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# DISEÑO, RESISTENCIA Y VALORES ESTRUCTURALES DE CERCHAS PREFABRICADAS CON MADERA DE PLANTACIÓN

## (DOCUMENTO I)

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# DISEÑO, RESISTENCIA Y VALORES ESTRUCTURALES DE CERCHAS PREFABRICADAS CON MADERA DE PLANTACIÓN

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## 2. RESUMEN

El presente trabajo tuvo como objetivo el diseño de dos cerchas tipo pratt con luces entre apoyos de 6 m y 9 m, construidas con madera de *Gmelina arborea* e *Hieronyma alchorneoides*, utilizando dos tipos de uniones (clavos y tornillos). Como complemento de este objetivo: (i) se evaluaron diferentes ángulos en las uniones que se pueden utilizar en la fabricación de cerchas (ii) se establecieron los valores de diseño de los estos ángulos y de las diferentes cerchas diseñadas para ser utilizadas en casas de habitación, (iii) se proponen el posible empaque para los dos tipos de cerchas y (iv) se proponen los manuales de armado y de uso de las mismas. En los resultados de resistencia se encontró que los valores de carga máxima en las cerchas construidas y tipo de uniones con madera de *H. alchorneoides* fueron mayores en comparación con las cerchas y uniones construidas con madera de *G. arborea*. Las tablas de diseño de las cerchas para estos dos tipos de madera y para los dos tipos de uniones (clavos o tornillos) fueron propuestas para luces entre apoyos de 4 m, 5 m, 6 m y 7 m. La propuesta de empaque que se propuso para cada largo de cercha consistió de dos cajas de cartón corrugado donde la primera caja de 2,5 m de largo agrupará las piezas más grandes, mientras que la segunda caja de 1,6 m de largo agrupará todas las piezas pequeñas. Los manuales de armado y uso muestran en detalle y de forma gráfica como deben armarse las cerchas y cuáles serían las condiciones de uso de las mismas.

### Design, assembly and user manuals of trusses fabricated with *Gmelina arborea* wood and *Hieronyma alchorneoides* from forest plantations trees in Costa Rica

### Abstract

The objective of this research is design two pratt framing trusses for two span, 6 m and 9 m, and fabricated with *Gmelina arborea* and *Hieronyma alchorneoides* wood, using two types of fastener (nails and screws). As a complement to this objective: (i) it was evaluated different angles in the joints that can be used in the manufacture of trusses (ii) it was established the design values of these joint and trusses for using in small housing building, (iii) proposal of packing for these wood trusses, and (iv) presents construction and user manuals. Results showed that the maximum load values in the trusses and joint fabricated with *H. alchorneoides* wood were higher compared to the trusses fabricated with *G. arborea* wood. The design tables of the trusses for these two species of wood and two types of fastener (nails or screws) were proposed for span of 4 m, 5 m, 6 m and 7 m. The packing proposal proposed that two boxes of corrugated paperboard were packing the wood truss: one box with 2.5 m long will packing the largest pieces and second box with 1.6 m long will packing small boards. The manuals of assembly and users detail graphically how the trusses should be assembled and the conditions of use.

## 3. PALABRAS CLAVE

Construcción liviana, estructura de madera, especies tropicales, empaque.

**Key words:** framing, wood structures, tropical species, packing.

## 4. INTRODUCCIÓN

La madera es un material muy importante que puede ser usado en diferentes formas, sus características son comparables con otros tipos de materiales estructurales (Kamala et al. 1999), pero la creciente demanda por madera ha causado una disminución de las fuentes forestales (Shukla et al. 2008). Una forma de facilitar el uso eficiente del recurso forestal y de esta manera dar una protección al medio ambiente, es la creación de materiales compuestos de uso intensivo a base de madera, utilizados por ejemplo en la construcción civil (Shukla et al. 2008).

En Costa Rica, a pesar de estas dos importantes ventajas, en los últimos 10 años el uso de este material ha decaído en las construcciones civiles, tales como las casas de pequeñas y edificaciones de mediana altura (Serrano y Moya, 2012). La madera ha sido desplazada por otros materiales, tales como el acero y el concreto y por otros materiales importados, que vienen respaldados por significativos avances tecnológicos, extensa información técnica y un mercadeo muy agresivo (Fournier 2008a). El sector de construcción tradicionalmente ha consumido más del 50% del volumen total de madera (Carrillo 2001), sin embargo cifras recientes indican una disminución a solo el 24% (ONF 2013).

A pesar de las ventajas ecológicas científicamente atribuidas a la madera, es uno de los materiales menos utilizados en la construcción en Costa Rica en la actualidad, de ahí la importancia por incentivar su consumo a través de la producción sostenible y productos con un mayor desarrollo tecnológico (ONF 2013). En Costa Rica solo una 10% de las estructuras son de madera, en contraste con cerca del 90% en EEUU y entre 40 y 45% en Japón e Inglaterra (ONF 2011). De acuerdo con Fournier (2008a), la madera es el material más noble, renovable, sano, sostenible, estético y confortable de la construcción. El conocimiento de la madera y el desarrollo de su tecnología en los aspectos de siembra, transformación, tratamientos de secado y preservación, encolados, acabados y otros, podrían garantizar su utilización en la construcción, convirtiendo la madera en el material del futuro.

Un problema de nuestro país, es el poco conocimiento de parte de los ingenieros y arquitectos, la escasa información técnica disponible de propiedades y procesamiento de la madera, la poca colaboración entre los actores del sector y la falta de agresividad comercial. Todos estos factores han contribuido al debilitamiento del uso de la madera en la construcción. Este sector representa el mayor potencial de mercado y crecimiento en Costa

Rica por la variedad de aplicaciones que pueda tener en la construcción. Sin embargo, la madera es limitada a obras rústicas o temporales, artesonados, acabados de piso y paredes divisorias, puertas y marcos de ventanas, elementos decorativos y muebles (Fournier 2008b).

No obstante, en los recientes años existe una tendencia a implementar casas más sostenibles con el ambiente, por lo que la madera ha sido el material por excelencia para este tipo de vivienda. No obstante, este material ha tenido poco suceso en casas de interés social, debido a su alto costos y la poca capacidad de los productores en ofrecer un producto accesible económicamente a los entes financiadores de este tipo de vivienda (Founier 2008a). Sin embargo algunos sistemas constructivos como Habicon desarrollado por la Escuela de Construcción han permitido una pequeña introducción de la madera en la utilización de este tipo de viviendas.

Finalmente, han existido algunas iniciativas importantes para la construcción de viviendas de interés social donde tienen un amplio uso de la madera como son los iniciativos de “UN TECHO PARA MI PAIS” o “MI TECHO”, que se caracterizan por presentar un sistema constructivo con un uso en madera casi en su totalidad. Así mismo algunos empresas, como, el Aserradero S & Q 2005, preocupados por el bajo uso de la madera han tomado la iniciativa de diseñar sistemas constructivos prefabricados de casas de interés social. Dichas viviendas se caracteriza por el hecho de ser construida en su totalidad de madera, orientado a construir casas más sostenibles y dar una mayor valor agregado a la madera que es producido en su aserradero.

Ante tal situación, el presente proyecto tuvo como objetivo determinar el comportamiento en relación a las cargas aplicadas, desplazamiento y esfuerzos de diseño de cerchas tipo pratt construidas con madera de plantaciones forestales de *G. arborea* y *H. alchorneoides*, utilizando dos tipos de fastener (clavos y tornillos), sometidas a cargas en flexión y para dos tipos de span (6 y 9 metros), y obtener las tablas de diseño y una propuesta de empaque para que estas sean utilizadas en el sector constructivo del país.

## 5. MARCO TEÓRICO

En los últimos 10 años el uso de la madera en las construcciones civiles en Costa Rica ha disminuido (Serrano y Moya 2011). En décadas pasadas el sector de construcción consumía más del 50% del volumen total de madera, sin embargo, cifras recientes indican una disminución a solo el 24% y se indica que solo un 10% de las estructuras son hechas de madera (ONF 2015). Las construcciones de madera en Costa Rica en el pasado se caracterizaban por ser de tipo “framing”, construidas de secciones transversales de 5.0 cm x 7.5 cm que se utilizaban para soportes estructurales de pisos y paredes y para la construcción de cerchas (Tuk 2010). No obstante, en la actualidad este tipo de estructuras en madera han sido desplazadas por otro tipo de materiales como el plástico, el acero y el concreto (Tuk 2010, Fournier 2008a).

Las wood trusses son uno de los componentes de las estructuras tipo framing que han sido ampliamente utilizadas a nivel mundial y datan desde el 6th century A.D. (Barbari et al. 2014). Las trusses tienen la característica de que maximizan la eficiencia estructural, ya que permiten alta rigidez en flexión y alta capacidad de carga, como consecuencia de que la estructura es dividida en un número determinado de piezas, cuyas dimensiones y métodos de

unión le conceden niveles de tensión más bajos en comparación con otro tipo de estructuras como lo son las vigas (Woods et al. 2016).
In wood trusses, the critical node of this system has the task of transmitting the thrust acting in upper-chord to the tie–beam by means of a post (Barbari et al. 2014). En esta acción de fuerzas que se presentan en la cercha se observan una serie de aspectos estructurales como el comportamiento del desplazamiento en relación a las cargas aplicadas, strength, desing load and stiffness values (Gebremedhin et al. 1992).

Durante más de 40 años el método de unión más utilizado a nivel mundial en la construcción de las trusses han sido las placas metálicas, las cuales se caracterizan por ser uniones semi rígidas (Gupta y Gebremedhin 1990). Estas uniones permiten cierto movimiento (axial, de traslación y de rotación) entre los diferentes componentes de las cerchas. Sin embargo, la deformación de las uniones puede ser responsable de una proporción sustancial de la deformación total de las trusses y, a menudo, tienen un impacto significativo en la distribución de las cargas internas de las piezas que conforman una truss (Gupta y Gebremedhin 1990).

En la actualidad existe mucha información referente al uso de las placas metálicas como uniones en trusses donde se han determinado sus características estructurales y modo de falla (Gupta 2005, Bayan et al. 2011, Bouldin et al. 2013). Sin embargo este tipo de información para uniones utilizando otros tipos de fastener como clavos o tornillos es escasa. Así mismo las uniones con este tipo de fastener han sido ampliamente utilizadas en construcciones civiles en países en vías de desarrollo, como es el caso de Costa Rica, principalmente debido al bajo costo en comparación con las placas metálicas y por el desconocimiento de su uso. Sin embargo, la información disponible sobre los aspectos de resistencia de las cerchas construidas con este tipo de fastener es escasa, especialmente en maderas de especies tropicales (Sawata et al. 2013).

Por otro lado, en muchos países se han presentado cambios en las especies utilizadas en procesos de construcción tipo “framing” (Wolfsmayr y Rauch 2014) y Costa Rica no es la excepción (Serrano y Moya, 2011). En este país, anteriormente se utilizaban especies del bosque natural con densidades sobre 0,6 g/cm$^3$, pero recientemente han surgido maderas de plantaciones forestales, entre las que destacan *Gmelina arborea* e *Hieronyma alchorneoides* (Malavassi 2010, Serrano y Moya 2011), las cuales poseen densidades inferiores a 0.6 g/cm$^3$ (Moya 2004, Tenorio et al. 2016). *G. arborea* ha sido ampliamente estudiada y se le señalan una serie de cualidades para ser utilizada con fines estructurales (Moya 2004, Tenorio et al. 2012, Moya et al. 2013). En tanto que *H. alchorneoides* ha sido utilizada para reforestación comercial en Costa Rica y el estudio de las propiedades de la madera de árboles de plantación ha mostrado altos valores de resistencia estructural (Moya et al., 2009, Tenorio et al., 2016).

Sin embargo, a pesar de la información disponible del uso de las maderas de plantación, en especial las especies *G. arborea* y *H. alchorneoides*, aún se carece del conocimiento de las propiedades estructurales de estas en los procesos de construcción tipo framing. En el caso de *G. arborea* wood proveniente de árboles en plantaciones ha mostrado que puede ser utilizada satisfactoriamente en la construcción de I-joist (Moya et al. 2013, Tenorio et al., 2014) o bien como web part in I-joist beam (Panigua y Moya 2014). En tanto que los usos de *H. alchorneoides* wood extraída de árboles de plantaciones aún son lìmitados, con la excepción del reciente estudio llevado a cabo por Leiva-Leiva et al (2017), donde muestran el usos de estas dos maderas de plantación en la fabricación de wall frames.

Ante tal situación, el presente proyecto tuvo como objetivo determinar el comportamiento en relación a las cargas aplicadas, desplazamiento y esfuerzos de diseño de cerchas tipo pratt construidas con madera de plantaciones forestales de *G. arborea* y *H. alchorneoides*, utilizando dos tipos de fastener (clavos y tornillos), sometidas a cargas en flexión y para dos tipos de span (6 y 9 metros) para ser utilizadas en el sector constructivo del país.

## 6. Artículos científicos:

**Objetivo específico 1: Diseño, fabricación y análisis de las cerchas**

# Mechanical performance in flexure for two spans of trusses made of *Hieronyma alchorneoides* and *Gmelina arborea* woods using nail and screw fastening

Roger Moya, Carolina Tenorio, Mauricio Carranza, Angel Navarro, Marta Saenz, Viviana Paniagua

### Abstract

The present work had the object to determine the behavior relative to loads, displacement and design load stiffness of Pratt-type trusses made from *Gmelina arborea* and *Hieronyma alchorneoides* lumbers, using two types of fastener (nails and screws) for two span categories (6 m and 9 m). It was found that the maximum load values were greater in *H. alchorneoides* lumber trusses than in *G. arborea* trusses. Design strains values showed that trusses fabricated with *H. alchorneoides* wood show higher design properties than *G. arborea* trusses. The trusses fabricate with a 6 m spanning showed strength and design strain values greater than those in 9 m trusses, but displacements are lower in 6 m trusses. No statistical differences appeared in the different types of fastener used. Nonetheless, behavior of load vs. strain or displacement suggested that trusses fabricated with screws presented better properties than those obtained with nails.

**Keywords:** framing, wood structures, tropical species, stiffness, truss joint.

### 1. Introduction

In the last ten years, use of lumber for civil constructions in Costa Rica has decreased (Serrano and Moya 2011). Over 50 percent of the total volume of lumber was consumed by the construction sector in previous decades; however, recent numbers indicate shrinkage to just 24 percent, and it is reported that only 10 percent of structures are currently being made of wood (ONF 2015). In the past, wooden constructions in Costa Rica were characterized for being of the framing type, built from 5.0 x 7.5 cm transversal sections that were used in structural supports for flooring and walls, as well as for truss-making (Tuk 2010). Nonetheless, currently this type of wooden structure has been displaced by other type of materials, such as plastic, steel and concrete (Tuk 2010; Fournier 2008).

Wood trusses are one of the most broadly employed framing-type structures globally, dating back to the 6th century CE (Barbari et al. 2014). Trusses have the quality of maximising structural efficiency, for they allow high stiffness in flexure and high load capacity as consequence of the structure being divided in a determinate number of pieces, whose dimensions and joint methods provide lower stress levels in comparison to other kind of structure such as beams (Woods et al. 2016).

In wood trusses, the critical node of this system has the task of transmitting the thrust acting in the top chord to the tie-beam by means of a post (Barbari et al. 2014). A series of structural aspects can be observed in operation of the forces present in the truss, such as displacement behavior in relation to loads applied, strength, design strains, as well as load and stiffness values (Gebremedhin et al. 1992).

For more than 40 years, globally metal plates have been the method most widely used for joints in truss assembly, characterized by being semi-rigid joints (Gupta and Gebrehedin 1990). These joints allow for some motion (axial, translational and rotational) of the various components in trusses. However, strain of joints can be responsible of a substantial proportion of the total deformation in trusses and, often, has a significant impact on the distribution of internal loads in truss components (Gupta and Gebrehedin 1990).

Presently, there exists much information referent to the use of metal plates as joints in trusses, where their structural characteristics and mode of failure have been determined (Gupta 2005; Bayan et al. 2011; Bouldin et al. 2014). However, this sort of information is scarce for joints using other kind of fastener, such as nails and screws. Moreover, joints with these types of fastener have been widely implemented in civil constructions in developing countries, as is the case in Costa Rica, mainly due to their low cost relative to metal plates and due to lack of knowledge on their use. Nevertheless, available information on the strength attributes of trusses built with this kind of fastener is limited, especially for lumber from tropical species (Sawata et al. 2013).

There have been changes in the species used in framing-type construction processes in many countries (Wolfsmayr and Rauch 2014) and Costa Rica is not an exception (Serrano and Moya, 2011). In this country, species used previously from natural forests had densities over 0.6 g/cm$^3$ but, recently, lumbers from forest plantations have grown in popularity, notably *Gmelina arborea* and *Hieronyma alchorneoides* (Malavassi 2010; Serrano and Moya 2011), which possess densities inferior to 0.6 g/cm$^3$ (Moya, 2004; Tenorio et al. 2016). *G. arborea* has been extensively studied and a series of qualities for structural purposes are attributed to it (Moya 2004; Tenorio et al. 2012; Moya et al. 2013). Meanwhile, *H. alchorneoides* has been used for commercial reforestation in Costa Rica and the study of its lumber from forest plantations has revealed high values of structural strength (Moya et al. 2009; Tenorio et al. 2016).

However, despite the available information on the use of plantation lumbers, especially *G. arborea* and *H. alchorneoides*, there is still lack of knowledge about their structural properties for framing-type construction processes. In the case of *G. arborea* wood from plantation trees, it has been shown that it can be satisfactorily employed in fabrication of I-joists (Moya et al. 2013; Tenorio et al. 2014) or also as web part in I-joists (Paniagua and Moya 2014). Meanwhile, known uses for *H. alchorneoides* wood extracted from plantation trees are still limited, with the exception of the recent study carried out by Leiva-Leiva et al. (2017), where uses of these two plantation lumbers are presented for elaboration of wall frames.

In face of this situation, the present study has the object to determine the behavior relative to flexural loads applied, displacement and design load stiffness of Pratt-type trusses built with lumber from forest plantations of *G. arborea* and *H. alchorneoides* using two types of fastener (nails and screws), for two span categories (6 m and 9 m).

## 2. Methodology

### Lumber used

The lumber 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). Wood from *G. arborea* was obtained from the sawmill Maderas S & Q 2005 (Pérez Zeledón, San José, Costa Rica) and wood of *H. alchorneoides* was provided by the company ECOCAJAS S.A. (Guápiles, Limón, Costa Rica). In green condition lumber presented dimensions of 7.5 cm wide and 2.5 cm thick and this lumber 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*. Target moisture content of 14% was established for both species.

