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STRENGTH AND DISPLACEMENT UNDER TENSION AND COMPRESSION OF WOOD JOINTS FASTENED WITH NAILS AND SCREWS FOR USE IN TRUSSES IN COSTA RICA

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ABSTRACT

The objective of the present study is to determine the behaviour of two typical types of fastener (nails and screws) used in trusses made of *Gmelina arborea* and *Hieronyma alchorneoides* timber. Wood joints with metal fasteners (nails and screws) and five angles (0°, 30°, 45°, 60° and 90°) were subjected to tension and compression loads in order to establish values of displacement in relation to applied loads, strength, stiffness values, mode of failure and a model for prediction of stiffness for intermediate orientations. Results indicate that the differences in loads and displacements appear among species in the compression test, whereas those differences appear among fasteners in the tension test. The results obtained for stiffness indicate that jointsof*H. alchorneoides* wood present the highest values. Models for prediction of stiffness for truss joints of intermediate orientations were: $k_\theta = (k_{//} * k_\perp)/(k_{//} * \sin^{(n=a*\theta+c)} * \theta + k_\perp * \cos^{(n=a*\theta+c)} * \theta)$ in compression, while for tension the model was $(k_{//} * k_\perp)/(k_{//} * \sin^{(n=a*\theta^2+b*\theta+c)} * \theta + k_\perp * \cos^{(n=a*\theta^2+b*\theta+c)} * \theta)$.

KEYWORDS: Framing, wooden structures, wood joint, stiffness, truss joint.

INTRODUCTION

Costa Rica is a small tropical country that presents little development in the standardisation of raw materials, among which wood can be remarked (Serrano and Moya 2011). This lack of development has led to a decrease in the use of wood in civil constructions such as houses and buildings in the last ten years (Serrano and Moya 2011). Previously, the civil construction sector consumed more than 50% of the total volume of timber. However, more recent studies indicate a decrease to just 24% (ONF 2015) and it is noted that only 10% of the structures are made from wood, in contrast to nearly 90% in USA and 40-45% in Japan and England (ONF 2015).

In the past, wooden constructions in Costa Rica were characteristically of the framed type, built from 37.5 cm2 (5.0 x 7.5 cm) transversal sections that were used for structural supports of floors and walls, as well as for construction of trusses (Tuk 2010). In this type of construction, woods with density over 0.6 g.cm^{-3} were employed, serving as structural as well as ornamental elements (Malavassi 2010). For this sort of construction system several types of fasteners are employed, among which nails and screws stand out as they oppose good shear strength against lateral forces (Sawata et al. 2013).

In current times, lumber in Costa Rica has been displaced by other construction materials such as plastics, steel, concrete and other imported materials backed by significant technological advances, extensive technical information and aggressive marketing (Fournier 2008, Tuk 2010). Another aspect that has contributed to a decrease in the use of lumber in construction is the scarce technical information on the behaviour of framing-type structures as a construction system in Costa Rica (Fournier 2008).

Among framing-type structures, trusses are one component that has been broadly used in various countries, including Costa Rica, and date back to the 6th century CE (Barbariet al. 2014). In wooden trusses, the critical node of this system has the task of transmitting the thrust acting on the top chord to the tie beam by means of a post. A series of structural aspects of the truss can be observed from the action of forces present in it, such as the behaviour of displacement in relation to applied forces, strength, stiffness values and the mode of failure of the joint (Gebremedhin et al. 1992). These aspects of strength are barely known in trusses built with tropical species, especially in developing countries (Sawata et al. 2013).

Mechanisms and behaviour of fasteners used in trusses are well known in countries with an ample tradition in the use of lumber, where metal plates are normally used (Gupta 2005, Bayan et al. 2011, Bouldin et al. 2013). In developing countries, however, fasteners such as nails and screws are still employed, mainly due to their low cost (Prevatt et al. 2014).

In the study of the structural behaviour of fasteners, a series of models is generated for load-displacement (P-Δ) curves relations and for determination of strength, stiffness values and the mode of failure of the joints (Gebremedhin et al. 1992). Countries such as USA or Canada are examples of places where various standards exist for determination of the previous parameters (ASTM 2012, Canadian Standards Association-CSA S347 1980). Additionally, different test models have been developed to evaluate joints in trusses in which several standard configurations of plate and wood grain to load orientations are included (Gebremedhin et al. 1992), and they simulate actual truss joint action under axial loading conditions.

This type of joints can be analysed as finite elements and can be rigid (Triche and Suddarth 1988) or semi-rigid (Maragechi and Itani 1984). Although various methods can be employed, these have to calculate the different parameters for strength and stiffness values based upon known angles and then extrapolate these to intermediate angles (Gebremedhin et al. 1992, McCarthy and Wolfe 1987). All these models and calculation forms, however, are developed for metal plates and not for other types of metal fasteners, such as nails and screws.

In many countries, many changes have taken place in the species used for framing-type construction processes (Wolfsmayr and Rauch 2014) and there is no exception for Costa Rica (Serrano and Moya, 2011). Previously, natural forest species with densities over 0.6 g.cm^{-3} were used in this country (Malavassi 2010). Nowadays, plantation-grown lumbers supply the wood market (Serrano and Moya 2011), among which two are of special relevance: *Gmelina arborea* and *Hieronyma alchorneoides*. *G. arborea* wood has been extensively studied (Moya 2004) and possesses a series of attributes for its use with structural purposes (Tenorio et al. 2012, Moya et al. 2013). Meanwhile, the wood of *H. alchorneoides* is characterised by presenting interlocked as well as spiral grain, giving it great strength in shear and when joined with nails, screws and bolts, hence its use as a structural element (Tuk 2010). Moreover, this species has been employed for commercial reforestation in Costa Rica and the study of wood properties from plantation-grown trees has yielded high structural strength values in relation to other species (Moya et al. 2009, Tenorio et al. 2016).

Nonetheless, despite the information available on these species, lack of knowledge about their structural properties in framing-type construction processes still remains. In the face of such situation, the present work has the objective to determine joint behaviour and displacement in relation to applied forces, as well as the strength, stiffness values and the mode of failure of joints made from wood of *G. arborea* and *H. alchorneoides*, for five construction angles (0°, 30°, 45°, 60° and 90°) and two types of fastener (nails and screws), subjected to loads in tension and compression. In addition, this work proposes a model for prediction of stiffness for truss joints of intermediate orientations.

