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ARTÍCULO

Physical and mechanical assessment of itauba wood welded by rotary friction♣

Ana Carolina Costa Viana[1] https://orcid.org/0000-0001-9411-4591♠
Renato Barbosa Sampaio[2] https://orcid.org/0009-0005-9074-2466
Poliana Dias de Moraes[1] https://orcid.org/0000-0002-0569-6209
Walter Lindolfo Weingaertner[3] https://orcid.org/0000-0001-8707-2776

[1]Universidade Federal de Santa Catarina (UFSC). Departamento de Engenharia Civil. Florianópolis, Brasil.
[2]Instituto Federal do Paraná (IFPR). Campus Cascavel. Cascavel, Brasil.
[3]Universidade Federal de Santa Catarina (UFSC). Departamento de Engenharia Mecânica. Florianópolis, Brasil.

♠Corresponding author: anacarolviana@outlook.com

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Abstract:
Rotary friction welding is a rapid and sustainable wood joining method, which eliminates the need for conventional adhesives or mechanical fasteners. Its application to Brazilian tropical hardwoods like itauba remains largely unexplored. The absence of established welding parameters for itauba-itauba (dowel-substrate) joints leads to unpredictable mechanical performance, limiting the industrial viability of this technique. This exploratory research aimed to evaluate the physical characteristics of the welded interface using scanning electron microscopy and assessed the influence of pre-drilled hole stage (one- and two-stage) and feed rate (300 mm/min, 400 mm/min, and 500 mm/min) on the mechanical performance of itauba welded joints. The ultimate objective was to determine the optimal welding parameters. The results demonstrate that the dowel wood fibers were covered by softened intercellular material, forming a smooth and uniform surface. The average taper rate of the dowels, from 3,72 % to 5,39 %, was influenced by the pre-drilled hole stage. The highest taper rates were obtained for two-stage pre-drilled holes, in which piece A had a smaller diameter (7 mm). Tensile testing demonstrated that specimens with a one-stage pre-drilled hole exhibited higher maximum pull-out loads than those with two-stages. The highest average shear strength, 1,21 MPa, was obtained for 1-stage pre-drilled hole and 300 mm/min or 400 mm/min of feed rate.

Keywords: Rotary friction welding, *Mezilaurus itauba,* dowel joints, shear strength, tensile shear strength testing, tropical hardwood.

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Introduction

Rotary friction welding (RFW) is a joining process that creates a strong bond between wood pieces by using mechanically induced frictional heat (Pizzi *et al.* 2004). The technique involves rotating a dowel at high speed while inserting it under pressure into a pre-drilled hole machined in a substrate at a specific feed rate (Pizzi *et al.* 2004). The resulting friction generated at the dowel-substrate interface causes wear, leading to a gradual increase and reduction in the diameter of the dowel and the pre-drilled hole, respectively (Leban *et al.* 2005).

The RFW process generates a rapid and significant increase in temperature at the interface. This heat induces darkening of the wood due to the hydrolysis of hemicelluloses and the oxidation of phenolic compounds from lignin (Delmotte *et al.* 2008, Li *et al.* 2021). Furthermore, the elevated temperatures fuse the wood polymers, which resolidify upon cooling into an amorphous and dense material that bonds the dowel to the substrate (Pizzi *et al.* 2004).

RFW technique is well-suited for industrial applications, including furniture manufacturing and the assembly of mass timber products (Li *et al.* 2021, Xu *et al.* 2022). Research has shown that the strength of RFW joints can surpass those of conventional polyvinyl acetate (PVAc) glued joints (Pizzi *et al.* 2004). However, the mechanical performance of RFW joints is highly dependent on welding parameters, such as the pre-drilled hole stage and the feed rate, which regulate frictional heat generation (Župčić *et al*. 2008, Auchet *et al*. 2010). Achieving a strong joint requires a precise balance between welding parameters to ensure adequate material softening at the interface without causing excessive carbonization (Belleville *et al*. 2013).

Recently, researchers have evaluated the potential of welding woods from tropical forests and have obtained promising results (Belleville *et al*. 2013, Belleville *et al*. 2016). However, a significant knowledge gap exists regarding RFW of Brazilian wood species. The limited published research has focused on determining the optimal parameters for welding itauba dowels into pine substrates (Viana *et al.* 2021, Viana *et al.* 2022). For joints made exclusively of itauba, a preliminary study confirmed the potential of the technique, achieving a shear strength of 0,81 MPa (Viana *et al.* 2024). However, the influence of varying the welding parameters on the mechanical performance of these specific joints has not yet been investigated.

Itauba (*Mezilaurus itauba* (Meissner) Taubert ex Mez) species, from the Amazon region, is a commercially available tropical hardwood valued for its high density and natural durability (IPT 2023). These characteristics make it a preferred wood for demanding applications in the furniture industry and in civil construction, including high-class furniture, flooring, paneling, decking, and structural components (IPT 2023).

