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Laminated Solid Timber Slab with Transverse Prestressing Using the Strategy of Interleaved Vertical Displacement of Lamellae

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Abstract: This article presents a study on the structural behavior of transversely prestressed laminated timber slabs, focusing on an innovative approach: vertically misaligned lamellae. This misalignment, achieved by sliding vertically the wooden lamellae rather than aligning them, enhances the slab's cross-section moment of inertia, thereby improving load-bearing capacity and stiffness. Testing involved two groups of structural size specimens: one with vertically aligned lamellae (control group) and the other with misaligned lamellae (study group). Results showed the study group exhibited 42% superior stiffness and 10% less load capacity compared to the control. Failures typically occurred individually in the lamellae, particularly in those with defects or lower modulus of elasticity, concentrated in the middle third of the slabs' free span where tensile stresses peak. Despite a higher number of failed lamellae, the study group demonstrated promising performance. Analysis of prestressing bar indicated no damage at all in the thread, suggesting potential for reducing bar diameter. These findings offer crucial insights into applying these slabs in timber construction as well as to any kind of construction.

Key words: Transversal prestressed slabs, wooden construction, plantation wood, flexural testing, design methodology.

1. Introduction

Growing concern about environmental impacts and the search for sustainable solutions have driven innovations in the construction industry [1]. In this scenario, eco-efficient construction materials and techniques that reduce the consumption of natural resources are increasingly necessary.

According to the *Global Status Report for Buildings and Construction*, this economy sector was responsible for 38% of all CO_2 emissions into the atmosphere and establishes that governments must prioritize low-carbon buildings in addition to updating their climate commitments to the planet [2].

According to Wang, Toppinen and Juslin [3], promoting the use of wood in civil construction can significantly contribute to achieving sustainable development objectives globally. In addition to having low energy consumption in its production, and flexibility in manufacture and assembly process, there is, nowadays, great availability of planted wood in Brazil.

Furthermore, it is a material that has a high strength/weight ratio being an excellent acoustic and thermal insulator, properties that make it a suitable construction material for countless applications, especially in the composition of structural elements, such as beams, columns, and floor systems [1]. However, the structural effectiveness of wood in civil construction applications requires innovative approaches to maximize performance.

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Traditionally, floors are composed of studs arranged orthogonally and fixed through metal connections (nails or screws) to a main structure. Despite being a lightweight, easy-to-construct and low-cost system, the way the elements are arranged does not guarantee uniform load distribution across the structure, behaving practically like a set of independent beams. Contrary to what happens in a structural plate, where the efforts are distributed in two directions, when a vertical load is applied to the floor, there is no association of the structure as a whole, and the transmission of efforts, in a greater proportion, occurs to the nearest beams [4].

Furthermore, the insulating layer from one floor to the room immediately below becomes a 20 mm layer corresponding to the thickness of the conventional solid wood board floor.

As a consequence, this deficiency in the floor's performance can cause damage to the most stressed areas of the structure and acoustic discomfort for residents. Movements of people such as walking, running or jumping, and object's falling off, can create structural vibrations, negatively affecting the efficiency of the system and consequently, the user's quality of life [5].

On the other hand, engineered wood products, such as CLT (cross laminated timber) or Glulam (glued laminated timber), which have more homogeneous mechanical properties, provide greater stability, the formation of larger and more complex structural sections and the reduction of defects, such as knots [6-8].

However, recent studies reveal a worrying reality: a substantial portion, reaching up to 47%, of wood is wasted during the visual grading stage in the manufacture of engineered products, such as CLT. Wood of smaller diameter and low quality often exhibits substantial defects, with twisting of pieces being one of the main reasons for rejection [9-11]. This alarming rate of wood disposal in the visual grading process not only implies an ineffective use of natural resources, but also generates a considerable increase in production costs [11].

Furthermore, the use of petroleum-based adhesives contributes to the emission of toxic gases, such as VOCs (volatile organic compounds) and formaldehyde, impairing the life cycle of CLT. The emission of atmospheric pollutants not only brings implications for air quality and human health, but also aggravates the challenges associated with the responsible disposal of the product, making its reuse and recyclability difficult, as highlighted by Sotayo et al. [8]. According to the authors, these adhesives make the wood separation and recovery process during disposal considerably more complex and costly. This complexity limits the ability to recycle and reuse the material efficiently.

Therefore, it is extremely important to search for new sustainable technologies in civil construction, mainly for the development of a massive structural element for slabs, showing high resistance, and minimize the transmission of vibrations and noise, being at once, sustainable and easy to execute.

In this context, transversely prestressed laminated wood slabs have been used mostly in the construction of bridges and walkways, representing a reliable and durable solution, however, the system still remains underused. This gap in the adoption of these slabs in new architectural contexts highlights the need for innovation and adaptation to expand their applicability.