MATERIALS AND METHODS

Raw materials employed

Wood used came from *H. alchorneoides* (Allemão) and *G. arborea* (Roxb. ex Sm.) trees approximately 15 years old. Both species are widely used in civil constructions in Costa Rica (Moya 2004, Solís and Moya 2003). Wood from *G. arborea* was obtained from the sawmill Maderas S&Q 2005 (Pérez Zeledón, San José, Costa Rica) and wood from *H. alchorneoides* was provided by the company ECOCAJAS S.A. (Guápiles, Limón, Costa Rica). While green, lumber presented dimensions of 7.5 cm wide and 2.5 cm thick and was dried in an experimental oven, following the drying schedule detailed in Muñoz and Moya (2008) for *G. arborea* and the one detailed by Tenorio et al. (2016) for *H. alchorneoides*. For both species, a target moisture content of 16% was established.

Joint design and manufacturing

Wood used for joint manufacturing was 2.2 cm thick by 7.2 cm wide (nominal measurements in green condition of 2.5 and 7.5 cm, respectively), dried and non-planed at the surface for both species. Joints were designed using angles of 0°, 30°, 45°, 60° and 90° and were joined by means of two types of fastener: nails and screws (Fig. 1f). Each combination of joint was replicated 10 times. In total, 200 joints were used for the compression test and another 200 for the tension test (5 angles x 2 fastener types x 2 species x 10 repetitions).

Screws used for joints were of the flat-head Phillips type, of 50mm in length x 4.3mm in external diameter, while nails used were 51mm in length x 2.8mm diameter (Fig.1f).Ten nails or screws were used for each entire joint, five in each piece. Distribution of nails and screws was the same for both species and is shown in Fig.1a-f.

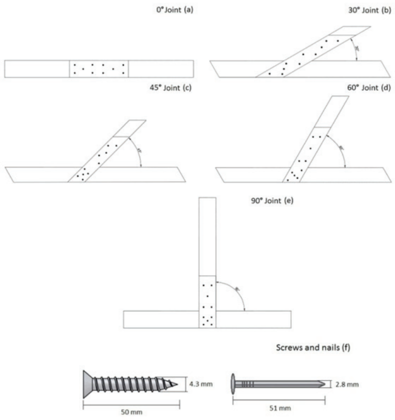

Fig. 1: Orientation of truss joint sand distribution of nails and screws and dimensions of the screws and nails used.

Joint tests and calculation of stress

Joints were tested in compression and tension. These tests were performed using a test frame device, designed specifically to receive the various joints (Fig. 2a). This device was attached to a test machine brand Tinius Olsen with a capacity of 60 tonnes. The test frame device was placed in such a way that the load was applied vertically upon the test machine (Fig. 2b). In the tension test, a mobile support was placed at the upper part of the joint (Fig. 2b), whereas in the compression test no support was needed. Each joint was placed in the test frame device by means of screws, which held it as the load was applied at a distance of approximately 33 cm from the centre of the joint, totalling a support distance of 66 cm. In both tests (compression and tension), the load was applied so that displacement of the joint followed the plane of the load, at a speed of 2mm.min^{-1}.

Tests in compression and tension were carried out utilising test conditions used by Gebremedhin et al. (1992) for similar joints fastened with dented metal plates. Additionally, in the same study, modifications were done to the test frame apparatus assembled, with the purpose of performing tests in a universal test machine. Each test took between 9 and 20 min. This lapse was consistent with ASTM D1761-06 standard, which states that failure must occur between 5 and 20 min (ASTM 2012).

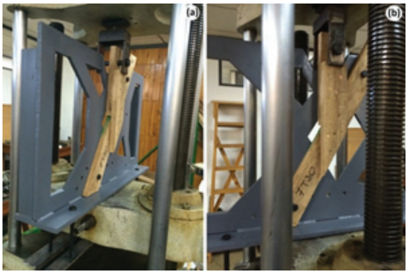

Fig.2: Test frame device employed for testing joints (a) and applying loads during tests(b).

Data analysis of tension and compression tests

During the test, values for loads and displacement of joints were recorded and then exported for their manipulation with Microsoft Excel software. In this program, a graphic of the load vs. displacement of the joint piece subjected to load (P-Δ) was made and, by means of the generated curve, the values of the load and displacement at the proportionality limit, maximum load and displacement, as well as displacement at 3.81 mm were obtained.

Once the values mentioned were determined, the calculation of design stress and critical displacement stress followed, in accordance with the procedure described in Gebremedhin et al. (1992). The design stress was calculated using Eq. 1, while critical displacement stress was calculated using Eq. 2; both equations are broadly detailed by Gebremedhin et al. (1992).

$$Design\ stress\ (MPa) = \left(\left(\frac{Maximum\ load\ (kg)}{Maximum\ displacement\ (cm)}\right)/3\right)/10.197 \tag{1}$$

$$Critical\ displacement\ stress\ (MPa) = \left(\frac{Load\ of\ 3.81\ mm\ (kg)}{0.0381\ (cm)}\right)/10.197 \tag{2}$$

After calculation of stress for every angle evaluated, calculation of intermediate stress followed. To this end, the formula described in Eq. 3 was used. This equation are broadly detailed by Gebremedhinetal (1992).

$$k_\theta = (k_{//} * k_\perp)/(k_{//} sin^n\theta + k_\perp cos^n\theta) \tag{3}$$

where: k_θ - predicted stress for an intermediate angle between 0° and 90°,
θ - angle between the applied load and grain orientation,
$k_{//}$ y $k_\perp$ - stress for angles 0° and 90°, respectively,
n - exponential factor,

In this case, exponential factors of 1 to 3.75 were utilised.

Mechanical and physical properties evaluated on lumber

Two mechanical properties (static bending and compression parallel to grain) were determined on the same dried wood used for making the joints. Samples employed for the static bending test were 5 x 5 x 78 cm, in compliance with ASTM D143-14 standard (ASTM 2014), while those used for the compression test were 2 x 2 x 6 cm, in accordance with the ASTM D143-14 standard method B (ASTM 2014). Thirty repetitions were tested for each mechanical property.

