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THE PRODUCTION OF ADHESIVE-FREE CROSS-LAMINATED TIMBER (CLT) PANEL USING PRODUCTS GENERATED BY THE SUSTAINABLE FOREST MANAGEMENT OF THE AMAZONIAN OLD GROWTH FOREST

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ABSTRACT: The dowel cross-lamella timber (DCLT) is a type of adhesive free construction system which uses wooden dowels as connectors between the lamella layers. The use of wood in construction is environmentally friendly because it is the only building material of renewable origin. This is true only if the wood comes from sustainable forest management plans. In this sense, This work aims to study physical and mechanical characteristics of four species in the Amazon Forest of sustained forest management, use these species for the production of dowels and to determine the rigidity of the connection. The species was Pau Rainha (*Brosimum Rubescens*), Matá Matá Amarelo (*Eschweilera Wachenheimi*), Cardeiro (*Scleronema micranthum)* and Breu Vermelho (*Protium altsonii*). Tests of compressive strength, shear, and density were performed according to the Brazilian Standard of Wooden Structures parameters and slip modulus was obtained by a test developed specifically for this purpose. Among the four wood species studied for use as a connecting element (dowel), only the Pau Rainha wood (*B. Rubescens*) and Matá Matá Amarelo (*E. Wachenheimi*) obtained good results. Mata Mata Amarelo did not get the best results, but in the criterion of abundance, that is, number of tree individuals per m² in the rain forest, it has advantages over the Pau Rainha. Thus, it is possible to apply the concept of sustainable forest management and rationally use this tree species.

KEYWORDS: Dowels, DCLT, Amazon Wood, Mass Timber, Hard Wood

1 INTRODUCTION

1.1 DCLT PANEL

Engineered wood market is expected to gain a market value of USD 4,9 million by 2030[1]. CLT panels are engineered timber products that have been standing out in the construction market mainly on the European continent, where they have been developed. However, for its production structural weather-resistant adhesives and a large hydraulic press are required to glue the panel layers together, which entails a high-cost production and makes recycling very difficult. The DCLT, on the other hand, uses dowels as a bonding agent to the lamellas disposed at 90° between themselves (Figure 1) and do not require neither the use of adhesive nor the press, reducing the process' costs and improving the environmental performance of the product [2]. The efficiency of the bonding is ensured by the moisture content variation between the oven dried dowels (48h at 100°C) and the lamellas [3].

In this process, it loses water impregnated in the wood cells, and consequently reduces its volume, facilitating the dowel insertion into the hole. After being placed in the hole, the dowel regains moisture from the environment, making its volume return to its original size, so that the dowel locks within the hole, providing a more efficient connection when compared to a dowel inserted without this drying process.

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Figure 1: *a) Dowels fabrication; b) Panel lay-up; c) Edges compressions; d) Drilling of holes; e) Dowel hammering; f) Final panels.*

Similar panels were developed in United Kingdom using densified wood by a hot-pressing process to give greater densities dowels. The results were promising inclusive with the fabrication and assembly of a prototype of a construction [4].
In Brazil there are hundreds of high-density tree species (> 1000 kg / m³) that can be used to produce dowels without the need for densification process. Many of these have no commercial value and, as a result, are little or no exploited. Thus, selective logging is concentrated on a few specific species [5, 6].
European experience shows that it is possible to manage forest resources (timber) to fabricate structural elements from small to large civil works, without degrading or destroying forests and the environment (sustainably). The implementation of sustainable forest management (SFM) is the best alternative to sustainably assure supply of hardwood in Tropical forests.
Typically, SFM in rainforest, such as the Amazon, is based on selective logging of specific species. Specifically, maintain a sustained income regime, whilst conduction natural regeneration of the forest, over a certain period, without compromising his natural structure and its initial capital [7].

1.2 STIFFNESS OF CONNECTIONS

In the DCLT panel the connection's stiffness is given by the mechanical connection between the dowel and the wood layers.
The deformation between two or more members that are connected results from elastic and non-elastic deformation in the connecting members and the fasteners. To describe this behaviour that Eurocode 5 calls a slip module, which refers to of Slope of the Load-Deformation Curve [8].