Consisting of solid wood boards, arranged in parallel and compressed transversely through prestressed steel bars (Fig. 1), this technology avoids gaps between the lamellae, as well as vertical slippage between two lamellae, due to the friction force generated by the pretension [12].

It is a relatively simple and effective technique for laminating wood and offers several advantages: it does not require sophisticated tools, parts or specialized labor, and can even be carried out on the construction site. This avoids expenses associated with large-scale presses, accessories and other complex industrial devices [13, 14] as shown in Fig. 1.

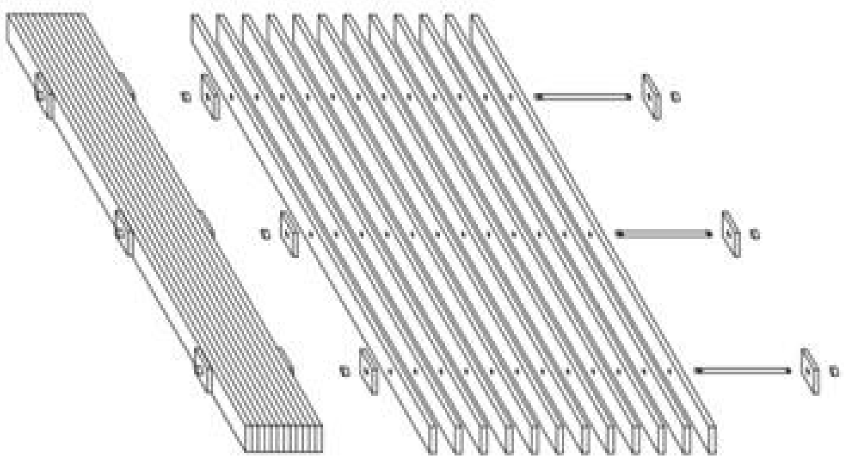

Fig. 1 Transversely prestressed wood lamellae [13].

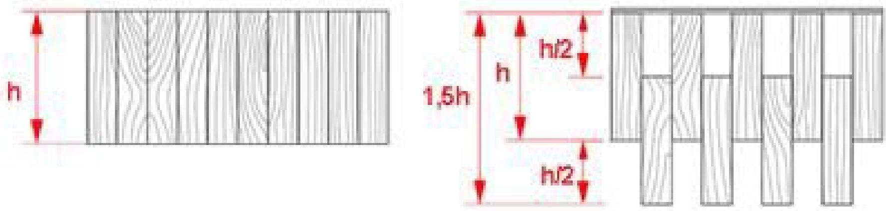

Fig. 2 Proposed displacement for the slab component.

In this way, this article presents research that seeks to revolutionize the use of transversely prestressed laminated wood slabs, traditionally restricted to bridge decks and walkways. The innovation study in this study focuses on the vertical misalignment of the lamellae (Fig. 2), a strategy that aims to optimize the performance of these structural elements, while reducing the volume of wood.

The study of vertical displacement of the lamellae represents a significant advance towards sustainability in construction. Reducing wood consumption, without compromising load capacity and rigidity (increasing both, actually), is a crucial contribution to mitigating the environmental impacts of the civil construction industry. Furthermore, this approach has the potential to optimize the use of natural resources, aligning to the principles of cleaner and more eco-efficient construction.

Therefore, the present study focuses on an innovative approach to improve the performance of prestressed laminated timber slabs. The approach of vertical misalignment of the lamellae as a strategy to increase the stiffness and load capacity of these structural elements is adopted.

The underlying hypothesis is that the misalignment can redistribute stresses and improve structural behavior under bending loads. To investigate this hypothesis, four-point bending tests were conducted on 6 full-scale structural size specimens of prestressed laminated timber slabs. From this total, 4 specimens had misaligned lamellae (study group) and 2 specimens, for comparison parameters, were built with aligned lamellae (control group), as their structural behavior can be found in several other studies in the literature. Furthermore, threaded bars were used as prestressing elements, which are easy to obtain on the market being low in cost, providing greater viability for the structural element.

The tests were carried out in accordance with current technical standards and included statistical analyses to evaluate the homogeneity of the groups as well as stiffness and strength gains. The results of this study will not only contribute to scientific knowledge about the structural performance of prestressed laminated timber slabs, but will also provide valuable information to construction professionals and contractors who seek more sustainable alternatives in their practices.

2. Materials and Methods

In this study, 120 boards of southern pine (*Pinus* spp.) were purchased from local suppliers in Londrina city, southern Brazil. In general terms, these boards averaged 3 m long, with a nominal cross-section of 20 mm × 25 mm and have not been subjected to any type of processing or machining procedure. They were stored in the laboratory for a long period of time, during which they were dried in open air. For the prestressing system, threaded bars with a nominal diameter of 5/8″, hexagonal nuts for applying the prestressing and flat washers with a diameter of 5/8″ were used.

