Structural Bamboo Tensile Connection with the Concept of Friction Using a Wooden Expander

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Bamboo has gained increasing recognition as a sustainable structural material; however, the development of reliable connection systems remains a critical challenge for its broader application in construction. This study investigated a tensile connection for bamboo culms based on the principles of internal expansion and lateral friction while addressing the material's inherent dimensional heterogeneity. The system was designed to facilitate installation, reduce costs, and require only minimal skilled labor, thereby improving the technical and practical feasibility of bamboo construction. An experimental program was conducted to evaluate the structural performance of the connection under tensile loading. The results demonstrated consistent mechanical behavior and significant load-bearing capacity, confirming the effectiveness of the internal expansion mechanism in accommodating geometric variability along the culm. Three main groups were tested, differing in the additives incorporated into the wood expander: sandpaper and polyurethane resin. The configuration incorporating polyurethane resin achieved the highest average ultimate tensile load (4.47 kN). The findings indicate that the proposed connection has strong structural potential and may contribute to the development of more reliable, scalable, and sustainable bamboo construction systems.

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INTRODUCTION

Bamboo has traditionally been used in many cultures as a craft-based material, primarily associated with the work of skilled artisans and the production of artistic or decorative objects. However, in some countries, bamboo has gained widespread recognition as a structural construction material. Colombia, for example, has become a leading reference in the use of bamboo culms for structural applications through the work of renowned architects such as Simón Vélez (Widyowijatnoko and Harries 2020).

It is also a material with low specific weight and requires low energy consumption in terms of transportation and handling, resulting in reduced construction costs (Pinto 2019). Other authors state that, depending on the related context and the species studied, high structural strength performance can be achieved (Carbonari *et al.* 2017).

A systematic bibliometric review published in 2023 (Gaffuri *et al*. 2023) showed that a significant increase in publications on bamboo applications across various fields has occurred only since 2010. Within the construction sector, most studies have focused on connections between bamboo elements. From the perspective of research and technological development, this relatively short period has not yet been sufficient to establish the structural reliability of bamboo connection systems conclusively. Relevant research proposals on bamboo connections have been documented since 1993, demonstrating that it has been a topic of interest to researchers for a long time and its main question remains an open challenge.

Thus, the major challenge lies in reconciling the natural variations in culm diameter, geometry, and mechanical behavior inherent to bamboo, as well as their mechanical behavior.

This study investigates a structural end connection for bamboo culms subjected to tensile forces, based on the concept of internal expansion and lateral friction, while considering the dimensional heterogeneity of the culm. The study seeks to provide practical support for bamboo construction through a connection system characterized by ease of installation, low added cost, and minimal requirements for skilled labor.

Literature Review

Moran and García (2019) define the bamboo culm as a circular tubular element reinforced by natural nodes distributed irregularly along its length. Its internal structure is axially reinforced by cellulose fibers embedded within a lignin matrix, contributing to its high mechanical efficiency and suitability for structural applications.

Lorenzo *et al.* (2020) and Librelotto and Ostapiv (2019), describe this structure (Fig. 1), stating that bamboo culms consist of irregular hollow tubes containing solid transverse diaphragms spaced along their length. These diaphragms correspond to the nodes externally visible along the culm surface and play a significant role in its structural behavior.

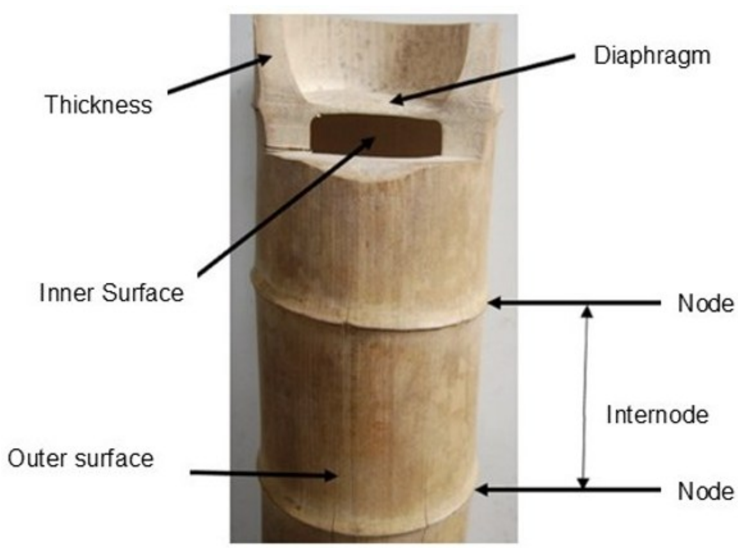

Fig. 1. Bamboo culms feature from Librelotto and Ostapiv (2019)

