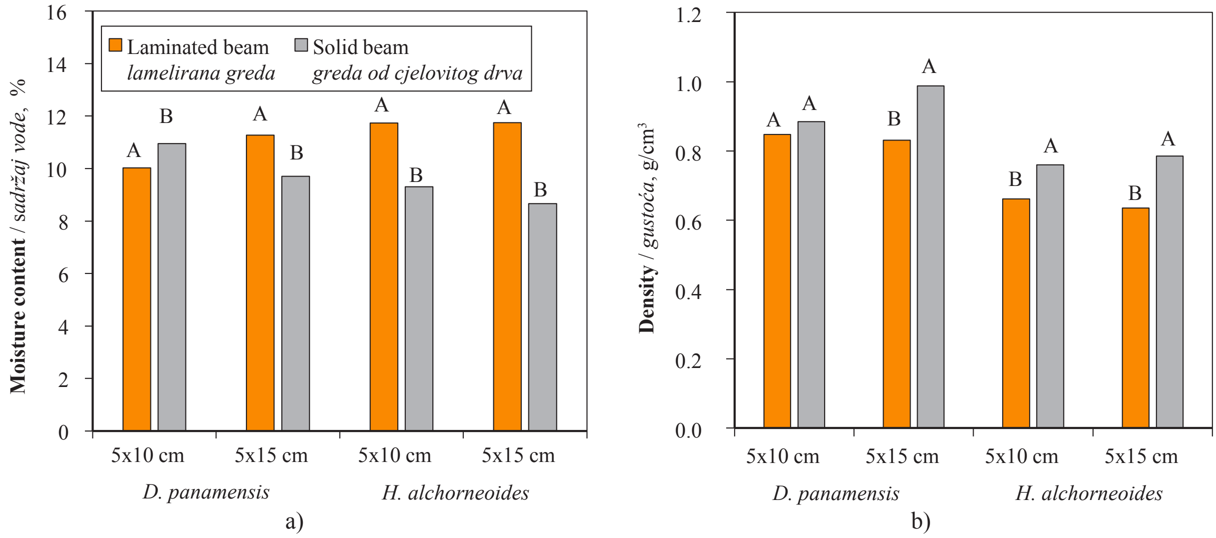

Figure 3 Moisture content (a) and density (b) of laminated and solid beams made of *D. panamensis* and *H. alchorneoides* timber
Slika 3. Sadržaj vode (a) i gustoća (b) lameliranih greda i greda od cjelovitog drva *D. panamensis* i *H. alchorneoides*

3.2 Bending and shear test
3.2. Ispitivanje na savijanje i smicanje

In the bending test for *D. panamensis,* no statistical differences were observed between laminated timber and solid timber beams in 5 cm × 10 cm cross section in terms of load at LP and deflection, but statistical differences were observed in terms of maximum load, with the glued laminated timber beams showed the highest values (Table 1). For cross sections of 5 cm × 15 cm of the same species, it was observed that there were statistical differences between the two types of beams, in the three parameters evaluated, where the solid timber beams showed the highest values (Table 1). In the case of *H. alchorneoides*, for 5 cm × 10 cm in cross section, differences were observed in load at *LP* and deflection at *LP*, where the solid timber beams showed the highest value; in the case of maximum load, no statistical differences were observed between

Table 1 Statistical values obtained in bending test for glued laminated timber and solid timber beams made of *D. panamensis* and *H. alchorneoides* timber
Tablica 1. Statističke vrijednosti dobivene ispitivanjem na savijanje lameliranih greda i greda od cjelovitog drva *D. panamensis* i *H. alchorneoides*