2 OBJECTIVE

In this work were studied physical and mechanical characteristics of four Amazonian hard wood tree species to determine its suitability to compose a DCLT panel.

3 MATERIALS AND METHODS

3.1 MATERIALS

Some species of trees with higher incidences in the Amazon Forest per unit area were chosen for the dowel tests.
Pequiarana wood (*Caryocar glabrum)* was chosen as lamellas for all specimens tested, while dowels were made of *Eschweilera wachenheimii* (Matá Matá Amarelo), *Scleronema micranthum* (Cardeiro), *Brosimum rubescens* (Pau-Rainha) and *Protium altsonii* (Breu Vermelho).

In this study no characterization tests of Pequiarana wood (*Caryocar glabrum*) were performed. However, data from the literature present the following physical and mechanical characteristics [9, 10]:

- Density = 690 kg/m³;
- Parallel compression stiffness ($f_{c0,m}$) = 59,8 MPa;
- Shear Stiffness ($f_{v0,m}$) = 14,42 MPa
- Bending stiffness ($f_{b0,m}$) = 103 MPa

The trees were obtained from the Tropical Silviculture Experimental Station (EEST) under the management of the Forest Management Laboratory (LMF) of the National Institute of Amazon Research (INPA) of Manaus, Brazil. Figure 2 presents its location.

Figure 2: *Location map of Experimental Station of Tropical Silviculture (EEST), from INPA .*

3.2 METHODS

Tests to determine compressive strength resistance, shear and density parameters were performed according to the Brazilian Standard of Wooden Structures NBR 7190 part 3 - Test Methods for characterization of defect-free specimens for timber of native forests [11]. The connection slip modulus (Kser) was obtained by the test proposed by Pereira *et.al*. [3] (Fig. 3).

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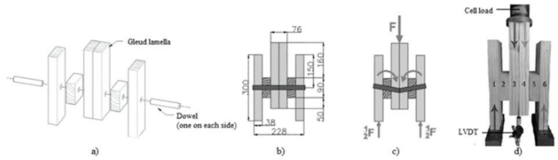

***Figure 3:** a) Assembly scheme; b) Specimen measurements (mm); c) Static layout and d) Real model during the test.*

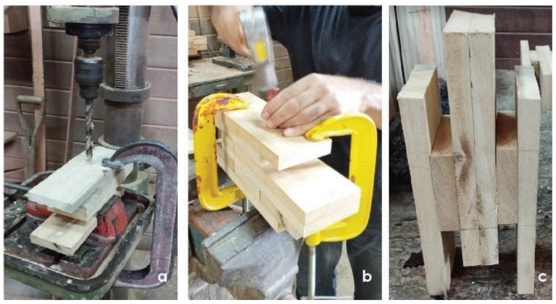

***Figure 4:** a) Positioning of the lamellas and drilling; b) Placement of dowels in the holes; c) Test Specimen*

The slip modulus determination test has been proposed simulating the forces applied to the dowels during the use of the panel in bi-supported bending, as shown in Figure 5. In this purpose, the dowel bonding is submitted to a compressive force parallel to the lamellas and perpendicular to the dowel.

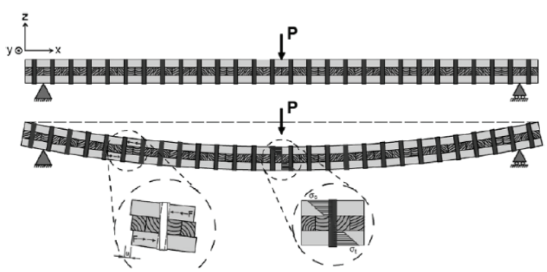

***Figure 5:** Y-axis bending of the 3-layer slab, highlighting of the shear and bending forces in the panel.*

The calculations for obeying the value of the slip module were made using the methods described in the European Norm EN 26891:1991, ISO 10984/2009 and in Brazilian standard ABNT 7190-7/2022. The methodology of ISO and EN are equal. European norms and the Brazilian norm have methodology similar but the calculation method is different, as shown in figure 06 and equations 1 and 2.

