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EVALUATION OF WOOD-TO-WOOD CONNECTIONS OF THE SPECIES *Campnosperma panamense* Standl. USING BOLTS AND NAILS SUBJECTED TO LATERAL LOADING

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ABSTRACT: The present work presents the behavior of wood-to-wood connections with bolted and nailed connections subjected to lateral load using air-dried wood from *Campnosperma panamenes* Standl., a native Colombian species of low density, for the adaptation of the connection design methodology in the new Colombian Seismic Resistant Standard. Ten (10) experimental tests were carried out per connector, observing that bolted connections presented a higher safety factor with respect to nailed connections, where for bolted connections, where for bolted connections, a single value below the minimum safety factor was obtained, while for nailed joints three (3) cases were presented. In addition, they found significant differences between the densities worked, indicating that the density of the wood used in the calculations has a considerable impact on safety factors.

KEYWORDS: Campnosperma panamense Standl, connections, bolt, nail, NSR

1 – INTRODUCTION

Wood is a material highly used in the construction area, where in recent years it has been taking an important role at the structural level, being a response to the current need to have sustainable consumption and production at a global level as part of the circular economy model [1]. The extensive use of this material can be attributed to the ease of handling at the time of construction since it does not require specialized tools, and in addition to the comfort it generates for people compared to other materials; Although the use and construction of wood has been increasing, wood has not had the same level of studies and research compared to those carried out in steel or concrete structures [2].

In Colombia, the use of wood as a structural material is limited, being the result of a combination of traditions, beliefs and ignorance of the potential and advantages of the material; There is a significant amount of presumptions about the use of this material for construction, either in economic terms (being a more expensive raw material than other conventional materials), status or distrust in the properties of the material, such as resistance and durability [3].

As part of the fundamental principle of structural design, timber structures require research and design regulations that satisfy safety standards and in turn meet the needs of the construction industry. [4]. For this purpose, there are different norms and standards for the timber design and construction; an example of this is the National Design Specification (NDS) developed by the Wood Design Standards Committee (AWC) and approved by the American National Standard (ANSI); Likewise, in Colombia there is the Colombian Seismic Resistant Construction Regulation (NSR).

One of the weak points of timber structures are the joints between their elements because the stability and load transmission is controlled by the behavior of their connections. It has been observed that timber connections can present different failure modes, where it has been found that they can fail out of the assembly, extraction, connector failure, breakage, buckling or splitting of the timber members [5]. Keeping that in mind, it is possible to determine the strength and structural safety level of the connection design, where current regulations consider the behavior of both the connections and the timber individually and as a whole [6]. Among the most used joints are glued, finger-joint, nailed, screwed and bolted connections, where the latter are the most common. [7].

The present work arises from the scarce reliable information available regarding the evaluation of the behavior of connectors, in particular, studies related to the behavior of connections using native Colombian woods of low density, as is the case of the Sajo (*Campnosperma panamense* Standl.). Therefore, the objective of the present document is to evaluate the behavior of wood to wood connections using bolts and nails, for the species Campnosperma panamense Standl., subjected to lateral load by means of experimental tests, allowing to compare the design capacity of connections used in structural designs, thus generating reliability in the design of timber connections, given that this type of timber is currently used for carpentry, cladding, furniture, moldings, among others. [8]

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2 – BACKGROUND

Timber constructions are energy efficient and sustainable. Mostly timber is used for family houses or small-scale constructions, however, there are large constructions such as buildings made of this material. In recent years, the demand for timber construction has increased, generating a parallel increase in innovations and improvements in the methodologies to be used when using wood. [9]

Several research have been developed around timber connections. In the first case, there are those related to the evaluation, modification and adaptation of the efficiency of existing methodologies for the design of timber connections such as the NDS by [10], the Eurocode 5 by [11] and the adaptation of formulas for the calculation of resistances in [7].

Similarly, other studies have compared experimental and theoretical data on resistance, load capacity and failure modes of connections, allowing to determine the predictive accuracy of the equations and tables presented in the standards, as in the case of ASTM with the studies of [12] and [13], and in the case of NDS, the study developed by [14].

