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Effect of Nail Models and Diameters on Withdrawal Strength of a Tropical Hardwood: A Preliminary Study

Utjecaj modela i promjera čavala na izvlačnu silu u tropskome tvrdom drvu: preliminarno istraživanje

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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 study was to evaluate the effect of different nail models and diameters on the withdrawal strength of Allantoma decandra wood and verify the efficiency of the existing prediction equations of nail withdrawal. 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 A. decandra wood specimens were used. Four nails were inserted 32 mm into each wood specimen and then withdrawn using a universal testing machine with a 600 kN capacity, according to the procedures of ASTM D143 (2014). The nail model was the most relevant factor in this study, having a direct influence on withdrawal strength. Annular nails presented the highest strength values, followed by helical and smooth nails. The nail diameter had no significant effect on the maximum load result. The equations for withdrawal strength prediction demonstrated considerable accuracy regarding the experimentally obtained data, being important tools to anticipate the behavior of wooden structures.*

KEYWORDS: *nail models; tropical wood; nail diameter; prediction models*

SAŽETAK • *Čavli su jednostavno i održivo rješenje za spajanje dijelova drvnih konstrukcija. Iako su najstariji i najtradicionalniji spojni elementi, postoji velik nedostatak znanja o upotrebi većih, navojnih čavala u tropskim tvrdim vrstama drva. Cilj ove studije bio je procijeniti utjecaj različitih modela i promjera čavala na izvlačnu silu u drvu Allantoma decandra i provjeriti učinkovitost postojećih jednadžbi predviđanja te sile. Ispitivanja izvlačenja provedena su s tri modela čavala (glatkima, spiralnima i prstenastim) dvaju različitih promjera (2,8 i 3,5 mm). Za svaku kombinaciju provedeno je istraživanje na deset uzoraka drva A. decandra. Četiri čavla umetnuta su 32 mm duboko u svaki uzorak drva, a zatim izvučena uz pomoć univerzalnoga ispitnog stroja kapaciteta 600 kN, prema postupcima opisanima normom ASTM D143 (2014). Model čavla bio je najrelevantniji čimbenik u ovom*

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istraživanju i izravno je utjecao na izvlačnu silu. Prstenasti čavli pokazali su najveće vrijednosti izvlačne sile, a zatim su slijedili spiralni i glatki čavli. Promjer čavala nije znatnije utjecao na rezultate izvlačne sile. Jednadžbe za predviđanje izvlačne sile pokazale su prilično veliku točnost s obzirom na eksperimentalno dobivene podatke, što ih čini važnim alatima za predviđanje ponašanja drvnih konstrukcija.

KLJUČNE RIJEČI: *modeli čavala; tropske vrste drva; promjer čavla; modeli predviđanja*

1 INTRODUCTION
1. UVOD

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 (Rammer, 2021). Among these, nails are the oldest and most traditional connection elements (De Paula *et al*., 1988; Ruan *et al.,* 2021). 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 (Hosseinzadeh *et al.,* 2022). Recently developed, the nail cross-laminated timber (NCLT) is a kind of engineered wood products that can be used for structural purpose, whose bear capacity and strength mainly relies on the nail withdrawal strength. Further information regarding NCLT can be found in Hosseinzadeh *et al.* (2022) and Pang *et al.* (2017).

Nail withdrawal strength is directly related to the tree species, wood density, nail diameter and insertion depth (Rammer and Zelinka, 2004; Mahdavifar *et al*., 2018; Kim, 2021). 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 strength (Rammer, 2001). This effect may be increased if the wood is exposed to constant drying and soaking processes (Rammer and Mendez, 2008). Gahagan and Scholten (1938) recorded a 57 % decrease in nail withdrawal strength 105 days after the nails were driven into the wood specimens.

Over time, different sizes and shapes of nails were tested with the aim of improving performance and withdrawal strength (Theilen *et al.,* 1998). The application of helical or annular threads, by compression, onto the nail shafts is one of the developed technologies (Wills *et al.,* 1996; Luszcki *et al.,* 2013). 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 (Rammer *et al.,* 2001). On the other hand, annular nails were developed with the specific purpose of increasing their withdrawal strength, and their threads are aligned perpendicular to the axis, at angles of approximately 90° (Skulteti *et al.,* 1997).