Moreover, samples were extracted from each type of joint in order to measure lumber density (mass volume $^{-1}$) and moisture content (MC) at the moment of the test. Each joint was weighed before the test and dimensions of each one of the pieces composing the joint were taken for calculation of volume. A small, 2.5 cm long sample was extracted for determination of MC. Samples were weighed (initial weight), then dried in an oven for 24 hours at 105° C and then weighed again (dry weight) in order to determine MC according to ASTM D4442-07 standard (ASTM 2007).

Statistical analysis

A descriptive analysis was developed (median, standard deviation, maximum and minimum values) for the variables involved: modulus of elasticity in bending and compression, modulus of rupture in bending and compression, moisture content, density, maximum load and load at proportionality limit, maximum displacement and displacement at proportionality limit, design stress and critical displacement stress. In addition, compliance of variables with the principles of normal distribution and homogeneity of variances was verified, as well as the presence of extreme data. A variance analysis was applied in order to confirm the existence of significant differences among the averages of variables ($P<0.05$) for each species, considering the type of fastener used (nails or screws) and the joint angle. A Tukey test was established for determination of statistical differences between the medians of the two fastener types (nails and screws) and the different angles.

RESULTS

Strength values in bending and compression and physical properties of the lumber used

In the evaluation of lumber used in construction of the various types of joints, it was found that properties of static bending and compression of *H. alchorneoides* show statistically higher MOE and MOR than those from *G. arborea* lumber (Tab. 1). Similar results are seen in the physical properties assessed, where *H. alchorneoides* lumber shows MC and density greater than those in *G. arborea* lumber (Tab. 1).

Tab.1: Mechanical and physical properties of H. alchorneoide sand G. arborealumbers used for manufacture of truss joints.

Species	Bending		Compression		Moisture content (%)	Density At %MC reported (kg.m^{-3})
	MOE (GPa)	MOR (MPa)	MOE (GPa)	MOR (MPa)		
G.arborea	64.1^{B} (21.7)	44.8^{B} (25.28)	5.8^{B} (15.2)	23.9^{B} (15.0)	12.0^{A} (13.1)	485.1^{B} (9.9)
H.alchorneoides	80.8^{A} (13.9)	68.1^{A} (15.9)	11.0^{A} (9.9)	37.1^{A} (10.1)	12.0^{A} (12.3)	541.9^{A} (25.6)

Note: MOE= modulus of elasticity; MOR=modulus of rupture; MC=moisture content. Values in parentheses correspond to the coefficient of variation of each datum. Letters and joined to a verages indicate significant statistical differences between species at 95%.

Types of failure present in joints

The various types of failure that appeared in tests for tension and compression of all five angles evaluated (0°, 30°, 45°, 60° and 90°), on both species, were mainly in the type of fastener employed (nails or screws) and no failure was observed in the lumber in any joint (Fig. 3). During realisation of the tests, it was possible to observe that in joints with nails, these did not break in applying the load; rather, they became bent (Fig. 3a-c), resulting in longitudinal cracking of the lumber in some cases (Fig. 3a). Conversely, screws of joints broke randomly (Fig. 3b-d) and, additionally, it was possible to observe separation of the joint pieces.

Fig.3: Types of fastener failure of nail sand screws in H. alchorneoides joints at 30°(aan db, respectively) and G. arborea joints at 30°(candd, respectively).

Maximum load and maximum displacement values

Maximum loads in the compression test were greater in *H. alchorneoides* (Figs. 4a-b) forall five angles evaluated of joints with nails as well as those with screws, with the exception of the 0° angle in joints with screws, wherein the maximum load was greater in *G. arborea* (Fig. 4b). In regards to joints with nails, it is possible to observe that the 0° joint shows the greater loads and, on the contrary, the 30° joint presents the lowest loads (Fig. 4a). Meanwhile, in joints with screws the greatest load appears for 90° joints and the lowest one for 0° joints in *H. alchorneoides*, where as for *G. arborea* the greatest load appears for 0° and the lowest loads for joints of 30° and 90° (Fig. 4b).

In the tension test, maximum loads were greater in *G. arborea* joints with nails for all five angles evaluated, except for the 0° angle (Fig. 3c). However, in both species the greatest loads appeared in 60° joints and the lowest in 0° joints (Fig. 4c).In the same test, when performed on joints with screws, it was observed that there appear practically no differences between species in the loads on joints of all five angles studied. It was found that 0° joints presented the highest values, while the lowest values appeared in the 90° joints (Fig. 4d).

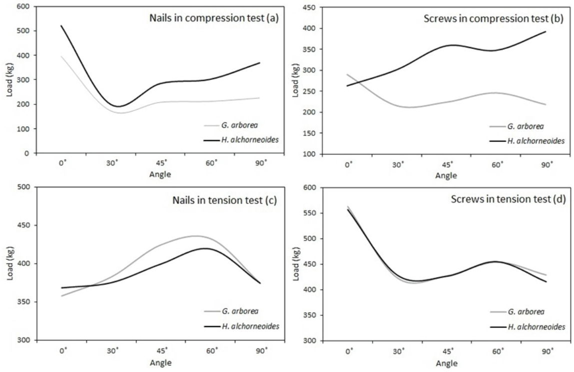

Fig.4: Maximum loads of truss joints constructed with G. arborea and H. alchorneoides lumbers using different angles and fasteners, tested in compression and tension.

In the compression test, displacement was greater for the five angles evaluated in *G. arborea* joints with nails (Fig. 5a). In both species, the greatest displacement value was shown in the 90°

joints, while the lowest values appeared for 30° joints in *H. alchorneoides* and for 60° joints in *G. arborea* (Fig. 5a). In the same test, when performed on joints with screws, it was observed that 90° joints from both species showed the highest displacement values, whereas joints with 0° angles presented the lower displacements (Fig. 5b).