### Design of truss

Pratt-type trusses were constructed, consisting of a bottom chord, two top chords joined at the center of the length of the truss, vertical posts working in compression and diagonal pieces working in tension (Figure 1). This kind of truss was chosen for being traditionally employed in Costa Rica (Nieto and

Solórzano 1993). This variety uses wooden pieces with dimensions adequate to the lumber obtained from forest plantations produced normally in Costa Rica. These dimensions are characterized by presenting low thickness, as well as widths and lengths not greater than 2.5 m (Serrano and Moya 2011). Trusses of *G. arborea* and *H. alchorneoides* were built in dimensions of 7.2 and 10.2 m, which can be used at spans of 6 and 9 m, respectively (6-span-truss and 9-span-truss; Figure 1a-b). A slope of 20 percent was applied to the design of both truss sizes. The 6-span-trusses presented 87.5 cm height at the center and 14.7 cm at the sides and were built using 6 vertical posts at 120 cm spacing between their centers and 7 diagonal pieces in between the vertical ones (Figure 1a). Furthermore, 9-span-trusses presented 114.5 cm height at the center and 14.7 cm at the sides, with 11 vertical posts at 120 cm spacing between their center and 8 diagonal pieces in between the vertical ones (Figure 1b).

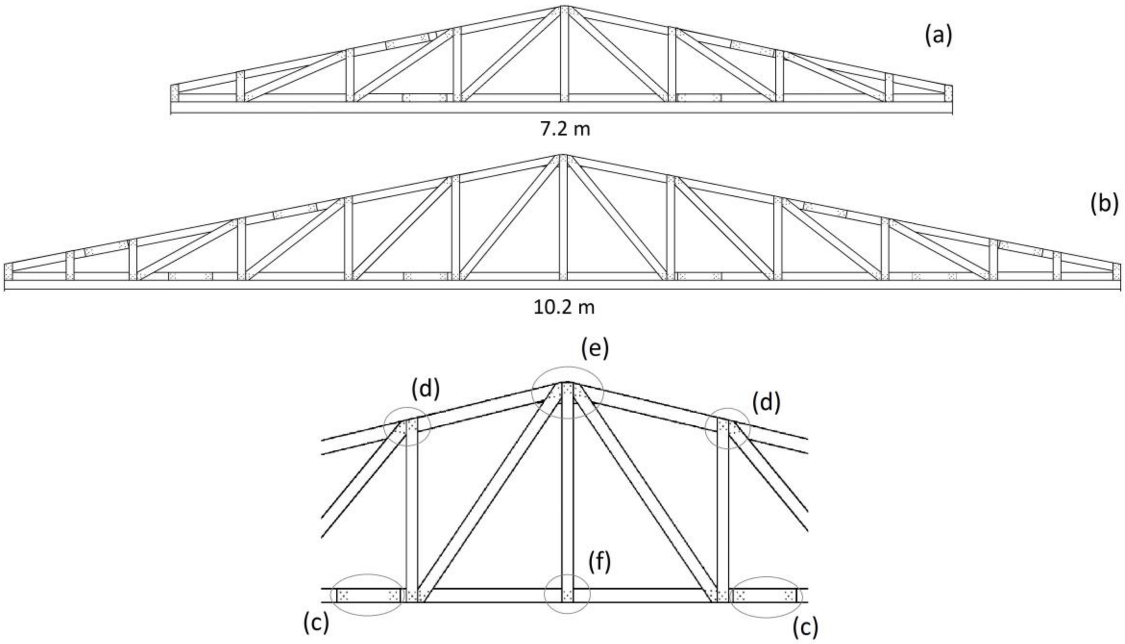

**Fig. 1.** Model of Pratt truss for 6-span-truss (a) and 9-span-truss (b); joint of the pieces at bottom and top chords (c); joint of vertical and diagonal pieces at bottom and top chords (d); joint at top part of truss or peak joint (e); and joint of king post with tie-beam (f).

### Truss construction

For all cases, lumber with dimensions of 7.5 cm wide, 2.5 cm thick and 2.5 m long was used, presenting respective nominal dimensions of 7.1 cm, 2.2 cm and 2.5 m for commercialization. During truss construction, the center of 2.5 m long piece was aligned with the center of the truss. Afterward, 2.5 cm thick pieces were placed toward the sides until reaching the ends of the truss. Regarding top chords, a 2.5 m long piece was first placed at the highest point and then 2.5 m long pieces were placed all the way to the ends of the truss. The joint of the pieces at the top chord was placed at half the distance between two vertical posts. In total, four kinds of joint were used in the assembly of the Pratt-type trusses:

- Joint 1: splice joint. In these joints, two wooden pieces were matched by placing a 30 cm patch piece at their ends (Figure 1c). This variety was employed in the joints of bottom and top chords.

- Joint 2: joint between a vertical post and top or bottom chord. This joint was used where vertical and diagonal (web) pieces meet the bottom or top chords (Figure 1d).
- Joint 3: topmost joint of truss or peak joint. This joint was placed at the highest part of the truss and is composed of two top chords, one vertical post and two web pieces. As this is the central part, it was reinforced with a 30 cm long patch piece fastening the vertical and web pieces (Figure 1e).
- Joint 4: joint of king post with bottom chord. This joint was placed at the lower central part of the truss and is formed of the union between a king post and bottom chord (Figure 1f).

### Types of fastener

Two fastening means were used: nails and screws. Screws used for joints were of the flat-head Phillips type, of 50 mm x 4.27 mm, while nails used were 51 mm x 2.8 mm. Five fasteners were inserted at each end of the wooden pieces. The number of fasteners in each joint was as follows: Joint 1 = 10, Joint 2 = 10, Joint 3 = 24, and Joint 4 = 5 (Figure 1c-f).

### Strength tests

Trusses were tested in static flexure. During the test, the truss was mounted on a simple supports system, each placed at 60 cm inward from the end (Figure 2a-b). In order to avoid sideways motion, the trusses were kept vertical by means of wooden elements (Figure 2b). Load was applied to three different spots: on the vertical post at the center of the truss and on the two vertical posts placed at each side of the central post (Figure 2a). For the application of these loads during the test, the construction of a device for the adequate distribution of loads was necessary. This device was made using metal *C* beams with dimensions of 5 cm x 7.5 cm and 6 mm thick, weighing 42 kg (Figure 2a), and was modelled as a finite element with SAP2000 software. It distributes 31 percent of the load in the nodes at the ends of the accessory and 38 percent at the central node, which means that of the 42 kg weight of the device, 17.2 kg were applied on the central node and 12.4 kg on the lateral nodes. For the test, two crackmeter-type sensors were placed in order to measure vertical displacements: one was placed on the king post and the other on the vertical post to the left of the king post (Figure 2a). Moreover, two strain gauges were placed to record unitary strain: one for measuring compression in one of the top chords, which was placed on one of the pieces connecting with the top chord, near the center of the truss; the other, placed on one of the pieces connecting with the bottom chord subjected to tension, also near the center of the truss (Figure 2a).

**Fig. 2.** System for application of loads in truss tests (a). Restrictive elements used to avoid sideways motion of trusses during tests (b).

**Parameters determined**

Several parameters were assessed: the first group was measured during the test, whereas the rest were determined after truss testing.

During the test, parameters measured were: (i) maximum load capacity of truss; (ii) displacement at center of truss; (iii) displacement at the side of the center of truss; (iv) strain in compression of top chord near the center of truss; and (v) strain in tension of bottom chord near the center of truss. These data for displacement (cm), unitary strain (μƐ) and load (kg) were recorded automatically every 5 seconds.

Once the test was carried out, graphs of load vs. displacement and load vs. strain were put together with the information obtained. Data for load and displacement at proportionality limit, as well as load and displacement at ⅓ maximum load were then obtained with the aid of the load vs. displacement graphs. Likewise, data for load and strain at proportionality limit of each truss were determined with the aid of those same curves. The weight of the device was added to the values of the load applied to each truss for graphing the curves.

Afterward, the values obtained were used in determining the design load, which corresponds to ⅓ the maximum load (Formula 1); displacement at given design load (Formula 2); design load stiffness (Formula 3); and stiffness of the truss (Formula 4).

$$Design\ load = \frac{Maximum\ load\ (kg)}{3} \quad (1)$$

$$Design\ displacement = \frac{Displacement\ at\ maximum\ load\ (cm)}{3} \quad (2)$$

$$Design\ load\ stiffness = \frac{Design\ load\ (kg)}{Design\ displacement\ (cm)} \quad (3)$$

$$Truss\ stiffness = \frac{Maximum\ load\ (kg)}{Displacement\ at\ maximum\ load\ (cm)} \quad (4)$$

**Experimental design and statistical analysis:**

An experimental factorial design type $2^2$ was established for the Pratt-type trusses of each species studied, the two spans (6 and 9 m) and the two fastening means (nails and screws). In total, 6 *G. arborea* wood trusses were built per span and per fastener type (2 spans × 2 fastener kinds × 6 repeats = 24 trusses), whereas 4 *H. alchorneoides* wood trusses were built per span and per fastener type (2 spans × 2 fastener kinds × 4 repeats = 16 trusses). Normality of the data was verified for every variable measured (maximum loads and displacements at proportionality limit, strains in tension and compression, design loads, displacement at design load, design load stiffness and truss stiffness). This was followed by a variance analysis (ANOVA) for each species (*G. arborea* and *H. alchorneoides*) considering 2 factors: span (6 and 9 m) and fastener treatment used in joints (nails and screws). Finally, for determination of significant differences between the treatments, a comparison was carried out by means of the Tukey test.

## 3. Results

### 3.1. Loads and displacements

Averages obtained for maximum load in *H. alchorneoides* trusses surpassed those obtained in *G. arborea* trusses (Figure 3): for the former, these were from 2.8 to 4.3 kN; for the latter from 2.0 to 2.8 kN. In regards to maximum load in trusses fabricated using *G. arborea* wood, no statistical differences were observed between the two fastening methods in both spans, while 6-span-trusses showed a higher average maximum load in comparison to 9-span-trusses (Figure 3a). Trusses built with *H. alchorneoides* lumber showed the same behavior as *G. arborea* trusses. No significant differences were observed between fastener kinds for both spans, yet 6-span-trusses showed the highest maximum load averages (Figure 3b). It must be noted that, although no statistical differences appeared between the two fastener kinds used, *G. arborea* trusses using screws showed the highest averages, whereas *H. alchorneoides* trusses using nails presented the highest maximum load values (Figure 3).

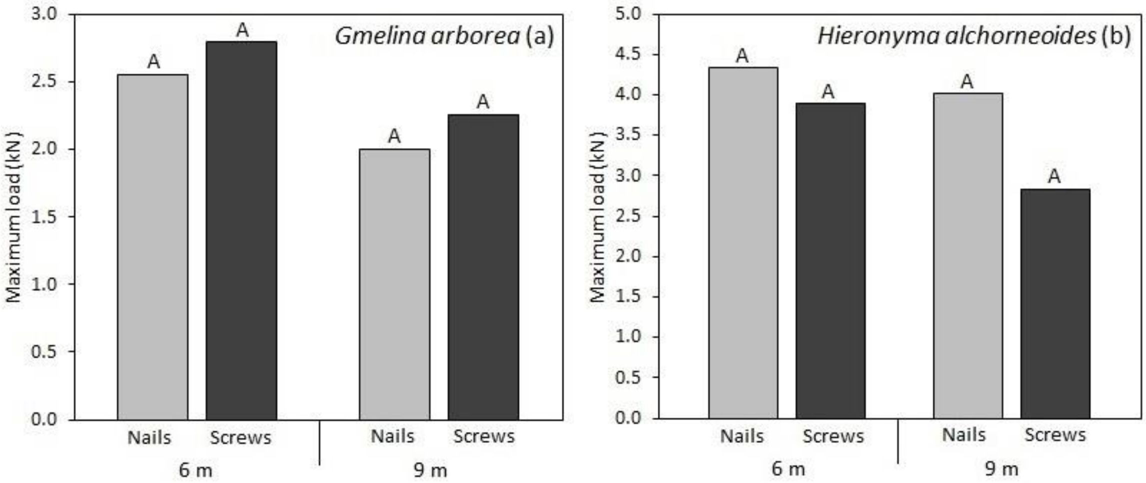

**Fig. 3.** Maximum load in trusses made of *G. arborea* (a) and *H. alchorneoides* (b) lumbers, per span

and per fastening method.

Regarding load averages at proportionality limit, it was found that these loads were greater in *H. alchorneoides* trusses in comparison to *G. arborea* lumber trusses (Figure 4). For the latter, no differences appeared in the loads at proportionality limit in either measurement point (central and side), fastening method or span used (Figures 4a-b). Whereas, for *H. alchorneoides* trusses, differences were observed in the load averages at the proportionality limit (central and side gauges) in 6-span-trusses, wherein those using nails showed the highest values; for 9-span-trusses, no statistical differences were shown between the two fastening methods employed (Figures 4c-d).

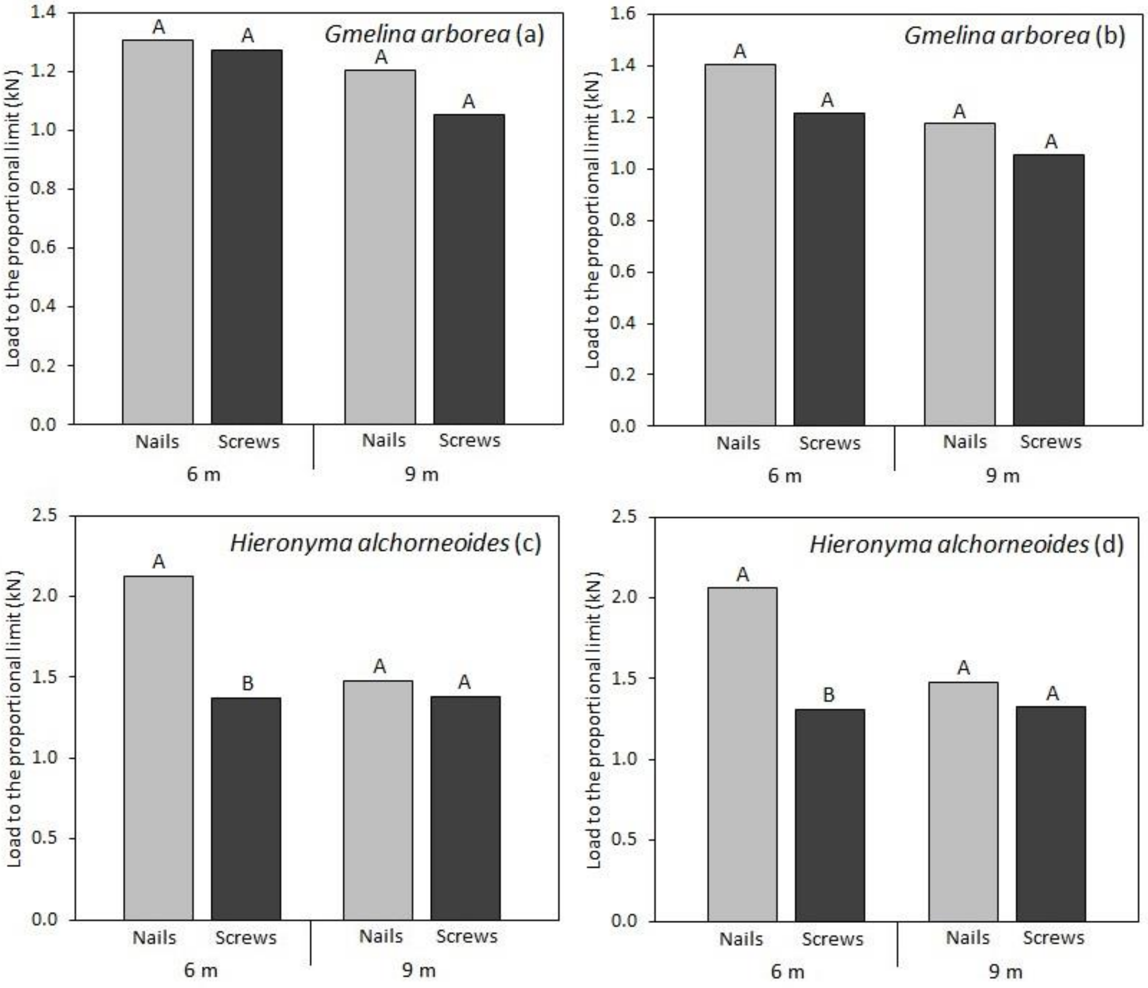

**Fig. 4.** Load at limit of proportionality at the center (a) and the side (b) for trusses made of *G. arborea* lumber; load at limit of proportionality at the center (c) and the side (d) for trusses made of *H. alchorneoides* lumber. Sorted per span and per fastening method used.

In the averages for maximum displacement at the proportionality limit obtained for *G. arborea* and *H. alchorneoides* lumber trusses, no statistical differences were observed between either fastening methods or spans studied (Table 1). Statistical differences were only present in 6-span-trusses of *H. alchorneoides* wood, where trusses using nails showed the highest displacement at the proportionality limit in both gauging points (central and side) (Table 1).

**Table 1.** Displacements obtained in trusses made of *G. arborea* and *H. alchorneoides* lumbers, per span and fastening method used.

| Species | Span (m) | Fastener | Maximum displacement - centre (cm) | Maximum displacement - side (cm) | Displacement at proportionality limit - centre (cm) | Displacement at proportionality limit - side (cm) |
|---|---|---|---|---|---|---|
| *G. arborea* | 6 | Nail | $3.96^{A}$ (28.92) | $3.38^{A}$ (32.04) | $0.43^{A}$ (53.97) | $0.47^{A}$ (50.56) |
| | | Screw | $3.60^{A}$ (38.95) | $3.70^{A}$ (36.28) | $0.41^{A}$ (8.04) | $0.39^{A}$ (12.96) |
| | 9 | Nail | $5.61^{A}$ (42.11) | $5.69^{A}$ (37.08) | $0.74^{A}$ (29.03) | $0.81^{A}$ (22.50) |
| | | Screw | $5.71^{A}$ (30.01) | $5.65^{A}$ (31.51) | $0.65^{A}$ (21.15) | $0.61^{A}$ (22.59) |
| *H. alchorneoides* | 6 | Nail | $4.63^{A}$ (26.48) | $4.61^{A}$ (27.43) | $0.75^{A}$ (34.20) | $0.76^{A}$ (37.71) |
| | | Screw | $3.53^{A}$ (4.61) | $3.41^{A}$ (14.80) | $0.27^{B}$ (28.75) | $0.28^{B}$ (29.20) |
| | 9 | Nail | $7.72^{A}$ (26.06) | $7.73^{A}$ (24.77) | $0.67^{A}$ (47.98) | $0.67^{A}$ (40.02) |
| | | Screw | $5.32^{A}$ (50.67) | $5.63^{A}$ (53.22) | $0.74^{A}$ (46.91) | $0.85^{A}$ (50.05) |

Flexural behavior of trusses is represented by load vs. displacement curves in Figure 5. Trusses of *H. alchorneoides* showed higher load and displacement values than those of *G. arborea* trusses at both points for gauging displacement. Specifically for *G. arborea* trusses, the two aspects to highlight are: (i) those joined with nails showed greater displacement for a given load; and (ii) 6- span-trusses presented higher loads at a given displacement at both measurement points (Figures 5a-b). Regarding *H. alchorneoides* trusses, it was found that those using nails in the 6-span-trusses showed similar load and displacement values to those using screws at both measurement points; however, there was failure of the screws at lower displacements than those in trusses using nails (Figures 5c-d). In 9-span-trusses of the same lumber, those using nails showed tendency to greater load for a given displacement in both measurement points as compared to those using screws (Figures 5c-d). Trusses using screws also failed at lower displacements than those in nail-bearing trusses (Figures 5c-d).