Unlike smooth-shank nails, which resist withdrawal merely by the friction forces between the wood fibers and the shaft, threaded nails also have mechanical strength, as during their insertion the wood fibers enchase between the crests of the threads (Luszcki *et al.,* 2013). 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 the same dimensions (Skulteti *et al.,* 1997; Rammer *et al.,* 2001; Skulteti *et al.,* 2013). 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 strength (Wills *et al.,* 1996; Rammer *et al.,* 2001). On the other hand, the presence of threads on the nail shaft requires 15 % more energy for insertion into wood (Ogurinde *et al.,* 2019). Furthermore, the deformations applied to create the threads result in slightly smaller diameters compared to smooth-shank nails of the same size (Wills *et al.,* 1996).

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 (Wang *et al.,* 2021; Ahn *et al.,* 2021; Abdoli *et al.,* 2022). This resumption and appreciation of wooden buildings, which has been called the mass 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, (Ahn *et al.,* 2021; Kim, 2021). Despite a high level of prefabrication of their components, all these techniques use and depend on metallic connection elements, such as nails. Most research has focused on smooth-shank nails, with small diameters, tested in coniferous wood species from temperate zones (Wills *et al.,* 1996).

Nowadays, available data regarding nail withdrawal strength for tropical hardwoods is still scarce. Specifically, in Brazil the first study was made by De Paula *et al.* (1988) who evaluated and the nail withdrawal strength of nine high density Amazonian tropical hardwoods. Recently, Ribeiro *et al.* (2018) determined only the screw withdrawal load for five hardwoods ranging from low to high density. Therefore, there is a considerable knowledge gap regarding the use of larger sized, threaded (helical and annular) nails 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 (Ehlbeck and Siebert, 1988; Rammer *et al.,* 2001), others suggest the use of the same equation for more multiple models (Blass and Uibel, 2007; AWC, 2018; Rammer, 2021). Although the equations were developed based on a restricted and specific dataset, they may be important tools to anticipate the behavior of wooden structures.

In this context, the objective of this study was to evaluate the effect of different nail models and diameters on the withdrawal strength of *Allantoma decandra* wood, and verify the efficiency of the existing prediction equations of nail withdrawal regarding the experimental results. *A. decandra,* which is native to the Amazon Forest, has no legal logging restrictions and has been explored in sustainable forest management projects (SFB, 2023).

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Wood material and test setup
2.1. Drvni materijali i postavka ispitivanja

The tests were carried out utilizing wood specimens obtained from ten trees identified as *A. decandra* (Ducke) S. A. Mori, Y. Y. Huang & Prance. The specie belongs to the Lecythidaceae family, and its wood has a specific gravity of approximately 0.57 g/cm^3, which had been previously evaluated by Pimentel *et al.* (2021). The specimens were produced from 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 (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, totalling six model/diameter combinations (Figure 1). To avoid material variation, all nails used in this study were produced by the same manufacturer (Gerdau S.A., Brazil). The withdrawal test was performed according to the procedures of ASTM D143 (2014). This way, for each combination, ten 50 mm × 50 mm × 150 mm (width, depth, and length) specimens were used. Two nails were driven on the radial face and two on the tangential face of the specimen, maintaining a minimum distance of 19 mm from the sides, 38 mm from the ends and 50 mm between the nails, while avoiding alignment. The nails were driven at right angles to the face of the specimen to a total penetration of 32 mm. 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 (Martins Campelo Testing Systems, Brazil) was used to carry out the tests at a speed rate of 2 mm/minute. Additionally, some physical and mechanical properties of the wood were also evaluated according to this same standard.

Figure 1 Nails used in withdrawal tests: smooth, helical, and annular with 2.8 mm and 3.5 mm of diameter, respectively
Slika 1. Čavli upotrijebljeni u testovima izvlačenja: glatki, spiralni i prstenasti, promjera 2,8 i 3,5 mm

2.2 Statistical and experimental analyses
2.2. Statističke i eksperimentalne analize

The experimental design consisted of six combinations of nail models and diameters. First of all, an analysis of variance (ANOVA) at 5 % significance was performed to evaluate the statistical difference between the maximum supported loads obtained by the radial and tangential faces. Next, a factor analysis of variance (Two-way ANOVA) at 5 % significance was performed to evaluate the most efficient model/diameter combination and the effect of each factor on the maximum supported loads. All analyses were executed using the IBM SPSS software. To verify the efficiency of the prediction equations of nail withdrawal 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.