In the test for tension, displacement values were greater for all five angles studied in *G. arborea* joints with nails (Fig. 5c). In both species, the greatest displacement was observed in 45° joints and the lowest in 0° joints (Fig. 5c). In the same test, when performed upon joints with screws, it was observed that no differences were shown between the two species in displacement values for all five angles studied. Joints with a 90° angle showed higher values, while those with a 45° angle showed the lowest displacements (Fig. 5d).

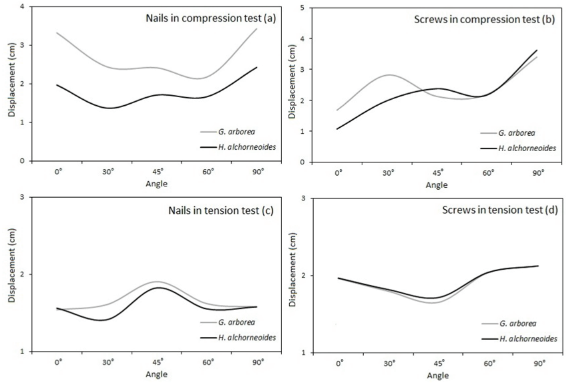

Fig.5: Maximum displacement in truss joints made using different angles and fasteners from G. arborea and H. alchorneoides, tested in compression and tension.

Behaviour of load vs. displacement of joint)

In the compression test performed on joints with nails and screws from both species, the 0° joints reach higher load values for one same displacement value in relation to the other angles studied. Following this angle, 45° and 60° joints reach medium load values for one same displacement. Finally, the lowest loads for one same displacement were achieved in 30° and 90° joints (Figs. 6a-d). In joints with nails, moreover, 0° and 90° joints reach maximum load at displacements greater than 3 cm and 2 cm in *G. arborea* and *H. alchorneoides* joints, respectively, whereas for the rest of the angles the values remain lower than those indicated (Figs. 6a-b). In regards to joints with screws, in both species the 90° joints reach their maximum load at displacement values superior to 3 cm, while the remaining angles reach their maximum load at lower displacement values (Figs. 6c-d).

In the tension test on joints with nails, similar behaviours can be observed in Load-Δ graphs for all five angles studied in both species (Figs. 6e-f).At displacements of less than 1 cm, 30° joints possess higher loads, followed by 60° and 90° joints with intermediate loads. Lastly, 0° and 45° joints present the lowest loads for one same displacement value. For displacements greater than 1 cm, 60° joints possess the highest loads for one same displacement, while 30° and 90° joints possess intermediate loads and 0° and 45° joints have the lowest loads for one same displacement value (Figs. 6e-f).In the same test, applied on joints with screws, the 0° joints show an almost linear behaviour of the Load-Δ relation and, for displacements over 1 cm, they show the highest loads in both species. Joints with 30°, 45° and 60° angles possess the greatest loads at one same displacement value, while the lowest ones correspond to 90° joints (Figs. 6g-h).

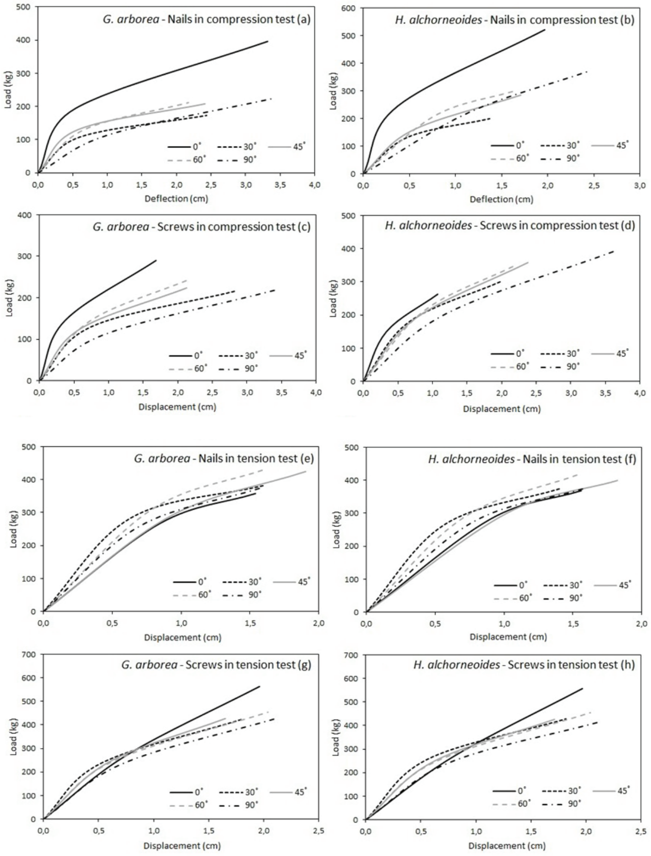

Fig. 6 : Load vs. displacement curves of truss joints made using various angles and fasteners in lumber from G. arborea and H. alchorneoides, tested in compression and tension.

Design values

The design stress and critical displacement averages obtained from compression and tension tests are, mostly, greater in *H. alchorneoides* joints than in *G. arborea* joints, in those employing nails as well as in those using screws (Tab 2).

There appear no differences among any of the angles studied when it comes to stress values obtained for *G. arborea* joints with nails in the compression test. In *H. alchorneoides* joints, however, the 0° joint possesses the greatest value, while 90°, 45° and 30° joints have the lower values (Tab. 2). In regards to critical displacement stress, similar values were found in *G. arborea* and *H. alchorneoides* lumbers, of which the highest value corresponds to the 0° joints (Tab. 2). Where joints use screws, a greater variability is observed among the angles studied. In design stress for *G. arborea* joints, the 0° joints show the highest value, while 90° and 30° joints present the lower values. For *H. alchorneoides*, 0° joints possess the greatest value and the remaining angles studied show the lower values (Tab. 2). Regarding critical displacement stress, 0° joints show the highest value and 90° joints have the lowest one in joints of both species studied (Tab. 2).

Tab.2: Design stress in truss joints made using various angles and fasteners from G. arborea and H. alchorneoides lumbers, tested in compression and tension.