Finally, some research to be mentioned concerning the study of the behavior of the connections, in terms of strength and load capacity, are [7], [13], [14], [15] and [16].

2.1 *Campnosperma panamense* Standl.

It belongs to the family Anacardiaceae, commonly known in Colombia as 'Sajo', 'Sajo conchecaimán' and 'vaguerá', the first being the most common. [17]. In the specific case of *C. panamense*, no studies were found regarding nailed and/or bolted connections, this may be due to the current use and perspective of *C. panamense*, which, despite being purely timber, in the case of Colombia is used in the manufacture of boards, boxes, furniture skeletons, molding, carpentry, veneer and other non-structural uses [8], this is due to its low basic density (average less than 0.4 g/cm^3) [18].

Thus, current studies of the species correspond to its anatomy, physical, mechanical and chemical properties, as presented in [18], [19], [20] and [21]. Compression, bending and shear tests have also been carried out to characterize timber of the species, as was done by [22]. In this way, there is a need to generate research to show the capacity of the species in structural terms and thus its potential uses in the field of construction.

3 – PROJECT DESCRIPTION

It was evaluated the behavior of wood-to-wood connections for Campnosperma panamense Standl., subjected to double-bolted connections, and to single-nailed connections. The configuration of the connectors was prepared in accordance with NDS-AWS-2018, taking into account that the configuration, for the case of bolts, was evaluated to withstand a load of one (1) ton (10 kN), while in the case of nails the configuration was performed with ten (10) units in total (five (5) on each side).

For each type of connector, ten (10) experimental units were tested, giving a total of twenty (20) experimental units that were subjected to a double shear test according to the parameters established in ASTM D5652 and ASTM D1761-20, numeral 19.1.

All activities took place at the Universidad Distrital Francisco José de Caldas, Vivero, Bogotá, Colombia.

3.1 Conectores

It was worked with two types of connectors, 5/8 ASTM A 139 Grade B7 bolts from a company located in the city of Medellín, Colombia and LBA660 nails made of electrogalvanized carbon steel [23] provided by Rothoblaas company with the measurements presented in Table 1.

Table 1: Connectors dimensions.

Connector	Code	Measurement	
		Diameter (mm)	*Long (mm)*
Bolts	P_16D_180L	16	180
Nails	C_6D_60L	6	60

4 – EXPERIMENTAL SETUP

Green boards were obtained (with initial moisture content values above 50%) of approximately three (3) meters long by eleven (11) centimeters wide and with two thicknesses (five (5) and three (3) centimeters), which were air-dried for 4 weeks (with weekly controls) until obtaining average moisture content values below 20%; subsequently, were dimensioned pieces 25 cm long, 8 cm wide and with two different thicknesses (2 cm and 4 cm), in order to be in accordance with the dimensions defined for each type of connection (Fig. 1 and Fig. 2).

It obtained green boards (with initial moisture content values above 50%) of approximately three (3) meters long and eleven (11) meters wide.

The moisture content and dimensions of each piece were determined to calculate the volume, which, together with the weight, two densities were calculated: (1) anhydrous density (Do) and (2) basic density (Db).

Having the values of densities, 3 pieces were organized and grouped according to their densities for the formation of the experimental units, with the objective of working with tests specimens as homogeneously as possible.

Then, four (4) densities per test specimen were determined:

- Minimum anhydrous density (Do min)
- Average anhydrous density (Do avg)
- Minimum basic density (Db min)
- Average anhydrous density (Db avg)

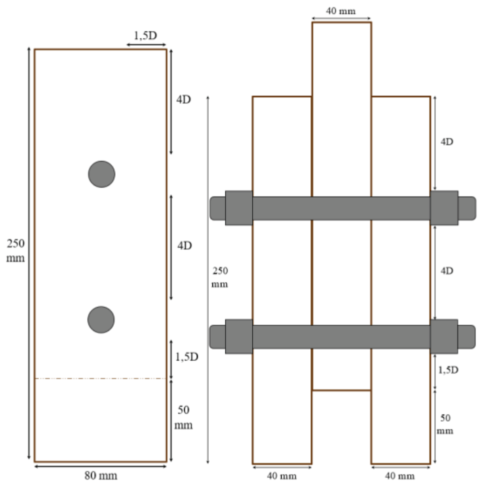

Fig 1. Bolts configuration design.