The lack of comprehensive data on RFW of itauba wood presents considerable practical and technical limitations. This knowledge gap hinders the application of this joining method, which offers a rapid and sustainable alternative to conventional adhesives and mechanical fasteners. Investigating itauba-itauba welded joints is particularly important because tropical hardwoods with high extractive content have challenges in RFW, considering the influence of these compounds during the welding process (Zhang *et al.* 2014). Providing data on the performance of tropical hardwoods under RFW would contribute to establishing a reliable and optimized welding process. Overcoming these challenges would unlock opportunities for applying the RFW technique in the furniture and mass timber industries.

This exploratory research evaluated the physical characteristics of the welded interface using scanning electron microscopy (SEM) and assessed the influence of pre-drilled hole stage and feed rate on the mechanical performance of itauba-itauba welded joints. The ultimate objective was to determine the optimal welding parameters. This study contributes to optimizing the RFW technique for hardwoods from Brazilian tropical forests and those with similar anatomical characteristics.

Materials and methods

Wood

Itauba (*Mezilaurus itauba* (Meissner) Taubert ex Mez), a native Brazilian tropical hardwood (Figure 1), with an average density of 824 kg/m^3 ± 8 kg/m^3 (12 % ± 0,13 % moisture content), was used. It has light brown heartwood, growth rings delimited by darker tangential fibrous zones and diffuse porosity. Itauba has low permeability and is moderately difficult to work with hand tools and machines, due to the presence of silica, however, it has a good surface finish (IPT 2023). It is commercially available in Brazil and is commonly used in the furniture industry and in civil construction.

Figure 1: Itauba wood.

Samples and specimens

Thirty specimens composed of itauba dowels and substrates were used. The dowels were smooth with 10 mm in diameter and 80 mm in length. The substrates were composed of two pieces, A’ and A”, with 63,5 mm × 50 mm × 25 mm each (Figure 2), adapted from the ABNT NBR 7190-3 (2022) standard for transverse tensile testing. The specimens were conditioned at 20 ºC ± 2 ºC and 60 % ± 5 % relative humidity, according to ISO 13061-17 (2017), before and after the RFW process to maintain 12 % of moisture content.

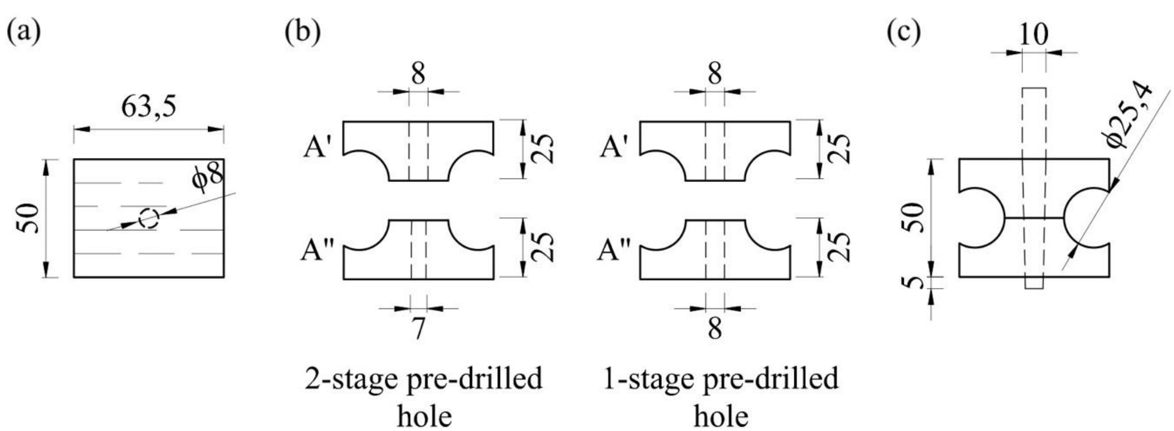


Figure 2: Specimens for the RFW process (dimensions in mm). (a) top view, (b) front view before RFW, (c) front view after RFW.

The specimens were divided into 6 groups with different rotary friction welding parameters (Table 1). Pre-drilled holes were machined in the center of the substrates, in the radial-tangential plane, perpendicular to the fibers and tangential to the growth rings (Figure 2b). In pieces A’, the pre-drilled holes had 8 mm in diameter (1,25 dowel/pre-drilled hole diameter ratio). In pieces A”, the pre-drilled holes varied between 7 mm and 8 mm in diameter (Viana *et al.* 2022), characterizing them as 1 and 2-stage, respectively. The dowels were welded into the holes with 300 mm/min, 400 mm/min or 500 mm/min of feed rate and 1000 rpm of rotation. Later, the specimens were submitted to mechanical tensile tests and microstructure evaluation.

Table 1: Welding parameters.

Group	Number of specimens	Pre-drilled hole stage	Feed rate (mm/min)
A	5	1 (8 mm and 8 mm)	300
B	5		400
C	5		500
D	5	2 (8 mm and 7 mm)	300
E	5		400
F	5		500

Specimens for SEM test

For the SEM test, a specimen with 8 mm × 10 mm × 5 mm, which contained part of the dowel, was used (Figure 3). It was extracted from a Group C specimen, after the mechanical tensile test, from a cut perpendicular to the dowel wood fibers and tangential to the growth rings.