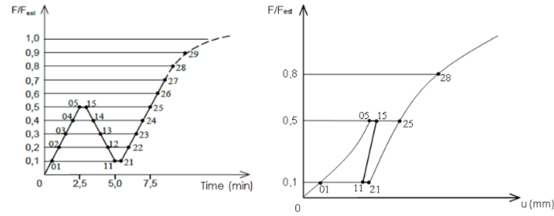

***Figure 6**: Form of loading application during testing (left); Force diagram versus connection slip (right).*

For the Brazilian norm, k_{ser} is calculated for equation 1.

$$K_{ser} = \frac{0{,}5 \cdot F_{est}}{\frac{5}{4}(u_{05} - u_{01})} \quad (1)$$

Where F_{est} is a force estimated for rupture, u_{05} is displacement for 50% of force, and u_{01} is displacement for 10% of force.

For European Norm EN 26891and ISO 10984, k_{ser} is calculated for equation 2.

$$K_{ser} = \frac{F_{04}}{\frac{4}{3}(u_{04} - u_{01})} \quad (2)$$

Where F_{04} is the force of 40% of rupture force, u_{04} is displacement for 40% of force, and u_{01} is displacement for 10% of force.

4 RESULTS

The results obtained for the tests performed are presented in the following items.

4.1 COMPRESSIVE STRENGTH TEST

The results of compressive strength test parallel to the fibres and the Modulus of Elasticity in Compression of the analysed woods are presented in Table 1.

***Table 1:** Compression and MOE in Compression parallel to the fibres*

Popular name	Matá Matá Amarelo	Breu Vermelho	Pau-Rainha	Cardeiro
Scientific Name	*Eschweilera wachenheimii*	*Protium altsonii*	*Brosimum rubescens*	*Scleronema micranthum*
$f_{c0,med}$ *(MPa)*	56.23	51.78	109.65	37.12
$f_{c0,k}$ *(MPa)*	58.95	48.16	120.0	38.76
St. Desv.	2.32	5.38	1.50	0.91
$E_{c0,med}$ *(MPa)*	12661	-	16243.74	6785
$E_{c0,k}$ *(MPa)*	14578	-	16523.44	5729
St. Desv.	1275	-	1653.25	7425

4.2 SHEAR TESTS

The results of shear tests of the analysed woods are presented in Table 2.

Table 2: *Shear stiffness results for the species*

Popular name	Matá Matá Amarelo	Breu Vermelho	Pau-Rainha	Cardeiro
Scientific Name	*Eschweilera wachenheimii*	*Protium altsonii*	*Brosimum rubescens*	*Scleronema micranthum*
$f_{v0,med}$ *(MPa)*	18.81	12.4	27.4	8.97
$f_{v0,k}$ *(MPa)*	14.30	11.3	31.41	7.91
St. Desv.	7.09	3.1	2.29	1.04

4.3 DENSITY TESTS

The results of density tests of the analysed woods are presented in Table 3.

Table 3: *Density results for the species*

Popular name	Matá Matá Amarelo	Breu Vermelho	Pau-Rainha	Cardeiro
Scientific Name	*Eschweilera wachenheimii*	*Protium altsonii*	*Brosimum rubescens*	*Scleronema micranthum*
Density med. (kg/m³)	810	605	910	590
St. Desv.	2.1	2.51	3.12	0.54

4.4 CONNECTION SLIP MODULUS TESTS

Figure 7 illustrates the *Pequiarana* wood specimen connected with *Pau rainha* dowel's during a binding test to determine the slip module. It is possible to observe that the cross layer was breaking by shear. This behaviour is similar to rolling shear in the ordinary CLT.

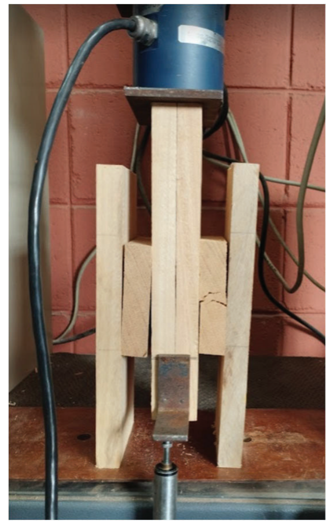

Figure 7: *Cross -sectional layer broke through shear*

Figures 8, 9 and 10 show the results of the connection sliding tests, of which the values used to calculate the K_{SER} were obtained, according to the European Standard and the Brazilian Standard of Wood Structures.