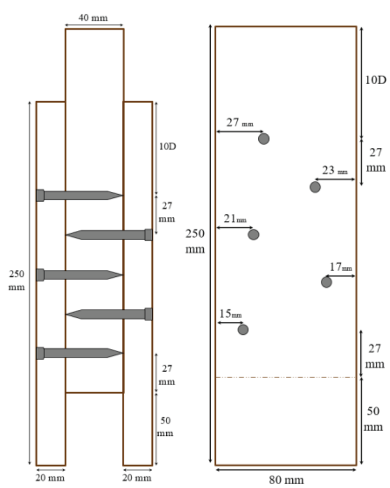

Fig 2. Nails configuration design.

For the assembly of the specimens, a pre-drilling guide was initially carried out using a tree drill, following the NSR-10, numeral G.6.7.5 and ASTM D1761, numeral 18.5 [24], using steel drills with diameters between 80% and 90% of the diameter of the connectors, so that for the pre-drilling of the nails the drill had a diameter of 5.16 mm, including a countersink, this to avoid the formation of cracks and facilitate the leveling of the head of the nails to the surface of the test specimen, this taking into account what is presented in ASTM D1761, numerals 18.3 and 18.5.

For bolts, a 14.2 mm (9/16") diameter (14.2 mm) paddle bit was used. Subsequently, ten (10) test specimens were assembled, consisting of 3 pieces, two of 2 cm thick and a central one of 4 cm thick, by screwing the bolts manually, and the other 10 triples were nailed manually with the help of a hammer.

Each of the experimental units was subjected to a shear test (double-bolts and single-nails connections), in accordance with ASTM D5652, which was carried out in the wood laboratory of the Universidad Distrital Francisco José de Caldas wood laboratory on the Instron EMIC 23-100 machine, with a test speed corresponding to 2.54 mm/min (according to the parameters of ASTM D1761-20, numeral 19.1).

To determine the termination of the load test of each nailed connection specimen, it was established that once the first failure occurs, a wait of 2 minutes (approximately) is given, in order to observe the behavior of the structure, where it is determined that once the first failure occurs, the load decreases with a certain resistance of the element, and subsequent small failures are generated; the other case is the bolted joints, since when the first failure occurs, the test is automatically terminated. In addition, the dimensions of each experimental unit were taken before and after the test, to determine the deformation of the specimens.

Once the test data were obtained, data processing was carried out. Initially, data were refined and corrected to obtain graphs and their corresponding analysis, having as main points the yield point, yield strength and maximum load, which allow the comparison between the data calculated theoretically and those obtained in the laboratory [25] (Fig. 3):

- Proportional limit Load (Le): A straight line located on the linear section of the displacement vs. load curve is drawn, and the division point of both lines is considered as the elastic limit.
- Yield point (Py): A line is drawn parallel to the first line, displacing to the right 5% of the connector diameter, and the point of intersection of with the displacement vs. load curve is considered the yield point.
- Ultimate load (Pu): It is the point where the maximum load was obtained during the test.