The American Wood Council (AWC, 2018) and the Forest Products Laboratory (Rammer, 2021) developed specific equations for smooth-shank and annular nails. Due to the absence of studies, both institutions suggest the use of smooth-shank nail equations to pre-

Table 1 Prediction equations of nail withdrawal strength
Tablica 1. Jednadžbe predviđanja izvlačne sile čavala

Nail shank model *Vrsta čavla*	**Equation** *Jednadžba*	**Unit** *Jedinica*	**Authors** *Autori*
Smooth *glatki*	$W = 1380\ G^{5/2}\ D\ L$	LB	AWC (2018)
	$W = 54{,}12\ G^{5/2}\ D\ L$	N	Rammer (2021)
Helical *spiralni*	$W = 36 \cdot 10^{-2}\ G^{2}\ D\ L$	N	Ehlbeck and Siebert (1988)
	$W = 29{,}6\ G^{1{,}28}\ D\ L$	N	Rammer *et al.* (2001)
	$W = 0{,}117\ D^{0{,}6}\ L\ G^{0{,}8}$	N	Blass and Uibel (2007)
	$W = 1380\ G^{5/2}\ D\ L$	N	AWC (2018)
	$W = 54{,}12\ G^{5/2}\ D\ L$	N	Rammer (2021)
Annular *prstenasti*	$W = 42{,}8\ G^{1.38}\ D\ L$	N	Rammer *et al.* (2001)
	$W = 0{,}117\ D^{0{,}6}\ L\ G^{0{,}8}$	N	Blass and Uibel (2007)
	$W = 1800\ G^{2}\ D\ L$	LB	AWC (2018)
	$W = 77{,}57\ G^{2}\ D\ L$	N	Rammer (2021)

**W* – maximum load; *G* – wood density; *D* – nail diameter; *L* – depth of insertion of the nail
**W – maksimalna sila; G – gustoća drva; D – promjer čavla; L – dubina umetanja čavla*

Table 2 Mean values and coefficients of variation (*CV*) of some physical and mechanical properties of *A. decandra* wood
Tablica 2. Srednje vrijednosti i koeficijenti varijacije (*CV*) nekih fizičkih i mehaničkih svojstava drva *A. decandra*

Property *Svojstvo*	**Unit** *Jedinica*	**Mean value** *Srednja vrijednost*	***CV*, %**
ρ_{12}	g/cm^3	0.7	7.8
ε_1	%	5.4	11.2
ε_2	%	7.5	12.5
ΔV	%	12.8	11.3
AC	-	1.4	8.4
f_{M}	MPa	115.6	7.4
E_{M0}	MPa	13817.0	12.5
$f_{\mathrm{v,0}}$	MPa	11.0	13.6
$f_{\mathrm{c,0}}$	MPa	54.2	9.6
$f_{\mathrm{c,90}}$	MPa	9.7	13.3

ρ_{12} – 12 % density; ε_1 – radial shrinkage; ε_2 – tangential shrinkage; ΔV – volumetric shrinkage; AC – anisotropic coefficient; f_{M} – bending strength; E_{M0} – bending stiffness; $f_{\mathrm{v,0}}$ – shear strength; $f_{\mathrm{c,0}}$ – parallel compression strength; $f_{c,90}$ – perpendicular compression strength
ρ_{12} – gustoća od 12 %; ε_1 – radijalno utezanje; ε_2 – tangentno utezanje; ΔV – volumno utezanje; AC – koeficijent anizotropnosti; f_M – čvrstoća na savijanje; E_{M0} – krutost pri savijanju; $f_{v,0}$ – smična čvrstoća; $f_{c,0}$ – čvrstoća na tlak paralelno s vlakancima; $f_{c,90}$ – čvrstoća na tlak okomito na vlakanca

dict the withdrawal strength of helical nails. Blass and Uibel (2007) developed a single equation for both helical and annular nails. The equations proposed by Rammer (2021) use 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 strength load divided by five to adjust to test conditions, safety, and load duration.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

