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Effect of Nail Models and Diameters on the Withdrawal Resistance of *Allantoma decandra* (Lecythidaceae) Wood

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Abstract: Nails are a simple and viable solution to connect sections of wooden structures. Although they are the oldest and most traditional connection elements there is a considerable knowledge gap concerning the use of larger sized, threaded nails, in tropical hardwoods. The objective of this project was to evaluate the effect of different nail models and diameters on the withdrawal resistance of *Allantoma decandra* wood and verify the efficiency of the existing nail withdrawal resistance prediction equations. Withdrawal tests were carried out using three nail models (smooth, helical, and annular), of two different diameters (2.8 mm and 3.5 mm). For each combination, ten *Allantoma decandra* wood specimens were used. Four nails were inserted 3.2 mm into each wood specimen and then withdrawn using a universal testing machine with 600 kN capacity, according to the procedures of ASTM D-143-2014. The nail model was the most relevant factor in this study, having a direct influence on withdrawal resistance. Annular nails presented the highest resistance values, followed by helical and smooth nails. The nail diameter had no significant effect on the maximum load result. The equations for withdrawal resistance prediction demonstrated considerable accuracy regarding the experimentally obtained data, being important tools to anticipate the behavior of wooden structures.

Keywords: Hardwood; helical; annular; connections

1. Introduction

The strength and stability of any structure depend primarily on the connections between its parts. A great advantage of wood as a structural material is the ease with which sections can be joined using a range of different elements [1]. Among these, nails are the oldest and most traditional connection elements [2,3]. Unlike other connectors such as screws and adhesives, nails are low cost, do not require specific infrastructure to be used, and can be inserted into wood manually or using pneumatic nail guns. Furthermore, they are a simple and viable solution for making connections between sections of wood with low adhesion capacity, especially tropical hardwoods with high density or high presence of extractives [4].

Nail-withdrawal resistance is directly related to the tree species, wood density, nail diameter and insertion depth [5–7]. The most used nails are the smooth-shank nails, which resist withdrawal forces due to the friction force between the wood fibers and the nail shaft. Friction forces have their maximum point immediately after nail insertion, but over time, the wood fibers relax with a consequent loss of withdrawal resistance [8]. This effect may be increased if the wood is exposed to constant drying and soaking processes [9].

Over time, different nail models were developed aiming performance enhancement and withdrawal resistance improvement [10]. Among the innovations is the application, by compression, of helical or annular threads onto the nail shafts [11]. Helical nails were originally developed to facilitate the insertion in high-density woods. Their threads are typically aligned at angles between 30° and 70° to the axis, and therefore tend to rotate during insertion (like screws), causing less damage to the adjacent wood fibers [8]. On the other hand, annular nails were developed with the specific purpose of increasing their withdrawal resistance, and their threads are aligned perpendicular to the axis, at angles of approximately 90° [12].

Unlike smooth-shank nails, which resist withdrawal merely by the friction forces between the wood fibers and the shaft, threaded nails also have mechanical resistance, as during their insertion the wood fibers enchase between the crests of the threads [11]. To withdraw a helical or annular nail it is necessary to tear the wood fibers, which requires a greater force than that of smooth-shank nails of same dimensions [12]. Threaded nails are ideal for situations of extreme load and adverse moisture conditions, as the relaxation and contractions of the fibers have less effect on their resistance [13]. On the other hand, the presence of threads on the nail shaft requires 15% more energy for insertion into wood [14], and the deformations applied to create the threads result in slightly smaller diameters compared to smooth-shank nails of the same size [13].

Due to the recent increase of environmental awareness and the ability of wood to embed carbon, timber constructions have emerged worldwide as an alternative for mitigating climate change while acting as a limitless carbon sink [15–17] . The "massive timber construction movement" is based on various wood engineered products and building technologies, such as: glued laminated timber (glulam), cross laminated timber (CLT), wood-frame and post-frame [5,16]. Despite having a high level of prefabrication of their components, all these techniques depend on metallic connection elements, such as nails. However, available data regarding nail withdrawal resistance is scarce. Most research has focused on smooth-shank nails, with small diameters, being tested in coniferous wood species from temperate zones [13]. Therefore, there is a considerable knowledge gap regarding the use of larger sized nails, with threaded shanks (helical and annular), being utilized in tropical hardwoods.