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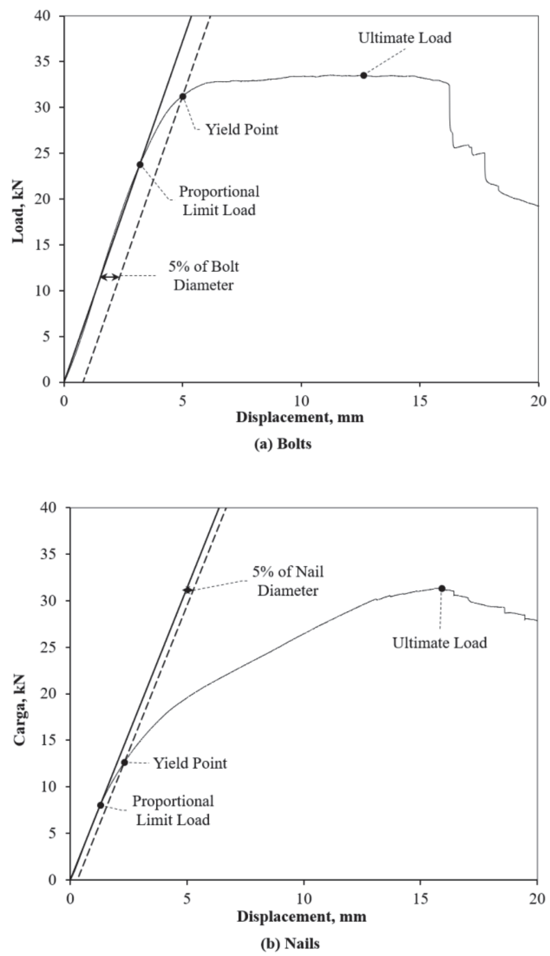

Fig 3. Points of experimental values to be found in bolted (right) and nailed (left) connections.

Adapted from ASTM D5652 – 21 [25]

Subsequently, the allowable load values were calculated according to the design procedures of NSR-10 and NDS-18, where the latter was calculated with the values of Do min, Do prom, Db min and Db prom of each test specimen.

With this data, the ratios were calculated, corresponding to the division between the experimental value (either the proportional limit load (Le) or the yield load (Py)) and the theoretical value. This allows knowing the degree of safety, where being greater than 1 are reliable values, because the theoretical value is less than the experimental, thus having a safety factor, and the higher the value of the ratio, the higher the safety factor in the configuration of the structure.

Having these data, the mean values (average value of the ratios per connector, per density) and the characteristic values (for each of the cases (nails and bolts) were obtained for the comparison and analysis between the experimental and theoretical values.

5 – RESULTS

5.1 Density

Table 2 shows the values of the four (4) types of densities per test specimen and the average and characteristic values per density, per connector.

Table 2: *Eigenvalues and densities of nailed and bolted connections.*

Connector	Test	Do min	Do avg	Db min	Db avg
Bolts	P1	0.31	0.31	0.19	0.19
	P2	0.32	0.33	0.19	0.19
	P3	0.37	0.37	0.21	0.21
	P4	0.34	0.34	0.20	0.20
	P5	0.35	0.35	0.20	0.20
	P6	0.35	0.35	0.20	0.21
	P7	0.35	0.35	0.21	0.21
	P8	0.36	0.36	0.21	0.21
	P9	0.36	0.36	0.21	0.21
	P10	0.36	0.36	0.21	0.21
Average		0.35	0.35	0.20	0.20
Eigenvalues		0.32	0.32	0.19	0.19
Nails	C1	0.37	0.37	0.21	0.22
	C2	0.39	0.40	0.22	0.23
	C3	0.39	0.40	0.22	0.23
	C4	0.39	0.39	0.22	0.22
	C5	0.39	0.40	0.22	0.23
	C6	0.37	0.39	0.21	0.22
	C7	0.37	0.39	0.21	0.22
	C8	0.38	0.39	0.22	0.23
	C9	0.39	0.40	0.22	0.23
Average		0.38	0.39	0.22	0.22
Eigenvalues		0.37	0.38	0.21	0.22

5.1 Experimental values

From the experimental results it was obtained that the proportional limit load (Le) mean values were 24.96 kN in bolts and 8.22 kN in nails, and the characteristic values respectively were 16.94 kN and 7.08 kN. In the case of yield load (Fy), the average value for bolts was 30.86 kN and the characteristic 24.76 kN, while for nails it was 11.83 kN and 9.06 kN, respectively. And finally, the average maximum loads (Pu) obtained are similar for both types of joints, being 32.45 kN for bolts and 32.57 kN for nails, while the characteristic values were 26.36 kN and 27.27 kN, respectively.