Table 2 presents some physical and mechanical properties obtained for *A. decandra* wood. According to the values presented, the wood showed radial, tangential, and volumetric shrinkages of 5.4 %, 7.5 %, and 12.8 %, respectively. According to Melo and Camargos (2016), the value of 12.8 % classifies the wood as having medium shrinkage. The anisotropic coefficient (ratio between tangential and radial shrinkage) calculated was 1.4, which, according to Durlo and Marchiori (1992), classifies it as having excellent dimensional stability. As presented in Table 2, the average values of the mechanical properties obtained were similar to those found in the Tropical Woods Database (LPF, 2022) for *Allantoma lineata* and *Couratari guianensis*, the two most exploited species of the Lecythidaceae family in Brazil (SFB, 2022). By analogy, the same uses cited by Melo and Camargos (2016) for the aforementioned species can be indicated for *A. decandra* wood: light structural uses, furniture, frames, musical instruments, household utensils, boats, packaging, linings, tool handles, barrels, and cladding.

Table 3 shows the maximum withdrawal strength load and coefficient of variation obtained by the six model/diameter nail combinations tested on *A. decandra* wood. The maximum nail withdrawal strength loads were initially analyzed separating the data obtained by the radial and tangential faces. For all nail models and dimensions, the tangential faces showed

Table 3 Maximum withdrawal strength loads and coefficients of variation (*CV*) obtained by six model/diameter nail combinations tested on *A. decandra* wood
Tablica 3. Maksimalne sile izvlačenja i koeficijenti varijacije (*CV*) dobiveni za šest kombinacija modela i promjera čavala testiranih u drvu *A. decandra*

Model/Diameter *Model/promjer*	**Maximum load, N** *Najveća sila,* N	***CV*, %**
Smooth/*glatki* 2.8 mm	1039.70 a	15.7
Smooth/*glatki* 3.5 mm	1088.32 a	19.7
Helical/*spiralni* 2.8 mm	1330.10 b	26.8
Helical/*spiralni* 3.5 mm	1557.32 b	23.5
Annular/*prstenasti* 2.8 mm	2050.09 c	24.3
Annular/*prstenasti* 3.5 mm	2244.55 c	25.4

Means followed by the same letter do not differ statistically from each other at 5% significance.
Srednje vrijednosti iza kojih slijedi isto slovo statistički se međusobno ne razlikuju, uz 5 % značajnosti.

greater withdrawal strength than the radial faces, which can be explained by the higher number of dense parenchyma layers crossed by the nails (Taj *et al.,* 2009). In this direction, there is greater interaction between the wood tissues and the nails, resulting in greater withdrawal strength and consequently greater damage to the wood surface (Abdoli *et al.,* 2022). However, after applying ANOVA, no statistically significant difference was found between the results obtained for the radial and tangential faces. As this observation had already been made by other authors in similar experiments (Aytekin, 2008; Teng *et al.,* 2018), it was decided to analyze the data jointly, as shown in Table 3.

The scientific literature on nails indicates a positive correlation between diameter and withdrawal strength (Gehloff, 2011; Mahdavifar, 2018; Ceylan and Girgin, 2020; Li, 2021). In this study, the increase in nail diameter generated an increase of 5 %, 17 % and 9.5 % in withdrawal strength for smooth, helical, and annular nails, respectively. However, the two-way ANOVA analysis showed that only the models had a significant effect at a 95 % confidence ($P < 0.05$), with no statistically significant difference between the means of different diameters of the same nail model.

As expected, annular nails showed the highest withdrawal strength value (2147 N), followed by helical nail (1443 N), while smooth nails had the lowest value (1064 N). As mentioned previously, smooth-shank nails resist withdrawal forces due to the friction force between the wood fibers and the nail shaft, while threaded nails also have mechanical strength, as during their insertion the wood fibers enchase between the crests of the threads (Luszcki *et al.,* 2013). This way, to withdraw these kinds of nails, a greater force is required in order to additionally tear the wood fibers (Skulteti *et al.,* 1997; Rammer *et al.,* 2001).

In accordance with data found in literature (Blass and Uibel, 2004), helical nails showed a strength increase of approximately 30 % to 40 % (according to nail diameter). Annular nails presented the highest withdrawal strength, being approximately twice the value presented by smooth-shank nails of the same diameter. This result is consistent with data presented by Skulteti *et al.* (1997) and Rammer (2021).

The values determined for the coefficients of variation 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 CV values presented lower variations than those obtained by Rammer *et al.* (2001) 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 explained through the curves formed by the displacement × load graphs (Figure 2) and wood failure modes (Figure 3).