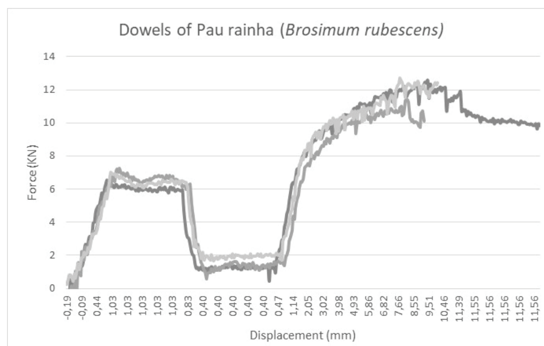

Figure 8: *Chart illustrating the force versus displacement during testing of the specimens using Pau rainha Dowel's.*

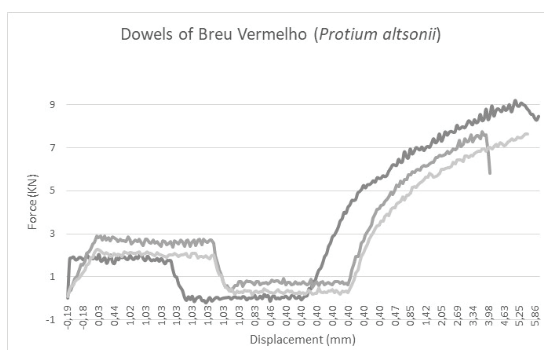

Figure 9: *Chart illustrating the force versus displacement during testing of the specimens using Breu vermelho Dowel's.*

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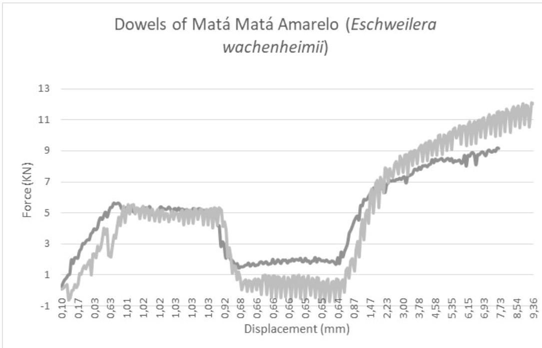

Figure 10: *Chart illustrating the force versus displacement during testing of the specimens using Matá Matá Amarelo Dowel's.*

The table 4 presents the values of the k_{ser} obtained using the calculations described in European and ISO standards and the Brazilian norm, for the tests performed.

Table 4: *Kser values for Brazilian and European Norms*

Wood of dowel (Ø16 mm)		$K_{ser,med}$ [N/mm]	
Popular Name	Scientific name	ABNT 7190-7/2022	ISO 10984 & EN 26891
Pau Rainha	*B. rubescens*	2061	3133
Breu Vermelho	*P. Altsonii*	1607	1216
Matá Matá Amarelo	*E. wachenheimii*	1754	807

The figure 11 presents some dowels after the test to determine the connection slip module.

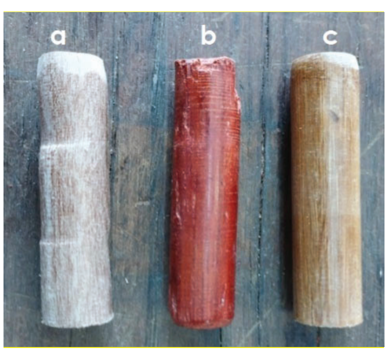

Figure 11: *Some dowels after slip test. a) Breu Vermelho; b) Pau rainha; c) Matá Matá Amarelo*

4.5 ANALYTIC CALCULUS

The analytical calculation of Slip Modulus was performed in accordance with the method described in the European Standard of wood structures - Eurocode 5, and in the current version of the Brazilian Standard of wood structures (NBR 7190/2022), which are equivalent [12, 13].