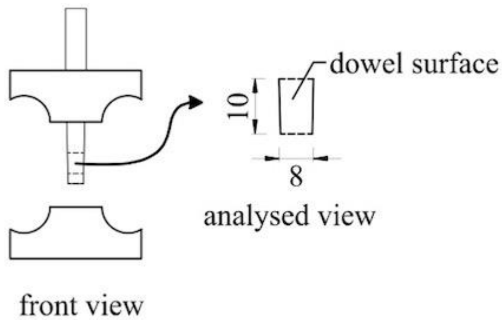


Figure 3: Specimen for the SEM test (dimensions in mm).

Welding process

The welding process was performed using a machining center ROMI D600. Initially, the specimens were fixed in a clamp and the X, Y and Z coordinates of tool movement were determined. Then, the pre-drilled hole machining and the dowel welding programs were created. For 1-stage pre-drilled holes, the machining process was performed in one step, whose hole dimensions were 8 mm in diameter and 50 mm in depth. For 2-stage pre-drilled holes, the machining process was performed in two steps. First, holes measuring 7 mm in diameter and 50 mm in depth were drilled. Second, holes measuring 8 mm in diameter and 25 mm in depth were drilled, in the same position as in the first step (Figure 2). Subsequently, the dowels were welded into the pre-drilled holes at a depth of 55 mm (Figure 4).

Figure 4: Dowel welding process.

Mechanical tensile test

The specimens were submitted to tensile tests to determine the shear engaged by tensile pull-out of the dowel. A universal testing machine Instron 5569 were used to apply a tensile force parallel to the dowel wood fibers and perpendicular to substrate wood fibers (Figure 5a). The load, recorded through an equipment data acquisition system, increased monotonically at 2 mm/min, due to the crossbar displacement, until the pull-out of the dowel (Figure 5b).

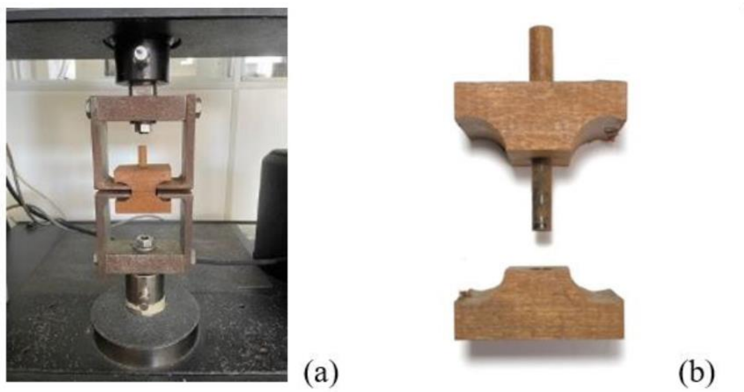


Figure 5: Mechanical tensile test. (a) Specimen before the test, (b) Specimen after the test.

Shear engaged by the tensile pull-out of the dowel

Shear engaged by the tensile pull-out of the dowel was determined by the ratio between the maximum force verified in the load × displacement curve and the welded surface area of the dowel in piece A" (Equation 1), where the joint breaks when pieces A′ and A″ have the same height (Figure 5b).

$$\tau = \frac{F_{max}}{\pi d h} \quad (1)$$

Where τ is the shear stress (MPa), F_{max} is the maximum force (N), d is the pre-drilled hole diameter of piece A" (mm), h is the height of piece A" (mm).

Dowel taper rate

The dowel taper rate was determined from measurements of the dowel diameters, at the top and the bottom of pieces A’ and A”, respectively, and the specimen height (Figure 2b). The measurements were performed using a caliper with an accuracy of 0,01 mm. The taper rate was determined according to Equation 2 (Smid 2003).

$$X = \left[\left(\frac{D - d}{L} \right) \right] x\ 100 \qquad (2)$$

Where X is the dowel taper rate (%), D is the diameter of the dowel at the top of piece A’ (mm), d is the diameter of the dowel at the bottom of piece A” (mm), L is the specimen height (mm).

SEM test

The specimen was stored for 24 hours in an oven at 40 °C to reduce the moisture content that could influence the quality of the micrographs, while preserving the welded interface. Thereafter, it was fixed on a stub, covered with gold in a LEICA EM SCD500 sputter coater, and placed in a sample holder. Subsequently, it was examined in the JEOL JSM-6390LV scanning electron microscope at an acceleration voltage of 10 kV, using a secondary electron signal, a working distance of 16 mm, and magnification levels of ×30 and ×200 .