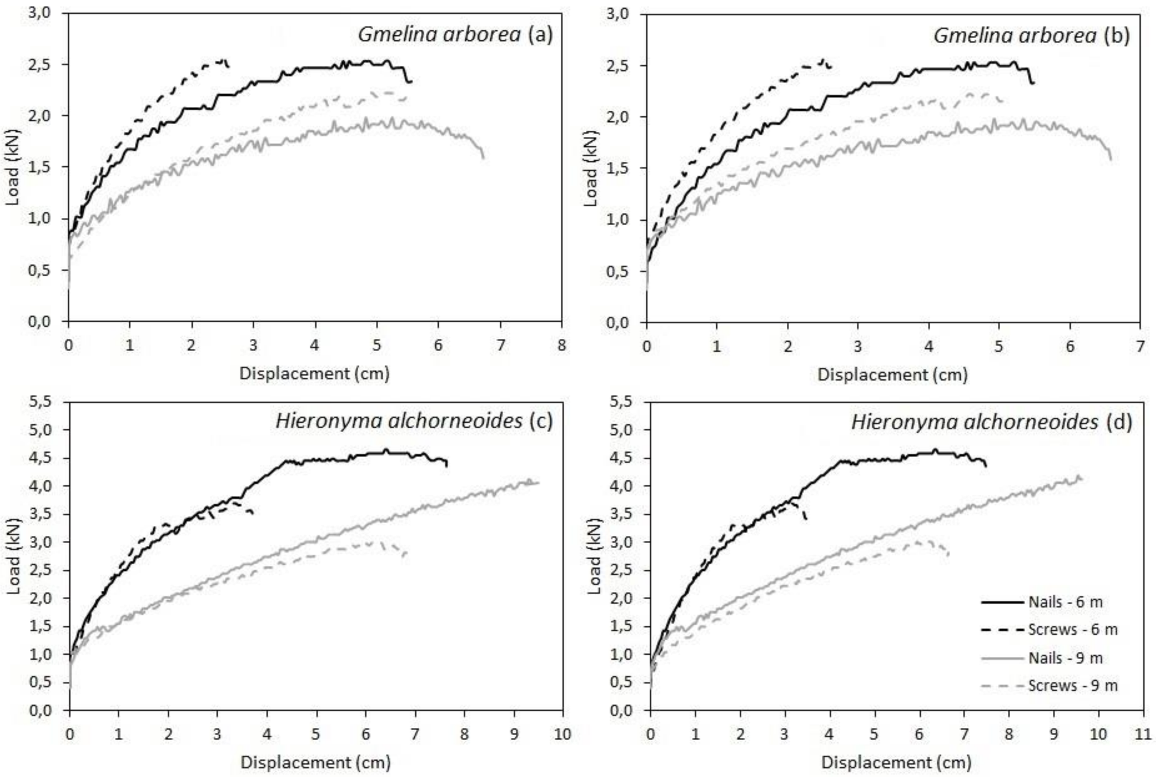

**Fig. 5.** Load vs. displacement curves: for *G. arborea* trusses at central gauge (a) and side gauge (b); for *H. alchorneoides* trusses at central gauge (c) and side gauge (d). Sorted per span and fastening method.

### 3.2. Strains

For both *G. arborea* and *H. alchorneoides* trusses, strain averages obtained for elements under tension as well as those under compression showed no statistical differences in either fastening means or spans used (Table 2). However, *H. alchorneoides* trusses showed higher strain averages in comparison to *G. arborea* trusses.

**Table 2.** Strain values obtained for *G. arborea* and *H. alchorneoides* trusses, per span and fastening means used.

| Species | Span (m) | Fastener | Strain in tension (μƐ) | Strain in compression (μƐ) |
|---|---|---|---|---|
| *G. arborea* | 6 | Nail | $34.63^{A}$ (40.99) | $-28.32^{A}$ (-76.77) |
| | | Screw | $28.36^{A}$ (32.98) | $-16.19^{A}$ (-68.03) |
| | 9 | Nail | $21.53^{A}$ (59.88) | $-33.57^{A}$ (-21.89) |
| | | Screw | $14.26^{A}$ (75.56) | $-33.19^{A}$ (-40.06) |
| *H. alchorneoides* | 6 | Nail | $81.82^{A}$ (81.49) | $-95.75^{A}$ (-88.56) |
| | | Screw | $83.23^{A}$ (84.20) | $-55.86^{A}$ (-48.34) |
| | 9 | Nail | $106.84^{A}$ (65.29) | $-30.64^{A}$ (-91.90) |
| | | Screw | $133.69^{A}$ (23.06) | $-15.70^{A}$ (-89.19) |

Figure 6 shows an example of load vs. strain curves obtained for trusses made of each species studied. There it can be observed that *H. alchorneoides* trusses showed higher strain values, where values of strain in tension are over 700 µƐ at loads of more than 3.5 kN for 9-span-trusses using nails (Figure 6b). In the case of *G. arborea* lumber trusses, the highest strain value was close to 100 µƐ at loads of 1.3 kN for 9-span-trusses using nails (Figure 6a). For both species, 6-span-trusses using nails showed the lowest strains for a given load (Figure 6).

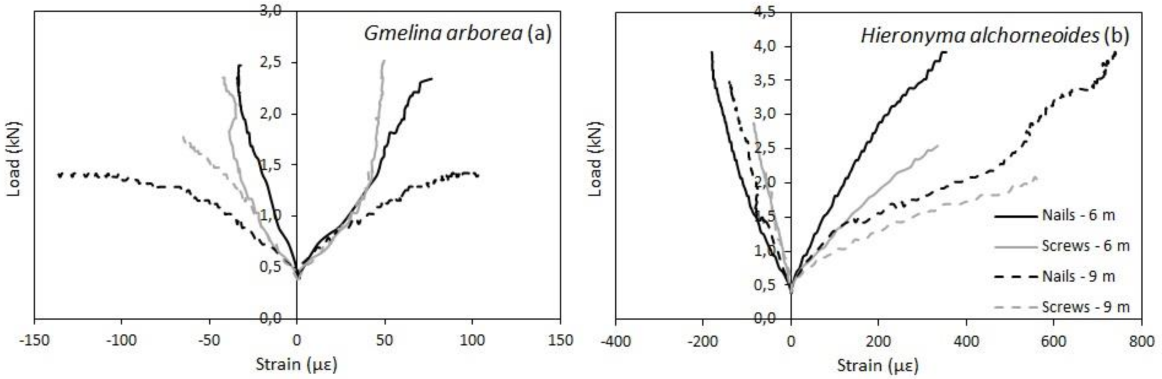

**Fig. 6.** Load vs. strain curves for *G. arborea* (a) and *H. alchorneoides* (b) trusses, per span and fastening method.

### 3.3. Design load stiffness

Design load stiffness averages calculated for trusses of the two species can be seen in Table 3. No statistical differences appeared among the averages obtained for any of the assessed parameters. However, design loads and design load stiffness (central and side) were greater in trusses fabricated with *H. alchorneoides* lumber. In regards to displacements at given design loads, those in *H. alchorneoides* trusses with 9 m span using nails presented the highest values (Table 3).

**Table 3.** Design strains obtained for *G. arborea* and *H. alchorneoides* trusses, per span and fastening method.

| Species | Span (m) | Fastener | Design load (kN) | Displacement at given design load - center (cm) | Displacement at given design load - side (cm) | Design load stiffness - center (kN/cm) | Design load stiffness - side (kN/cm) |
|---|---|---|---|---|---|---|---|
| *G. arborea* | 6 | Nail | 0.85$^A$ (13.57) | 1.32$^A$ (28.92) | 1.13$^A$ (32.04) | 0.69$^A$ (32.42) | 0.83$^A$ (35.08) |
| | | Screw | 0.93$^A$ (21.98) | 1.20$^A$ (38.95) | 1.23$^A$ (36.28) | 0.87$^A$ (37.28) | 0.82$^A$ (29.45) |
| | 9 | Nail | 0.67$^A$ (20.52) | 1.87$^A$ (42.11) | 1.90$^A$ (37.08) | 0.38$^A$ (22.73) | 0.37$^A$ (18.96) |
| | | Screw | 0.75$^A$ (14.87) | 1.90$^A$ (30.01) | 1.88$^A$ (31.51) | 0.41$^A$ (16.43) | 0.42$^A$ (17.50) |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| *H. alchorneoides* | 6 | Nail | $1.44^{A}$ (11.10) | $1.54^{A}$ (26.48) | $1.54^{A}$ (27.43) | $0.97^{A}$ (21.98) | $0.98^{A}$ (23.10) |
| | | Screw | $1.30^{A}$ (17.92) | $1.18^{A}$ (4.61) | $1.14^{A}$ (14.80) | $1.10^{A}$ (15.30) | $1.14^{A}$ (5.18) |
| | 9 | Nail | $1.34^{A}$ (20.38) | $2.57^{A}$ (26.06) | $2.58^{A}$ (24.77) | $0.53^{A}$ (16.43) | $0.53^{A}$ (14.30) |
| | | Screw | $0.94^{A}$ (21.83) | $1.77^{A}$ (50.67) | $1.88^{A}$ (53.22) | $0.60^{A}$ (32.80) | $0.58^{A}$ (36.10) |

For both species, 6-span-trusses showed higher average stiffness values relative to 9-span-trusses, and *H. alchorneoides* trusses showed higher truss stiffness values in general (Figure 7). No statistical differences appeared between both fastening means used for either span or species.

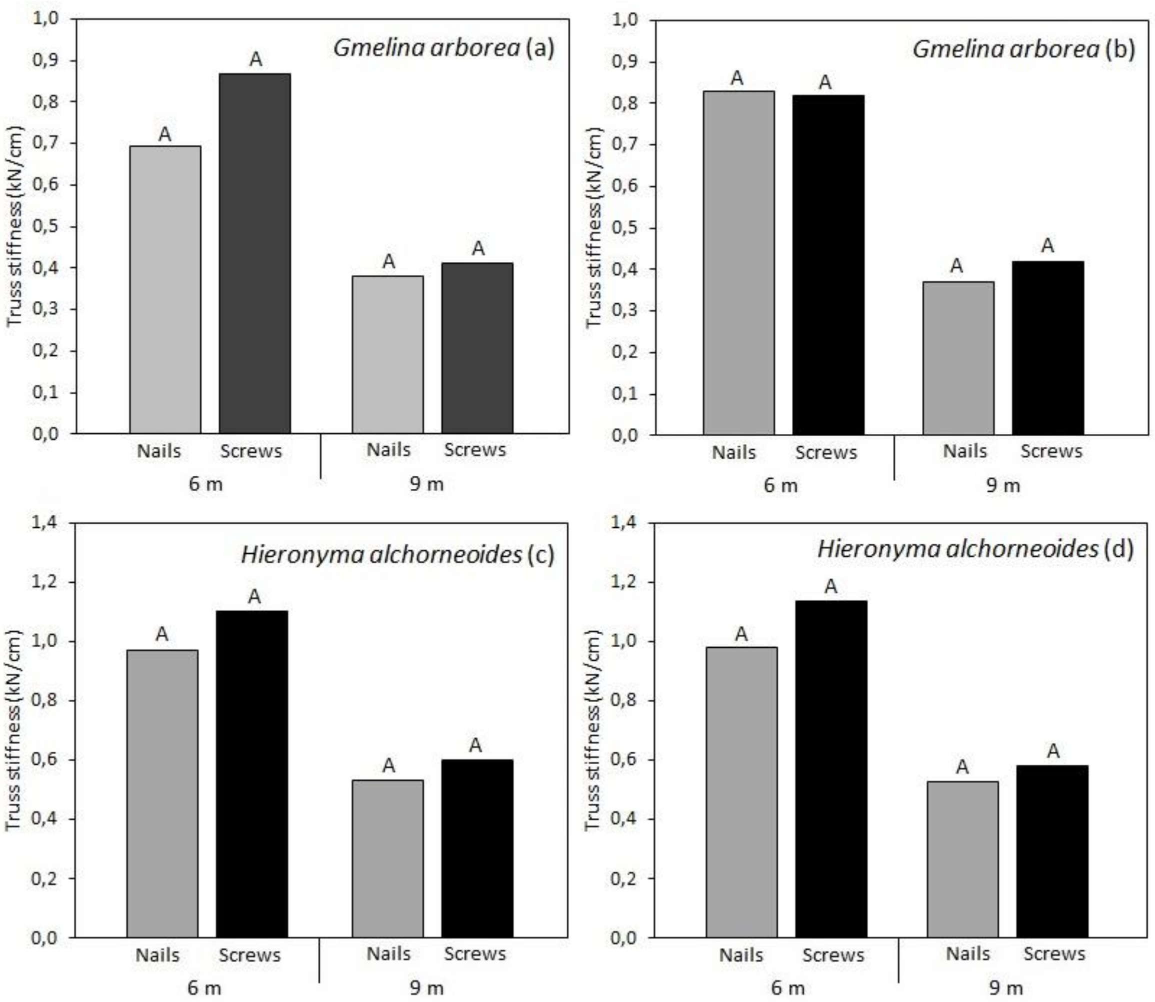

**Fig. 7.** Truss stiffness for: *G. arborea* trusses, at central gauge (a) and side gauge (b) for *H. alchorneoides* trusses, at central gauge (c) and side gauge (d). Sorted per span and fastening method.

## 4. Discussion

Regarding the highest values obtained in *H. alchorneoides* trusses (for both spans and fastening means) for the maximum load and displacement averages, as well as those at the proportionality limit (Figures 3 and 4; Table 1), these reflect the base specific gravity (SG) of the lumber. Several studies consider that SG is one of the properties best defining mechanical behavior of wood (Wiemann and Williamson 1989). Therefore, differences in the load and displacement averages at the maximum load and the proportionality limit between trusses built with *G. arborea* and *H. alchorneoides* are a consequence of the higher SG present in *H. alchorneoides* lumber. The SG reported for *H. alchorneoides* lumber from forest plantations is 0.45 (Tenorio et al. 2016), whereas for *G. arborea* the value reported ranges from 0.30 to 0.40 (Moya and Tomazello 2007).

The behavior observed in this study, the lower strength of *G. arborea* trusses, agrees with the work of Leiva-Leiva et al. (2017) concerning prefabricated timber wall frames of the same two species. These authors found that the greater strength and lower displacements appeared in structures fabricated with *H. alchorneoides*, which allow for better structural performance of the truss.

Trusses with 6 m span showed higher load and lower displacement values as compared to 9-span-trusses (Figures 3 and 4; Table 1), in both species and for both fastening methods. This behavior is explained by the high tension forces produced at the lower central part of the structure in 9-span-trusses, which translate into lower strength and greater displacement (McMartin et al. 1984), as opposed to 6-span-trusses where such forces are lesser. Nonetheless, it is normal for trusses with longer spans to show lower strengths and high strains relative to trusses with lower spans (Caruso et al. 2016).

Concerning the effect of shear forces on trusses, *H. alchorneoides* trusses using nails showed greater load and displacement values at the proportionality limit than those using screws for the 6-span-trusses, but this behavior was not the same in 9-span-trusses of the same species (Figures 4c-d; Table 1). For *G. arborea* lumber trusses, no differences appeared between the fastening means for both 6-span-trusses and 9-span-trusses (Figures 4a-b). These results indicate that when trusses are built using lumbers of high SG (as is *H. alchorneoides*) and short spans are implemented (6 m), where shear force is lower (McMartin et al. 1984), nails provide more strength relative to screws; whereas in trusses using low-SG wood there is no difference between using nails or screws, as strength of the truss is likely limited by the fastener choice and not by the span size. The opposite is true for 9-span-trusses, where loads applied produce great deal of shear forces and strength is thus limited by the lumber type —and not the fastener— used in the construction of trusses.

An important aspect to clarify of this study is that few statistical differences were observed between both fastening means in the load and displacement averages at both the maximum point and the proportionality limit, with the exception of *H. alchorneoides* trusses with 6 m span (Figures 3 and 4; Table 1). However, this consideration is to be taken with caution, as the lack of differences could be due to the limited amount of samples assessed, between 4 and 6 trusses per fastener and span length. A small amount of samples limits the degrees of freedom in the ANOVA model established (O'brien 1979) and therefore there is less precision in the evidence of differences between the types of truss evaluated. In this way, in the event of having a greater number of samples, statistical differences would likely be evident. In fact, in the graphs of load vs. displacement curves for *G. arborea*, it can be seen that trusses using screws showed greater loads than those using nails for a given displacement, in both spans and at the two gauging points (Figures 5a-b). A tendency to present better structural behavior (high loads and little displacement) is therefore observed in trusses using screws, as compared to those using nails. In comparing *H. alchorneoides* trusses with nails to those with screws, the same displacement for a given load was observed until the moment where the screwed trusses failed. After this point, however, nailed trusses presented a slightly higher load and high displacement (Figure 5c-d). This indicates that screwed trusses hold similar loads as do nailed trusses, yet yield lower displacements, which shows that screws produce stiffer joints than nails (Aytekin 2008). Furthermore, 6-span-trusses were stiffer than 9-span-trusses in *H. alchorneoides*, as displacements for a given load were lower in the former.

Although no differences appeared statistically between strain averages of *G. arborea* and *H. alchorneoides* lumbers, in most cases nailed trusses showed higher strain values than screwed trusses (Table 2). This tendency reiterates that components wherein strain was measured suffered greater deflection when nailed joints were implemented. The higher strain in trusses with nails was due to trusses showing greater displacement or failing at higher loads, presenting more deformation in wood.

The different structural behavior between 6-span-trusses and 9-span-trusses is made evident by the different strain values of each truss kind. In both species, 6-span-trusses presented greater strain than 9-span-trusses for a given load, especially for elements under tension (Figure 6). This indicates less deflection for 6-span-trusses relative to 9-span-trusses.

Another important aspect to highlight in regards to strain is that, for both species, spans and fastening means, elements in tension showed higher deflection values for a given load than those in compression. This situation is to be expected as the element in tension is at the point of maximum deflection, whereas the element in compression is affected by the presence of the king post and thus has more stability (Figure 6).

Results obtained for design load stiffness (Table 3) and truss stiffness (Figure 7) reflect the strength previously explained in the maximum load and displacement values. Trusses made with *H. alchorneoides* lumber show the highest values as a consequence of the higher SG of the species. Likewise, 6-span-trusses showed the highest stiffness values due to the greater inherent stiffness of this truss size, allowing for maximum performance of the truss as compared to 9-span-trusses (Figure 7).

## 5. Conclusions

Strength values obtained for *G. arborea* are lower than those presented in *H. alchorneoides* and these differences appear to a greater extent in 9-span-trusses. These results are reflected in the design strain values derived from the tests, where trusses of *H. alchorneoides* showed higher design values than those obtained for *G. arborea*.

Between the two fastening means utilized in truss fabrication no statistical differences appeared, with the exception of those in *H. alchorneoides* trusses at 6 m span. However, load vs. strain behavior suggests that trusses built with screws presented better properties than those obtained in trusses with nails, as was found in *H. alchorneoides* trusses at 6 m span.