Furthermore, several authors and institutions developed model design equations to predict the withdrawal performance of smooth and threaded nails. The equations are based on wood density, nail diameter and depth of insertion, and while some authors developed exclusive equations for each nail model [8,18], others suggest the use of the same equation for more multiple models [1,19,20]. Although the equations were developed based on a restricted and specific dataset, they may be important tools to anticipate the behavior of wooden structures.

The purpose of this research was to evaluate the effect of different nail models and diameters on the withdrawal resistance of *Allantoma decandra* wood; and verify the efficiency of the existing nail withdrawal prediction equations regarding the experimental results. Our study results indicated that the nail model was the most relevant factor, having a direct influence on withdrawal resistance. The equations for withdrawal resistance prediction demonstrated considerable accuracy regarding the experimentally obtained data.

2. Materials and Methods

2.1. Specimens

The tests were carried out utilizing wood specimens obtained from ten trees collected in the Jacundá National Forest, Rondônia, Brazil, identified as *Allantoma decandra* (Ducke) S. A. Mori, Y. Y. Huang & Prance. The specie belongs to the Lecythidaceae family, is native to the Amazon Forest, and its trees may reach 40 meters in height, having a cylindrical trunk and diameter at breast height (DBH) between 45 and 250 centimeters [21]. *A. decandra* has no legal logging restrictions, being explored in sustainable forest management projects [22]. Its wood has a specific gravity of approximately 0.57 g/cm^3 [23], and is currently being used for low commercial value products, such as crates and tool handles. However, preliminary studies suggest that it is possible to use it in the manufacturing of higher value engineered products, such as glued-laminated timber (glulam) and cross-laminated timber panels (CLT) [23].

The specimens were produced form clear wood (i.e., free from knots, cracks, frays, etc.), and were deposited in an acclimatization room with controlled temperature and humidity (20 ± 3°C and

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65 ± 1%), until moisture content stabilization (± 12%). For theoretical testing purposes, the volume and mass of the specimens was also calculated at 0% moisture content (oven dry).

Three nail models (smooth, helical, and annular) of two different diameters (2.8 mm and 3.5 mm) were tested on the tangential and radial faces of the wood specimens, totaling 12 model/diameter/face combinations (Figure 1) To avoid material variation, all nails used in this study were produced by the same manufacturer. For each combination, ten 50 x 50 x 150 mm (width, depth, and length) specimens were used. The nails were inserted 3.2 mm into the wood, using a hammer, without pre-drilled holes. Two nails were fixed on the radial face and two on the tangential face, maintaining a minimum distance of 19 mm from the sides, 38 mm from the ends and 50 mm between the nails, while avoiding alignment. All 240 nails (40 repetitions per combination) were withdrawn within a maximum one-hour period after insertion. A universal testing machine with a 600 kN capacity was used to carry out the tests, which were performed according to the procedures of ASTM D-143 [24].

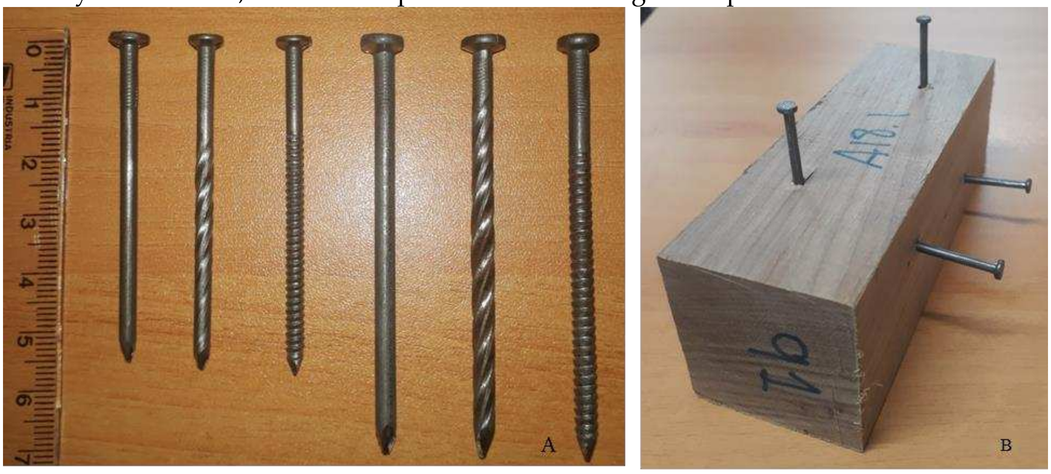

Figure 1. (A) Nails used in the withdrawal tests: smooth, helical, and annular with 2.8 mm and 3.5 mm of diameter. **(B)** *Allantoma decandra* test specimen.