Test	Fastener	Angle	*Gmelina arborea*		*Hieronyma alchorneoides*	
			Design stress (MPa)	**Critical displacement stress (MPa)**	**Design stress (MPa)**	**Critical displacementstress (MPa)**
Compression	Nails	0	4.1^{A}(20.8)	4.59^{A}(19.2)	8.5^{A}(16.8)	6.75^{A}(15.1)
		30	3.0^{A}(40.4)	2.24^{B}(8.2)	5.4^{B}(30.3)	2.92^{B}(10.8)
		45	3.1^{A}(35.2)	2.64^{B}(9.2)	5.3^{B}(8.5)	3.21^{B}(19.9)
		60	3.5^{A}(29.9)	2.42^{B}(12.4)	6.7^{AB}(34.0)	3.26^{B}(14.7)
		90	2.3^{A}(32.6)	1.74^{B}(24.0)	5.1^{B}(15.6)	2.52^{B}(20.6)
	Screws	0	5.7^{A}(12.6)	4.02^{A}(22.0)	8.3^{A}(18.7)	4.33^{A}(18.2)
		30	2.5^{C}(23.2)	2.40^{B}(16.8)	4.9^{B}(24.9)	3.30^{B}(12.6)
		45	3.7^{B}(31.8)	2.56^{B}(19.0)	4.9^{B}(22.8)	3.20^{B}(22.7)
		60	3.7^{B}(22.4)	2.40^{B}(19.9)	5.0^{B}(28.8)	3.19^{B}(31.1)
		90	2.0^{C}(23.9)	1.67^{C}(11.2)	3.8^{B}(18.8)	224^{C}(16.1)
Tension	Nails	0	8.0^{A}(21.6)	3.32^{C}(14.0)	8.1^{A}(22.2)	3.70^{AB}(17.4)
		30	8.4^{A}(25.7)	4.97^{AB}(20.7)	9.5^{A}(36.0)	4.94^{A}(29.3)
		45	7.4^{A}(17.8)	3.34^{C}(14.9)	7.1^{A}(19.3)	3.42^{B}(18.0)
		60	9.0^{A}(22.5)	3.88^{BC}(27.8)	9.2^{A}(25.0)	4.55^{AB}(19.9)
		90	8.2^{A}(25.1)	3.67^{C}(27.6)	8.2^{A}(25.1)	4.07^{AB}(26.4)
	Screws	0	9.4^{A}(10.3)	4.07^{A}(24.7)	9.3^{A}(11.0)	3.95^{AB}(24.6)
		30	7.8^{ABC}(16.1)	4.73^{A}(19.8)	7.8^{B}(17.0)	4.71^{A}(25.0)
		45	8.9^{AB}(24.5)	4.33^{A}(18.5)	8.1^{AB}(13.7)	4.52^{AB}(13.9)
		60	7.3^{BC}(9.1)	3.96^{AB}(17.3)	7.3^{BC}(9.9)	4.49^{AB}(19.6)
		90	6.4^{C}(14.6)	3.01^{B}(12.6)	6.3^{C}(15.4)	3.50^{B}(10.1)

Note: Values in parentheses correspond to the coefficient ofvariation of each datum. Letters ad joined to averages indicate significant statistical differences between species at 95%.

Concerning results obtained for design stress in the tension test for joints with nails, no differences appeared among the angles studied in both species (Tab. 2). In critical displacement stress, the 30° joints showed the highest value in both species; 0°, 45° and 90° joints showed the lower values in *G. arborea*, whereas it was 45° joints that showed the lowest value in *H. alchorneoides* (Tab. 2). Results obtained for joints with screws for design stress showed, in both species, that 0° joints present the highest value, while 90° joints have the lowest one (Tab. 2). In critical displacement stress for *G. arborea* joints, 0°, 30° and 45° joints possess the highest values, while the lowest one was exhibited by 90° joints. For joints from *H. alchorneoides*, the 30° joints have the highest value, as opposed to 90° joints (Tab. 2).

Prediction of stiffness for intermediate orientations

Critical stress values obtained by means of Eq. 3, using exponential values of *n* (variation range of 1 to 3.75) close to those obtained from the real mechanical tests (Tab. 2) are detailed in Tab. 3. It is possible to observe that there was no uniform exponential value of n to predict the critical stress for the various angles in both species and with both fasteners used (Tab. 3). For joints tested in compression using nails, the n exponent varied from 1.25 to 3.00 between 0° and 90° joints in *G. arborea*, whereas it was from 1.00 to 2.50 in

H. alchorneoides joints. For joints with screws, the n exponent varied from 1.50 to 3.00 in *G. arborea* and from 1.75 to 3.00 in *H. alchorneoides* (Tab. 3). Regarding joints tested in tension using nails, the exponential value of n for prediction of stress for angles between 0° and 90° varied from 1.75 to 3.75 in *G. arborea* joints, while in *H. alchorneoides* joints it varied from 1.75 to 3.00. For those joints with screws, the exponent n varied from 2.75 to 3.00 for *G. arborea* joints and from 2.50 to 3.00 for *H. alchorneoides* (Tab. 3).

Tab. 3: Stres sprediction for intermediate angles of truss joints made using various angles and fasteners from G.arborea and H.alchorneoides lumbers, tested in compression and tension.

Test	**Fastener**	**Angle**	***Gmelina arborea***			***Hieronyma alchorneoides***		
			Real stress (MPa)	**Stress obtained (MPa)**	**K**	**Real stress (MPa)**	**Stress obtained (MPa)**	**K**
Compression	Nails	0	453.9			674.8		
		30	224.2	234.9	1.25	292.2	306.2	1.00
		45	264.4	274.2	2.25	320.8	308.7	1.50
		60	241.7	249.4	3.00	326.1	330.1	2.50
		90	173.9			252.2		
	Screws	0	401.7			432.9		
		30	237.7	242.5	1.50	330.4	320.4	1.75
		45	255.6	257.2	2.50	320.0	322.3	2.25
		60	240.0	238.0	3.00	318.8	314.1	3.00
		90	167.0			224.4		
Tension	Nails	0	332.4			370.4		
		30	497.4	511.0	3.75	493.9	485.3	3.00
		45	330.4	319.9	1.75	342.1	355.7	1.75
		60	388.4	384.0	2.25	454.7	456.2	2.50
		90	367.0			407.0		
	Screws	0	407.0			394.8		
		30	473.1	465.6	2.75	471.3	469.4	2.75
		45	433.1	449.2	2.75	452.2	441.1	2.50
		60	396.5	406.2	3.00	448.7	460.1	3.00
		90	301.5			349.7		