Finally, the length of the span shows an effect on truss strength. Trusses fabricated for 6 m span showed greater strength and design load stiffness values than 9 m span trusses, but displacements are lower in the 6 m span, a behavior considered normal as less strains are produced in trusses at shorter spans.

## 6. Acknowledgments

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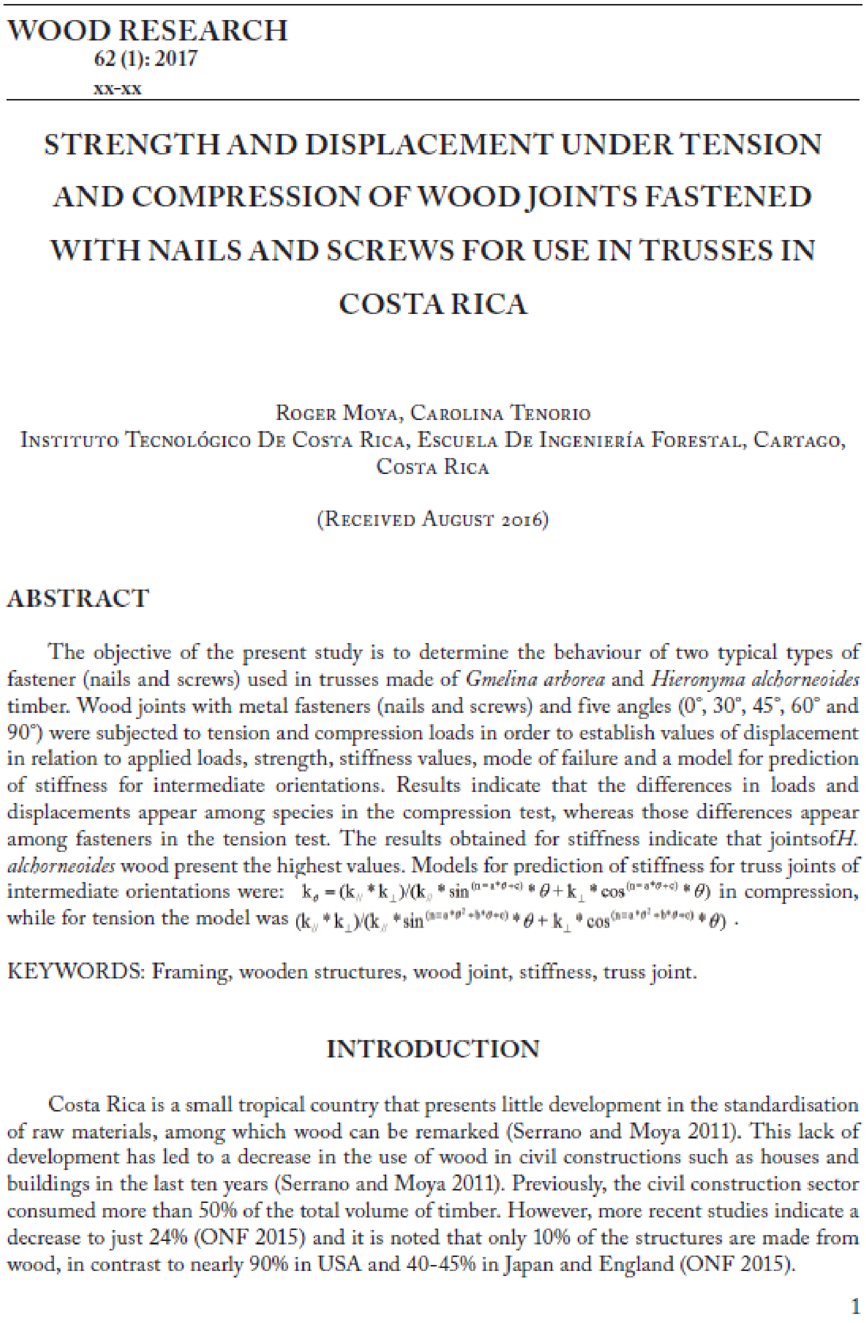
**Objetivo específico 2: Diseñar y calcular la resistencia de las uniones por utilizar en las cerchas a cada especie.**



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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).

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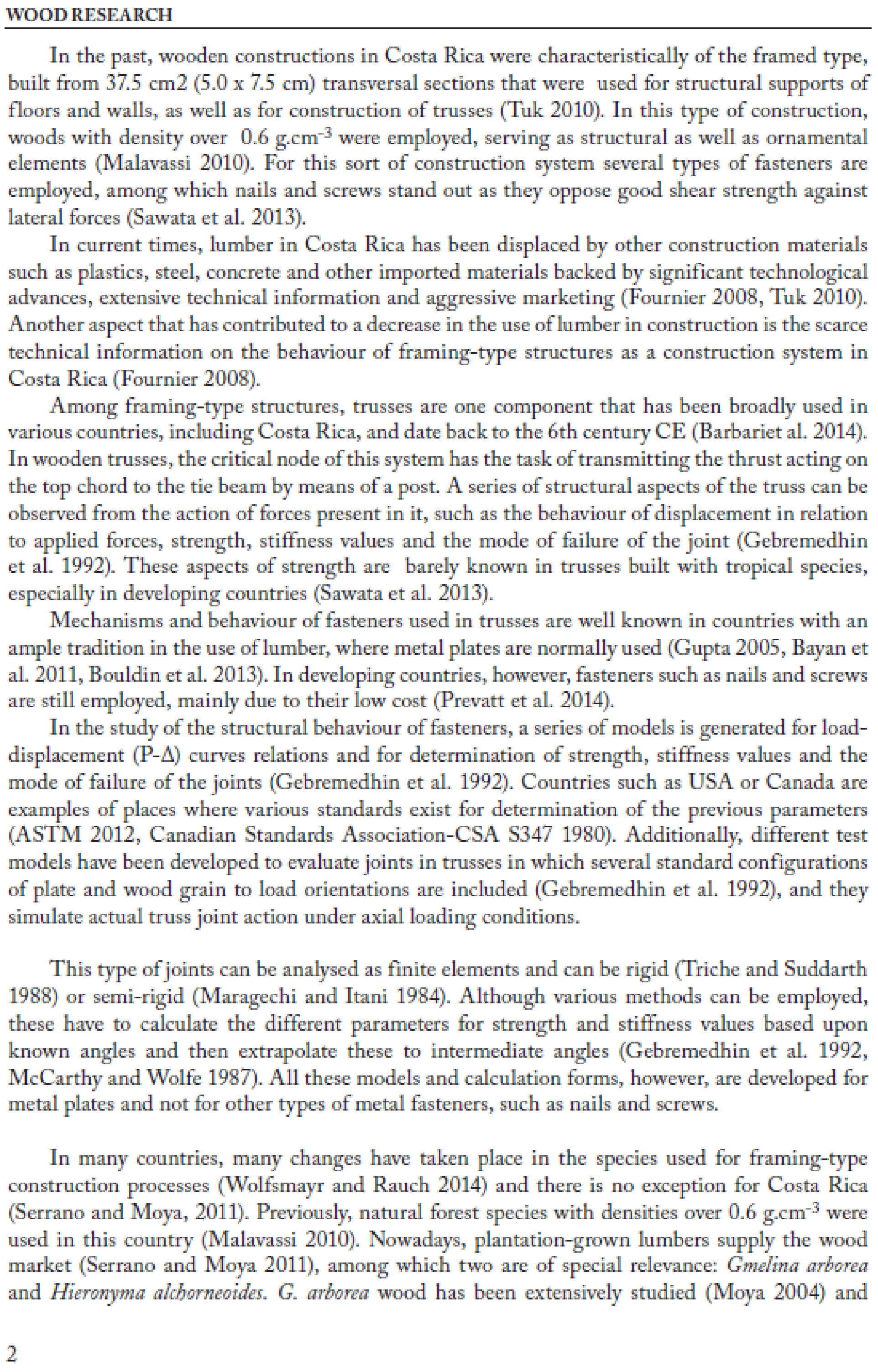


In the past, wooden constructions in Costa Rica were characteristically of the framed type, built from 37.5 cm2 (5.0 x 7.5 cm) transversal sections that were used for structural supports of floors and walls, as well as for construction of trusses (Tuk 2010). In this type of construction, woods with density 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-$\Delta$) 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.

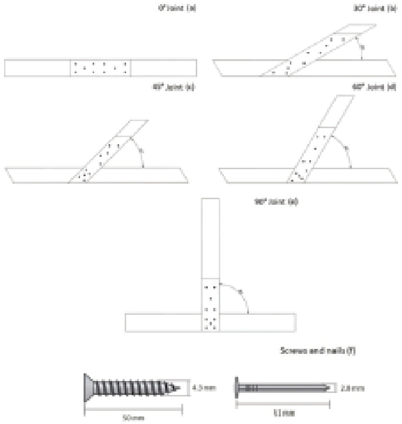


*Fig. 1: Orientation of truss joint sand distribution of nails and screws and dimensions of the screws and nails used.*

## 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).

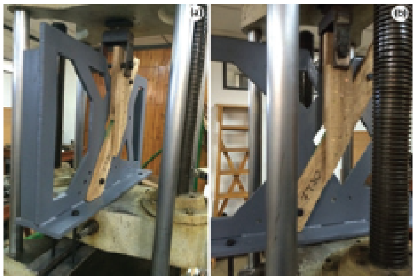


*Fig.2: Test frame device employed for testing joints (a) and applying loads during tests(b).*

## 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).

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

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

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).

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

where: $k_\theta$ - 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.

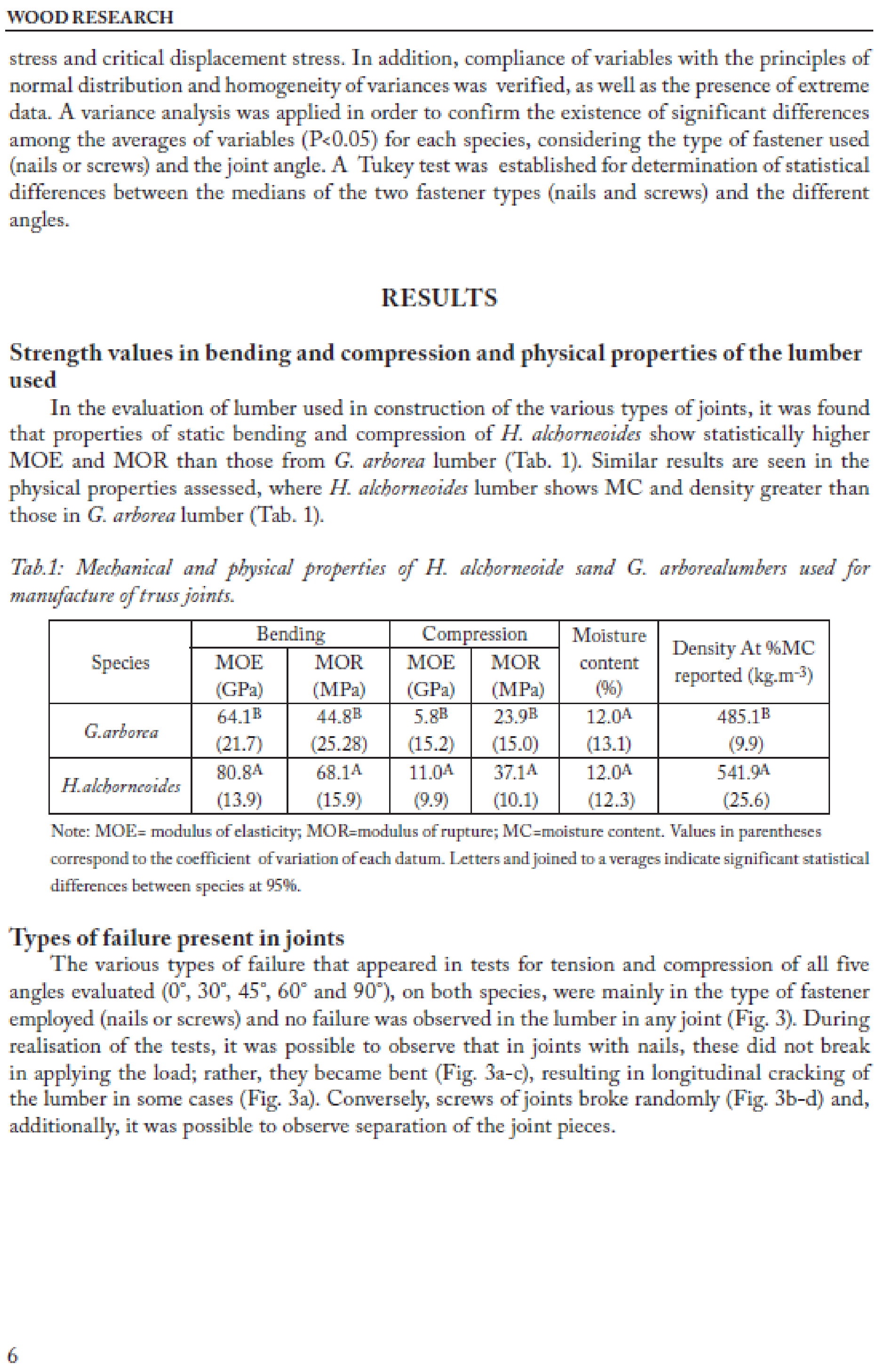
## Mechanical and physical properties evaluated on lumber

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$^{B}$<br>(21.7) | 44.8$^{B}$<br>(25.28) | 5.8$^{B}$<br>(15.2) | 23.9$^{B}$<br>(15.0) | 12.0$^{A}$<br>(13.1) | 485.1$^{B}$<br>(9.9) |
| *H.alchorneoides* | 80.8$^{A}$<br>(13.9) | 68.1$^{A}$<br>(15.9) | 11.0$^{A}$<br>(9.9) | 37.1$^{A}$<br>(10.1) | 12.0$^{A}$<br>(12.3) | 541.9$^{A}$<br>(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).

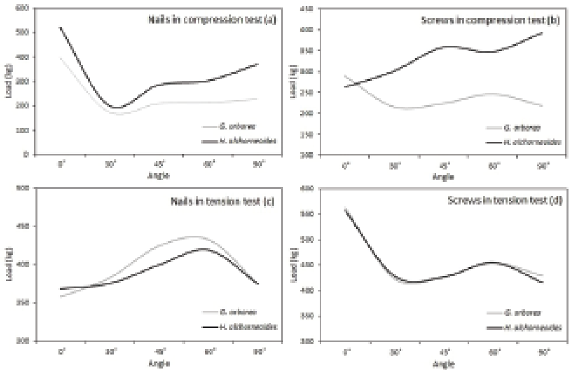
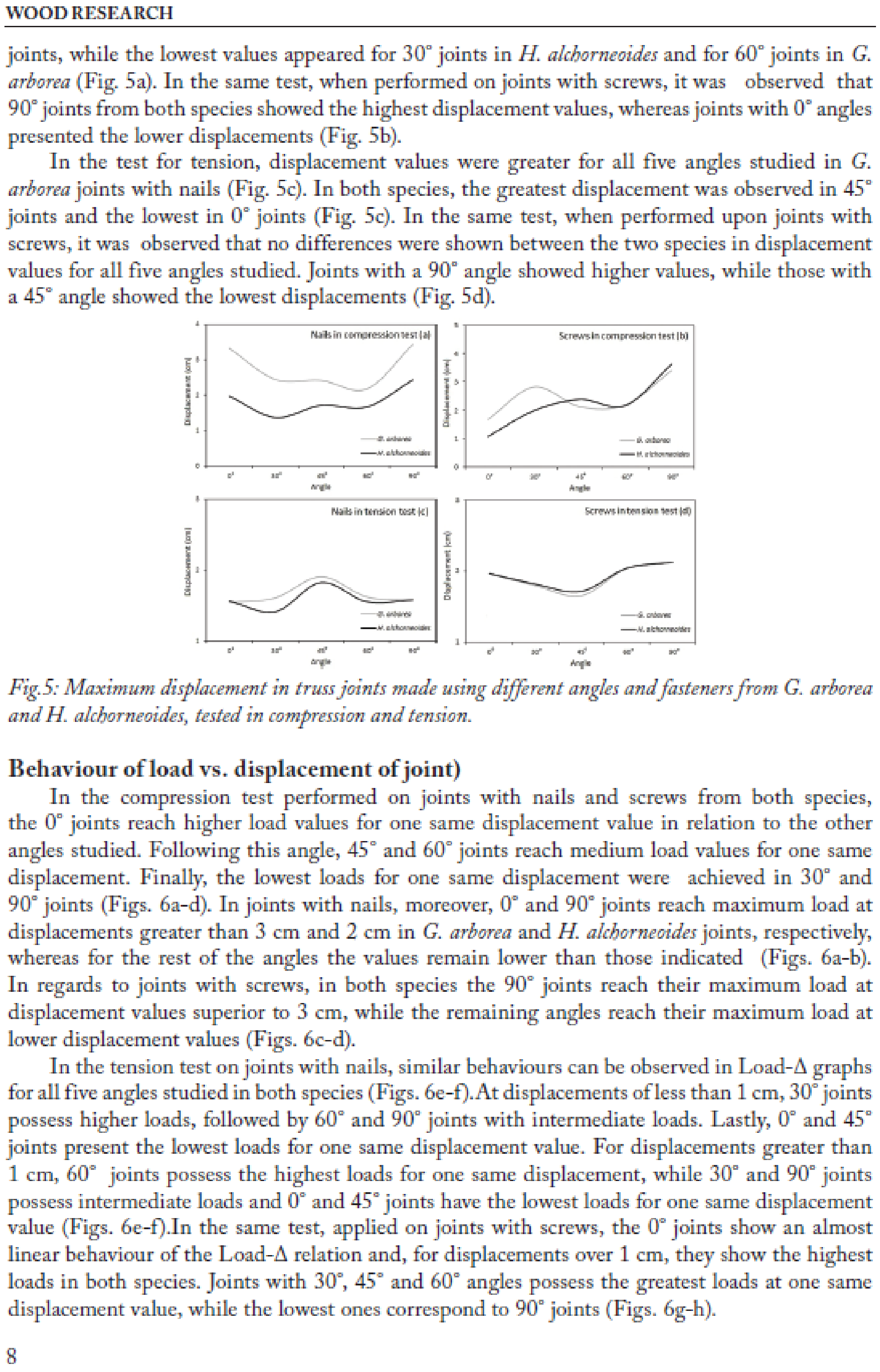


*Fig.4: Maximum loads of truss joints constructed with G. arborea and H. alchorneoides lumbers using different angles and fasteners, tested in compression and tension.*

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).