In the context of experimental research, the process was conducted in three distinct phases: Firstly, due to the high occurrence of defects in the lamellae, a visual and mechanical grading was carried out, in which parts with serious defects, such as cracks, presence of big knots, were discarded and then the parts were mechanical graded following the recommendations of NBR 7190 [15]. In the second stage, the specimens were built, which involved the process of drilling the boards, assembly and, at the end, the application of prestressing. Finally, in the third phase, the specimens were subjected to mechanical bending tests.

2.1 Assembly of Tests

To make better use of the boards, doubling the number of test specimens, it was decided to saw the boards in half. Therefore, the pieces that were originally 25 cm wide ended up being, on average, 12 cm. In this way, 6 full-scale specimens were built. From this total, four were configured with alternately displaced lamellae (study group: CP 1, 2, 3 and 5), which constitute the central focus of this research. Each specimen in the study group measured 180 mm × 800 mm × 3,000 mm, with a displacement of 60 mm, as shown in Fig. 3.

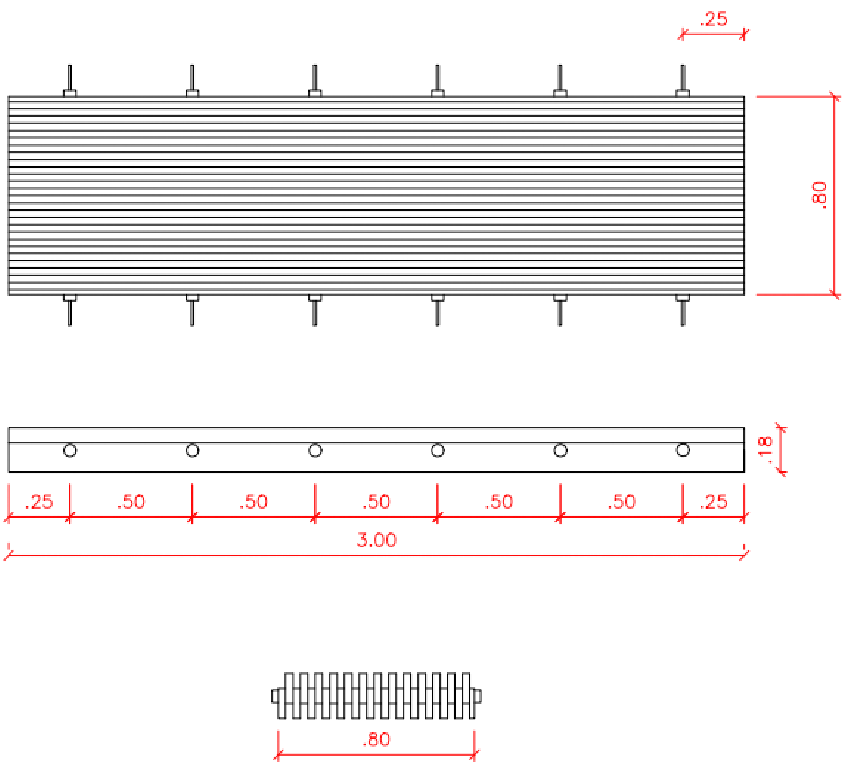

Fig. 3 Proposed test specimen.

Fig. 4 Drilling template.

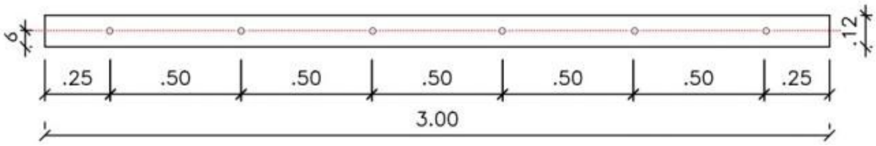

Fig. 5 Template A (dimensions in m).

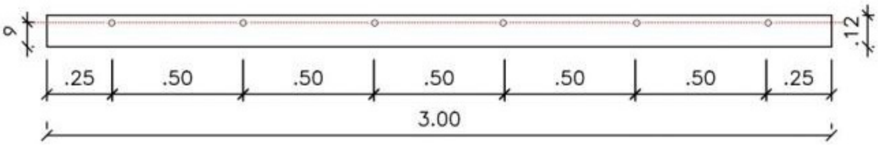

Fig. 6 Template B (dimensions in m).

After separating the lamellae into 6 groups, holes were drilled to pass the threaded bars to proceed the prestressing. To carry out the process of drilling the lamellae, drills with a diameter of 5/8″ and two lumber pieces were also used as a template (Fig. 4).

As can be seen, letter "A" (Fig.5) represents the template for the lamellas referring to CP4 and 6 (control group), that is, with centralized drilling. Letter "B" (Fig. 6) refers to the template that was used for specimens CP1, 2, 3 and 5 (study group). The following images illustrate the features of the templates.