In both cases, these values were higher than those obtained theoretically in the design of each one, which are presented in Table 3. This showed that by working with the NSR-10 and NDS-18 methodology, there is an adequate safety factor, generating reliability at the time of the design of the connections. Despite working with the minimum limits presented by the standards, since in some cases no specific values were found for the density worked and the bolt dimensions.

Table 3. Theoretical design value.

Connector	NSR-10	NDS-18
	Permissible capacity Pes (kN) Db	***Design Load Z (kN) D0***
Bolts	7.74	7.33
Nails	7.99	9.60

Fig. 4 shows the behavior of both types of connections, being load vs. displacement curves, where it can be observed that the maximum loads are similar, but the behavior differs, since the bolts present an elastoplastic behavior, in other words, they have a linear behavior much higher than nailed connections, followed by a "flat" nonlinear behavior; while the linear behavior in nailed connections is lower and the nonlinear behavior is higher and ascending, having also a higher displacement before presenting the main failure.

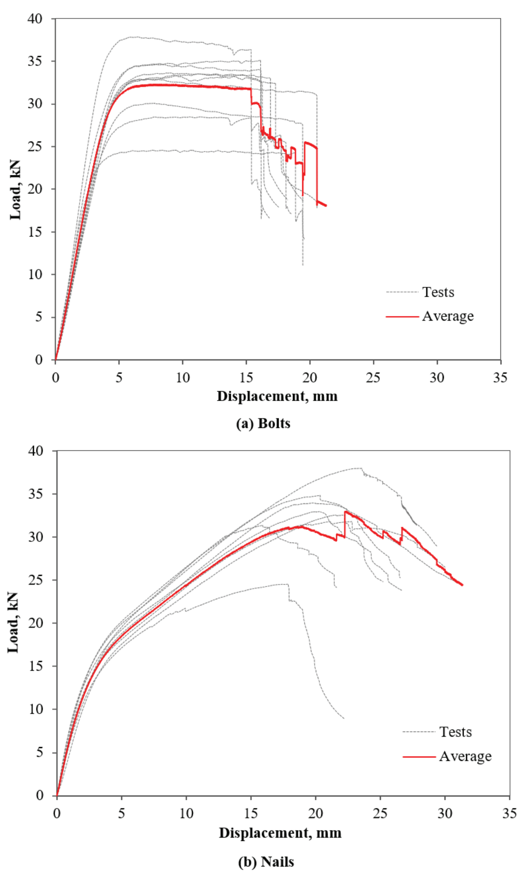

Fig 4. Average load vs. displacement curves of nailed (left) and bolted (right) connections

The behavior of the bolted connections analyzed showed some differences with respect to those observed by [12]. In their research, the nonlinear behavior increased the load, whereas in this case, the load gradually decreased until the moment of failure. It is worth mentioning that [12] identified different patterns of curve behavior, determined by the dimensions of the connector and thickness of the lateral members, and the failure modes differ according to these parameters. From this it can be inferred that when working with large dimensions and stiffness connectors, fragile behavior can be generated, which leads to the behavior observed in this type of bolted joint.

1.1 Proportional limit load and yield load

In Fig. 5, the experimentally obtained values (represented by bars) are shown together with those calculated using the NDS18 and NSR-10 methodology (represented by dotted lines). In the case of the bolts, all the tests performed exceeded the design values, doubling the value of the estimated load, except for specimen P7, indicating a significant degree of reliability in the results (Fig 5a).