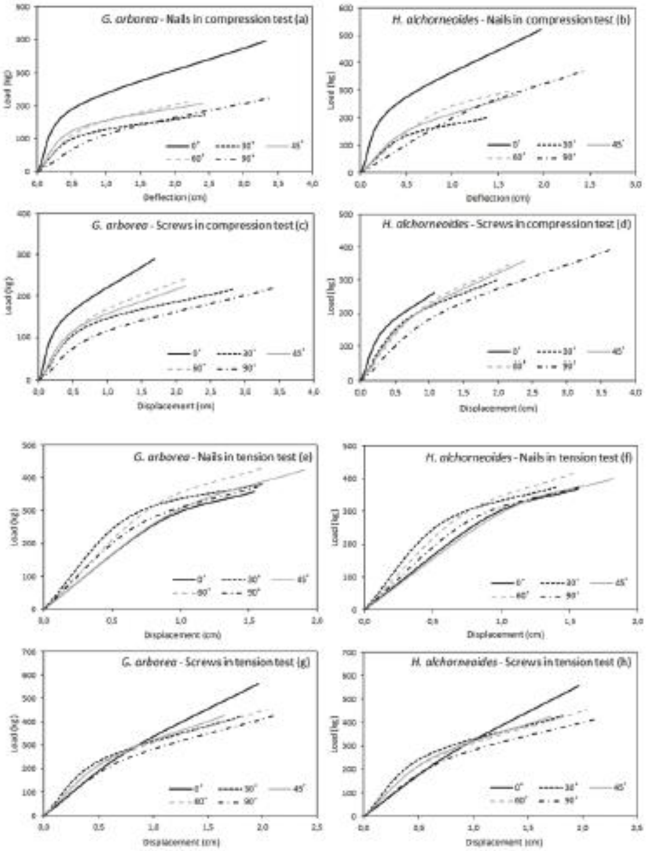
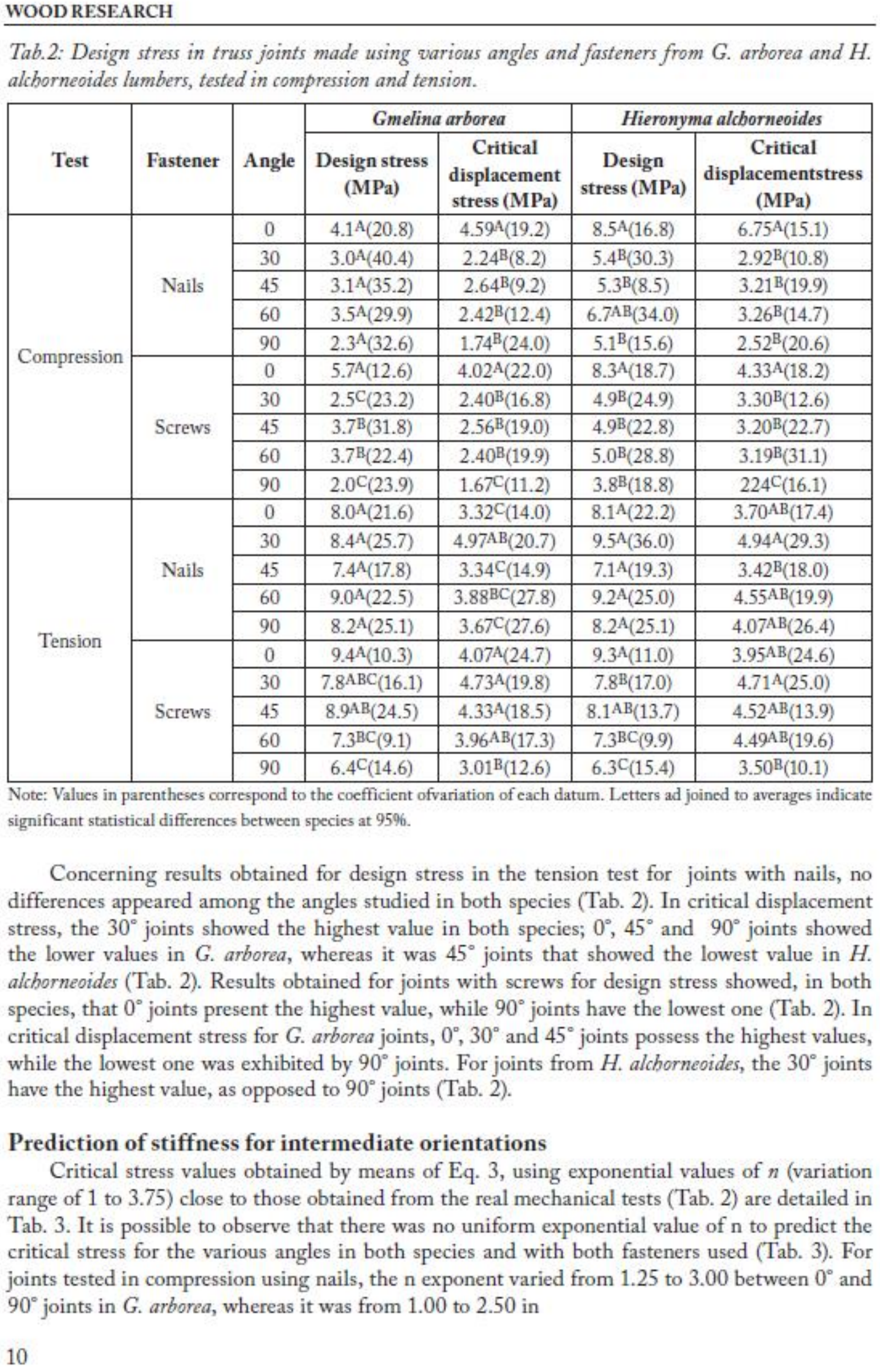


*Fig. 6 : Load vs. displacement curves of truss joints made using various angles and fasteners in lumber from G. arborea and H. alchorneoides, tested in compression and tension.*

## 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 ($K_\theta$) for intermediate angles in trusses are detailed in Tab. 4.

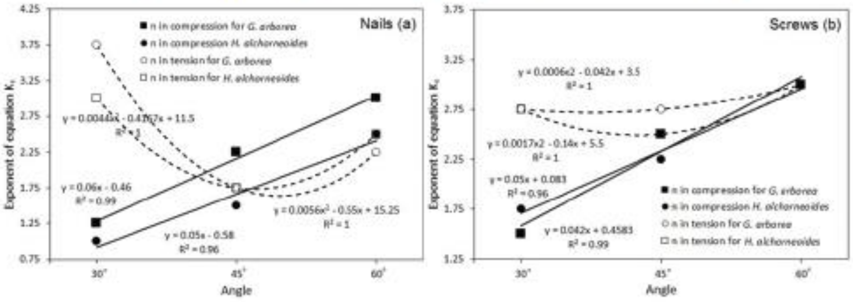
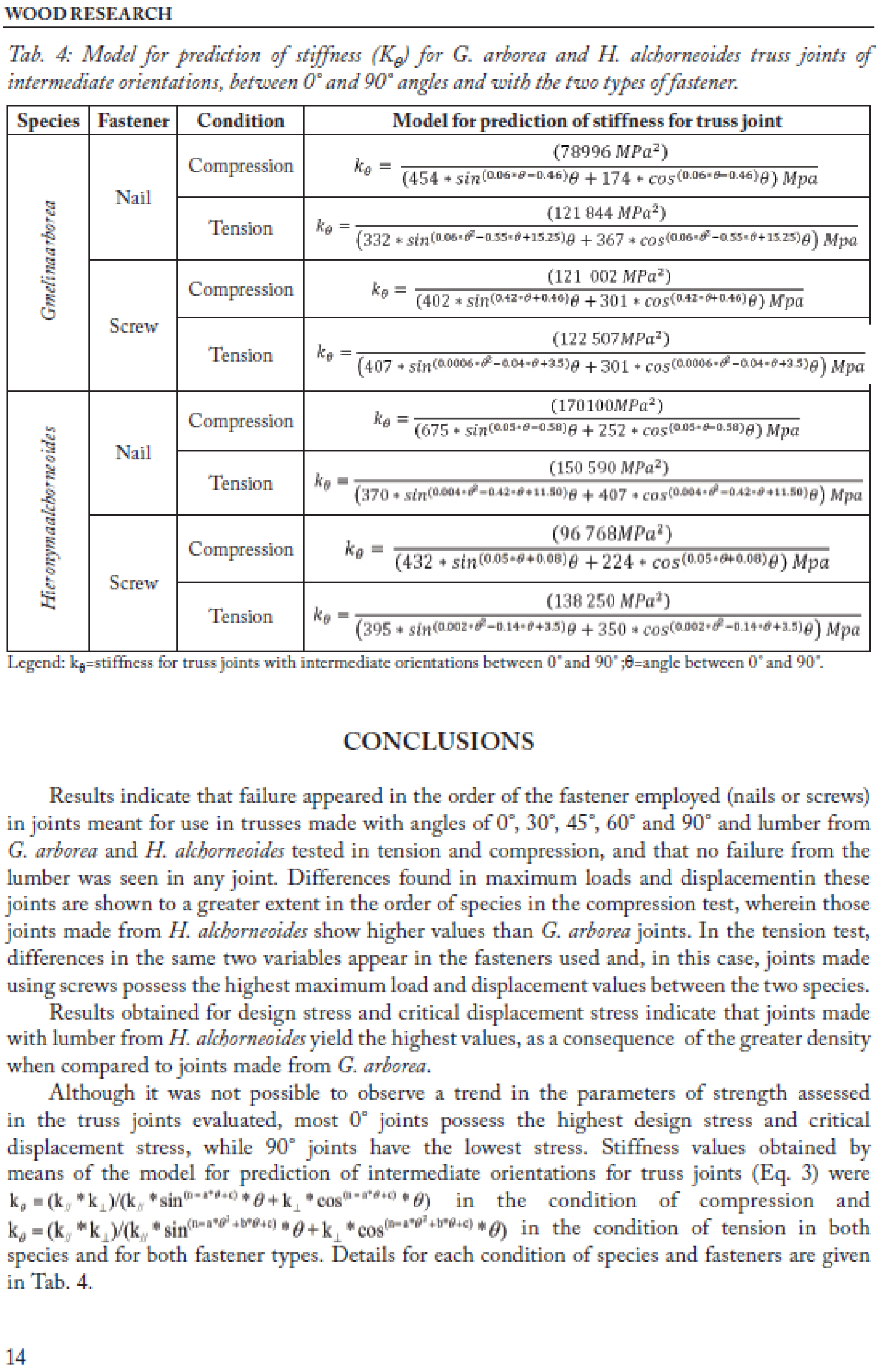


*Fig. 7: Prediction of n exponent for use in equation for prediction of stiffness ($K_\theta$) for G. arborea and H. alchorneoides truss joints of intermediate orientations between 0° and 90° angles.*



WOOD RESEARCH

*Tab. 4: Model for prediction of stiffness ($K_\theta$) 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: $k_\theta$=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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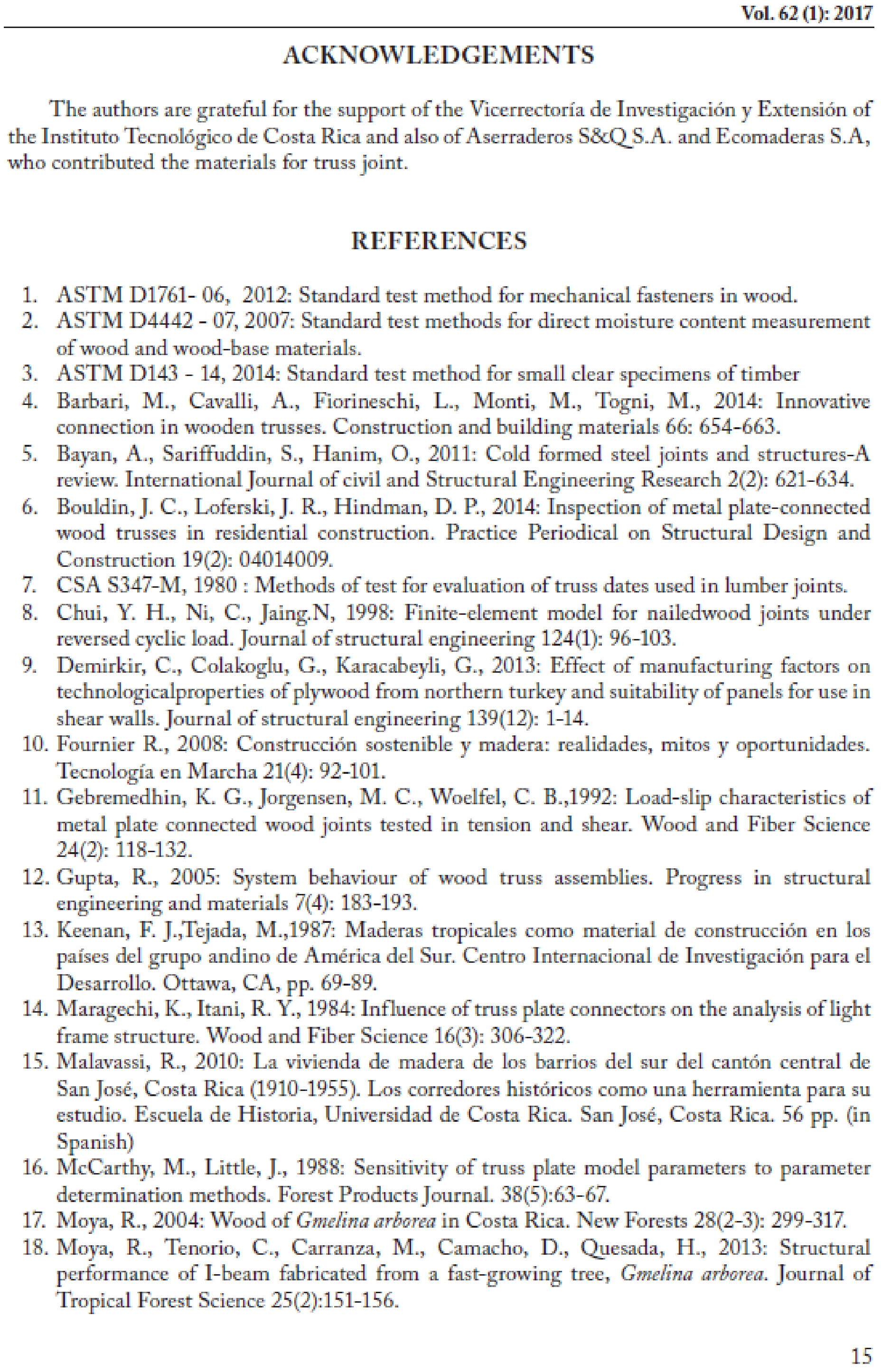

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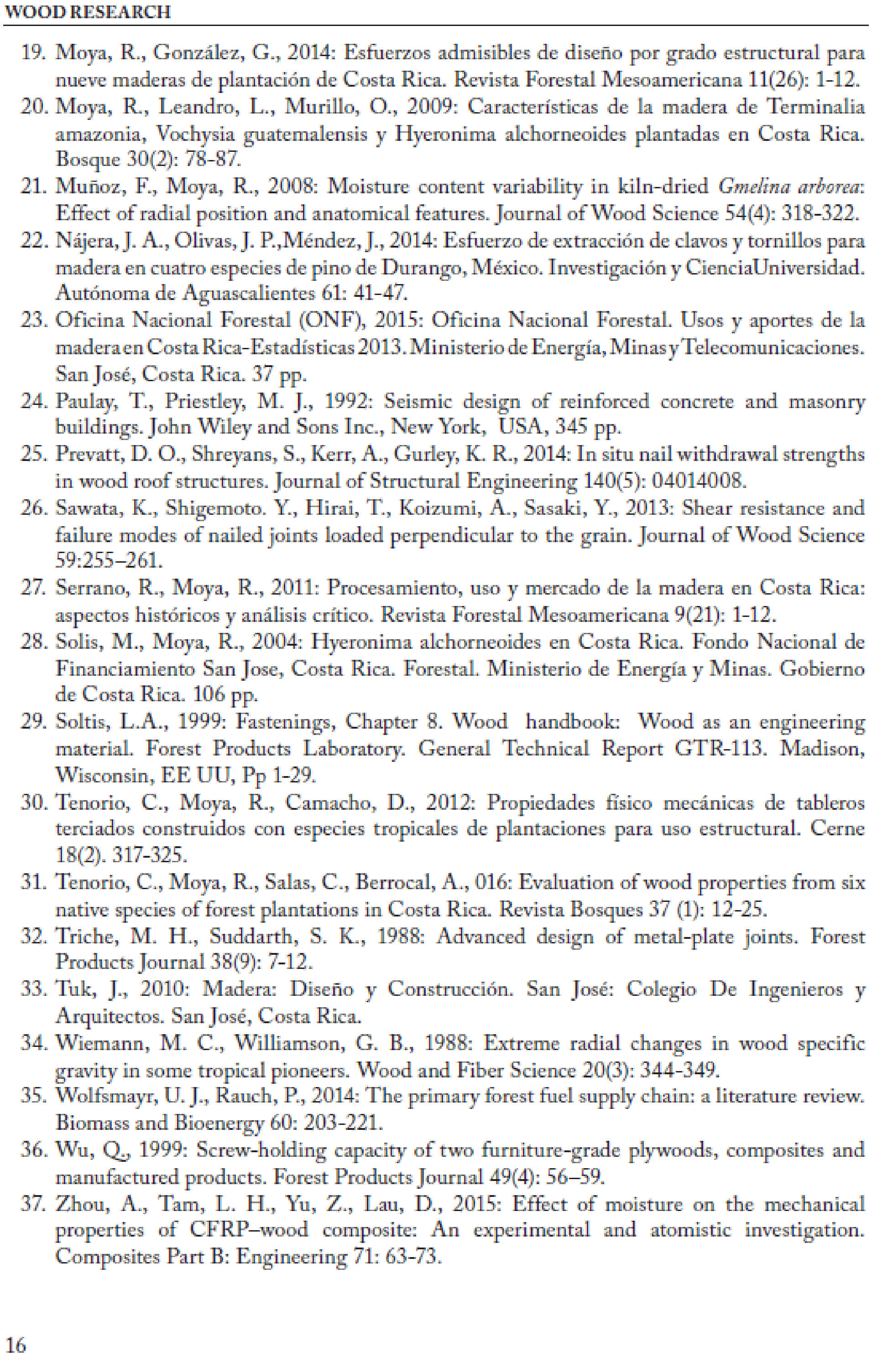

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## Objetivo específico 3: Tablas de diseño y propuesta de empaque y establecer el manual de técnico de la cercha y diagrama de armado.

# Diseño, ensamblaje y manuales de uso de cerchas construidas con madera de *Gmelina arborea* e *Hieronyma alchorneoides* de plantaciones forestales en Costa Rica

Carolina Tenorio[1], Roger Moya[2], Marta Saenz[3], Mauricio Carranza[4], Angel Navarro[5], Viviana Panigua[6]

## RESUMEN

El presente trabajo tuvo como objetivo el diseño de dos cerchas tipo pratt con luces entre apoyos de 6 m y 9 m, construidas con madera de *Gmelina arborea* e *Hieronyma alchorneoides*, utilizando dos tipos de uniones (clavos y tornillos). Como complemento de este objetivo: (i) se establecen los valores de diseño de estas cerchas para ser utilizadas en casas de habitación, (ii) se proponen los posibles empaques para los dos tipos de cerchas y (iii) se proponen los manuales de armado y de uso de las mismas. En los resultados de resistencia se encontró que los valores de carga máxima en las cerchas construidas con madera de *H. alchorneoides* fueron mayores en comparación con las cerchas construidas con madera de *G. arborea*, entre 286 kg a 438 kg y entre 204 kg a 286 kg, respectivamente. Las tablas de diseño de las cerchas para estos dos tipos de madera y para los dos tipos de uniones (clavos o tornillos) fueron propuestas para luces entre apoyos de 4, 5, 6 y 7 m. La propuesta de embalaje que se propuso para cada largo de cercha consistió de dos cajas de cartón corrugado donde la primera caja de 2,5 m de largo agrupará las piezas más grandes, mientras que la segunda caja de 1,6 m de largo agrupará todas las piezas pequeñas. Los manuales de armado y uso muestran en detalle y de forma gráfica como deben armarse las cerchas y cuáles serían las condiciones de uso de las mismas.