According to Li *et al.* (2021), nail withdrawal causes various levels of stress at the interface between the threads and the wood components, leading to a combination of shear and traction 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 strength is reached, the static friction is overcome, and the graph shows a sudden drop. From this moment on, strength depends only on the dynamic friction, which continues losing strength until the nail is completely withdrawn. As the insertion of smooth-shank nails occurs exclusively by the separation of the wood fibers, their withdrawal occurs without causing major damage to the wood specimen (Figure 3A).

As mentioned by Rammer (2021), all the equations for nail-withdrawal resistance indicate that density has a great influence on the nail withdrawal strength, and therefore, denser wood species usually require higher withdrawal loads in comparison with lower density ones. Nevertheless, these lighter wood species should not be disqualified for uses requiring high resistance to withdrawal, since they do not suffer from cracks as expected for denser ones, which can be an opportunity for increasing the diameter, length, and number of the nails to counterbalance its lower nail withdrawal resistance. It is assumed that it can happen for any type of nail.

Although helical nails tend to rotate around their axis during insertion into wood, the rotating movement does not occur during withdrawal, and therefore, the

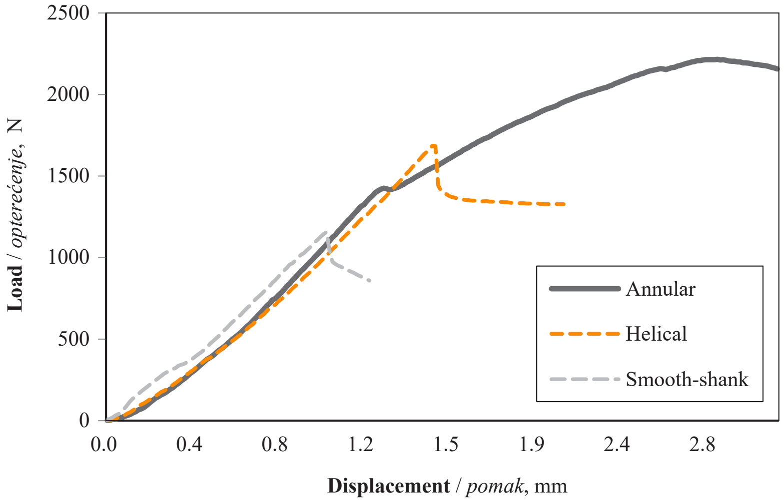

Figure 2 Typical displacement × load graphs for threaded and smooth-shank nails during withdrawal
Slika 2. Tipični grafovi pomaka i opterećenja za spiralne, prstenaste i glatke čavle tijekom izvlačenja

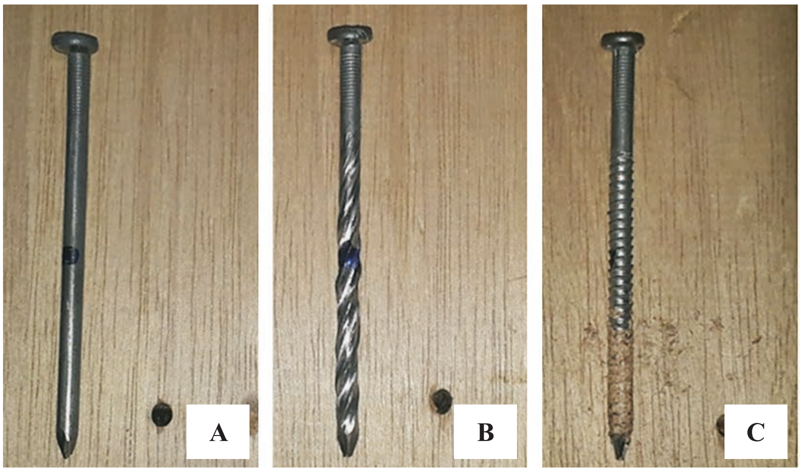

Figure 3 Typical modes of wood failure after nail withdrawal: A) smooth-shank nails cause minimal damage to the wood; B) helical nails withdraw small amounts of wood fibers; C) annular nails extract a column of wood fiber fragments adhered to its threads
Slika 3. Tipični načini loma drva nakon izvlačenja čavala: A) glatki čavli uzrokuju minimalna oštećenja drva; B) spiralni čavli izvlače male količine drvnih vlakana; C) prstenasti čavli izvlače stupac fragmenata drvnih vlakana prilijepljenih za njegove navoje