DISCUSSION

Characters of lumbers employed

It can be seen that differences appeared in the MC between species (Tab. 1); however, although this property affects the mechanical properties of the species to a great extent (Zhou et al. 2015), in this case differences between species are mostly determined by their density (Moya and González 2014). Various studies consider that density is one of the properties that best defines mechanical behaviour of lumber (Wiemann and Williamson 1989). Said behaviour could be confirmed in the present study: *H. alchorneoides* lumber with its greater density, showed statistically higher MOE and MOR values in static bending and compression than those found in *G.arborea* lumber (Tab. 1). Nonetheless, this difference in strength between species can be compensated by increasing dimensions of the structural elements or, also, establishing strength categories for *G. arborea* wood (Keenan and Tejada 1987, Moya and González 2014).

Load and displacement values

Failures in compression and tension tests appeared in the order of fasteners used. Gebremedhin et al. (1992) mention that this behaviour occurs because strength in tension and compression of lumber is greater than the shear strength of the fastener. The same result is also confirmed by Demirkir et al. (2013), though these authors used plywood for joint elements. Although this type of failure is undesirable in joints, failure of the fastener is essential to prevent instantaneous collapse of the structure during subjection to loads

(Chui et al. 1998). Fasteners, such as nails and screws in the joints studied, play an important role as these are ductile elements meant to absorb loads applied and thus generally they suffer ductile deformations until failure happens (Chui et al. 1998). Structures containing fragile elements such as nails and screws have the ability to suffer ductile deformation without significant stress (Paulay and Priestley 1992), which allows failure of the structures not to be instantaneous.

In regards to differences in the maximum load and displacement values in the compression test, it can be observed that these appear in the order of species and not the fastener used. *H. alchorneoides* joints show higher values in relation to *G. arborea* joints (Figs. 3 and 4). This result agrees with the studies done by Wu (1999), Demirkir et al. (2013) and Sawata et al. (2013), which found differences between species, with the distinction that those authors used different *Pinus* species with plywood joints and nails, subjected to shear test. Differences between species are associated to the capacity for friction between the fastener (nail or screw) and the inner surface of the orifice it has made in the lumber (Chui et al. 1998). *H. alchorneoides* lumber shows a thicker cellular wall than lumber from *G. arborea* (Tab. 1), which yields greater friction during the shear stress produced from subjecting the joint to shear loads. This causes the first species to show greater maximum load and displacement values.

In the tension test the result is different from that obtained from the compression test. Maximum load and displacement values obtained for the first type of stress did not reveal differences between species, as was the case in the compression test but, rather, in the type of fastener used. Joints with screws show greater loads and displacements for both species (Figs. 4 and 5). The greater strength of joints with screws is attributed to the greater adherence to the lumber fibres permitted by the threaded zone of the screw, which exerts greater resistance to withdrawal during shear test (Soltis 2010). Likewise, screws show greater ductility properties than do nails, insomuch as these share ampler contact surface with the wood (Nájera et al.2014).

It was not possible to observe a trend in performance of each joint in relation to the angles studied, but in most cases joints with 0° and 90° angles showed the highest maximum load and displacement values, respectively, for both species (Figs. 4 and 5). The same behaviour was confirmed in the Load-Δ curves: joints with 90° angles showed displacement values superior to 3 cm and 1.5 cm in compression and tension tests, respectively (Fig. 6). In the same manner, 0° joints show greater loads along the entire Load-Δ curve in the compression test, whereas in the tension test it is only in joints with screws for displacements over 1 cm (Fig. 6). This behaviour was also found by Gebremedhin et al. (1992) for the same angles studied, save it was for joints made using metal plates and the authors attributed the differences to variations that appeared in the wood used in fabrication of the various joints. However, in the present study it is not possible to explain this, as the lumber density in general was similar in all joints.

In 0° joints, the greater strength in compression of joints with nails and the greater strength in tension of joints with screws for both species (Figs. 4a and 4b) can be attributed to the piece of lumber forming the joint, as it allows forces to become distributed and thus contributes to with stand the loads. On the other hand, in joints with intermediate angles, diagonal forces generated are causing a greater shear force on the fastener and the distance between fasteners is not uniform as occurs in the 0° joint — the distribution of nails thus affects the forces (Sawata et al. 2013). But, in regards to joints with nails in tension, the 60° joint (Fig. 4c) indicates that the position of the lumber piece in the joint contributes to withstand lateral tension forces and achieve greater strength.

Design values

Results obtained for design stress and critical displacement stress indicate, as expected, that *H. alchorneoides* joints show the highest values, as a consequence of this species' higher density (Tabs. 1 and 2). However, the greater differences between the two fasteners and the various angles appear mainly in the compression test (Tab. 2). Concerning tension tests, it is possible to observe that differences in the order of species and fastener are scarce and a greater variation can be seen among the various angles studied (Tab. 2).

Regarding variation amongst angles, most 0° joints possess the highest loads and design stress, while 90° joints present the lowest stress (Tab. 2). This behaviour is similar to that of the aforementioned maximum loads and displacements of joints (Section 4.2). In 0° joints the applied forces run parallel to the lumber piece serving as support in the joint, which contributes to withstand loads. While in joints with intermediate angles, diagonal forces generated cause a greater shear force upon the fastener (Gebremedhin et al. 1992), decreasing design stress.

Prediction of stiffness for intermediate orientations

The n exponent of the equation for prediction of critical stiffness (Eq. 3) did not present a uniform value in all truss joint angles, species and fasteners studied (Tab. 3). For the condition of compression, the n exponent of the model was linear (y = mx + b) in both fasteners and species (Fig. 7). In tension, meanwhile, the n exponent was a second degree polynomial type (y = a*x + b*x + c) (Fig. 7). Models for each one of the evaluated conditions, the two species (*G. arborea* and *H. alchorneoides*) and both fastener types (nails and screws) are detailed in Fig. 7. Then, models for prediction of stiffness (K_θ) for intermediate angles in trusses are detailed in Tab. 4.