After the process of drilling the boards, the assembly of the test specimens began. Special care was taken to ensure that the pieces on the edges had the highest modulus of elasticity in the whole set to avoid crushing resulting from prestressing. The internal positioning of the lamellae was randomly distributed. To facilitate the fitting of the lamellae, the specimens were vertically assembled (Fig. 7). Initially, all 6 threaded bars were placed in an edge lamella, to facilitate the guidance of the following ones. In this process, it was necessary to apply paraffin to the threaded bars to facilitate their passage into the holes. No care was taken regarding the positioning of knots and other defects on the lamellae. With this respect, the specimens were randomly assembled.

The specimens had their mass measured and, according to the initial estimate, they weighed 130 kg on average. Once the assembly of the 6 specimens was completed (Fig. 8), the application of prestressing began. Hexagonal nuts with 5/8″ flat wide-flap washers to improve the stress distribution were used for the prestressing application. This choice, proved to be economically advantageous.

Fig. 7 Lay up of the pieces.

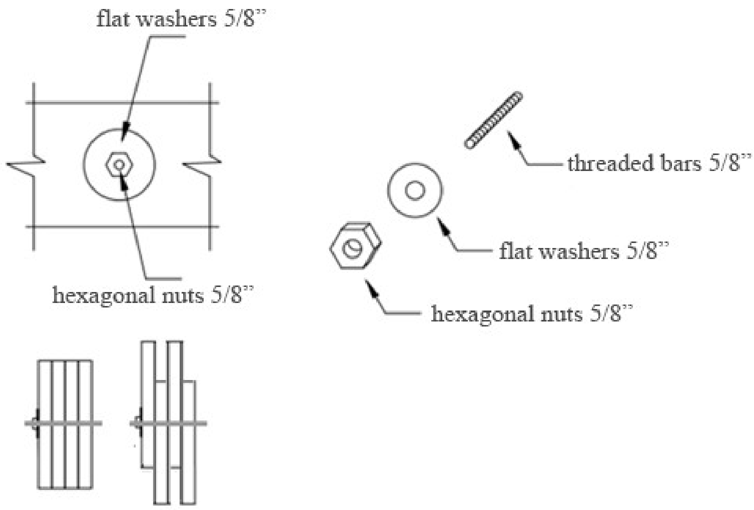

Fig. 8 Illustrative scheme of the prestressing system.

Fig. 9 Application of prestressing.

The prestressing was carried out manually, with the aid of a torque wrench (Fig. 9), and carried out in three stages following the method by Taylor and Csagoly [16] and Ritter [17] who suggest how to prestress: The initial value is 2.5 times the design value, and at least 2 more re-stressing applications to the initial design value level.

In this way, the first prestress occurred immediately after the test specimen was constructed with an applied torque of 2.5 × design value, that is, 62,181 N·mm. The prestressing sequence was carried out from the center of the component length towards the ends, following the standard recommendations for prestressing in concrete structures (Fig. 10). This approach helps to minimize the influence on loads distribution among the bars during the prestressing process.

After two days, the first re-stressing was carried out on the specimens. The calculation torque corresponds to 24,872 N·mm on each bar in the set of test pieces. In this first application of pre-stressing, there was no need to adjust the initial level applied immediately after assembly.

Later on, in the 8th week after assembling, the calculation torque was reapplied (24,872 N·mm). It is worth noting that the focus of this study is not the analysis of loss of prestressing. However, during the last re-stressing, the specimens had lost a significant part of the initial prestressing, which was 2.5 times the calculation torque. Consequently, it became necessary

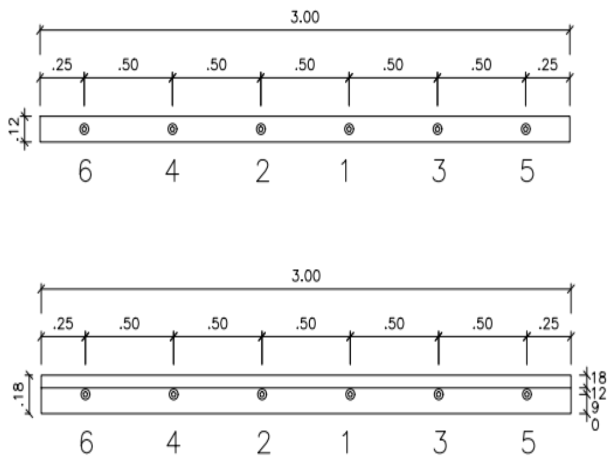

Fig. 10 Sequence of prestressing application.

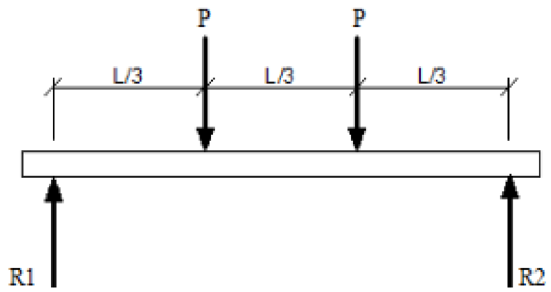

Fig. 11 Four-point bending test [18].