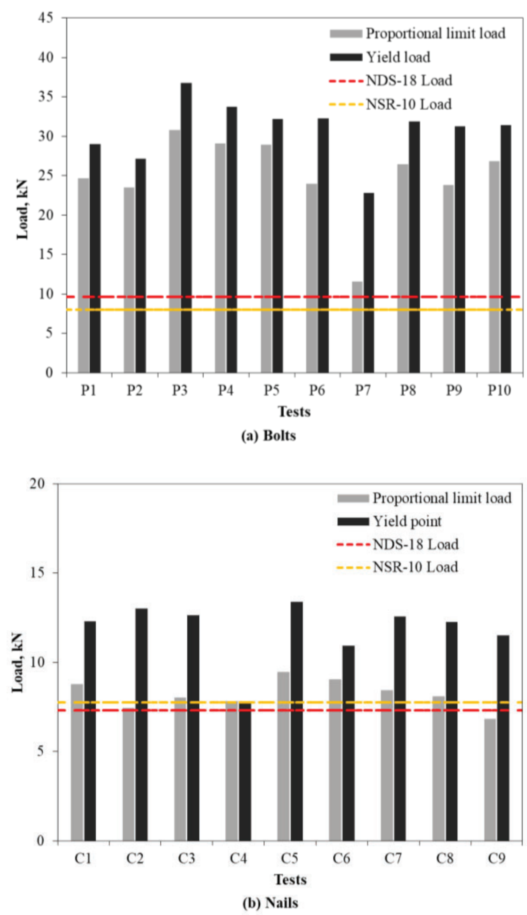

Figure 5. Experimental Proportional limit load and yield load in bolted (a) and nailed (b) connections.

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On the contrary, the nailed joints showed experimental values very close to theoretical values. In three cases (C2, C4, and C9) the yield load was lower than the design load calculated by the NSR-10 methodology, and only one case (C9) was lower than that calculated by the NDS-18 methodology (Fig. 5b).

1.2 Ratio of experimental load vs. design load

On the other hand, ratios were calculated, which were obtained by dividing the experimental value (either the proportional limit load (Le) or the yield load (Py)) by the theoretical value. This allows us to know the degree of safety, where being greater than 1 are reliable values, because the theoretical value is less than the experimental, thus having a safety factor, and the higher the value of the ratio, the higher the safety factor in the configuration of the structure.

Table 4 and Fig. 6 show that, in the ratios calculated for the proportional limit load (Le), most of the values are higher than 1, except for specimen P7, with a value of 0.72. In the case of the ratios calculated for yield load (Py), it was observed that, in all cases, the ratio is greater than 1.0.

Table 4. Ratios values bolted connections.

Test	Le					Py				
	NDS-18		NSR-10			NDS-18		NSR-10		
	$D_{o\,min}$	$D_{o\,avg}$	$D_{b\,min}$	$D_{b\,avg}$	D_b	$D_{o\,avg}$	$D_{o\,min}$	$D_{b\,avg}$	$D_{b\,min}$	D_b
P1	3.24	3.24	5.32	5.32	1.54	3.81	3.81	6.27	6.26	1.82
P2	2.96	2.96	4.95	4.90	1.47	3.42	3.42	5.72	5.67	1.70
P3	3.36	3.36	5.85	5.85	1.93	4.02	4.02	6.99	6.98	2.30
P4	3.47	3.47	5.84	5.83	1.82	4.02	4.02	6.77	6.75	2.11
P5	3.36	3.36	5.77	5.75	1.81	3.74	3.74	6.42	6.40	2.02
P6	2.79	2.79	4.74	4.74	1.50	3.75	3.75	6.38	6.37	2.02
P7	1.35	1.35	2.28	2.27	0.72	2.65	2.65	4.49	4.48	1.43
P8	2.96	2.96	5.16	5.15	1.65	3.57	3.57	6.22	6.21	1.99
P9	2.66	2.66	4.59	4.58	1.49	3.50	3.50	6.02	6.01	1.96
P10	3.00	3.00	5.15	5.14	1.68	3.52	3.52	6.03	6.02	1.97
Avg.	2.92	2.92	4.96	4.95	1.56	3.60	3.60	6.13	6.12	1.93
Eigenv.	1.94	1.94	3.32	3.31	1.06	3.00	3.00	5.04	5.01	1.55

Note. Do min=minimum anhydrous density; Do avg=average anhydrous density; Db min=minimum basic density; Db avg=average basic density. The characteristic values represent the results of 95% of the population.