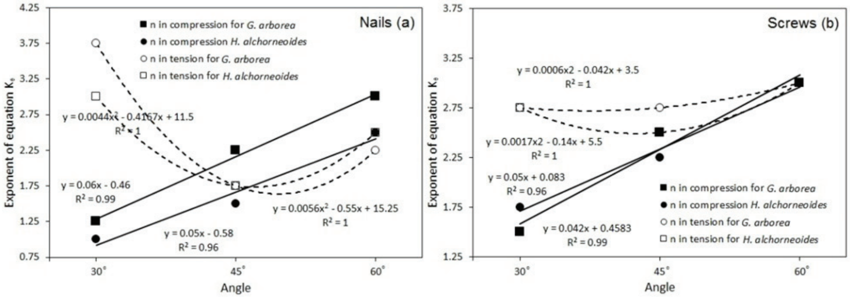

Fig. 7: Prediction of n exponent for use in equation for prediction of stiffness (K_θ) for G. arborea and H. alchorneoides truss joints of intermediate orientations between 0° and 90° angles.

Tab. 4: Model for prediction of stiffness (K_θ) for G. arborea and H. alchorneoides truss joints of intermediate orientations, between 0° and 90° angles and with the two types of fastener.

Species	Fastener	Condition	Model for prediction of stiffness for truss joint
Gmelinaarborea	Nail	Compression	$k_\theta = \frac{(78996\ MPa^2)}{(454 * sin^{(0.06*\theta-0.46)}\theta + 174 * cos^{(0.06*\theta-0.46)}\theta)\ Mpa}$
		Tension	$k_\theta = \frac{(121\,844\ MPa^2)}{(332 * sin^{(0.06*\theta^2-0.55*\theta+15.25)}\theta + 367 * cos^{(0.06*\theta^2-0.55*\theta+15.25)}\theta)\ Mpa}$
	Screw	Compression	$k_\theta = \frac{(121\ \ 002\ MPa^2)}{(402 * sin^{(0.42*\theta+0.46)}\theta + 301 * cos^{(0.42*\theta+0.46)}\theta)\ Mpa}$
		Tension	$k_\theta = \frac{(122\,507 MPa^2)}{(407 * sin^{(0.0006*\theta^2-0.04*\theta+3.5)}\theta + 301 * cos^{(0.0006*\theta^2-0.04*\theta+3.5)}\theta)\ Mpa}$
Hieronymaalchorneoides	Nail	Compression	$k_\theta = \frac{(170100 MPa^2)}{(675 * sin^{(0.05*\theta-0.58)}\theta + 252 * cos^{(0.05*\theta-0.58)}\theta)\ Mpa}$
		Tension	$k_\theta = \frac{(150\,590\ MPa^2)}{(370 * sin^{(0.004*\theta^2-0.42*\theta+11.50)}\theta + 407 * cos^{(0.004*\theta^2-0.42*\theta+11.50)}\theta)\ Mpa}$
	Screw	Compression	$k_\theta = \frac{(96\,768 MPa^2)}{(432 * sin^{(0.05*\theta+0.08)}\theta + 224 * cos^{(0.05*\theta+0.08)}\theta)\ Mpa}$
		Tension	$k_\theta = \frac{(138\,250\ MPa^2)}{(395 * sin^{(0.002*\theta^2-0.14*\theta+3.5)}\theta + 350 * cos^{(0.002*\theta^2-0.14*\theta+3.5)}\theta)\ Mpa}$

Legend: k_θ=stiffness for truss joints with intermediate orientations between 0° and 90°;θ=angle between 0° and 90°.

CONCLUSIONS

Results indicate that failure appeared in the order of the fastener employed (nails or screws) in joints meant for use in trusses made with angles of 0°, 30°, 45°, 60° and 90° and lumber from *G. arborea* and *H. alchorneoides* tested in tension and compression, and that no failure from the lumber was seen in any joint. Differences found in maximum loads and displacementin these joints are shown to a greater extent in the order of species in the compression test, wherein those joints made from *H. alchorneoides* show higher values than *G. arborea* joints. In the tension test, differences in the same two variables appear in the fasteners used and, in this case, joints made using screws possess the highest maximum load and displacement values between the two species.

Results obtained for design stress and critical displacement stress indicate that joints made with lumber from *H. alchorneoides* yield the highest values, as a consequence of the greater density when compared to joints made from *G. arborea*.

Although it was not possible to observe a trend in the parameters of strength assessed in the truss joints evaluated, most 0° joints possess the highest design stress and critical displacement stress, while 90° joints have the lowest stress. Stiffness values obtained by means of the model for prediction of intermediate orientations for truss joints (Eq. 3) were $k_\theta = (k_{//} * k_\perp)/(k_{//} * \sin^{(n=a*\theta+c)} * \theta + k_\perp * \cos^{(n=a*\theta+c)} * \theta)$ in the condition of compression and $k_\theta = (k_{//} * k_\perp)/(k_{//} * \sin^{(n=a*\theta^2+b*\theta+c)} * \theta + k_\perp * \cos^{(n=a*\theta^2+b*\theta+c)} * \theta)$ in the condition of tension in both species and for both fastener types. Details for each condition of species and fasteners are given in Tab. 4.