Equation 3 presents the analytical calculation to estimate the connection slip modulus. According to the standards, if the characteristic density of the joint members is different ($\rho_{k,1}$ and $\rho_{k,2}$), then calculating the stiffness may be taken as presented in equation 4.

$$K_{ser} = \rho_{med}{}^{1,5} \cdot \frac{d}{23} \quad (3)$$

Where ρ_{med} is the average specific density in kg/m³, given by multiplication of the apparent density characteristic by the value 1.20; *d* is the effective diameter of the dowel, expressed in millimetres (mm).

$$\rho_{med} = \sqrt{\rho_{k1} \cdot \rho_{k2}} \quad (4)$$

Where ρ_{k1} and ρ_{k2} are the density values of woods 1 e 2.

The Table 4 presented results for analytical values for the species studied.

Wood	Density ρ_k (Kg/m³)	Density ρ_{med} (Kg/m³)	Kser (N/mm)
Pequiarana	*690*	-	-
Breu vermelho	605	646	11425
Pau rainha	910	792	15517
Mata Mata Amarelo	810	748	14220
Cardeiro	590	638	11212

5 DISCUSSION

5.1 PHYSICAL AND MECHANICAL PROPERTIES OF WOOD

Through the characterization tests it was possible to conclude that the Pau Rainha (*B. rubescens)* obtained the highest values of the physical and mechanical properties, reaching a 120 MPa in parallel compression ($f_{c0,k}$). The Matá Matá Amarelo (*E. wachenheimii*) species also obtained good values for use in dowels, because the Brazilian standard recommends use of wood from class D60 for dowels. The value obtained for parallel compression ($f_{c0,k}$) by Matá Matá Amarelo did not exceed 60 MPa but was very close. The other two species, Breu Vermelho (*P. Altsonii*) and Cardeiro (*Scleronema micranthum*) obtained the lowest values, with parallel compression ($f_{c0,k}$) 48 and 38 MPa, responsively.

The Cardeiro species was excluded from the tests as a connection element because besides low mechanical resistance, it has traumatic channels, an anatomical feature that increases wood fending during machining.

Differences in perpendicular and parallel resistances the fibres of the three species studied can be seen in the image of the dowels after the test to determine the slip module, (Figure 11). It is clear that the Breu Vermelho scare has been compressed perpendicular to fibres while those of

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Matá Matá Amarelo and Pau Rainha this compression was not evident.

5.2 SLIP MODULE TEST

The results of the rigidity tests of the connection according to the parameters of the Brazilian standard showed that Pau Rainha (*B. Rubescens*) obtained the highest value of k_{ser}, followed by Matá Matá Amarelo (*E. Wachenheimi*) and finally the Breu Vermelho wood (*P. Altsonii*). These results are aligned with the values of the physical and mechanical properties presented in tables 1, 2 and 3, where the Pau Rainha (*B. Rubescens*) presents the highest values of resistance and rigidity to compression parallel to fibres, resistance to shear and density, followed by Matá Matá Amarelo (*E. Wachenheimi*) and finally the Breu Vermelho wood (*P. Altsonii*).

The results of binding rigidity tests according to the parameters of EN26891 and ISO 10984 did not show the same behaviour. In the comparison between the values obtained by the method of calculating the Brazilian standard and the EN26891 and ISO 10984, the values range from 30 to 200%.

5.3 ANALYTIC CALCULUS RESULTS

The results of the analytical calculation indicated in Eurocode 5 and the Brazilian Standard of Wood Structures did not converge for the values obtained for the connection slip test. Other authors estimate k_{ser} using other relationships that also take into account the density of the wood and the dowel diameter, but with different equation [2]. New calculations using these other equations will be performed to obtain an analytical equation more consistent with the use of the dowelled connection in cross -lamella panels.

6 CONCLUSION

Among the four wood species studied for use as a connecting element (dowel), only the Pau Rainha wood (*B. Rubescens*) and Matá Matá Amarelo (*E. Wachenheimi*) obtained good results. Mata Mata Amarelo did not get the best results, but in the criterion of abundance, that is, number of tree individuals per m² in the rain forest, it has advantages over the Pau Rainha. Thus, it is possible to apply the concept of sustainable forest management and rationally use this tree species.

The preparation of cross-lamelas wood panels using high density wood caves from the Amazon rainforest presents itself as an alternative for the use of little-known species and great abundance in the forest. New studies are being conducted to validate these results, varying the diameter of the dowels and the lamellas woods.

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