Physical and mechanical analysis

Physical analysis consisted of evaluating the microstructure of the itauba dowel surface, based on the micrographs obtained in the SEM test, which were compared with those of other wood species from literature. It also consisted of statistically evaluating the taper rate of the dowels, which was the dependent variable, while the pre-drilled hole stage and the feed rate were the independent variables (Table 2). The analysis was conducted using Real Statistics software. The normality and homogeneity of the dependent variable data were verified using the Shapiro-Wilk and Levene tests (Field *et al.* 2012). The influence of welding parameters was evaluated using the two-way analysis of variance (ANOVA) test, followed by the Tukey test to compare the means, since the data were normal and homogeneous (Field *et al.* 2012). Mechanical analysis consisted of statistically evaluating the shear engaged by the tensile pull-out of the dowels, which was the dependent variable, while the pre-drilled hole stage and the feed rate were the independent variables (Table 2). The normality and homogeneity of the dependent variable data were verified using the Shapiro-Wilk and Levene tests (Field *et al.* 2012). The influence of welding parameters was evaluated using the Kruskal-Wallis non-parametric test, followed by the Conover test to compare the group medians, since the data did not present normality and homogeneity (Field *et al.* 2012, Montgomery and Runger

2003). The statistical tests were performed considering 5 % probability of error. After statistical analysis, the optimal welding parameters were determined.

Table 2: Dependent and independent variables.

Dependent variable	Independent variable
Taper rate of the dowel	Pre-drilled hole stage (1 or 2-stage)
	Feed rate (300 mm/min, 400 mm/min or 500 mm/min)
Shear engaged by tensile pull-out of the dowel	Pre-drilled hole stage (1 or 2-stage)
	Feed rate (300 mm/min, 400 mm/min or 500 mm/min)

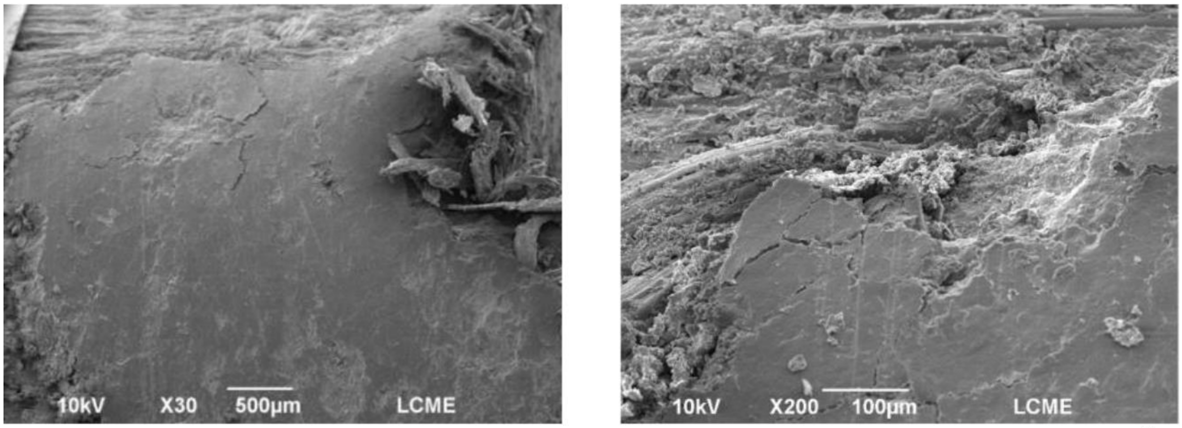
Results and discussions

In the following sections, the results and discussions regarding the physical and mechanical analysis, which include the microstructure of the itauba dowel surface, the taper rate of the dowels, the load × displacement curves and the shear engaged by the tensile pull-out of the dowels, are presented.

Microstructural analysis

Figure 6 illustrates the micrographs of the dowel surface from Group C specimen, after the mechanical tensile test. The fusion of wood fibers with the intercellular material resulted in a smooth and uniform surface (Figure 6a), different from that described for European wood species such as european beech (*Fagus sylvatica* L.) and european spruce (*Picea abies* (L.) H. Karst.), whose fibers intertwined with the softened intercellular material and have been pulled out during the tensile test (Pizzi *et al.* 2004). This difference is probably due to the low permeability of itauba, which is considered extremely resistant to treatments according to CIRAD (2023) since its pores are obstructed by tilos and oleoresins (IPT 2023). Furthermore, itauba has a high extractive content of 7,7 % (Viana *et al*. 2024). These characteristics make it difficult to impregnate the softened intercellular material, as well as to form the welded joint.

Zang *et al.* (2014) reported that high extractive content in tropical wood species impacts the final bonding strength of the welding, however, research in this field is very limited. This provides an explanation for the superficial adhesion observed in Figure 6, which raises concerns about the long-term performance and structural integrity of itauba-itauba joints. This behavior suggests that for low-permeability, oleoresinous woods like itauba, preparing the surfaces of both the dowel and the pre-drilled hole, before welding, is required to facilitate deep impregnation of the softened intercellular material. According to Rowell (2005), surface preparation methods like solvent cleaning, mechanical techniques (sanding), or oxidation can improve adhesion in such woods. Therefore, future studies are required to verify whether the surface preparation of itauba can promote deeper impregnation.