A systematic literature review conducted by Gaffuri *et al.* (2023) identified two main unresolved challenges regarding bamboo culm connections.

This challenge has been recognized for several decades. Over the years, many authors and researchers have proposed connection systems for natural bamboo culms (Arce-Villalobos 1993; Sonar and Siddhaye 2009; Trujillo 2009; Widyowijatnoko 2012; Barnet and Jabrane 2019; Correal *et al.* 2021; Harries *et al.* 2022). This bibliographic survey indicates that an ideal connection model for bamboo culms—capable of straightforward industrialization and broad application in the construction sector—has yet to be established.

The first unresolved aspect concerns the development of connections that do not require perforations of the culm for installation. Since bamboo fibers are primarily oriented along the longitudinal direction, any perforation may weaken the connection region. In metallic connections, the considerably higher stiffness of steel compared with bamboo tissue may induce stress concentrations, the use of metallic bolts in such joints may induce cracks and fissures, thereby reduce connection strength and compromise structural performance.

According to Gaffuri *et al.* (2023), connections between bamboo culms can be classified into four typologies: Bolted Connections, Steel Member Joints and Steel Plate Joints, Filler-Reinforced Joints, and Parametric Connections.

Bolted Connections consist of systems using bolts to connect two or more bamboo elements. These joints are generally simple to execute; however, their fabrication remains highly dependent on manual skills and site-specific adjustments. Steel Member Joints and Steel Plate Joints incorporate additional metallic components to form a structural system. In such cases, bolts, threaded rods, steel bars, and steel plates are employed to compose the joint assembly. An example of this classification was published in Paraskeva *et al.* (2019), which presents a connection system for a trussed beam.

This connection typology enables the assembly of architecturally expressive structural systems. However, because tensile and shear forces are locally concentrated at the bolts and/or threaded rods that perforate the culms, cracking and splitting frequently occur. In addition, the system is typically executed through manual and artisanal fitting processes, which limits reproducibility and scalability on construction sites.

Filler-Reinforced Joints, in addition to bolts and threaded rods, incorporate internal infill materials, generally expansive compounds such as cementitious grout or mortar. When combined with mechanical fasteners, the grouted system can achieve high resistance levels, in some cases producing structural performance comparable to conventional concrete systems. An example is presented in Fig. 2 proposed by Awaludin and Andriani (2014).

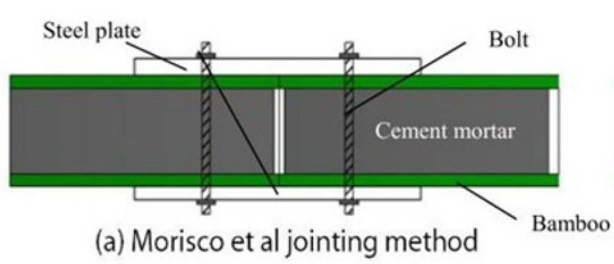

Fig. 2. Connection proposal with filler reinforced joints (Awaludin and Andriani 2014)

The execution of this system involves considerable complexity, as the expansive infill material may detach from the internal culm fibers—an issue frequently reported—thereby compromising structural integrity. Furthermore, cracking and localized failure around bolt insertion points are observed, negatively affecting long-term performance.

The final category identified Gaffuri *et al.* (2023) comprises Parametric Connections. These designs seek to incorporate contemporary technologies into their development and fabrication processes, including computational scanning of culms, Building Information Modelling (BIM), and additive manufacturing techniques such as 3D printing. Wu *et al.* (2019), for instance, proposed a BIM-designed connection component divided into two interlocking parts that clamp the bamboo culms (Fig. 3), subsequently fabricated using 3D printing technology.