Fig. 12 Positioning.

to reapply 5% of the initial prestressing (approximately ¼ turn on the torque wrench) to adjust the tension of the bar to the calculated torque.

2.1.1 Four-Point Bending Test

A four-point bending test consists of 2 support points, and 2 internal points (at the thirds of the length) to the load application (Fig. 11).

Loading carried out in this way results in a constant bending moment along the central third of the beam, providing a uniform state of stress in this region, avoiding shear stresses, which results in pure bending. This system allows displacements in the center of the beam not to be affected by stress concentration points, since the loads are concentrated in the middle thirds. In summary, this four-point loading experimental arrangement minimizes uncertainties, propagated errors and the dispersion of results [19]. The bending tests were carried out in the State University of Londrina structures laboratory with the help of a steel compression frame. Among the equipment used, there is a hydraulic actuator with a capacity of 500 kN, load cells of 2, 10 and 30 tons, and a LVDT (linear variable differential tranducer) of 50 mm, to measure vertical displacements. The loads were applied from top to bottom through the hydraulic actuator, on a metal I bar that transferred the load to two beams placed on the thirds of the theoretical span (Fig. 12). The positioning of the elements is detailed below.

All specimens were covered by boards transverse to the length of the component. This decision aims to add a floor regularization element (in a real situation), which could be carried out using a plywood sheet nailed onto the compressed fiber of the slab component. Solid boards were used for cost reasons. The bending test occurred in two phases. It began with the application of three load cycles of 8 kN with the aim of accommodating the lamellae and then verifying the necessary load for the test specimens to reach the maximum displacement (1) established by the ABNT NBR Standard 8800 [20].

where:

$$L/350 \tag{1}$$

L = theoretical span (mm)

In this way, L = 290 cm was considered to be the theoretical span, being a value for the displacement equal to 1.16 cm. In the second phase, the maximum load to cause the specimen to fail was verified, as well as its displacement at that moment.

Initially, a theoretical span of 2,900 mm and a 10-ton load cell were established for the tests. However, after the first test (CP6), a resistance greater than that predicted for the specimen was recorded (discussed in more detail in the results session). For safety, the first load cell was replaced by another one with the capacity of 30 tons.

With all the needed adjustments, the theoretical span was reduced from 2,900 mm to 2,800 mm determining a maximum standard displacement of 8 mm.

3. Results and Discussion

In Table 1, the values of the loads obtained at the standard maximum vertical displacement (L/350 for floor beam), according to annex C of NBR 8800 [20] and at the failure of the specimens are presented.

Table 1 Loads.

	$L/350$ = 8 mm	Fracture
	Load (kN)	Load (kN)
CP6 Control	19,127	91,072
CP4 Control	19,207	74,593
Average control	19,167	83,283
Standard deviation (STD)	58	11,233
COV% (coefficients of variation)	0.3	13.2
CP1	22,262	83,522
CP2	23,408	64,247
CP3	29,928	75,178
CP5	32,687	79,76
Average study	27,071	75,677
Standard deviation (STD)	2,863	2,564
COV%	10.4	3.3

Regarding the ultimate load, the specimens in the control group (CP4 and CP6) supported, on average, a load approximately 10% greater than the other CPs (CP1, CP2, CP3 and CP5). However, the analysis of the COV% (coefficients of variation) of the two groups of PCs (control and study) shows that the specimens of the study group reached a higher level of homogeneity.

Regarding the loading relative to the standard maximum displacement $L/350$, despite the COV% being higher in the study group, a relatively low value is still observed, varying only 10.4%, which points out to the reliability of the system. Furthermore, a stiffness gain of 41.2% was observed in relation to the control group. Figs. 13 and 14 illustrate the loads at failure and $L/350$, respectively.

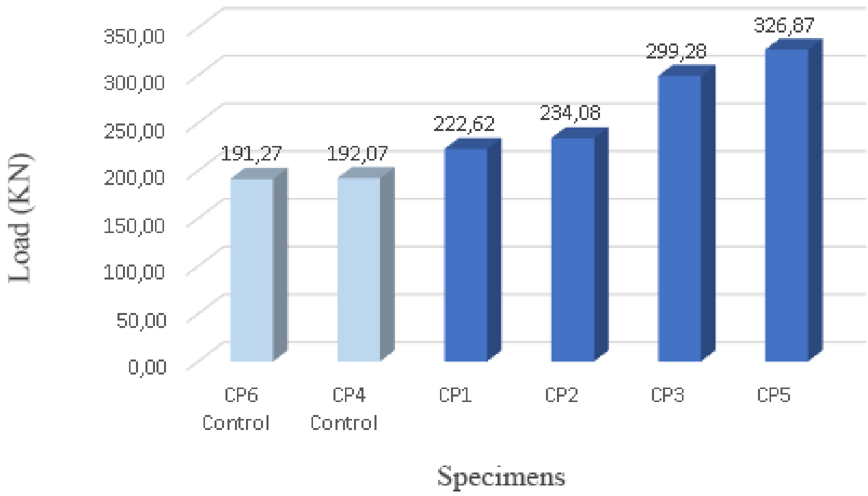

Fig. 13 Load at $L/350$.