Specie *Vrsta*	**Parameter** / *Parametar*		**Type of beam** / *Vrsta grede*			
			5 cm × 10 cm cross section *Presjek* 5 cm × 10 cm		**5 cm × 15 cm cross section** *Presjek* 5 cm × 15 cm	
			Glued laminated timber *Lamelirano drvo*	**Solid timber** *Cjelovito drvo*	**Glued laminated timber** *Lamelirano drvo*	**Solid timber** *Cjelovito drvo*
D. panamensis	Load at PL *opterećenje pri PL*	Average (kN)	8.38^{A}	9.04^{A}	10.84^{B}	32.43^{A}
		SD (kN)	2.84	4.17	4.61	14.73
		CV (%)	33.82	46.16	42.47	45.42
	Deflection at PL *deformacija pri PL*	Average (mm)	35.20^{A}	43.73^{A}	20.58^{B}	64.86^{A}
		SD (mm)	7.55	15.46	7.29	14.40
		CV (%)	30.74	35.36	35.41	22.20
	Maximum load *maksimalno opterećenje*	Average (kN)	17.81^{A}	12.83^{B}	24.96^{B}	35.69^{A}
		SD (kN)	4.73	4.99	7.63	13.19
		CV (%)	26.56	38.91	30.56	36.97
H. alchorneoides	Load at PL *opterećenje pri PL*	Average (kN)	5.47^{B}	12.67^{A}	7.38^{B}	30.08^{A}
		SD (kN)	2.27	4.16	4.02	6.64
		CV (%)	41.49	32.80	54.49	22.06
	Deflection at PL *deformacija pri PL*	Average (mm)	20.48^{B}	56.90^{A}	17.28^{B}	63.00^{A}
		SD (mm)	7.54	11.97	8.18	9.49
		CV (%)	36.83	21.03	47.36	15.06
	Maximum load *maksimalno opterećenje*	Average (kN)	11.03^{A}	14.18^{A}	16.27^{B}	31.95^{A}
		SD (kN)	4.05	4.57	7.70	7.62
		CV (%)	36.75	32.24	47.33	23.84

Note: *PL* – proportional limit / *granica proporcionalnosti*, *SD* – standard deviation / *standardna devijacija*, *CV* – coefficient of variation / *koeficijent varijacije*