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REFERENCES

1. ASTM D1761- 06, 2012: Standard test method for mechanical fasteners in wood.
2. ASTM D4442 - 07, 2007: Standard test methods for direct moisture content measurement of wood and wood-base materials.
3. ASTM D143 - 14, 2014: Standard test method for small clear specimens of timber
4. Barbari, M., Cavalli, A., Fiorineschi, L., Monti, M., Togni, M., 2014: Innovative connection in wooden trusses. Construction and building materials 66: 654-663.
5. Bayan, A., Sariffuddin, S., Hanim, O., 2011: Cold formed steel joints and structures-A review. International Journal of civil and Structural Engineering Research 2(2): 621-634.
6. Bouldin, J. C., Loferski, J. R., Hindman, D. P., 2014: Inspection of metal plate-connected wood trusses in residential construction. Practice Periodical on Structural Design and Construction 19(2): 04014009.
7. CSA S347-M, 1980 : Methods of test for evaluation of truss dates used in lumber joints.
8. Chui, Y. H., Ni, C., Jaing.N, 1998: Finite-element model for nailedwood joints under reversed cyclic load. Journal of structural engineering 124(1): 96-103.
9. Demirkir, C., Colakoglu, G., Karacabeyli, G., 2013: Effect of manufacturing factors on technologicalproperties of plywood from northern turkey and suitability of panels for use in shear walls. Journal of structural engineering 139(12): 1-14.
10. Fournier R., 2008: Construcción sostenible y madera: realidades, mitos y oportunidades. Tecnología en Marcha 21(4): 92-101.
11. Gebremedhin, K. G., Jorgensen, M. C., Woelfel, C. B.,1992: Load-slip characteristics of metal plate connected wood joints tested in tension and shear. Wood and Fiber Science 24(2): 118-132.
12. Gupta, R., 2005: System behaviour of wood truss assemblies. Progress in structural engineering and materials 7(4): 183-193.
13. Keenan, F. J.,Tejada, M.,1987: Maderas tropicales como material de construcción en los países del grupo andino de América del Sur. Centro Internacional de Investigación para el Desarrollo. Ottawa, CA, pp. 69-89.
14. Maragechi, K., Itani, R. Y., 1984: Influence of truss plate connectors on the analysis of light frame structure. Wood and Fiber Science 16(3): 306-322.
15. Malavassi, R., 2010: La vivienda de madera de los barrios del sur del cantón central de San José, Costa Rica (1910-1955). Los corredores históricos como una herramienta para su estudio. Escuela de Historia, Universidad de Costa Rica. San José, Costa Rica. 56 pp. (in Spanish)
16. McCarthy, M., Little, J., 1988: Sensitivity of truss plate model parameters to parameter determination methods. Forest Products Journal. 38(5):63-67.
17. Moya, R., 2004: Wood of *Gmelina arborea* in Costa Rica. New Forests 28(2-3): 299-317.
18. Moya, R., Tenorio, C., Carranza, M., Camacho, D., Quesada, H., 2013: Structural performance of I-beam fabricated from a fast-growing tree, *Gmelina arborea*. Journal of Tropical Forest Science 25(2):151-156.

19. Moya, R., González, G., 2014: Esfuerzos admisibles de diseño por grado estructural para nueve maderas de plantación de Costa Rica. Revista Forestal Mesoamericana 11(26): 1-12.
20. Moya, R., Leandro, L., Murillo, O., 2009: Características de la madera de Terminalia amazonia, Vochysia guatemalensis y Hyeronima alchorneoides plantadas en Costa Rica. Bosque 30(2): 78-87.
21. Muñoz, F., Moya, R., 2008: Moisture content variability in kiln-dried *Gmelina arborea*: Effect of radial position and anatomical features. Journal of Wood Science 54(4): 318-322.
22. Nájera, J. A., Olivas, J. P.,Méndez, J., 2014: Esfuerzo de extracción de clavos y tornillos para madera en cuatro especies de pino de Durango, México. Investigación y CienciaUniversidad. Autónoma de Aguascalientes 61: 41-47.
23. Oficina Nacional Forestal (ONF), 2015: Oficina Nacional Forestal. Usos y aportes de la madera en Costa Rica-Estadísticas 2013. Ministerio de Energía, Minas y Telecomunicaciones. San José, Costa Rica. 37 pp.
24. Paulay, T., Priestley, M. J., 1992: Seismic design of reinforced concrete and masonry buildings. John Wiley and Sons Inc., New York, USA, 345 pp.
25. Prevatt, D. O., Shreyans, S., Kerr, A., Gurley, K. R., 2014: In situ nail withdrawal strengths in wood roof structures. Journal of Structural Engineering 140(5): 04014008.
26. Sawata, K., Shigemoto. Y., Hirai, T., Koizumi, A., Sasaki, Y., 2013: Shear resistance and failure modes of nailed joints loaded perpendicular to the grain. Journal of Wood Science 59:255–261.
27. Serrano, R., Moya, R., 2011: Procesamiento, uso y mercado de la madera en Costa Rica: aspectos históricos y análisis crítico. Revista Forestal Mesoamericana 9(21): 1-12.
28. Solis, M., Moya, R., 2004: Hyeronima alchorneoides en Costa Rica. Fondo Nacional de Financiamiento San Jose, Costa Rica. Forestal. Ministerio de Energía y Minas. Gobierno de Costa Rica. 106 pp.
29. Soltis, L.A., 1999: Fastenings, Chapter 8. Wood handbook: Wood as an engineering material. Forest Products Laboratory. General Technical Report GTR-113. Madison, Wisconsin, EE UU, Pp 1-29.
30. Tenorio, C., Moya, R., Camacho, D., 2012: Propiedades físico mecánicas de tableros terciados construidos con especies tropicales de plantaciones para uso estructural. Cerne 18(2). 317-325.
31. Tenorio, C., Moya, R., Salas, C., Berrocal, A., 016: Evaluation of wood properties from six native species of forest plantations in Costa Rica. Revista Bosques 37 (1): 12-25.
32. Triche, M. H., Suddarth, S. K., 1988: Advanced design of metal-plate joints. Forest Products Journal 38(9): 7-12.
33. Tuk, J., 2010: Madera: Diseño y Construcción. San José: Colegio De Ingenieros y Arquitectos. San José, Costa Rica.
34. Wiemann, M. C., Williamson, G. B., 1988: Extreme radial changes in wood specific gravity in some tropical pioneers. Wood and Fiber Science 20(3): 344-349.
35. Wolfsmayr, U. J., Rauch, P., 2014: The primary forest fuel supply chain: a literature review. Biomass and Bioenergy 60: 203-221.
36. Wu, Q., 1999: Screw-holding capacity of two furniture-grade plywoods, composites and manufactured products. Forest Products Journal 49(4): 56–59.
37. Zhou, A., Tam, L. H., Yu, Z., Lau, D., 2015: Effect of moisture on the mechanical properties of CFRP–wood composite: An experimental and atomistic investigation. Composites Part B: Engineering 71: 63-73.

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