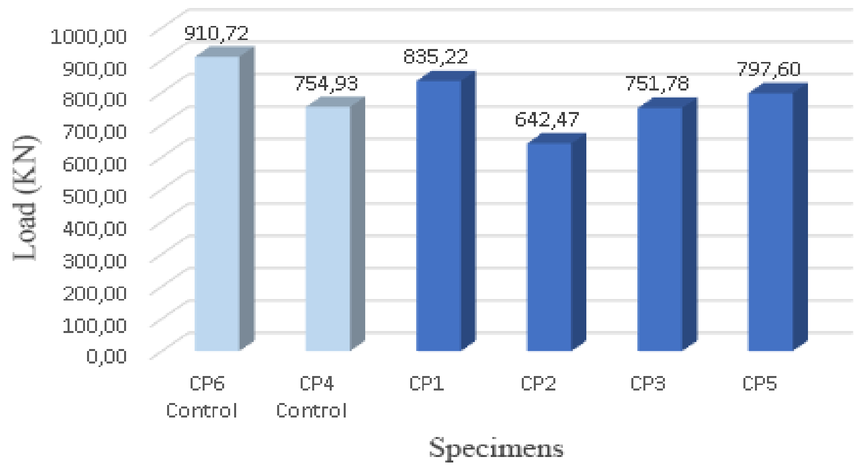

Fig. 14 Ultimate load.

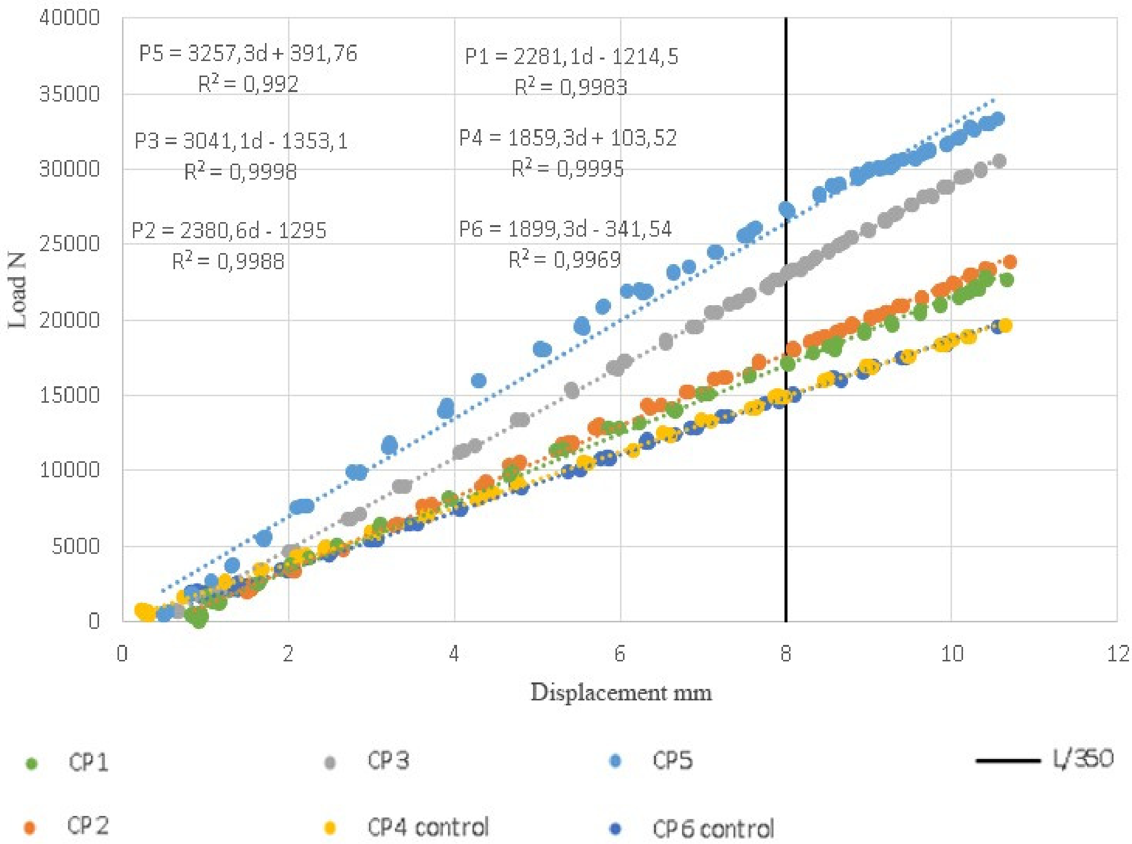

Fig. 15 Comparative stiffness.