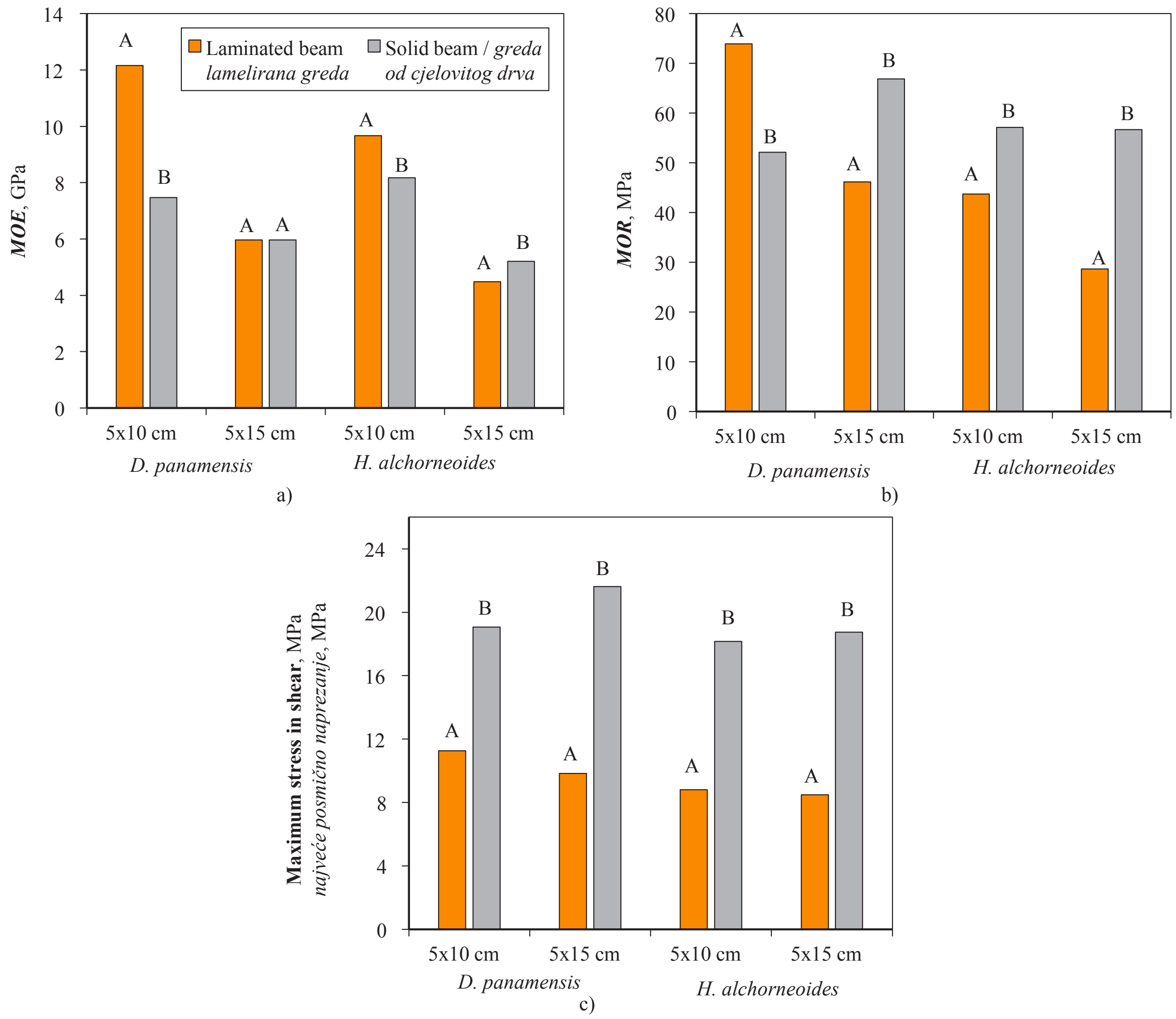

Figure 4 *MOE* (a) and *MOR* (b) obtained in bending test and maximum stress in shear parallel to grain (c) for glued laminated timber and solid timber beams made of *D. panamensis* and *H. alchorneoides* timber
Slika 4. *MOE* (a) i *MOR* (b) dobiveni pri ispitivanju savijanja i najvećega posmičnog naprezanja u smjeru drvnih vlakanaca (c) lameliranih greda i greda od cjelovitog drva *D. panamensis* i *H. alchorneoides*

the two types of beams (Table 1). For the 5 cm × 15 cm in cross section, there were differences in the three parameters evaluated, where the solid timber beams showed the highest values in relation to the glued laminated timber beams (Table 1).

Figure 4 presents the *MOE* and *MOR* values obtained for the bending test for the beams of the two species. For *D. panamensis* in cross section of 5 cm × 10 cm, the glued laminated timber beams showed the highest *MOE* value, while for 5 cm × 15 cm in cross section there were no statistical differences in *MOE* (Figure 4a). For *H. alchorneoides*, the glued laminated timber beams showed the highest *MOE* in cross section of 5 cm × 10 cm, while the lowest value of MOE was observed in the cross section of 5 cm × 15 cm (Figure 4a). As for the *MOE*, the solid timber beams showed the highest values for the two species and cross sections of beams, except for the 5 cm × 10 cm cross section of *D. panamensis,* where the glued laminated timber beams showed the highest value (Figure 4b).

In the load vs. deflection curves obtained in the bending test, it is observed that for both species at the same deflection value, the 5 cm × 15 cm cross section beams for solid wood and glulam beams show the highest load value, followed by the 5 cm × 10 cm cross section beams for glued laminated timber and solid wood beams (Figure 5). In addition, it is observed that the beams made of *D. panamensis* wood show higher load values in relation to the beams made of *H. alchorneoides* for the same deflection (Figure 5). Regarding the maximum stress in the shear test parallel to the grain, it was observed that the solid timber beams showed the highest values for the beams of two species and two cross sections used (Figure 4c).