**Palabras claves:** construcción liviana, estructura de madera, especies tropicales, empaque, embalaje.

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# Design, assembly and user manuals of trusses fabricated with *Gmelina arborea* wood and *Hieronyma alchorneoides* from forest plantations trees in Costa Rica

## Abstract

The objective of this research is design two pratt framming trusses for two span, 6 m and 9 m, and fabricated with *Gmelina arborea* and *Hieronyma alchorneoides* wood, using two types of fastener (nails and screws). As a complement to this objective: (i) it was established the design values of these trusses for using in small housing building, (ii) proposal of packing for these wood trusses, and (iii) presents construction and user manuals. Results showed that the maximum load values in the trusses fabricated with *H. alchorneoides* wood were higher compared to the trusses fabricated with *G. arborea* wood, between 286 kg to 438 kg and between 204 kg to 286 kg, respectively. The design tables of the trusses for these two species of wood and two types of fastener (nails or screws) were proposed for span of 4, 5, 6 and 7 m. The packaging proposal proposed that two boxes of corrugated paperboard were packing the wood truss: one box with 2.5 m long will packing the largest pieces and second box with 1.6 m long will packing small boards. The manuals of assembly and users detail graphically how the trusses should be assembled and the conditions of use.

**Key words:** framing, wood structures, tropical species, packing.

## Introducción

En los últimos 10 años el uso de la madera en las construcciones civiles en Costa Rica ha disminuido (Serrano y Moya, 2011). En décadas pasadas, el sector de construcción consumía más del 50% del volumen total de madera, sin embargo, cifras recientes indican una disminución a solo el 24% y se indica que solo un 10% de las estructuras son hechas de madera (ONF, 2015). Por otra parte, las construcciones civiles de madera, principalmente casas de habitación, en Costa Rica en el pasado se caracterizaban por ser de tipo "liviana" o "framing" (en inglés) en el mercado de Estados Unidos. Para este tipo de construcciones se utilizan secciones transversales de madera aserrada de 5.0 cm x 7.5 cm o 2.5 cm x 7.5 cm, los cuales se utilizaban para soportes estructurales de pisos y paredes y para la construcción de cerchas (Tuk, 2010). No obstante, en la actualidad este tipo de estructuras en madera han sido desplazadas por otro tipo de materiales como el plástico, el acero y el concreto (Tuk, 2010; Fournier, 2008).

Las cerchas de madera son uno de los componentes de las "estructuras livianas" que han sido ampliamente utilizadas a nivel mundial y datan desde el siglo 6to A.C. (Barbari, Cavalli, Fiorineschi, Monti y Togni, 2014). Las cerchas tienen la característica de que maximizan la eficiencia estructural, ya que permiten alta rigidez en flexión y alta capacidad de carga, como consecuencia de que la estructura es dividida en un número determinado de piezas, cuyas dimensiones y métodos de unión le conceden niveles de tensión más bajos en comparación con otro tipo de estructuras como lo son las vigas (Woods, Hill y Friswell, 2016).

Por otro lado, en Costa Rica y muchos países se han presentado cambios en las especies utilizadas en procesos de construcción (Wolfsmayr y Rauch, 2014; Serrano y Moya, 2011). En Costa Rica, anteriormente se utilizaban especies del bosque natural con densidades sobre 0,6 g/cm$^3$, pero recientemente han surgido maderas de plantaciones forestales, entre las que destacan *Gmelina arborea* e *Hieronyma alchorneoides* (Malavassi, 2010; Serrano y Moya, 2011), las cuales poseen densidades inferiores a 0.6 g/cm$^3$ (Moya, 2004; Tenorio, Moya, Salas y Berrocal, 2016). *G. arborea* ha sido ampliamente estudiada y se le señalan una serie de cualidades para ser utilizada con fines estructurales (Moya, 2004; Tenorio, Moya y Camacho, 2012; Moya, Tenorio, Carranza, Camacho y Quesada, 2013). En tanto que *H. alchorneoides* ha sido utilizada para reforestación comercial en Costa Rica y el estudio de las propiedades de la madera de árboles de plantación ha demostrado altos valores de resistencia estructural (Moya, Leandro y Murillo, 2009; Tenorio et al., 2016a).

Así mismo, Serrano y Moya (2011) haciendo un análisis histórico sobre la comercialización de la madera en Costa Rica, indican que durante la mayor parte del siglo pasado la madera aserrada era comercializada sin mayor criterio técnico; esta se vendía sin dificultad en el mercado y no se necesitaba de técnicas avanzadas de comercialización. También indican que entre 1990 y 2010, debido a la escasez de maderas del bosque natural, y el surgimiento de nuevos productos para la construcción, los industriales se preocuparon más por la falta de materia prima y no por mejorar los estándares de calidad y productos de la madera. Pero en la última década, los industriales que producen madera de plantación, han buscado nuevas formas y productos para mejorar la comercialización y sobre todo mejorar los estándares de la madera aserrada para ser utilizada en construcción.

Hoy en día varios productos de madera pueden ser marca registrada, tal es el caso de los productos Amatek®, Mateco®, Vigamel®, Plymel®, Tablamel®, entre otros. Estos productos además de su marca registrada cuentan con información técnica, que puede ser consultada en páginas en internet o bien por asesoría de los vendedores técnicos de las empresas. Sin embargo, estos productos no cuentan con empaques para su comercialización.

En referencia a esto, el empaque juega un rol crítico en el manejo y distribución de los diferentes productos que se comercializan en el mercado (Pathare, Opara, Vigneault, Delele y Al-Said, 2012; Pthare y Opara, 2014). Entre la funciones que se le señalan al empaque son: protección física del producto, conservación, facilidad de transporte y almacenamiento (Pathare et al., 2012). Además que un buen empaque contiene o incluye información técnica y gráfica sobre el uso y cuidado del producto (Hägglund and Carlsson, 2011). Los materiales usados para la fabricación de los empaques son de varios tipos, pero el material que domina este mercado es el cartón corrugado, debido a su bajo peso (importante en el transporte), versatilidad de diseño, buena resistencia, fácil manipulación y rotulación y por ser reciclable (Pathare et al., 2012). En el caso de Costa Rica, la disponibilidad de productos de madera debidamente empacados, incluyendo información sobre su ensamble y condiciones de uso, son limitados. Este tipo de productos se comercializan únicamente en las grandes ferreterías y por lo general son importados de países como USA, Canadá o China.

En el caso del uso de las maderas de plantación, en especial las especies *G. arborea* y *H. alchorneoides*, aún se carece del conocimiento de las propiedades estructurales de estas en los procesos de construcción de “estructuras livianas”. En el caso de la madera de *G. arborea* proveniente de árboles en plantaciones se ha demostrado que puede ser utilizada satisfactoriamente en la construcción de Vigas-I (Moya et al., 2013, Tenorio, Moya y Carranza, 2014; Paniagua y Moya, 2014). En tanto que los usos de la madera de *H. alchorneoides* extraída de árboles de plantaciones aún son limitados, con la excepción del reciente estudio llevado a cabo por Leiva, Moya y Navarro (2017), donde muestran el usos de estas dos maderas de plantación en la fabricación de “estructuras livianas”. Así mismo es importante, diseñar productos con empaque y que contengan la información técnica y de ensamble como lo hacen otros productos que se presentan en el mercado.

Ante tal situación, el presente trabajo tiene como objetivo determinar los esfuerzos y tablas de diseño de cerchas tipo pratt construidas con madera de plantaciones forestales de *G. arborea* y *H. alchorneoides*, utilizando dos tipos de uniones (clavos y tornillos), sometidas a cargas en flexión y para dos distancias entre luces (6 m y 9 m). Además de que se presenta la propuesta de empaque y manual de técnico y de ensamble para estos dos tipos de luces.

## Materiales y métodos

### Madera utilizada

Se utilizó madera de *Hieronyma alchorneoides* (Allemão) y *Gmelina arborea* (Roxb. ex Sm.) de aproximadamente 15 años de edad. La primera especie fue seleccionada por que la madera procedente de bosque natural fue tradicionalmente utilizada para la fabricación de cerchas (Tuk, 2010). En tanto que la segunda especie, fue seleccionada por su alta tasa de reforestación en Costa Rica y por qué está siendo utilizada en la construcción de cerchas para casas de habitación. La madera de *G. arborea* y de *H. alchorneoides* fue obtenida de los aserraderos Maderas S&Q 2005 situado en el cantón de Pérez Zeledón, San José, Costa Rica y ECOCAJAS S.A ubicado en el cantón de Guápiles, Limón, Costa Rica, respectivamente. La madera utilizada presentaba dimensiones de 2,5 cm de espesor por 7,5 cm de ancho y largo de 2,5 metros. Luego del aserrío ambos tipos de maderas fueron secadas en un horno experimental siguiendo el programa de secado detallado por Muñoz y Moya (2008) en *G.arborea* y Tenorio, Moya y Salas (2016b) para *H. alchorneoides*. En ambos casos la madera fue secada a un contenido de humedad final del 14%.

### Diseño de la cercha

Se construyeron cerchas tipo Pratt, la cual consta de una cuerda inferior, dos cuerdas superiores unidas al centro de la longitud de la cercha, piezas verticales que trabajan en compresión y piezas diagonales que trabajan en tensión (Figura 1). Se seleccionó este tipo de cercha debido a que es la cercha que tradicionalmente es utilizada en Costa Rica (Nieto y Solórzano, 1993). Este tipo de cercha utiliza piezas de madera con dimensiones que se adaptan a la madera obtenida de plantaciones forestales que se produce normalmente en Costa Rica. Dichas dimensiones se caracterizan por presentar poco espesor y ancho y largos no mayores a los 2,5 m (Serrano y Moya, 2011). Se construyeron cerchas con madera de *G. arborea* y de *H. alchorneoides* con largos totales de 7,2 m y 10,2 m, las cuales se pueden utilizar en distancias o luces entre apoyos de 6 m a 9 m, respectivamente (Figura 1a-b). Los dos tipos de cerchas se diseñaron con una pendiente de 20%. La cercha de 7,2 m presentó con una altura en la parte central de 87,5 cm y en los extremos de 14,7 cm, además fue construida con 6 piezas verticales, con separaciones de 120 cm entre los centros de las piezas y 7 piezas diagonales entre las verticales (Figura 1a). En tanto la cercha de 10,2 m presenta una altura en la parte central de 114,5 cm y en los extremos de 14,7 cm y de 11 piezas verticales con separaciones de 120 cm entre los centros de las piezas y 8 diagonales entre las verticales (Figura 1b).

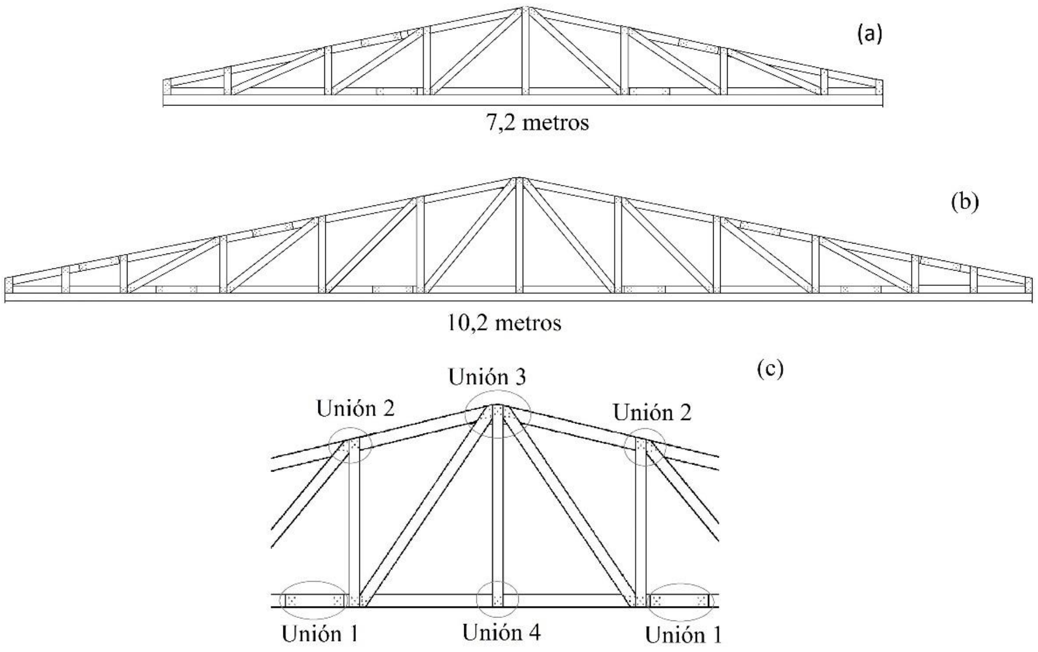


Figura 1. Cercha tipo pratt para distancias entre apoyo de 6 m (a) y 9 m (b) y los cuatro tipos de uniones (c) presentes en las cerchas construidas con madera de *Gmelina arborea* e *Hieronyma alchorneoides*

**Construcción de la cercha**

En todos los casos se utilizó madera aserrada en condición de aserrío con dimensiones de 7,5 cm de ancho, 2,5 cm de espesor y 2,5 m de largo, los cuales presentan medidas nominales para la comercialización de 7,1 cm, 2,2 cm y 2,5 m respectivamente en estado seco. Durante la construcción de la cercha se buscó que el centro de una pieza de 2,5 m de largo coincidiera con el centro de la cercha. Luego se fueron colocando hacia los lados piezas de 2,5 cm hasta llegar a los extremos de la cercha. En el caso de las cuerdas superiores se empezó con una pieza de 2,5 m de largo del punto más alto y luego fueron colocándose piezas de 2,5 m largo hasta el extremo de la cercha. En la cuerda superior se buscó que la unión de las piezas quedará a la mitad de la distancia de dos piezas verticales. En la construcción de cercha tipo pratt se utilizaron cuatro tipos de uniones (Figura 1c):

- Unión 1: unión por extremo, en este tipo dos piezas de madera fueron unidas por los extremos colocando una pieza de 30 cm tipo parche. En este tipo de unión se utilizó en las uniones de las cuerdas inferior y superior de la cercha.
- Unión 2: consiste de la unión de una pieza vertical con una cuerda superior o inferior. Esta unión se utilizó donde se unen una pieza vertical y una diagonal con la cuerda inferior o superior.
- Unión 3: está unión se ubicó en la parte más alta de la cercha y se compone de la unión de las dos cuerdas superiores, una pieza vertical y dos piezas diagonales. Por tratarse de la parte central, esta fue reforzada con una pieza como parche de 30 cm de largo sujetando las piezas verticales y las dos diagonales.
- Unión 4: esta unión se ubicó en la parte central inferior de la cercha y se compone de la unión de la pieza vertical central con la cuerda inferior.

**Tipos de elemento en las uniones**

Las uniones de las cerchas fueron hechas mediante dos elementos de unión, los cuales permiten una conexión semirrígida y que además son los elementos más usados en Costa Rica para construcciones livianas. Los dos elementos de unión fueron: tornillo y clavo. Los tornillos usados fueron de cabeza plana tipo phillips en dos tamaños. En las uniones 1 y 2 fue usada una medida de 75 mm x 4,93 mm (tornillo #10) y en las uniones 3, 4 y 5 se usó tornillo de 50 mm x 4,27 mm (tornillo #8). Los clavos usados también fueron de 51 mm x 2,8 mm (clavo #12,5). Finalmente los clavos o tornillos se colocaron aproximadamente a 2,5 cm del extremo de cada pieza para lograr un distanciamiento aproximado de 2,5 cm entre cada elemento de unión. Se utilizaron clavos o tornillos en cada extremo de las piezas de madera, por lo que en la unión 1, 2, 3 y 4, se usaron 10, 10, 24 y 5 fastener respectivamente (Figura 1c-f).

**Pruebas de resistencia**

La cercha fue ensayada en flexión estática. Durante el ensayo la cercha fue colocada sobre un sistema de apoyos simples colocados a 6 m y 9 m (correspondiente a la distancia entre apoyo), dejando 60 cm hacia adentro del extremo de la cercha (Figura 2a). Las cerchas fueron mantenidas verticalmente, para evitar el movimiento lateral, mediante el uso de elementos de madera (Figura 2b). La carga se aplicó en tres diferentes puntos: sobre la pieza vertical en la parte central de la cercha y en dos piezas verticales ubicadas a cada lado de la pieza vertical del centro (Figura 2a). Para la aplicación de estas cargas durante el ensayo de la cercha fue necesaria la construcción de un aditamento para la adecuada distribución de las cargas. Este aditamento fue fabricado utilizando vigas de metal en C de 5,0 cm x 7,5 cm con 6,0 mm de espesor y un peso de 42 kg (Figura 2a). Este aditamento de ensayo fue modelado como elemento finito en el programa SAP2000. Se logró determinar que distribuye un 31% de la carga en los nodos de los extremos del accesorio y un 38% en el nodo central. Esto significa que de los 42 kg del peso del aditamento, 17,2 kg fueron aplicados en el nodo central y 12,4 kg en los otros dos nodos (laterales). Para el ensayo se colocó un sensor tipo crackmeter para medir el desplazamiento vertical en el centro de la cercha (Figura 2a).

Figura 2. Sistema de aplicación de carga en los ensayos de las cerchas (a), elementos de restricción utilizados para evitar el pandeo lateral de las cerchas durante los ensayos (b).

### Parámetros determinados

Durante el ensayo se fue registrando cada 5 segundos la carga y el desplazamiento en la parte central de la cercha (Figura 1a) de manera automática por medio de un datalogger. Luego con esta información se construyeron gráficos de carga vrs desplazamiento de todas las cerchas. Con la ayuda de estos gráficos se obtuvo la carga máxima o “carga de falla” ($F_{falla}$) que representa la carga máxima que soporta la cercha. Así mismo se obtiene el desplazamiento en el punto de proporcionalidad o límite elástico de la cercha y a este se le llama “desplazamiento elástico”. El tercer parámetro determinado corresponde al desplazamiento máximo que tiene la cercha en el momento que falla esta y este término es llamado como “desplazamiento máximo experimental” ($\Delta_{experimental}$). En el momento de graficar dichas curvas el peso del aditamento fue sumado a los valores de carga aplicada sobre cada cercha. Estos parámetros fueron determinados por tipo el largo de la cercha, especie y tipo de elementos de unión (Cuadro 1).