(a) (b)

Figure 6: Welded dowel surface. (a) ×30, (b) ×200.

Taper rate of the dowels

Figure 7 illustrates the taper rate of the dowels welded in 1 and 2-stage pre-drilled holes with 300 mm/min, 400 mm/min and 500 mm/min of feed rate. The two-way ANOVA test revealed that the pre-drilling hole stage is the welding parameter that influences the taper rate of the dowels ($p = 0{,}0001$). The Tukey test indicated that there are statistically significant differences between the means of groups B and D, B and E, B and F, C and D, C and E, C and F.

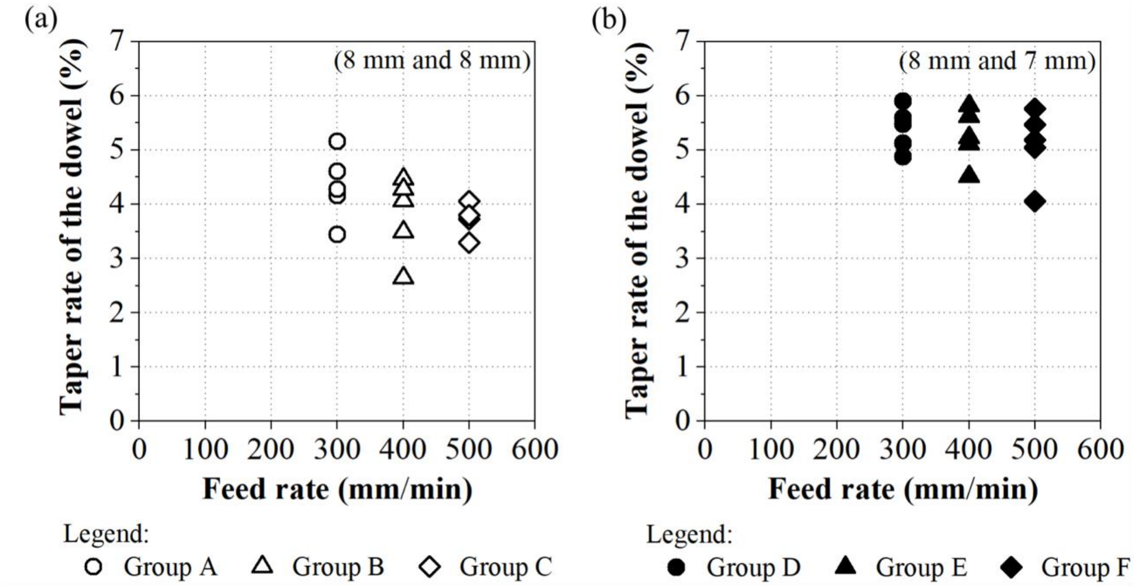


Figure 7: Taper rate of the dowels × feed rate. (a) 1-stage pre-drilled hole, (b) 2-stage pre-drilled hole.

According to Ganne-Chedeville *et al.* (2005), cylindrical dowels always develop a conical appearance when rotated and inserted into pre-drilled holes of smaller diameter. This taper results from different levels of compressive force and frictional heating as the dowel passes through the hole (Zhu *et al.* 2017). The welding parameters significantly influence the extent of this non-uniform wear (Li *et al.* 2021, Viana *et al.* 2022).

In Table 3, the average taper rate of the dowels from groups A to F are presented. The highest taper rates were obtained for 2-stage pre-drilled holes, whose piece A" has a smaller diameter (7 mm), causing greater wear of the dowel during its insertion into the pre-drilled hole. This result reflects those of Viana *et al*. (2022) and Li *et al*. (2021). Viana *et al*. (2022) welded itauba dowels, with 10 mm in diameter, into 1 and 2-stage pre-drilled holes machined in loblolly pine (*Pinus taeda* L.) substrates. They adopted 1000 rpm of rotation and 100 mm/min to 500 mm/min of feed rate (Viana *et al*. 2022). Li *et al*. (2021) welded moso bamboo (*Phyllostachys pubescens* Mazel ex J. Houz.) (680 kg/m^3) dowels, with 10 mm in diameter, into pre-drilled holes of 6 mm, 7 mm, 8 mm and 9 mm in diameter, machined in *Populus* sp. (450 kg/m^3) substrates. They adopted 1500 rpm of rotation and 400 mm/min to 450 mm/min of feed rate (Li *et al*. 2021). In general, the welding parameters of Viana *et al*. (2022) and Li *et al*. (2021) are similar to those of the present research.