2.2. Statistical Analysis

The experiment consisted of a factorial design of 12 combinations of nail models, diameters, and specimen faces. A factorial analysis of variance (ANOVA) at 5% significance was performed to evaluate the effect of each factor, followed by a Tukey test to evaluate the existence of significant statistical differences between the means of each treatment. All analyses were executed using the IBM SPSS software.

2.3. Theoretical Analysis

To verify the efficiency of the nail withdrawal prediction equations presented by several authors (Table 1), the maximum loads for each nail model/diameter combination were calculated and then compared to the results obtained experimentally.

Table 1. Nail withdrawal resistance prediction equations.

Nail Shank Model	Equation[1]	Unit	Authors
Smooth	$W = 1380\ G^{5/2}\ D\ L$	LB	AWC [20]
	$W = 54.12\ G^{5/2}\ D\ L$	N	Rammer [1]
Helical	$W = 36 \times 10^{-2}\ G^{2}\ D\ L$	N	Ehlbeck & Siebert [18]
	$W = 29.6\ G^{1,28}\ D\ L$	N	Rammer et al. [8]
	$W = 0.117\ D^{0,6}\ L\ G^{0,8}$	N	Blass & Uibel [19]
	$W = 1380\ G^{5/2}\ D\ L$	N	AWC [20]
	$W = 54.12\ G^{5/2}\ D\ L$	N	Rammer [1]
Annular	$W = 42.8\ G^{1.38}\ D\ L$	N	Rammer et. al. [8]
	$W = 0.117\ D^{0,6}\ L\ G^{0,8}$	N	Blass & Uibel [19]

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$W = 1800\ G^2\ D\ L$	LB	AWC [20]
$W = 77.57\ G^2\ D\ L$	N	Rammer [1]

[1] W= maximum load; G= wood density; D= nail diameter and L= depth of insertion of the nail.

The American Wood Council (AWC) [20] and Rammer [1] developed specific equations for smooth-shank and annular nails. Due to the absence of studies, both suggest the use of smooth-shank nail equations to predict the withdrawal resistance of helical nails. Blass & Uibel [19] developed a single equation for both helical and annular nails. The equations proposed by Rammer [1] uses wood specific gravity based on oven dry weight and 12% moisture content volume. All other authors use specific gravity values based on oven dry weight and volume. The values predicted by the AWC equations represent the maximum resistance load divided by five to adjust to test conditions, safety, and load duration.

3. Results and Discussion

3.1. Withdrawal resistance

The maximum nail withdrawal resistance loads were initially analyzed separating the data obtained by the radial and tangential faces. All nail models and diameters inserted into the tangential faces required higher loads to be withdrawn than those inserted into the radial faces, which can be explained by the higher number of dense parenchyma layers pierced by the nails [25]. In this direction, there is greater interaction between the wood tissues and the nail shanks, resulting in greater withdrawal resistance and consequently greater damage to the wood´s surface [17]. However, after applying a factorial ANOVA, no statistically significant difference was found between the mean results obtained for the radial and tangential faces (P value = 0.125). As this observation had already been made by other authors in similar experiments [26,27], it was decided to analyze the data jointly, as shown in table 2.

Table 2. Maximum withdrawal resistance loads and coefficients of variation (C.V.) obtained by the six model/diameter nail combinations tested on *A. decandra* wood.

Model/Diameter	Maximum load (N)	C.V. (%)
Smooth/2.8 mm	1039.70 a	15.7
Smooth/3.5 mm	1088.32 a	19.7
Helical/2.8 mm	1330.10 b	26.8
Helical/3.5 mm	1557.32 b	23.5
Annular/2.8 mm	2050.09 c	24.3
Annular/3.5 mm	2244.55 c	25.4

Means followed by the same letter do not differ statistically from each other at 5% significance.