To better visualize the results, Fig. 15 shows the behavior of all specimens with the respective regression lines, in the loading section up to the maximum standard displacement (8 mm), as well as the respective equations and determination coefficients R^2.

The graph shows that the behavior of all specimens is practically linear, which can be seen by the R^2 values of the adjustment regression lines close to 1, indicating excellent correlation between the theoretical line and the experimental points.

It is also clear that the control specimens (CP4 and CP6) exhibited very similar behavior with overlapping points, indicating that, in this section, the specimens' responses are very homogeneous. Despite this, a lower load capacity is observed being the least rigid in the study, with an average load of 19,545N to reach the standard limit deflection.

The specimens of the study group (CP1, CP2, CP3 and CP5) presented more dispersed results than those of the control group (CP4 and CP6), however, they all showed superior stiffness under an average applied load of 27,606 N at the limit deflection.

In this way, an increase, on average, of 41.2% in the stiffness is observed through the strategy of interspersed vertical displacement of the lamellae of the cross-section, compared to the geometric arrangement with aligned lamellae.

Fig. 16 shows the behavior of displacements in each test of the specimens from the control group (CP6) maintained a constant linear displacement of up to 40 mm and then gradually began the failure process until collapse. CP4 (control) presents a drop in stiffness of approximately 18 mm and then follows the same trend as its CP6 pair. On the other hand, to the other specimens, displacement variations from 18 mm are observed. From the beginning, small non-linear breaks can be observed on the graph, which intensify as the final break approaches.

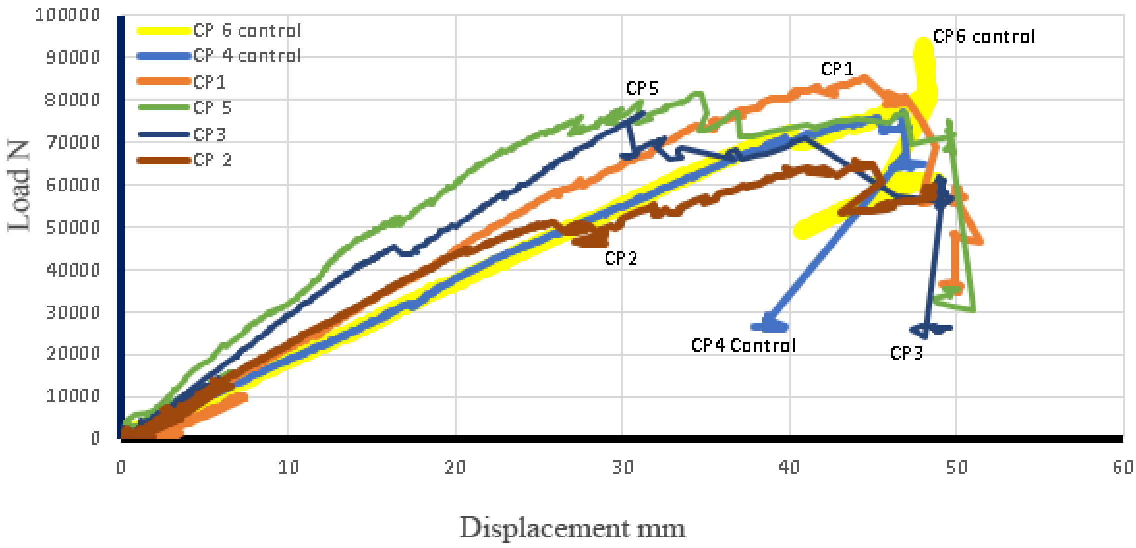

Fig. 16 Load x displacement diagram.

3.1 Rupture Mode

In general, what is observed in rupture is the failure of individual lamellae, starting with those that have some defect or with lower modulus of elasticity.

In Figs. 17 and 18, the side faces of the specimens at the moment of rupture, as well as an analysis of the pattern of board ruptures can be observed.

As expected, the failure occurred at the middle third of the component length, where the bending moment is maximum, concentrating the tensile stresses, diagonally with respect to the central axis of the component. Furthermore, in few cases the lamellae broke into more than two parts, and in most cases, only cracks were observed. Furthermore, most ruptures occurred where defects already existed in the lamellae, such as knots (Fig. 19).

It was also found that, in the control group, the number of broken lamellae was lower. Table 2 shows that the greater contact between the lamellae, in a way, stiffens the assembly and, at failure, the more resistant lamellae support the less resistant ones.