Research within this category demonstrates the potential integration of emerging digital fabrication technologies applied to construction processes into bamboo connection systems. However, such solutions do not necessarily present superior mechanical performance compared to previously mentioned typologies. Further investigation remains necessary to validate their structural efficiency.

Therefore, none of the identified connection systems has yet demonstrated a simplified assembly procedure that eliminates dependence on multiple tools and complex fabrication processes, which reinforces the predominantly artisanal character of current solutions. As a result, installation tends to be time-consuming and requires skilled labor with advanced practical knowledge. Even parametrically designed connections have not yet fully addressed the existing gaps required to achieve a bamboo culm connection system characterized by ease of execution, low cost, high structural resistance, and commercial viability (Wu *et al.* 2019).

Fig. 3. Wu *et al.* (2019) proposal for parametrical joints

In addition to the categories identified by Gaffuri *et al.* (2023) proposed a further classification: Connections with Internal Expanders. In this category, the incorporation of additional materials—such as timber—does not function merely as internal infill, as observed in Filler-Reinforced Joints. Instead, the inserted element assumes a structural role, directly contributing to tensile load resistance and enabling enhanced connection performance.

The connection system investigated in this study is framed within this category. The assembly is based on the principle of increasing lateral friction between the connection element and the internal wall of the bamboo culm. By mobilizing frictional resistance through controlled internal expansion, the proposed system aims to enhance tensile load transfer while avoiding direct perforation of the bamboo culm and preserving its structural integrity.

EXPERIMENTAL

The connection system was designed and experimentally evaluated using culms of the bamboo species *Dendrocalamus asper (D. asper)*, commonly known in Brazil as Giant

Bamboo. This species presents large culm diameters and thick wall sections, characteristics that provide significant structural potential (Librelotto and Ostapiv 2019). Furthermore, it was readily available in the region where the research was conducted (Londrina, Paraná, Brazil). Figure 4 presents a flowchart illustrating the entire process.

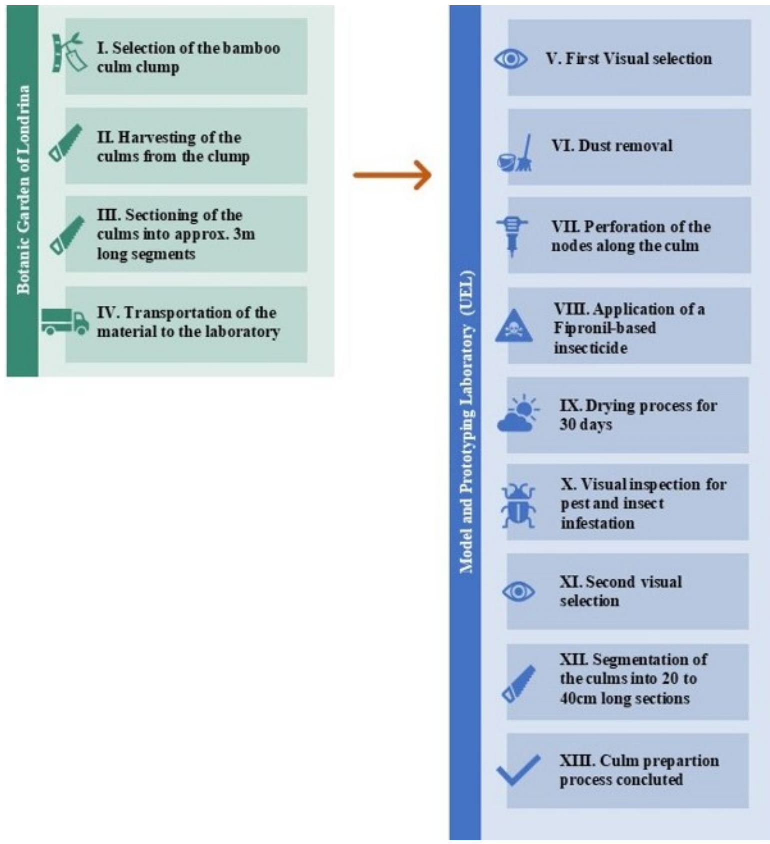

Fig. 4. Flowchart of the material collection process

All material was collected from the Botanical Garden of Londrina. The bamboo clumps at the collection site were selected through a visual assessment, prioritizing the most mature culms with the largest diameters. All culms used in the experimental program were harvested from the same clump. The bamboo culms were harvested by cutting immediately above the first node at the base, thereby allowing the plant to continue its natural growth. After harvesting, all culms were sectioned on-site into segments approximately 3 m in length, depending on node positioning. Each cut was performed 10 cm above the nodes, considering that this region presents greater geometric stability and avoids direct interference with the node diaphragm.