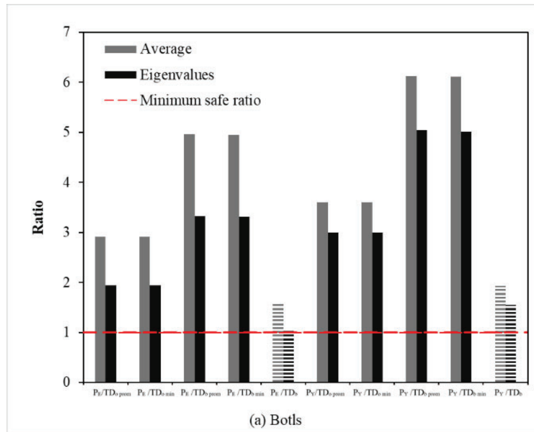

Fig 6. Experimental values/theorical values(ratios) of bolted connections.

Table 5 and Fig. 7 show that most of the values of the ratios calculated for the proportional limit load (Le) are greater than one (1), except for test specimen C9 with a value of 0.94 in minimum anhydrous density (Do min) and 0.92 in average anhydrous density, and the one calculated with the NSR-10 methodology with 0.92. These factors affect the characteristic value similarly in the three cases, obtaining values of 0.97, 0.95 and 0.96, respectively. In contrast, the ratios for the yield load (Py) are, in all cases, greater than 1.

Table 5. Ratios values nailed connections.

Test	Le					Py				
	NDS-18		NSR-10			NDS-18		NSR-10		
	$D_{o\,min}$	$D_{o\,avg}$	$D_{b\,min}$	$D_{b\,avg}$	D_b	$D_{o\,avg}$	$D_{o\,min}$	$D_{b\,avg}$	$D_{b\,min}$	D_b
C1	1,26	1,25	3,11	3,09	1,19	1,76	1,75	4,34	4,32	1,66
C2	1,02	1,00	2,48	2,37	1,01	1,79	1,73	4,32	4,14	1,76
C3	1,10	1,06	2,66	2,54	1,08	1,73	1,68	4,19	3,99	1,71
C4	1,08	1,06	2,61	2,56	1,06	1,08	1,06	2,61	2,56	1,06
C5	1,29	1,25	3,11	2,96	1,28	1,83	1,77	4,41	4,20	1,81
C6	1,30	1,24	3,21	3,00	1,23	1,56	1,50	3,87	3,62	1,48
C7	1,21	1,15	2,98	2,77	1,14	1,80	1,71	4,45	4,14	1,70
C8	1,13	1,09	2,74	2,63	1,10	1,70	1,66	4,14	3,97	1,66
C9	0,94	0,92	2,27	2,19	0,92	1,58	1,54	3,83	3,70	1,56
Avg.	1,15	1,11	2,80	2,68	1,11	1,65	1,60	4,02	3,85	1,60
Eigenv.	0,97	0,95	2,35	2,26	0,96	1,27	1,24	3,10	2,98	1,22

Note. Do min=minimum anhydrous density; Do avg=average anhydrous density; Db min=minimum basic density; Db avg=average basic density. The characteristic values represent the results of 95% of the population.

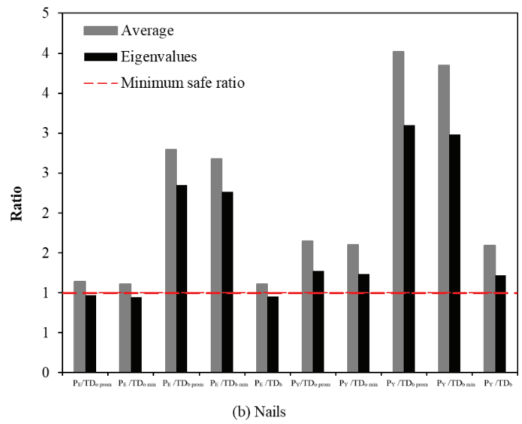

Fig 7. Experimental values/theorical values(ratios) of nailed connections.