In the most severe loading regime, the individual weaknesses of the lamellae become less important as the contact area of the interface increases. In other words, there is a "pulverization" of the importance of defects in the slab component as a whole, as described by Fleming and Ramage [13].

Fig. 17 Prototype 3.

Fig 18 Specimen 4.

Fig. 19 Knot failures.

Table 2 Number of broken lamellae.

	Number of lamellae	
	Broken	Not broken
CP1	27	13
CP2	21	19
CP3	31	9
CP4	38	2
CP5	24	16
CP6	19	21

On the contrary, at the same load level, in the element with misaligned lamellae (study group), individual defects on the tensioned edge, above all, assume a more critical role, especially at rupture, leaving this area of the lamellae without lateral support, exposing the defect to tensile stresses originated from loading.

In none of the cases the prestressing bars failed, nor was the thread damaged, showing the possibility of reducing the diameter of the bars.

In none of the cases, a fragile, instantaneous rupture was observed. The failure always occurred gradually as the lamellae failed individually, demonstrating the great advantage of the system's redundancy.

4. Conclusions

The results show different behavior between the specimens of the control group and the study one when subjected to flexural loads. It was observed that the control group at rupture supported, on average, a load approximately 10% greater than the others. Furthermore, the two specimens in the group showed very similar behavior, maintaining a constant linear displacement of up to 40 mm and then gradually starting the rupture process until collapse. On the other hand, they showed significantly lower load capacity relative to the level of displacement of the standard limit deflection, being the less rigid specimens.

The studied specimens presented excellent results. In relation to the load at failure, a variation of only 3.3% was observed, compared to 13.2% in the control group. In this way, it can be stated that the specimens have a very acceptable level of reliability, presenting itself as the most homogeneous group. Regarding the load relative to the standard deflection $L/350$, when compared to the control group, a significant increase in stiffness, on average, of 41.2% was observed. Assuming that every structure in service must comply with the Service Limit State, translated by the value of the elastic deflection, this arrangement presents a clear advantage in relation to the control group. Therefore, the strategy followed in this research to carry out vertical displacements interspersed in the cross-sectional lamellae of transversely prestressed laminated wood slab, proves to be highly effective, presenting a significant increase in their stiffness.

In the study group, those individual defects in the lamellae located in the tension fiber, present in the center of the span, where the tensions are higher and which are uncovered without lateral bracing, play a preponderant role in the failure of the component. This effect is smaller in the control group in which each lamellae is fully compressed across the entire width of its cross-section.

One way to reduce this effect would be to carry out judicious prior lay-up, positioning the defects, knots and inclined fibers, in the upper compressed fiber of the slab, a condition in which the defects have less influence on failure.

Another possibility is to add a continuous nailed rigid plane (plywood sheet, for example) connecting all the protruding sections of the lamellae, bracing them all and making them work together.

A study to be undertaken is the influence of the variation in vertical displacement between sheets on the behavior of the component, as well as the spacing of prestressing steel threaded bars along the length of the slab. The study component, in this aspect, is disadvantageous, as the hole in the bar happens very close to the edges and, in the case of proximity to the tensioned edge. Since the failure is enhanced by the presence of the steel bar hole, the increase in the area of distribution of the traction force caused by the prestressing of the bar would be desirable and easily achievable by increasing the contact washer area between the wood and the nut or then, replacement with a metal flange with larger area than the washers.

It was observed that in the first prestressing procedure, which applied a pressure 2.5× higher than the calculation torque, there was crushing of the wood around the hole. A very simple solution would be to introduce two lamellae of high-quality wood with high resistance to normal compression at the lateral edges of the slab.

It was also concluded that the prestressing bar was oversized and did not suffer damage in any of the experiments. Despite the calculation indicating a smaller diameter bar, a 5/8″ bar due to its availability in the laboratory was adopted. A thinner bar would at the same time be more economical and mitigate the effect of the hole diameter on the failure behavior of the slab component. Furthermore, these bars come in commercial lengths of up to 3 m, increasing the possibility of widths for the slab component, which in most buildings is usually the width of a room in most houses in Brazil. It would also be possible to position several slabs adjacently to cover a free span greater than 3 m, juxtaposing several components side by side, a very interesting solution for small and medium buildings.

The component thus designed becomes a massive element compared to solid concrete slabs, a great benefit for wooden construction.

In bending, wooden elements present an elastic-fragile behavior, very dependent on individual defects of the piece. This system turns the behavior into an elastic-plastic one. In both groups, a gradual rupture was observed, with "warnings" for each failed lamellae, which in terms of structural safety, is largely positive.

The conclusions presented here represent a promising start for new research to be carried out following the adaptation study in this research, in the transversely prestressed wooden slabs mostly used in the bridge construction.

In this way, using this technology as a structural element of solid slabs in residences, could contribute to solving acoustic problems, as well as the mechanical deformations observed in wooden flooring systems.

Acknowledgments

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