3.3 Types of failures
3.3. Vrste lomova

Due to the different configurations of the two types of beams, the types of failures were different (Table 2). In the case of the solid timber beams, the type of

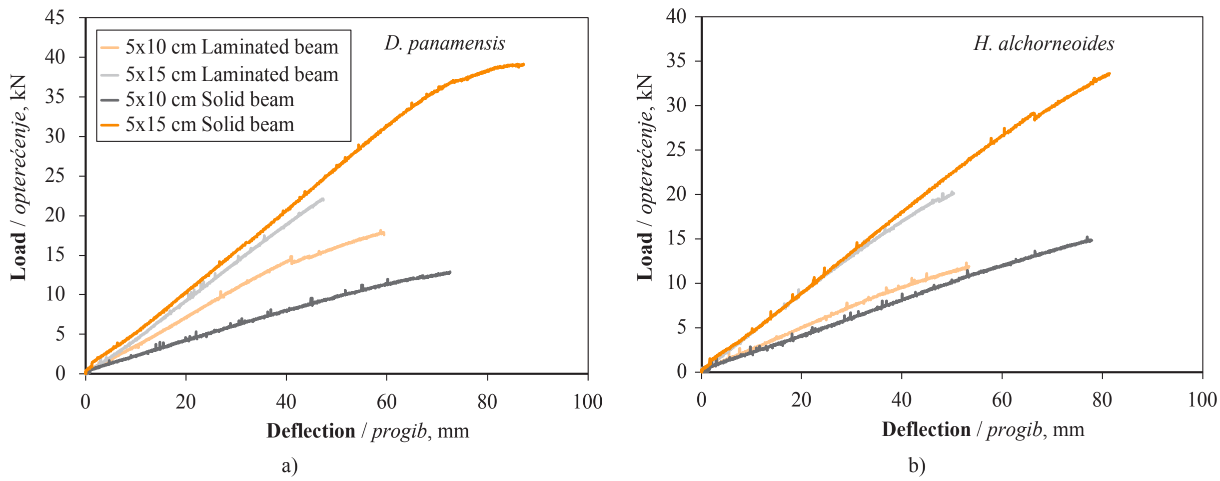

Figure 5 Average load versus deflection plots obtained in bending test for glued laminated timber and solid timber beams made of *D. panamensis* and *H. alchorneoides* wood
Slika 5. Grafički prikazi prosječnog opterećenja s obzirom na progib, dobiveni ispitivanjem na savijanje lameliranih greda i greda od cjelovitog drva *D. panamensis* i *H. alchorneoides*

failure was different by species and cross section (Table 2). Horizontal shear was the most frequent type of failure in the solid timber beams made of *D. panamensis* of 5 cm × 10 cm in cross section, followed by simple failure and cross-grain tension, while in the 5 cm × 15 cm beams, horizontal shear and splintering tension showed the highest percentages. In the solid timber beams made of *H. alchorneoides*, cross-grain and splintering tension failure were the most frequent in the 5 × 10 cm dimension, while the splintering tension failures were the most frequent in the beams of 5 × 15 cm in cross section, followed by cross-grain and simple tension failure (Table 2).

Typical failures of solid timber beams are those involving tension (cross-grain, splintering or simple tension) (Nadir and Nagarajan, 2014), as occurred in two species and two cross sections of beams tested (Table 2). According to Conrad *et al.* (2003), the lack of ductility between fibers in solid timber beams causes the beam to fail in tension, as evidenced by the results of the solid timber beams in the present study.