It is worth mentioning that both nailed and bolted connections showed that the ratio with the highest values was obtained with the minimum density, followed by the average density, minimum anhydrous density and average anhydrous density.

For the case of bolts is different from nails, in Table 15 and Figure 12 there is only one value lower than 1 (0.72), being the P7 specimen in the calculation performed with the NSR-10 methodology, in the proportional limit load.

The above allows us to determine that there is an acceptable safety factor in the theory, however, there is a higher factor when working with the basic density, since in all cases the highest values were obtained with these densities. Additionally, the highest ratios were calculated with the minimum basic density.

1.2 Failure analysis

The bolted connections evidenced in all cases a rupture in the main member, implying a splitting failure [7] (Fig. 8). The opposite was the case for the nailed connections, since there were three (3) failure behaviors: (1) failure in the main member, (2) failure in one of the secondary members, and (3) failure in the main and secondary members (Fig. 9).

However, both cases may indicate brittle behavior, since the failure occurred in the wood and not in the connectors [26].

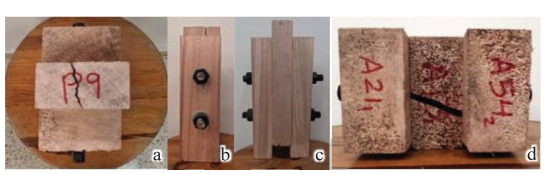

Fig 8. Typical failure mode for bolted connections in top (a), side (b), front (c), and bottom (d) views.

Fig 9. Failure modes encountered for nailed joints bottom (a, b, c) and top (d) and front (e, f, g) views.

6 – CONCLUSION

Through the use of the NDS18 methodology for the determination of the design configuration for bolted and nailed joints, it was obtained that in the case of bolted joints, 2 connectors are required for a load of 1.0 tons, while for nailed connections, the use of ten (10) connectors is required, arranged five by five on both sides of the structure, will support a load of 0.7 tons. Subsequently, based on the opinions of the two methodologies (NDS18 and NSR), the design (distribution) of the connectors was determined, respecting the minimum distances established.

Likewise, the load vs. displacement curves allows observing the behavior of the tests, where in the case of bolts the behavior is unusual, since it is of a fragile nature, this is the result of working with a low-density wood with large and rigid connectors (bolts), thus generating a small elastic range and small plastic deformations. This is corroborated with the behaviors obtained by [12], where in the nonlinear ranges different groups of behaviors were presented, this according to the dimensions of the connector and the design of the structure (dimensions). On the contrary, nailed connections, where the dimensions and stiffness are smaller, have a ductile behavior, where the linear range is smaller, and the non-linear range is much larger than that of bolted connections.

Having the experimental data cleaned and processed, the graphs were obtained for each of the trials and their average. Subsequently, the corresponding ratios were calculated, allowing us to conclude that there is greater reliability in the results when working with the basic density values, since all their values are greater than 1, while in the case of anhydrous density there were few values below 1. Therefore, it is recommended to perform the configuration calculations with the minimum basic density, since the ratios obtained with this density were the highest, so there is a higher level of safety.

It is worth mentioning that specimen P6, at the time of data processing, presented an unusual behavior at the beginning of the test, generating greater data cleaning

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than the one performed with the other data, so it is considered as a test.

As previously affirmed, when supporting loads higher than those used in the design phase, it is concluded that the methodologies do present good predictions in their equations, being considered as conservative [14]. Now then, there is a greater safety factor when working with the local minimum density, given that when working with this density the highest data of the ratios were obtained, which consequently has greater reliability in the results.

Finally, the behavior of the structure as a whole is affected, not only by the density of the wood, but also by the dimensions, shape, quantity and distribution of the connectors used [7], [12], [13] and [16], but also by the dimensions of both the main and secondary members [11], [12] and [13], so it is important to take all these factors into account when designing timber structures.

7 – REFERENCES

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