The harvested material was transported to the Model and Prototyping Laboratory of the State University of Londrina (UEL). The culms were visually selected and classified according to linearity, diameter, and overall visual quality. After transportation, the culms were cleaned to remove dust. A drilling tool was used exclusively to perforate the internal diaphragms, allowing penetration of the preservation solution throughout the culm length. This procedure was performed only as part of the preservation treatment and was not related to the proposed connection system. Subsequently, the preservation treatment was carried out using a Fipronil-based insecticide applied with a backpack sprayer. The material was stored in the laboratory for approximately 30 days for drying and verification of treatment effectiveness.

The selection of this treatment and procedure was based on the adaptation and adjustment to the space and equipment available in the laboratory. Before the culms were further sectioned for the preparation of the test specimens, a visual inspection was performed, and no damage caused by pests or insects was identified. During the storage period, no damage caused by pests or insects was identified, and no cracks or fissures were observed; however, it required removal of the internal diaphragms.

After the preservation treatment and drying process, a second visual selection was performed to separate the culms with lower curvature along their length. This procedure was adopted to optimize material utilization for the preparation of the test specimens, since excessive curvature could compromise the geometric configuration of the specimens.

The selected culms were then further sectioned into smaller segments ranging from 20 to 40 cm in length. This variation resulted from the cutting procedure, in which the sections were always obtained 10 cm above the node position. Since the spacing between nodes is not symmetrical along the entire culm length, variations in the final segment dimensions occurred. These bamboo segments were subsequently used as the test specimens during the experimental phase of this investigation.

All bamboo culms used as test specimens in the tensile capacity tests described in the following sections underwent the same drying, storage, and cutting procedures. This approach was adopted to minimize potential sources of variability and ensure the greatest possible consistency among the specimens.

Nevertheless, bamboo is a natural material with inherent heterogeneity in its anatomical structure. Consequently, despite careful material selection and standardized processing procedures, variability in mechanical behavior cannot be completely eliminated.

The bamboo culm generally exhibits a non-circular cross-section, whereas the expander has a cylindrical cross-section. Consequently, the geometric center of the expander does not always coincide with the geometric center of the culm cross-section.

When a tensile load is applied, slight vertical misalignment of the anchor bolt may occur, resulting in load eccentricity that may affect the overall performance of the connection. At this stage of the research, this aspect was considered a secondary issue, since the primary objective of this study was to minimize cutting and machining operations on the bamboo culm, thereby reducing the operational costs of the proposed connection system.

One possible approach to mitigate this effect is to machine the inner surface of the bamboo culm. This process would both smooth and homogenize the internal surface and reshape the cross-section to more closely approximate a circular geometry. Consequently, the geometric center of the culm cross-section can be better aligned with that of the expander.

As a continuation of this research, this issue is being addressed through the development of a portable machining device specifically designed for the internal machining of bamboo culms. The proposed equipment is intended to be low-cost, easy to operate, and suitable for transportation to construction sites.

The present study focused on evaluating the feasibility of the proposed connection system. In the subsequent stages of this research, additional aspects related to its structural performance, including the effect discussed above, are being investigated.

Although this species was selected for laboratory testing, it is important to emphasize that the objective of the internal expansion system is to enable adaptability to different diameters across various species while preserving mechanical performance. Therefore, the connection is intended to be applicable to other species used in structural systems.

Internal Wood Expander Connection Design

Considering the aspects described above, a connection system was designed to achieve the following objectives:

- Adaptability to different internal culm diameters;
- Avoidance of culm perforations that may interrupt longitudinal vascular bundles and reduce local strength;
- Minimization of the number of components, allowing rapid assembly, preferably pre-installed in a prefabricated structure;
- Use of low-cost components and an assembly procedure understandable to construction workers.