### Diseño experimental y análisis estadístico

Se estableció un diseño experimental factorial $2^2$ para las cerchas fabricadas de cada una de las especies estudiadas, dos luces entre apoyo (6 m y 9 m) y dos elementos de unión (clavos y tornillos). Se construyeron seis cerchas de *G. arborea* para cada distancia entre apoyos y cada tipo de elemento de unión (2 distancia entre apoyo x 2 tipo de elemento de unión x 6 repeticiones = 24 cerchas en total), mientras que para *H. alchorneoides* se construyeron cuatro cerchas para cada distancia entre apoyos y cada tipo de elemento de unión (2 distancia entre apoyo x 2 tipo de elemento de unión x 4 repeticiones= 16 cerchas en total). De cada ensayo se obtuvieron diferentes parámetros: promedio, valor máximo y mínimo, el rango, desviación estándar, mediana y varianza. Para la carga máxima y el desplazamiento máximo se verificó la normalidad de los datos. Seguidamente se procedió a realizar el análisis de varianza (ANOVA) para cada una de las especies (*G. arborea* y de *H. alchorneoides*), considerando dos factores, distancia entre apoyos (6 m y 9 m) y elemento de unión utilizado (clavos y tornillos). Finalmente para determinar si existían diferencias significativas entre los tratamientos, se realizó una comparación de los tratamientos por medio de la prueba de Tukey.

**Calibración del modelo**

La calibración del modelo de la cercha consistió en ajustar los datos de desplazamiento en la parte central de la cercha y la carga de falla en un modelo digital mediante el programa de modelación SAP2000 (Ecuación 1). El objetivo es lograr que el modelo proporcione la deformación obtenida experimentalmente en la carga máxima. No es frecuente encontrar este ajuste en los modelos de simulación, de forma que para lograr las mismas deformaciones obtenidas experimentalmente, en el modelo se debe cambiar la rigidez de las uniones de las cerchas (*K*), en este caso en la unión 4 (Figura 1c) que es donde se está midiendo la deformación. Para lograr esto, en el programa de SAP2000 a cada una de las cerchas se le aplica la carga de falla y se va cambiando la rigidez hasta tener la “deformación máxima experimental” (Ecuación 2). Estos modelos fueron aplicados para cada tipo de cercha, de acuerdo con la distancia entre apoyos, los tipos de elementos de unión y la especie de madera utilizada.

$$k = \frac{F}{\Delta} \qquad (1)$$

$$\Delta_{modelo} = \frac{F_{falla}}{K} \qquad (2)$$

Dónde: F: fuerza, $\Delta$: deformación, K rigidez, $\Delta_{modelo}$: Deformación del modelo que debe ser igual a la desplazamiento experimental ($\Delta_{experimental}$), $F_{falla}$: fuerza máxima de falla obtenida experimentalmente, K: rigidez de la cercha en la unión 4.

Como segunda etapa y como los datos experimentales mostraron que las cerchas fallaron en las uniones tipo 1, en el modelo se colocan piezas de 10 cm de largo en estas uniones para darle mayor resistencia a la unión. Así mismo, las uniones en las cerchas se cambiaron de uniones rígidas a momentos, con un valor cercano a cero, y este se torno un valor constante, logrando así que la deformación y carga de falla correspondiente a los valores de resistencia de la cercha obtenida en los ensayos reales.

En el tercer paso, se buscó determinar la separación (S) entre una cercha y otra, utilizando las cargas máximas obtenidas experimentalmente y las propiedades de rigidez determinadas por el modelo SAP2000. Para esto en las cerchas se coloca una carga distribuida sobre la cuerda superior nuevamente utilizando el programa SAP2000. Esta carga distribuida se varía hasta que la cercha alcance la deformación máxima, la cual es L/360, siendo L la longitud entre apoyos (6 m y 9 metros). Al tener que llegar a la deformación máxima permitida, se obtiene la carga máxima que soporta la cercha. A partir de dicha carga obtenida, se puede conocer la carga adicional que se puede colocar a la cercha, así como la distancia a la que se pueden colocar las cerchas entre sí (S).

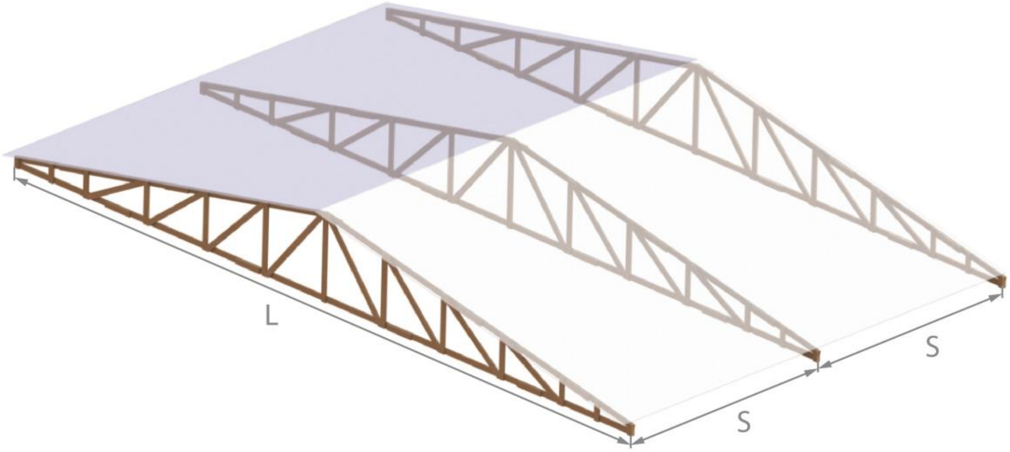


Figura 3*.* Separación entre cerchas y longitud en las tablas de diseño para cerchas construidas con madera de *Gmelina arborea* e *Hieronyma alchorneoides.*
Nota: S = separación entre cerchas, L = luz de la cercha

### Propuesta de embalaje

Para el desarrollo de la propuesta de embalaje, se tomó en cuenta la cantidad y dimensiones de las piezas que conforman las dos longitudes finales de cerchas (7,2 m y 10,2 m). Luego de cuantificadas y clasificadas por tamaños las piezas de cada cercha se diseñó el empaque, el cual debía tener las siguientes características:

1. El empaque debía permitir al producto ser auto-soportante.
2. El empaque debía ser fabricado con el material más barato posible.
3. El peso máximo del producto (madera y empaque) no debe sobrepasar los 25 kg, en concordancia con las especificaciones dadas por la Organización Internacional de Trabajo (OIT) para el peso máximo de un embalaje de manejo individual.
4. En el empaque debía estar contenido todo el material (madera y elementos de unión), y las instrucciones de armado de la cercha (manual de armado).

### Manuales de Armado y técnico

Para completar la propuesta de comercialización y usos de las cerchas prefabricadas de una estructura liviana se desarrollaron dos tipos de manuales:

1. Manual de armado, dirigido a las personas que se encargarán de armar la cercha para su colocación. Este manual debe cumplir los siguientes aspectos: (1) debía ser lo más esquemático posible, (ii) debía representar la secuencia de pasos necesarios para el armado de las cerchas, (iii) los pasos de armado debían tener un orden lógico y (iv) debía ser una sola hoja ubicada dentro del empaque de la cercha.
2. Manual técnico, dirigido a ingenieros o arquitectos y debe contener: (i) la información de las características generales de la madera, (ii) los valores de diseño de las cerchas y (iii) forma de colocación de las cerchas en un techo.

## RESULTADOS Y DISCUSIÓN

### Resistencia de las cerchas

Los promedios de carga máxima obtenidos para las cerchas de pilón fueron mayores a los obtenidos en las cerchas melina, para la primera especie fueron de alrededor de 285,52 kg a 438,48 kg (Figura 4b) y para la segunda de 203,94 kg a 285,52 kg (Figura 4a). Con respecto a la carga máxima, en las cerchas construidas de madera de melina para luces entre apoyo de 6 m y 9 m, se observó que no se presentaron diferencias estadísticas entre los dos tipos de elementos de unión utilizados, y que las cerchas para luces entre apoyo de 6 m presentaron un promedio de carga máxima mayor en comparación con las cerchas para luces entre apoyo de 9 m (Figura 4a). Las cerchas construidas con la madera de pilón presentaron el mismo comportamiento que las cerchas construidas de madera de melina, no se observaron diferencias significativas entre los dos tipos de elemento de unión utilizados para los dos luces entre apoyo, pero las cerchas para luces entre apoyo de 6 m presentaron los promedios de carga máxima más altos (Figura 4b). Es importante destacar que si bien no se presentaron diferencias estadísticas entre los dos tipos de elementos de unión utilizados, las cerchas fabricadas con madera de melina con tornillos presentaron los promedios más altos, mientras que las cerchas fabricadas con madera de pilón con clavos presentaron los valores de carga máxima más altos (Figura 4a).

En los promedios de los desplazamientos máximos obtenidos para las cerchas fabricadas con madera de melina y pilón no se observaron diferencias estadísticas entre los dos tipos de elementos de unión utilizados para las dos luces o tamaños de cercha (Figura 1c-d). Solo se presentaron diferencias estadísticas en las cerchas fabricadas con madera de pilón en las luces entre apoyo de 9 m, donde las cerchas construidas con clavos presentaron los desplazamientos en el límite de proporcionalidad en los dos puntos de medición (central y lateral) más altos (Cuadro 1). En relación a otros parámetros determinados en las diferentes cerchas se observa que la carga máxima presenta rangos de variación muy amplios, sobre 100 kg, en tanto que el resto de los parámetros son presentados en el Cuadro 1.

Cuadro 1. Estadísticos determinados para los parámetros de carga y deformación en cerchas construidas con madera de *Gmelina arborea* e *Hieronyma alchorneoides*.

| **Especie** | **Tipo de unión** | **Luz entre apoyos (m)** | **Parámetros** | **Promedio** | **Máximo** | **Mínimo** | **Rango** | **Desviación Estándar** | **Mediana** | **Varianza** |
|---|---|---|---|---|---|---|---|---|---|---|
| *G. arborea* | Clavos | 6 | Carga máxima (kg) | 260,83 | 319,66 | 215,49 | 104,17 | 38,12 | 255,22 | 1253,47 |
| | | | Desplazamiento elástico (mm) | 44,33 | 56,60 | 28,78 | 27,82 | 10,43 | 46,07 | 98,58 |
| | | | Desplazamiento máximo (mm) | 60,36 | 72,20 | 46,49 | 25,71 | 10,11 | 63,51 | 1116,26 |
| | | 9 | Carga máxima (kg) | 206,03 | 269,39 | 144,97 | 124,42 | 34,51 | 202,10 | 1847,47 |
| | | | Desplazamiento elástico (mm) | 62,72 | 90,10 | 48,15 | 41,95 | 18,70 | 52,12 | 349,68 |
| | | | Desplazamiento máximo (mm) | 77,45 | 125,01 | 52,81 | 72,20 | 29,85 | 62,52 | 890,75 |
| | Tornillos | 6 | Carga máxima (kg) | 285,60 | 394,56 | 224,23 | 170,33 | 67,25 | 263,62 | 3974,52 |
| | | | Desplazamiento elástico (mm) | 37,45 | 56,57 | 19,54 | 37,03 | 14,52 | 39,60 | 179,51 |
| | | | Desplazamiento máximo (mm) | 49,84 | 57,62 | 42,07 | 15,55 | 7,29 | 50,74 | 46,27 |
| | | 9 | Carga máxima (kg) | 231,36 | 283,86 | 184,22 | 99,64 | 38,26 | 233,37 | 1265,65 |
| | | | Desplazamiento elástico (mm) | 58,83 | 82,40 | 37,57 | 44,83 | 16,30 | 56,20 | 233,19 |
| | | | Desplazamiento máximo (mm) | 66,15 | 93,6 | 52,28 | 41,32 | 16,90 | 62,15 | 235,08 |
| *H. alchorneoides* | Clavos | 6 | Carga máxima (kg) | 442,81 | 492,12 | 392,38 | 99,74 | 47,84 | 443,37 | 2288,8 |
| | | | Deformación en falla (mm) | 49,50 | 64,27 | 41,75 | 22,52 | 10,44 | 46,01 | 108,93 |
| | | | Deformación máximo (mm) | 71,76 | 77,44 | 60,77 | 16,67 | 7,62 | 74,42 | 58,03 |
| | | 9 | Carga máxima (kg) | 455,95 | 578,33 | 290,58 | 287,75 | 122,94 | 477,45 | 15114,67 |
| | | | Desplazamiento elástico (mm) | 92,29 | 122,00 | 67,58 | 54,42 | 24,85 | 89,79 | 617,38 |
| | | | Desplazamiento máximo (mm) | 117,56 | 148,99 | 83,1 | 65,89 | 27,67 | 119,09 | 765,52 |
| | Tornillos | 6 | Carga máxima (kg) | 396,63 | 465,24 | 306,26 | 158,98 | 71,08 | 407,53 | 5051,66 |
| | | | Desplazamiento elástico (mm) | 36,24 | 39,95 | 33,72 | 6,23 | 2,72 | 35,65 | 7,41 |
| | | | Desplazamiento máximo (mm) | 43,48 | 50,67 | 39,96 | 10,71 | 4,87 | 41,65 | 23,7 |
| | | 9 | Carga máxima (kg) | 288,85 | 368,95 | 226,81 | 142,14 | 63,07 | 279,82 | 3977,62 |
| | | | Desplazamiento elástico (mm) | 55,49 | 93,12 | 27,24 | 65,88 | 28,29 | 50,81 | 800,20 |
| | | | Desplazamiento máximo (mm) | 62,67 | 96,58 | 29,13 | 67,45 | 28,27 | 62,48 | 798,91 |

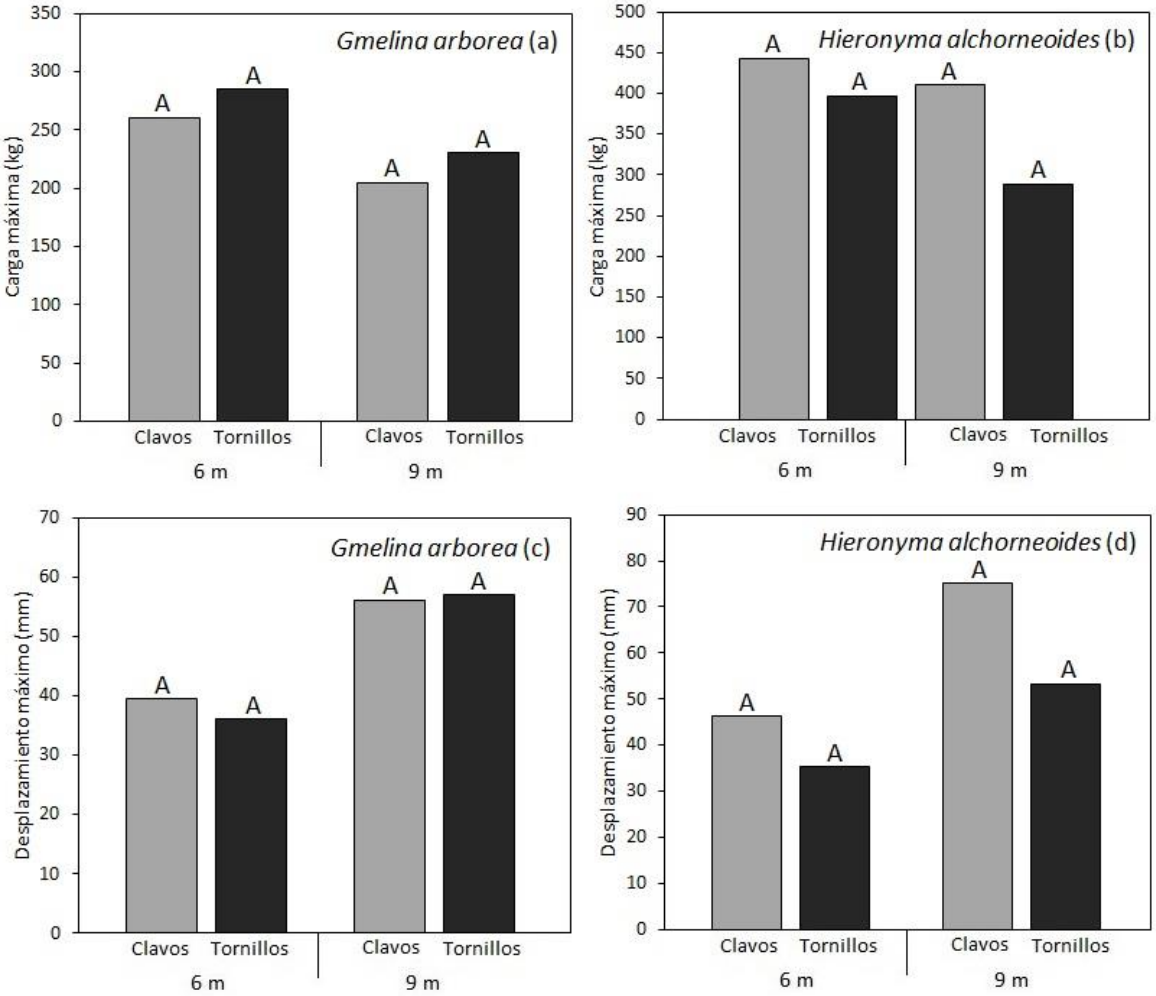


Figura 4. Carga máxima (a y b) y desplazamiento máximo (c y d) obtenidos para cerchas construidas con madera de *Gmelina arborea* e *Hieronyma alchorneoides*.

## Modelo de simulación y tablas de diseño

Además de determinar el valor de rigidez (k) para los dos tipos de cerchas, fueron calculados valores de rigidez para cerchas con separación entre apoyos de 4 y 5 metros. Los resultados mostraron que el valor de K fue mayor en las cerchas de mayor distancia entre apoyos, por lo que la rigidez decrece (Tabla 2). Así mismo es evidente que la rigidez es más alta en las cerchas construidas con tornillos y con madera de pilón.

En relación con la separación (S) entre las cerchas se derivó que se deben utilizar para 4 diferentes luces entre apoyo (Figura 3), 4, 5, 6 y 7 metros en madera de melina y pilón y los dos tipos de elementos de uniones. Así mismo se presenta las respectivas cargas máximas para esas separaciones y la carga máxima temporal que soportarían las cerchas si estás tienen un separación entre cercha de 1 metro.