In the case of glued laminated timber beams, delamination was the most frequent failure in the beams made of *D. panamensis* of two cross sections tested and in cross section of 5 cm × 15 cm of *H. alchorneoides*, followed by tensile failure in these dimensions. In cross section of 5 cm × 10 cm of beams made of *H. alchorneoides*, tension failure was the most frequent failure (Table 2). This behavior was different from that found by Nadir and Nagarajan (2014) for

Table 2 Percentage of presence of different types of failure for glued laminated timber and solid timber beams of *D. panamensis* and *H. alchornoides*
Tablica 2. Postotak različitih vrsta loma za lamelirane grede i grede od cjelovitog drva *D. panamensis* i *H. alchorneoides*

Type of beam *Vrsta grede*	**Type of failure, %** *Vrsta loma, %*	***D. panamensis* beam** *Greda od D. panamensis* **5 cm×10 cm cross section** *Presjek* 5 cm×10 cm	***D. panamensis* beam** *Greda od D. panamensis* **5 cm×15 cm cross section** *Presjek* 5 cm×15 cm	***H. alchorneoides* beam** *Greda od H. alchorneoides* **5 cm×10 cm cross section** *Presjek* 5 cm×10 cm	***H. alchorneoides* beam** *Greda od H. alchorneoides* **5 cm×15 cm cross section** *Presjek* 5 cm×15 cm
Solid *greda od cjelovitog drva*	Cross-grain tension *napetost u poprečnom presjeku*	14.3	20.0	46.7	26.7
	Horizontal shear *horizontalni pomak*	57.1	40.0	0.0	6.7
	Simple tension / *jednostavna napetost*	28.6	0.0	6.7	26.7
	Brash tension / *trzajna napetost*	0.0	0.0	6.7	0.0
	Splintering tension / *cijepanje*	0.0	40.0	40.0	40.0
Glued laminated *lamelirana greda*	Delamination / *delaminacija*	58.3	90.9	0.0	64.3
	Delamination and shear *delaminacija i pomak*	0.0	0.0	0.0	7.1
	Shear / *pomak*	0.0	9.3	14.3	0.0
	Tension / *napetost*	41.7	0.0	85.7	14.3
	Tension and shear / *napetost i pomak*	0.0	0.0	0.0	14.3

glued laminated timber beams of rubber wood tested in flexure, where tensile was the most frequent type of failure, while delamination was the least frequent. In this regard, these authors explain the different types of failures that occur in glued laminated timber beams tested in flexure and this may explain the results of the present study:

Due to the different configurations of the two types of beams, the types of failures were different (Table 2). In the case of solid timber beams, the type of failure was different by species and cross sections (Table 2). Horizontal shear was the most frequent type of failure in the solid timber beams of *D. panamensis* of 5 cm × 10 cm cross section, followed by simple failure and cross-grain tension, while in the 5 cm × 15 cm beams, horizontal shear and splintering tension were the most frequent failures. In the solid timber beams of *H. alchorneoides*, cross-grain and splintering tension failure were the most frequent failures in the 5 cm × 10 cm dimension and splintering tension failures were the most frequent in the beams of 5 cm × 15 cm cross sections, followed by cross-grain and simple tension failure (Table 2).

Typical failures of solid timber beams are those involving tension (cross-grain, splintering or simple tension) (Nadir and Nagarajan, 2014), as occurred in two species and two cross sections of beams tested (Table 2). According to Conrad *et al*. (2003), the lack of ductility between fibers in solid timber beams causes the beam to fail in tension, as evidenced by the results of the solid timber beams in the present study.

In the case of glued laminated timber beams, delamination is the most frequent type of failures in the beams of *D. panamensis* of two cross sections tested and in cross section of 5 cm × 15 cm of *H. alchorneoides*, followed by tensile failure in these dimensions. In the cross section of 5 cm × 10 cm of *H. alchorneoides*, tension was the most frequent failure (Table 2). This behavior is different from that found by Nadir and Nagarajan (2014) for glued laminated timber beams of rubber wood tested in flexure, where tensile was the most frequent type of failure, while delamination was the least frequent. In this regard, these authors explain the different types of failures that occur in glued laminated timber beams tested in flexure and this may explain the results of the present study:

i. A delamination failure in glued laminated timber beams can occur when there is a defectively glued area within the lamella, as then the cracks start to propagate through the adhesive surface. However, when a very strong glued area appears, it passes through the wood and another type of failure occurs (Nadir and Nagarajan, 2014). Thus, the results of high occurrence of delamination failure (Table 2) in the beams of *D. panamensis* of two cross sections tested and in *H. alchorneoides* beams of 5 cm × 15 cm cross section indicate that these lamellae had problems of adhesion between the lamellae.
ii. Tensile failure is the type of failure that is expected to occur and occurs when the joints are perfectly bonded and there are few defects in the timber that could have an adverse effect on the laminates. This results in failures starting from bottom lamina and spreading to the top (Nadir and Nagarajan, 2014). Finally, the *H. alchorneoides* beams of 5 cm × 10

Table 3 Design values for glued laminated timber and solid timber beams made of *D. panamensis* and *H. alchorneoides* wood
Tablica 3. Projektirane vrijednosti za lamelirane grede i grede od cjelovitog drva *D. panamensis* i *H. alchorneoides*

Species / *Vrsta drva*	**Type of beam** / *Vrsta grede*		f_v, **MPa**	f_b, **MPa**	***MOE*, GPa**
D. panamensis	5 cm × 10 cm	Glued laminated timber / *lamelirano drvo*	0.67	17.61	5.41
		Solid timber / *cjelovito drvo*	2.58	6.24	4.37
	5 cm × 15 cm	Glued laminated timber / *lamelirano drvo*	0.29	9.83	4.99
		Solid timber / *cjelovito drvo*	1.81	6.22	2.14
H. alchorneoides	5 cm × 10 cm	Glued laminated timber / *lamelirano drvo*	0.34	6.94	7.27
		Solid timber / *cjelovito drvo*	2.43	11.07	5.81
	5 cm × 15 cm	Glued laminated timber / *lamelirano drvo*	0.39	2.16	3.58
		Solid timber / *cjelovito drvo*	1.80	15.42	4.36

Table 4 Design values for glulam and solid wood beams made of *D. panamensis* and *H. alchorneoides*
Tablica 4. Projektirane vrijednosti lameliranih greda i greda od cjelovitog drva *D. panamensis* i *H. alchorneoides*

Species / *Vrsta drva*	**Type of beam** / *Vrsta grede*		ΦMn, **kN·m**	ΦVn, **kN**	EI, **kN·m^2**
D. panamensis	5 cm × 10 cm	Glued laminated timber / *lamelirano drvo*	3.17	4.85	22.56
		Solid timber / *cjelovito drvo*	1.12	18.55	18.22
	5 cm × 15 cm	Glued laminated timber / *lamelirano drvo*	3.98	3.13	70.16
		Solid timber / *cjelovito drvo*	2.52	19.57	30.13
H. alchorneoides	5 cm × 10 cm	Glued laminated timber / *lamelirano drvo*	1.25	2.46	30.28
		Solid timber / *cjelovito drvo*	1.99	17.48	24.20
	5 cm × 15 cm	Glued laminated timber / *lamelirano drvo*	0.87	4.24	50.38
		Solid timber / *cjelovito drvo*	6.24	19.44	61.29