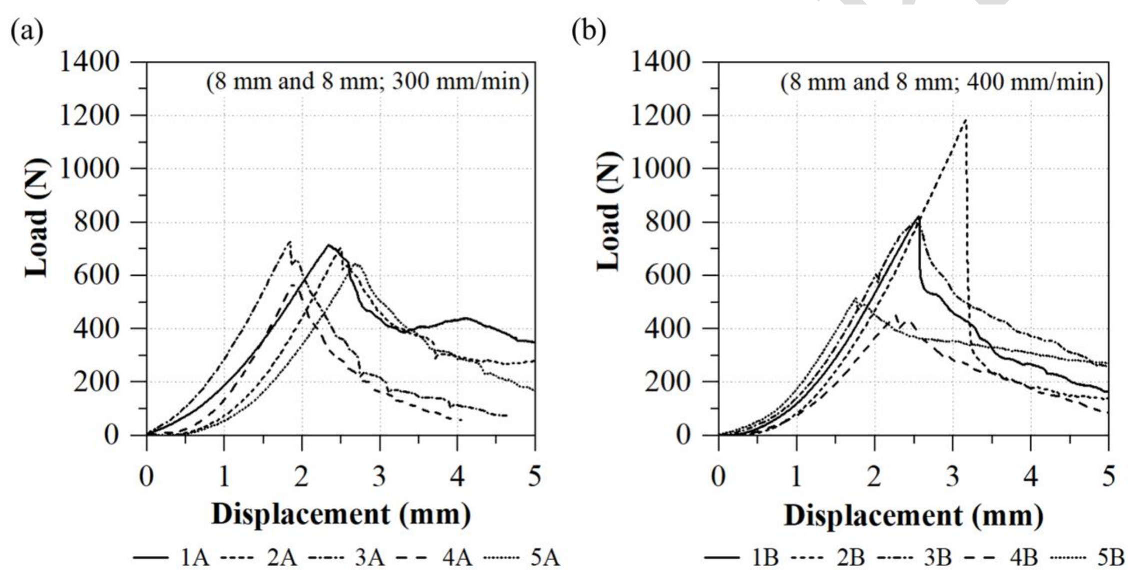
Table 3: Average taper rate of the dowels.

Group	Pre-drilled hole stage	Feed rate (mm/min)	Average taper rate (%)	Coefficient of variation (%)
A	1 (8 mm and 8 mm)	300	4,33	15
B		400	3,79	19
C		500	3,72	9
D	2 (8 mm and 7 mm)	300	5,39	7
E		400	5,25	10
F		500	5,11	13

Load × displacement curves

Figure 8 illustrates the load × displacement curves for specimens from groups A to F. It is apparent from the graphs that the load increases linearly with displacement until reaching a peak. Beyond this point, the load decreases progressively with further displacement.

Specimens with 1-stage pre-drilled hole (Figure 8a, Figure 8b, Figure 8c) exhibit higher maximum loads than those with 2-stage (Figure 8d, Figure 8e, Figure 8f). The highest maximum load of 1182 N was obtained for a Group B specimen, with 1-stage pre-drilled hole and 400 mm/min of feed rate. In contrast, the lowest maximum load of 218 N was obtained for a Group F specimen, with 2-stage pre-drilled hole and 500 mm/min of feed rate. According to Belleville *et al.* (2016), the optimal dowel to pre-drilled hole diameter ratio is closely related to the density of the wood species. For high-density woods such as itauba (824 kg/m^3), 1-stage pre-drilling hole, with 8 mm diameter in piece A", facilitates dowel insertion while minimizing excessive wear, thereby improving the bond between the dowel and the substrate surfaces.