Cuadro 2. Luces entre apoyo, rigidez y separación entre cerchas construidas con madera de *Gmelina arborea* e *Hieronyma alchorneoides.*

| **Especie** | **Elemento de unión** | **Luz entre apoyos (m)** | **Rigidez de unión 4 (kg-mm)** | **Separación (m)** | **Carga máxima (kg/m)** | **Carga máxima temporal con 1 m de separación (kg/m$^2$)** |
|---|---|---|---|---|---|---|
| *G. arborea* | Clavos | 4 | 63,22 | 0,72 | 31,00 | 28,69 |
| | | 5 | 66,65 | 0,61 | 27,00 | 24,51 |
| | | 6 | 70,07 | 0,61 | 26,80 | 24,36 |
| | | 9 | 80,34 | 0,27 | 13,20 | 10,72 |
| | Tornillos | 4 | 90,93 | 1,02 | 43,00 | 40,67 |
| | | 5 | 92,51 | 0,84 | 36,75 | 33,77 |
| | | 6 | 94,10 | 0,80 | 34,50 | 32,06 |
| | | 9 | 98,86 | 0,34 | 16,15 | 13,67 |
| *H. alchorneoides* | Clavos | 4 | 93,85 | 1,10 | 47,27 | 44,09 |
| | | 5 | 98,23 | 0,92 | 19,45 | 36,64 |
| | | 6 | 102,60 | 0,93 | 39,50 | 37,06 |
| | | 9 | 115,75 | 0,39 | 19,45 | 15,73 |
| | Tornillos | 4 | 135,56 | 1,55 | 49,50 | 61,84 |
| | | 5 | 133,95 | 1,25 | 21,40 | 50,14 |
| | | 6 | 132,35 | 1,18 | 49,50 | 47,06 |
| | | 9 | 127,54 | 0,44 | 21,42 | 17,72 |

### Diseño o propuesta de embalaje

En la propuesta del diseño de empaque (Figura 5), se propuso que todas las piezas que componen las cerchas con luces de 6 m y 9 m (Figura 6a, sección de piezas) formarán dos paquetes: uno que contiene las piezas de 2,5 m de largo y otro paquete que contiene las piezas verticales y diagonales de las cerchas. Las dimensiones de cada uno de los paquetes en cada una de las cerchas son detalladas en la figura 5 (a-b). El empaque así tiene las siguientes características:

- Los paquetes no sobrepasan los 25 kg de peso.
- El embalaje no solo protege la madera sino que mantiene todas las piezas juntas también.
- El embalaje es fabricado con cartón corrugado flauta C, es que es el material más barato para empaque. Este cartón corrugado es un material liviano, cuya resistencia se basa en el trabajo conjunto y vertical de estas láminas de papel
- El empaque de cartón es producido por una máquina troqueladora que indica los dobleces de las cajas y sale de forma plana y este se dobla cuando se empaca la cercha (Figura 5d).
- En los extremos se coloca una capucha con corte de troquel y luego se arma y se coloca mediante el uso de flejes en los extremos de la caja (Figura 5d).
- Es necesaria la colocación de 3 flejes, adicionales a los de los extremos, distribuidos en el largo de las cajas de 2,5 m, y de un fleje en el caso de la caja de 1,35 m (Figura 5d).

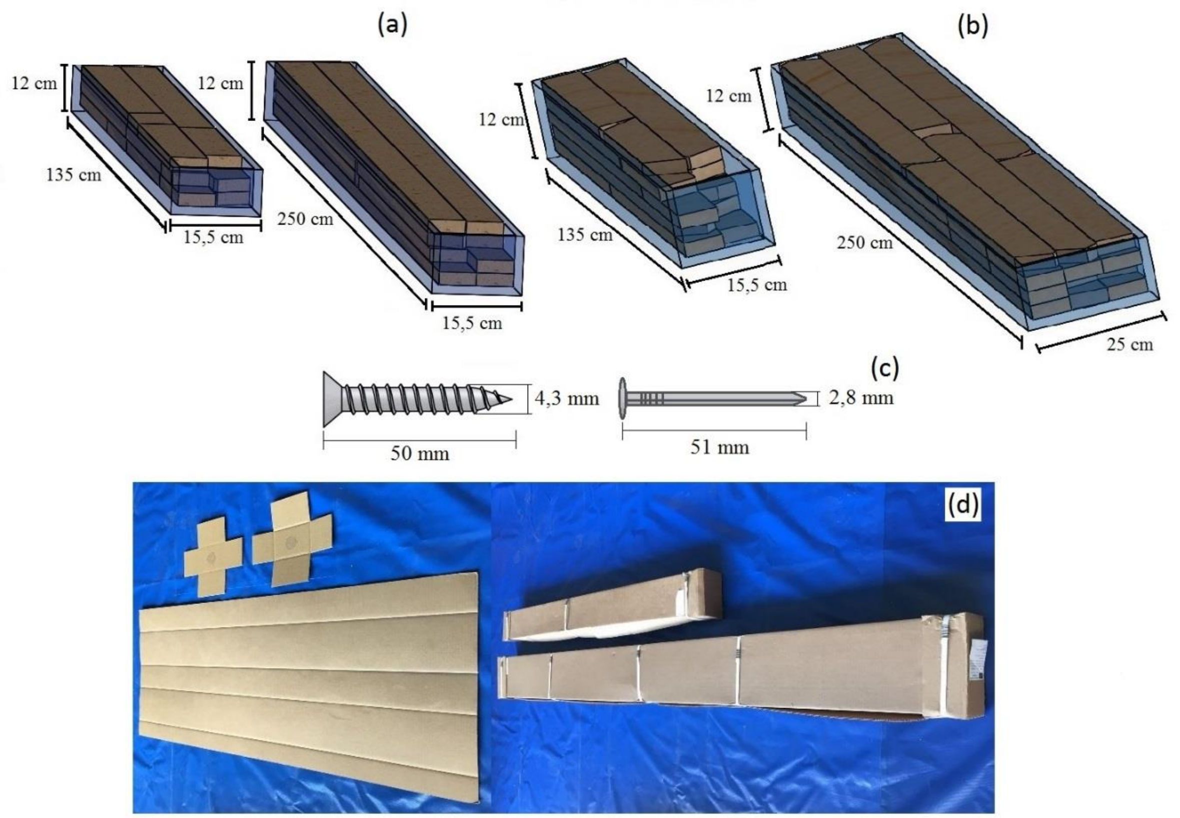


Figura 5. Diseño de acomodo y empaque para las piezas de las cerchas con luces de 6 m (a) y 9 m (b), clavos y tornillos utilizados en la fabricación de las cerchas (c) y propuesta de embalaje (d) para las cerchas construidas con madera de *Gmelina arborea* y *Hieronyma alchorneoides*.

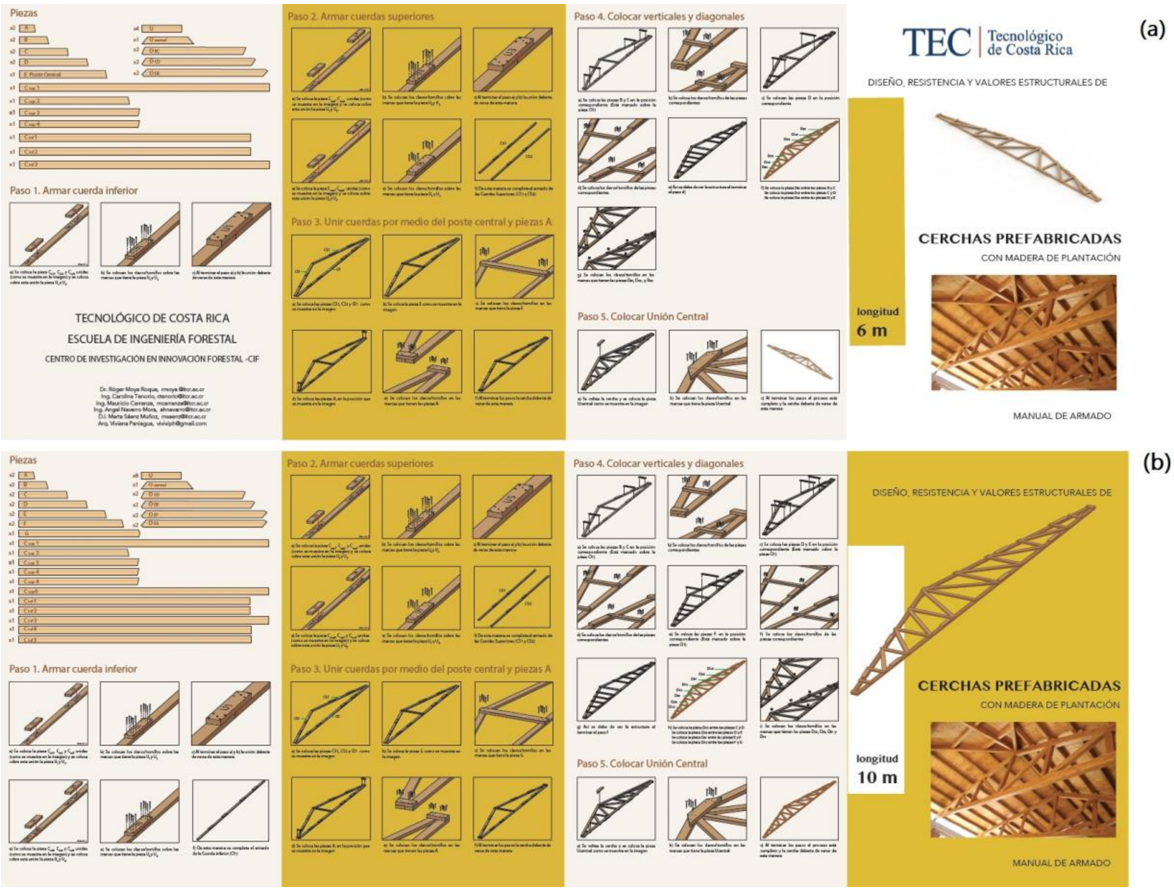
## Manuales de armado y técnico

Para completar la propuesta de comercialización y uso de las cerchas prefabricadas de una estructura liviana fueron desarrollados dos tipos de manuales:

- Un primer tipo de manual de armado, que está dirigido a las personas que se encargarán de armar la cercha para su colocación. Este manual debe cumplir los siguientes aspectos: (1) debe ser lo más esquemático posible, (ii) debe representar la secuencia de pasos necesarios para que el armado de las cerchas, (iii) los pasos que se presenten en el manual de armado deben estos deben tener un orden lógico y (iv) debe ser una sola hoja y que se encuentre dentro del empaque de la cercha.
- Manual técnico: este manual debe está dirigido a ingenieros o arquitectos y debe contener: (i) la información de las características generalas de la madera, (ii) los valores de diseño de las cerchas y (iii) forma de colocación de las cerchas en un techo.

## Manuales de Armado y técnico

Primeramente el manual de armado, fue diseñado de manera gráfica (Figura 6) y consiste de hoja tamaño carta en donde se encuentran debidamente enumeradas todas las piezas. En este se van detallando cada uno de los pasos que se deben seguir para el armado de cada una de las cerchas de las dos longitudes de apoyo (Figura 6) y este debe estar contenida en el empaque (Figura 5). En forma general se indica que la cercha debe armarse: (1) armar la cuerda inferior, (2) armar la cuerda superior, (3) unir estas dos cuerdas por medio de la pieza central, (4) colocar las piezas verticales y diagonales y por último armar la unión central.


(a)

Piezas

Paso 1. Armar cuerda inferior

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Paso 2. Armar cuerdas superiores

Paso 3. Unir cuerdas por medio del poste central y piezas A

Paso 4. Colocar verticales y diagonales

Paso 5. Colocar Unión Central

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DISEÑO, RESISTENCIA Y VALORES ESTRUCTURALES DE

CERCHAS PREFABRICADAS

CON MADERA DE PLANTACIÓN

longitud
6 m

MANUAL DE ARMADO

(b)

Piezas

Paso 1. Armar cuerda inferior

Paso 2. Armar cuerdas superiores

Paso 3. Unir cuerdas por medio del poste central y piezas A

Paso 4. Colocar verticales y diagonales

Paso 5. Colocar Unión Central

DISEÑO, RESISTENCIA Y VALORES ESTRUCTURALES DE

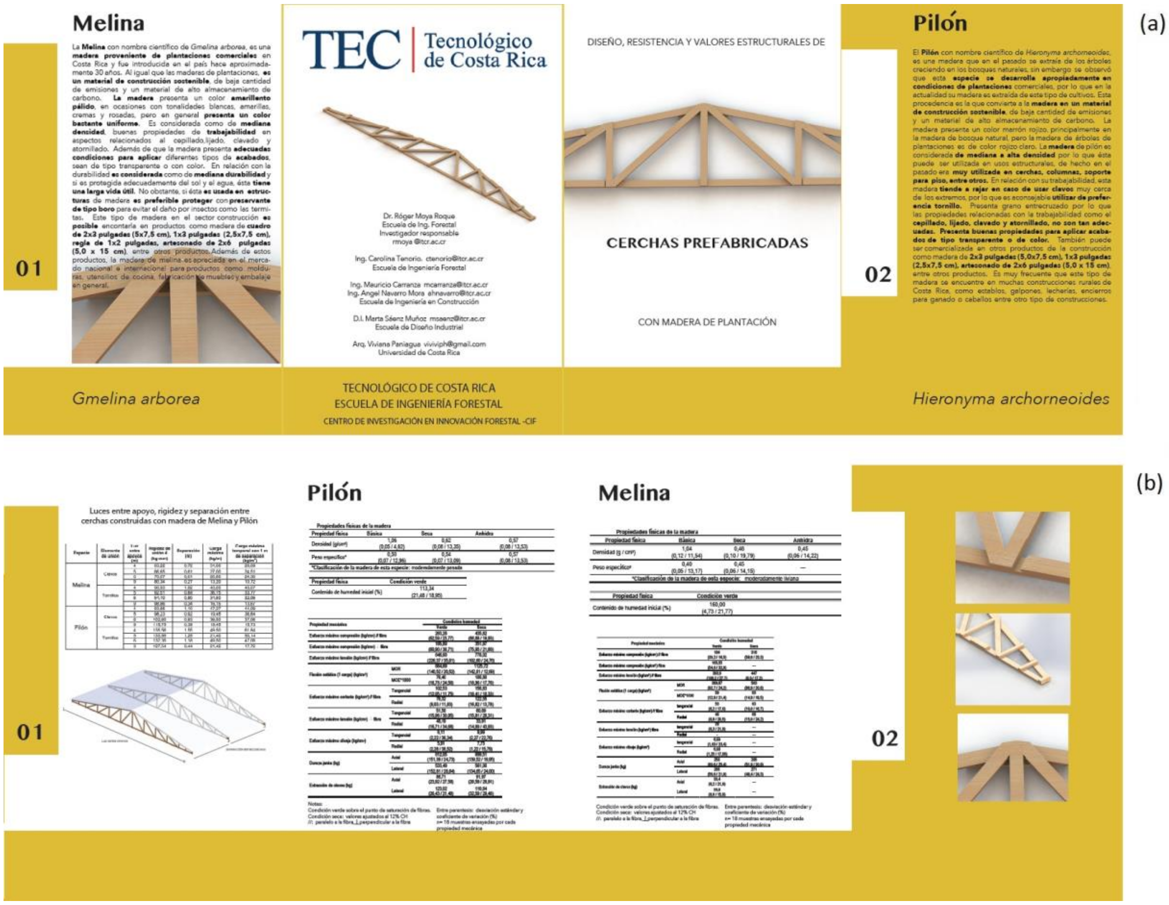
CERCHAS PREFABRICADAS

CON MADERA DE PLANTACIÓN

longitud
10 m

MANUAL DE ARMADO

Figura 6. Manual de armado para cerchas con luz de 6 m (a) y 9 m (b) construidas con madera de *Gmelina arborea* y *Hieronyma alchorneoides*



## Melina

La **Melina** con nombre científico de *Gmelina arborea*, es una **madera proveniente de plantaciones comerciales** en Costa Rica y fue introducida en el país hace aproximadamente 30 años. Al igual que las maderas de plantaciones, **es un material de construcción sostenible**, de baja cantidad de emisiones y un material de alto almacenamiento de carbono. **La madera** presenta un color **amarillento pálido**, en ocasiones con tonalidades blancas, amarillas, cremas y rosadas, pero en general **presenta un color bastante uniforme**. Es considerada como de **mediana densidad**, buenas propiedades de **trabajabilidad** en aspectos relacionados al cepillado,lijado, clavado y atornillado. Además de que la madera presenta **adecuadas condiciones para aplicar** diferentes tipos de **acabados**, sean de tipo transparente o con color. En relación con la durabilidad **es considerada** como de **mediana durabilidad** y si es protegida adecuadamente del sol y el agua, ésta **tiene una larga vida útil**. No obstante, si ésta **es usada en estructuras** de madera **es preferible proteger** con **preservante de tipo boro** para evitar el daño por insectos como las termitas. Este tipo de madera en el sector construcción **es posible** encontarla en productos como madera de **cuadro de 2x3 pulgadas (5x7,5 cm), 1x3 pulgadas (2,5x7,5 cm), regla de 1x2 pulgadas, artesonado de 2x6 pulgadas (5,0 x 15 cm)**, entre otros productos.Además de estos productos, la madera de melina es apreciada en el mercado nacional e internacional para productos como molduras, utensilios de cocina, fabricación de muebles y embalaje en general.

*Gmelina arborea*

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CON MADERA DE PLANTACIÓN

## Pilón

El **Pilón** con nombre científico de *Hieronyma archorneoides*, es una madera que en el pasado se extraía de los árboles creciendo en los bosques naturales, sin embargo se observó que esta **especie se desarrolla apropiadamente en condiciones de plantaciones** comerciales, por lo que en la actualidad su madera es extraída de este tipo de cultivos. Esta procedencia es la que convierte a la **madera en un material de construcción sostenible**, de baja cantidad de emisiones y un material de alto almacenamiento de carbono. La madera presenta un color marrón rojizo, principalmente en la madera de bosque natural, pero la madera de árboles de plantaciones es de color rojizo claro. La **madera** de pilón es considerada **de mediana a alta densidad** por lo que ésta puede ser utilizada en usos estructurales, de hecho en el pasado era **muy utilizada en cerchas, columnas, soporte para piso, entre otros.** En relación con su trabajabilidad, esta madera **tiende a rajar en caso de usar clavos** muy cerca de los extremos, por lo que es aconsejable **utilizar de preferencia tornillo.** Presenta grano entrecruzado por lo que las propiedades relacionadas con la trabajabilidad como el **cepillado, lijado, clavado y atornillado, no son tan adecuadas. Presenta buenas propiedades para aplicar acabados de tipo transparente o de color.** También puede ser comercializada en otros productos de la construcción como madera de **2x3 pulgadas (5,0x7,5 cm), 1x3 pulgadas (2,5x7,5 cm), artesonado de 2x6 pulgadas (5,0 x 15 cm)**, entre otros productos. Es muy frecuente que este tipo de madera se encuentre en muchas construcciones rurales de Costa Rica, como establos, galpones, lecherías, encierros para ganado o caballos entre otro tipo de construcciones.

*Hieronyma archorneoides*

Luces entre apoyo, rigidez y separación entre cerchas construidas con madera de Melina y Pilón

## Pilón

Propiedades físicas de la madera

## Melina

Propiedades físicas de la madera

Figura 7. Parte interior (a) y parte exterior (b) del manual de técnico para cerchas construidas con madera de *Gmelina arborea* y *Hieronyma alchorneoides.*

En el caso del manual técnico: este manual está dirigido a ingenieros o arquitectos y muestra de forma gráfica como deben ser ancladas las cerchas en diferentes tipos de soporte, sea madera, concreto o metal. Se presentan los valores las luces entre apoyo y separación para las cerchas construidas con los diferentes tipos de madera y los dos tipos de elementos de unión, que corresponde a la tabla 2 de este artículo. Así mismo se da una descripción de las dos especies de madera utilizada para construir las cerchas (Figura 7).

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