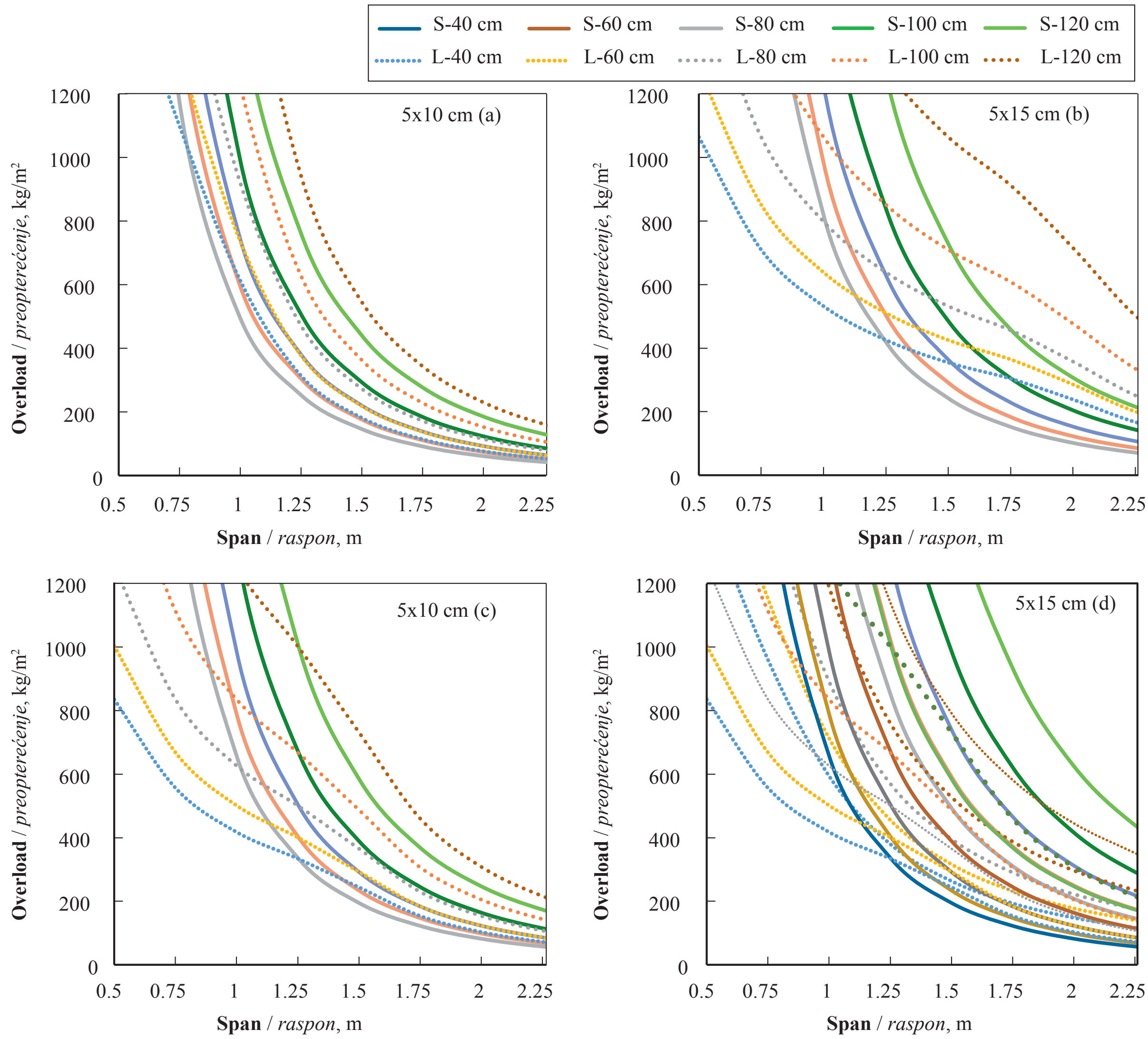

Figure 6 Overload vrs span for glued laminated timber and solid timber beams made of *D. panamensis* (a and b) and *H. alchorneoides* (c and d) wood
Slika 6. Preopterećenje u odnosu prema rasponu za lamelirane grede i grede od cjelovitog drva *D. panamensis* (a i b) te *H. alchorneoides* (c i d)

cm cross section, where tension was the most frequent type of failure (Table 2), was the type of beam made ofout problems of laminate adhesion and therefore only normal failures occurred.