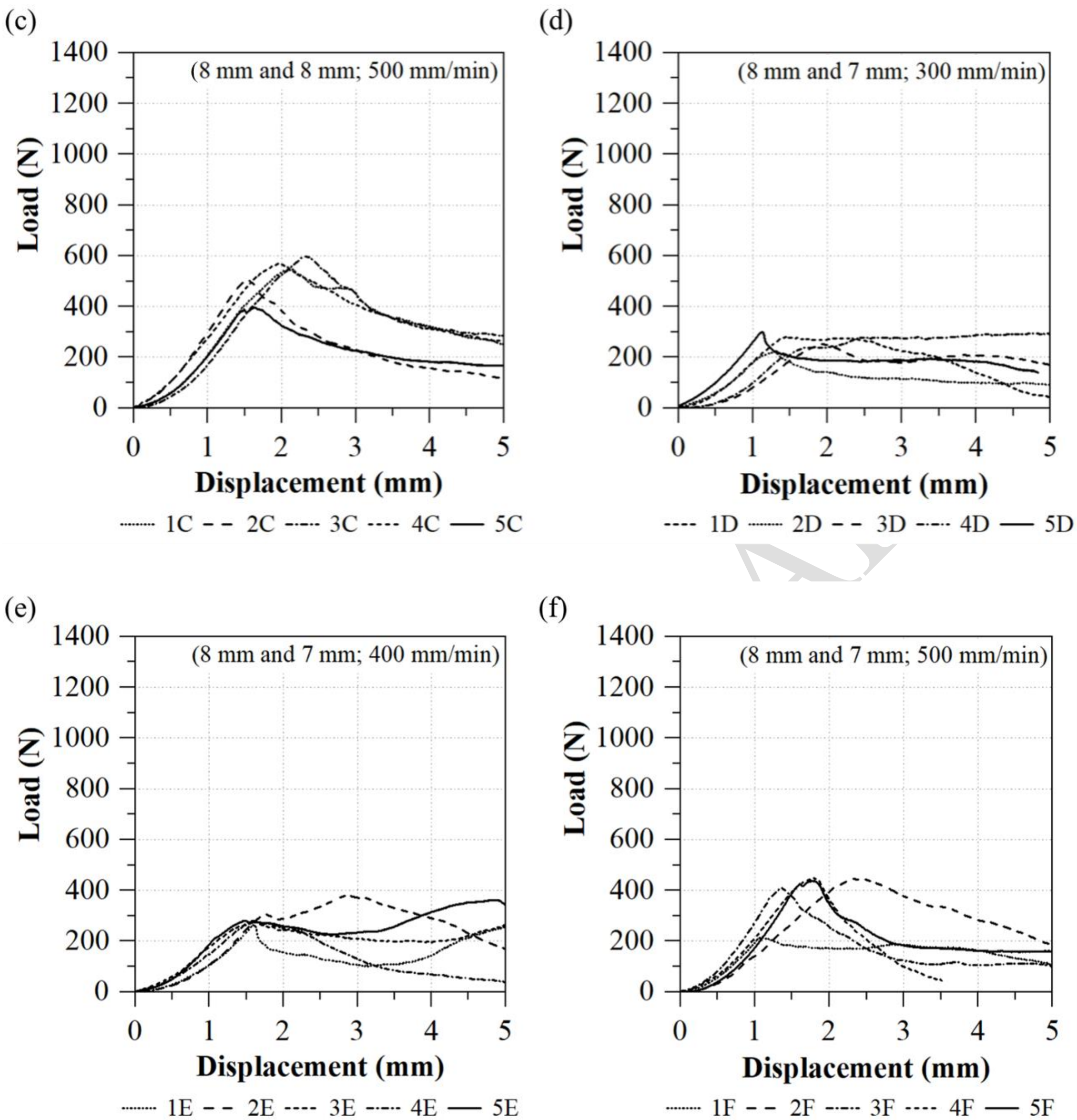


Figure 8: Load × displacement curves.

Shear engaged by the tensile pull-out of the dowels

Figure 9 illustrates the shear engaged by the tensile pull-out of the dowels for 1 and 2-stage pre-drilled holes and 300 mm/min, 400 mm/min and 500 mm/min of feed rate. The non-parametric Conover test indicated that there are statistically significant differences between the means of groups A and C, A and D, A and E, A and F, B and C, B and D, B and E, B and F, C and D, C and E, D and F. This denotes that the welding parameters influence the shear engaged by the tensile pull-out of the dowels.

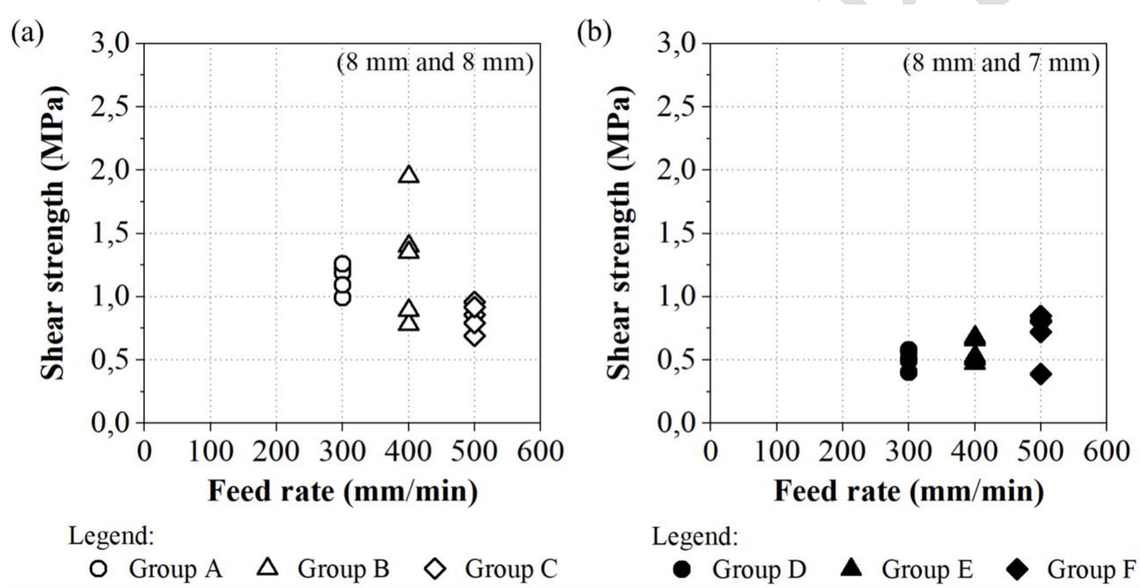


Figure 9: Shear engaged by the tensile pull-out of the dowels × feed rate. (a) 1-stage pre-drilled hole, (b) 2-stage pre-drilled hole.