The scientific literature on nails indicates a positive correlation between diameter and withdrawal resistance [7,28,29]. In this study, the increase in nail diameter generated an increase of 5%, 17% and 9.5% in withdrawal resistance for smooth, helical, and annular nails, respectively.

As expected, smooth-shank nails had the lowest withdrawal resistance values. In accordance with data found in literature [19], helical nails showed a resistance increase of approximately 30 to 40% (according to nail diameter), while the annular nails presented the highest withdrawal resistance, approximately twice the values presented by smooth-shank nails of same diameter. This result was consistent with data presented by Rammer [1] and Skulteti et al. [12].

Despite the numerical difference for both factors, the Tukey test identified that the difference between the means of different diameter nails of the same model was not statistically significant at a 95% confidence. Therefore, the Tukey test defined three homogeneous subsets, exclusively based on the nail models.

The values determined for the coefficients of variation (C.V.) ranged between 15% and 27%. Despite being high, they are considered satisfactory for nail withdrawal tests as the manual insertion of the nails is subject to operator-caused variations. Nevertheless, the C.V. values presented lower

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variations than those obtained by Rammer et al. [8] for the same three nail models: annular = 17% to 32%, helical = 12% to 41% and smooth = 22% to 48%.

In addition to the maximum load values, the behavior of the different types of nails tested can also be understood observing the curves formed by the "displacement x load" graphs (Figure 2) and typical wood failure modes (Figure 3).

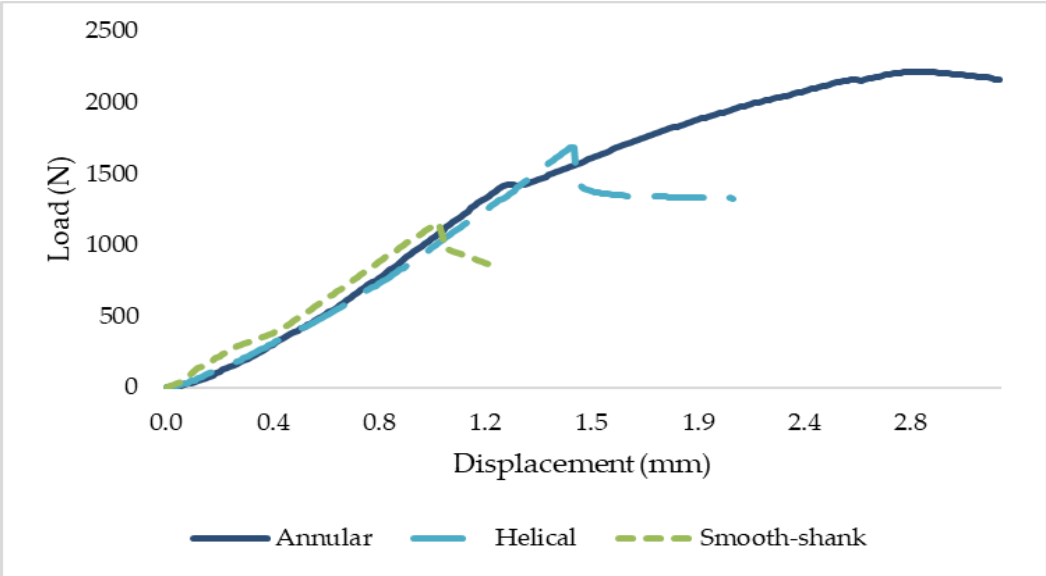

Figure 2. Typical displacement x load graphs for threaded and smooth-shank nails during withdrawal.

Figure 3. (A) Equipment setup used for the nail withdrawal tests. Typical failure modes: **(B)** Smooth-shank nails cause minimal damage to the wood; **(C)** Helical nails withdraw small amounts of wood fibers; **(D)** Annular nails extract a column of wood fiber fragments adhered to its threads.