threads increase the friction surface of nails, ensuring prolonged strength, which allows higher maximum loads than smooth nails (Luszcki *et al.,* 2013). After reaching maximum load during the tests, helical nails present a sudden drop and then a tendency to stabilize. During this moment, the threads still exert dynamic friction against wood fibers, and the connection is still capable of resisting considerable load while the nail is detached from the wood. As can be seen in 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 strength 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 cut, 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, strength is only due to friction, being similar to the behavior shown by smooth nails (Luszcki *et al.,* 2013; Ceylan *et al.,* 2019).

Based on the wood density of *A. decandra*, nail diameters and nail insertion depth, maximum loads of withdrawal strength for the six combinations model/diameter of nails were estimated using the equations found in the specialized literature (Table 4).

The AWC (2018) and Rammer's (2021) equations overestimated the maximum withdrawal loads of the 2.8 mm and 3.5 mm smooth nails by approximately 30 and 60 %, respectively. All the equations tested for

Table 4 Maximum load values (N) obtained experimentally and estimated by equations for each combination of nail model/diameter
Tablica 4. Maksimalne vrijednosti sile (N) dobivene eksperimentalno i procijenjene jednadžbama za svaku kombinaciju modela i promjera čavla

Nail models *Model čavla*	**Experimental values, N** *Eksperimentalne vrijednosti,* N	**Ehlbeck and Siebert (1988)**	**Rammer *et al.* (2001)**	**Blass and Uibel (2007)**	**AWC (2018)**	**Rammer (2021)**
Smooth *glatki* 2.8 mm	1040	-	-	-	1452	1359
					(+40 %)	(+31 %)
Smooth *glatki* 3.5 mm	1088	-	-	-	1815	1762
					(+67 %)	(+62 %)
Helical *spiralni* 2.8 mm	1330	1363	1528	1236	1452	1359
		(+2 %)	(+15 %)	(-6 %)	(+9 %)	(+2 %)
Helical *spiralni* 3.5 mm	1557	1704	1910	1413	1815	1762
		(+9 %)	(+23 %)	(-9 %)	(+17 %)	(+13 %)
Annular *prstenasti* 2.8 mm	2050	-	2116	1236	2344	2936
			(+3 %)	(-40 %)	(+14 %)	(+43 %)
Annular *prstenasti* 3.5 mm	2245	-	2645	1413	2941	3671
			(+18 %)	(-37 %)	(+31 %)	(+64 %)

The values in parentheses (%) refer to the difference between the estimated values and those observed experimentally.
Vrijednosti u zagradama (%) odnose se na razliku između procijenjenih i eksperimentalno dobivenih vrijednosti.

helical nails showed results close to those obtained experimentally, especially the equation by Blass and Uibel (2007), which underestimated the maximum load by 6 % for 2.8 mm nails and approximately 9 % for 3.5 mm nails. To predict the maximum strength load of annular nails, the most precise equation was that of Rammer *et al.* (2001), which overestimated the withdrawal strength by approximately 3 % and 18 % for 2.8 mm and 3.5 mm nails, respectively. It is important to note that, for structural project calculation, it is more appropriate to use equations that underestimate the strength values, increasing the project's safety margin, than the opposite. Therefore, the equation by Blass and Uibel (2007) can be considered the most suitable.

4 CONCLUSIONS
4. ZAKLJUČAK

In this study three nail models and two nail diameters were evaluated, and it was found that the nail model was the most relevant factor, having a direct influence on withdrawal strength, while the nail diameter had no significant effect. It was also found that there was no statistically significant difference between the results of withdrawal load for the radial and tangential faces. Annular nails presented the highest strength values, followed by helical and smooth nails. The five evaluated equations to predict the withdrawal strength demonstrated considerable accuracy regarding the experimentally obtained data, being important tools to anticipate the behavior of wooden structures. Nevertheless, the predictability was different between nail models, and the values of withdrawal strength for smooth and annular nails were overestimated, while for helical nails the models were more precise presenting a slight underestimation. It can be concluded that this tropical hardwood can be used for structural purposes or to manufacture forest products that need to be nailed.

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