In Table 4, the average shear engaged by the tensile pull-out of the dowels from groups A to F are presented. The highest average shear strengths were obtained for groups A and B, with 1-stage pre-drilled hole and 300 mm/min or 400 mm/min of feed rate. These results are lower than that obtained by Viana *et al*. (2022) when welding itauba dowels into 1-stage pre-drilled holes machining on loblolly pine (*Pinus taeda* L.) substrates (3,6 MPa), using 1000 rpm of rotation and 500 mm/min of feed rate. This difference must be associated with the greater porosity of pine, which allows the softened intercellular material to impregnate in its pores, contributing to the dowel and substrate join (Viana 2023).

Belleville *et al*. (2016) also reported higher mechanical strength results for larger diameter pre-drilled holes when welding spotted gum (*Corymbia maculata* (Hook.) K.D.Hill & L.A.S.Johnson) (1 MPa) and Blackbutt (*Eucalyptus pilularis* Sm.) (2,7 MPa) hardwood species, with 965 kg/m^3 and 925 kg/m^3, respectively. They adopted 1,11, 1,26 and 1,45 dowel/pre-drilled hole diameter ratio and 1230 rpm of rotation. According to these authors, for high-density woods, larger diameter pre-drilled holes facilitate the insertion of the dowel, avoiding excessive wear.

Further experiments should evaluate other pre-drilled hole stage configurations, from 1 to 4 stages (Župčić *et al.* 2008), and a broader range of feed rate, between 100 mm/min and 1500 mm/min (Auchet *et al.* 2010, Kanazawa *et al.* 2005, Belleville *et al*. 2013). Subsequently, verify whether they can improve the shear engaged by the tensile pull-out of the dowels for itauba-itauba joints.

Table 4: Average shear engaged by the tensile pull-out of the dowels.

Group	Pre-drilled hole stage	Feed rate (mm/min)	Average shear strength (MPa)	Coefficient of variation (%)
A	1 (8 mm and 8 mm)	300	1,15	10
B		400	1,27	37
C		500	0,84	13
D	2 (8 mm and 7 mm)	300	0,51	14
E		400	0,57	17
F		500	0,71	26

The optimal welding parameters

In Table 5, the optimal welding parameters are presented. Considering the pre-drilled hole stage and the feed rate adopted in this research, the best parameter combinations were those from groups A and B. The pre-drilled hole of piece A" with the largest diameter (8 mm), associated with the lower feed rates (300 mm/min and 400 mm/min), contributed to a higher average shear strength, probably due to a better balance between welding time and interface carbonization.

The scope of this research was limited to a feed rate between 300 mm/min to 500 mm/min and 2 pre-drilled hole configurations. Considerably more work will need to be done to evaluate a wider feed range and different pre-drilled hole configurations to determine whether they can improve the shear engaged by the tensile pull-out of the dowels for itauba-itauba joints. Furthermore, the rotation of the dowel, which generally varies between 1000 rpm and 1500 rpm (Xu *et al.* 2022, Belleville *et al.* 2013, Biwôlé *et al.* 2022, Rodriguez *et al.* 2010), must be investigated, since it favors the generation of heat at the welding interface, which causes the fusion of wood polymers in this region and the dowel and substrate join. In addition, optimized welding parameters should be integrated with effective surface preparation techniques to promote deep impregnation of the softened intercellular material.

Table 5: Optimal welding parameters.

Pre-drilled hole stage	Feed rate (mm/min)	Average shear strength (MPa)	Coefficient of variation (%)
1 (8 mm and 8 mm)	300 or 400	1,21	27

Conclusions

This research evaluated the physical characteristics of the welded interface and the influence of pre-drilled hole stage and feed rate on the mechanical performance of itauba-itauba joints to determine optimal welding parameters. The results indicate that:

A one-stage pre-drilled hole with an 8 mm diameter, combined with lower feed rates of 300 mm/min or 400 mm/min, yielded the highest average shear strength of 1.21 MPa. This configuration proved superior to a more constrictive two-stage pre-drilled hole (8 mm and 7 mm diameter), as it mitigated excessive dowel wear. This finding establishes an initial set of optimized welding parameters for itauba-itauba joints.

The inherent properties of itauba wood, specifically its low permeability and high extractive content, lead to a superficial adhesion layer that inhibits the deep interlocking of wood fibers required for a robust bond. This finding advances the understanding of tropical hardwood welding by demonstrating that the natural characteristics of the wood constitute a primary barrier to successful joint formation. Future research should focus on integrating optimized welding parameters with effective surface preparation techniques to promote deep impregnation of the softened intercellular material, a critical step toward achieving industrially viable joints.

Authorship contributions

A. C. C. V.: Conceptualization, methodology, investigation, data curation, formal analysis, writing – original draft, writing – review & editing. R. B. S.: Investigation, writing – review & editing. P. D. M.: Conceptualization, methodology, writing – review & editing, supervision. W. L. W.: Conceptualization, methodology, supervision.

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Conflict of interest

There is no conflict of interest associated with this work.

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