3.4 Derivation of design values
3.4. Deriviranje projektiranih vrijednosti

Table 3 shows the f_v, f_b and *MOE* parameters derived from the bending tests of the two types of beams. These values were used to determine the maximum allowable length for each beam at *ΦMn*, *ΦVn* and *EI*, respectively. The results obtained first show that the two types of beams made of *D. panamensis* timber have higher values than the beams made of *H. alchorneoides* timber in some parameters, while some other parameters are lower than those of the beams made of *H. alchorneoides* timber (Table 3 and 4), meaning that both species have similar structural properties. It is also observed that solid timber beams have higher values of fv than those of glued laminated timber beams (Table 3). However, the fb parameter is higher in glued laminated timber beams than in solid timber beams. In the case of the MOE parameter, there is a tendency of higher values for glued laminated timber beams, except for the 5 cm × 15 cm cross section.

With respect to the nominal bending strength (*ΦMn*), the two species and different cross sections of the beams show different behavior (Table 4). In the beams of *D. panamensis,* the glued laminated timber beams showed higher values than the solid timber beams. However, the behavior of *H. alchorneoides* beams was quite the opposite as the solid timber beams showed higher values of *ΦMn*. As to the nominal shear strength (*ΦVn*), the solid timber beams of the two tested species showed higher values than the glued laminated timber beams. The bending stiffness (*EI*) was higher in the glued laminated timber beams of *D. pana-*

mensis in two cross sections, while in the beams of *H. alchorneoides,* there is no clear trend; the glued laminated timber beams of 5 × 10 cm cross section showed the highest value of *EI*, while 5 cm × 15 cm cross section showed the lowest (Table 4).

Figure 6 represents the maximum allowable lengths and overload for the use of beams as floors with spans of 40, 60, 80, 100 and 120 cm for the two species and two cross sections of beams, commonly used in Costa Rica. For example, in solid timber beams of *D. panamensis* of 5 × 10 cm cross sections with a spacing of 60 cm and a load of 500 kg/m^2, it is necessary to use a span of approximately 1.2 m, but if the beam is fabricated in laminated form, the span increases to 1.35 m (Figure 6a). On the other hand, if the cross section of *D. panamensis* beams is 5 × 15 cm, the span for solid timber beams is 1.45 m and 1.95 m for glued laminated timber beams (Figure 6b). The same behavior was observed in the beams of *H. alchorneoides*, with the difference that the span was slightly smaller in the two cross sections of each type of beam (Figure 6c-d).

According to the classification proposed by the Andean Group for the tropical woods of South American countries, Group D can include species with basic specific gravity from 0.56 to 0.70 (Keenan *et al*., 1987). Thus, the two species studied can be classified in this species group. For the species classified in this group, design values in bending of 15 MPa for fb are presented, which in most cases is higher than the obtained results, so they are categorized in group C, since they present values close to 10 MPa, which is the range proposed by the classification for the Andean Group. This behavior and the presented overload results (Figure 6) show that glued laminated timber beams, as expected, show a better behavior in bending parameters and therefore in design values, resulting in wider span values than those used for solid timber beams (Ndong Bidzo *et al*., 2021).

4 CONCLUSIONS
4. ZAKLJUČAK

Although problems have been reported for its commercialization due to the lack of products of higher engineering value, Costa Rican plantation timbers such as *D. panamensis* and *H. alchorneoides,* whose characteristic is a high basic specific gravity, are a viable option for commercialization and fabrication of glue laminated timber beams. Such beams can become an engineered product with adequate bending design values when compared to solid timber beams or to design values used for tropical timbers of similar densities. Therefore, it is possible to reach wider spans when the proposed glued laminated timber beams are used as floors.

Other conclusions can also be derived from the present study: (1) the glued laminated timber beams made of *D. panamensis* wood show similar bending parameters as the glued laminated timber beams made of *H. alchorneoides* wood and (2) two cross sections studied for glued laminated timber beams show different values in the bending strength parameters, so for each one it is necessary to establish the design values separately.

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