According to Li et al. [29], nail withdrawal causes various levels of stress at the interface between the threads and the wood components, leading to a combination of shear and tension of the fibers. Due to static friction, during the initial stage of the test, the smooth-shank nails present a linear behavior between displacement and load. After the maximum resistance is reached, the static friction is overcome, and the graph shows a sudden drop. From this moment on, the resistance of the connection depends exclusively on the dynamic friction, which declines rapidly until the nail is completely withdrawn. As the insertion of smooth-shank nails occurs exclusively by separating the wood fibers, their withdrawal occurs without causing major damage to the wood specimen (Figure 3A).

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Although helical nails tend to rotate around their axis during insertion, the rotating movement does not occur during withdrawal, and therefore, the threads increase the nail´s friction surface, ensuring prolonged resistance, which allows higher maximum loads than smooth nails [11]. During the withdrawal tests, the helical nails also exhibit an initial linear behavior between displacement and load, but unlike the smooth nails, after reaching maximum load, they present a sudden drop and then a tendency to stabilize. This is caused by the presence of the threads, which still exert dynamic friction against the wood fibers, and consequently, the connection is still capable of resisting considerable load while the nail is withdrawn from the wood. As can be seen on Figure 3B, the withdrawal of helical nails causes the tearing of small portions of wood fiber.

In general, annular nails exhibit initial linear elastic behavior, provided by the mechanical resistance of the wood fibers lodged between the threads. As the fibers begin to tear, the graphs assume a non-linear (inelastic) behavior until they reach the maximum load values. After the peak, the load decreases quickly, as the wood fibers are torn, pulled out and brought to the surface in the form of a column of fragments adhered to the nail shaft (Figure 3C). From this moment on, resistance is only due to friction, being similar to the behavior shown by smooth nails [11,28].

Based on the wood density of *A. decandra*, nail diameters and nail insertion depth, maximum loads of withdrawal resistance for the six model/diameter nail combinations were estimated using the equations found in the literature (Table 3).

Table 3. Maximum load values (N) obtained experimentally and estimated by the equations, for each combination of nail models/diameter.

Nail Models	**Experimental Values (N)**	**Ehlbeck & Siebert** [18]	**Rammer et. al.** [8]	**Blass & Uibel** [19]	**AWC** [20]	**Rammer** [1]
Smooth 2.8 mm	1040	-	-	-	1452 (+40%)[1]	1359 (+31%)
Smooth 3.5 mm	1088	-	-	-	1815 (+67%)	1762 (+62%)
Helical 2.8 mm	1330	1363 (+2%)	1528 (+15%)	1236 (-6%)	1452 (+9%)	1359 (+2%)
Helical 3.5 mm	1557	1704 (+9%)	1910 (+23%)	1413 (-9%)	1815 (+17%)	1762 (+13%)
Annular 2.8 mm	2050	-	2116 (+3%)	1236 (-40%)	2344 (+14%)	2936 (+43%)
Annular 3.5 mm	2245	-	2645 (+18%)	1413 (-37%)	2941 (+31%)	3671 (+64%)

[1] The values between parentheses (%) refer to the difference between the estimated values and those observed experimentally.

The AWC [20] and Rammer [8] equations overestimated the maximum withdrawal loads of the 2.8 mm and 3.5 mm smooth nails by approximately 30 and 60%, respectively, not being suitable. All the equations tested for helical nails showed results close to those obtained experimentally, especially the equation by Blass and Uibel [19], which underestimated the maximum load by 6% for 2.8 mm nails and approximately 9% for 3.5 mm nails. To predict the maximum resistance load of annular nails, the most precise equation was that of Rammer et al. [8] which overestimated approximately 3% and 18% for 2.8 mm and 3.5 mm nails, respectively. It is important to register that, for structural project calculus, it is more appropriate to use equations which underestimate the resistance values, increasing the project's safety margin, than the opposite. Therefore, Blass and Uibel [19] can be considered the most suitable equation.

4. Conclusions

The nail model was the most relevant factor, having a direct influence on withdrawal resistance. Annular nails presented the highest resistance values, followed by helical and smooth nails. The nail diameter had no significant effect on the maximum load result. The equations for withdrawal resistance prediction demonstrated considerable accuracy regarding the experimentally obtained data, being important tools to calculate and anticipate the behavior of wooden structures.

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