The design concept was inspired by the expansion mechanism of high-strength metallic anchors commonly used for fixing elements in concrete structures, commercially known in Brazil as "Parabolts" (Fig. 5). The main principle of this type of anchor is the expansion of the base, consisting of a slotted tube and a straight-shank screw equipped with a conical nut, which moves up as the screw is rotated (Fig. 5).

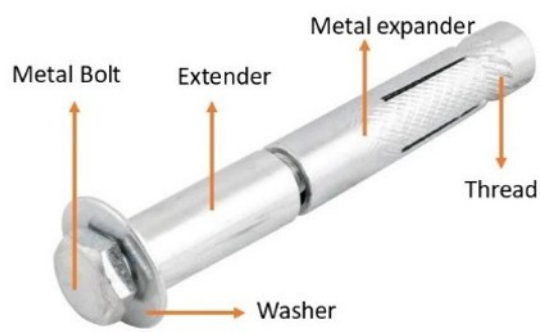

Fig. 5. Parabolt components

The connection adopts the same anchor assembly illustrated in Fig. 5, installed in a cylindrical wooden element positioned inside the bamboo culms to act as an expander. Along its lateral surface, the wooden piece contains vertical grooves that expand toward the culm walls, generating friction and resistance. This mechanism ensures efficient structural performance under tensile and pull-out forces.

The internal wood element, named the "Expander," was fabricated from commercially available *Pinus* spp. timber. It houses the metallic anchor and primarily functions to promote friction with the internal culm wall. Six longitudinal grooves were machined along the wooden element, corresponding to the length of the metallic anchor. The top of the cylindrical piece includes an area corresponding to the "extender" portion of the metallic anchor (Fig. 6).

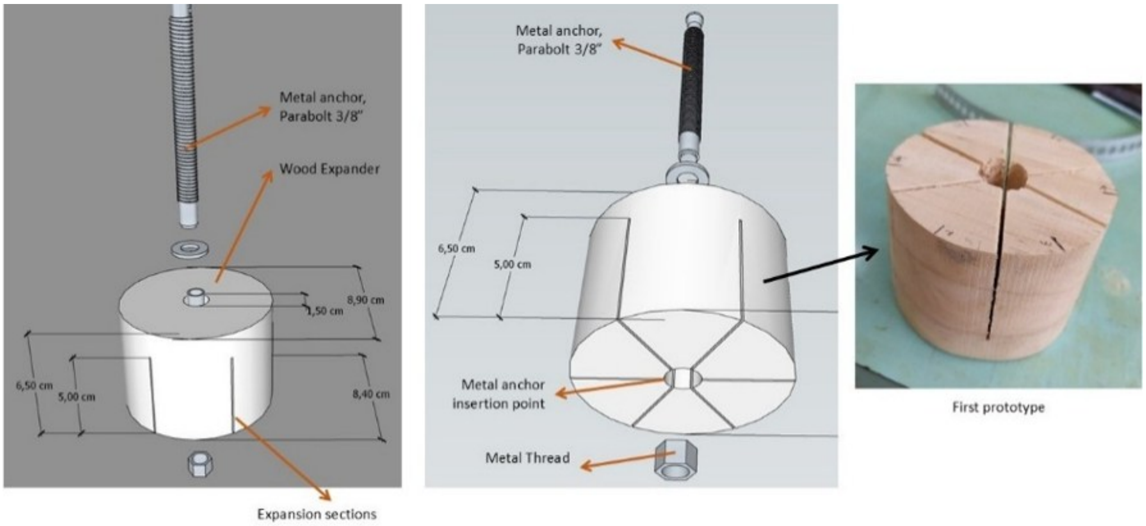

Fig. 6. Connection conception and first prototype

The use of a widely commercially available metallic anchor ensures system functionality and ease of execution. Additionally, these anchors are high-strength, low-cost components originally designed to fix metal elements in reinforced concrete structures. Considering the culm diameter of *D. asper*, a 3/8” metallic anchor was selected.

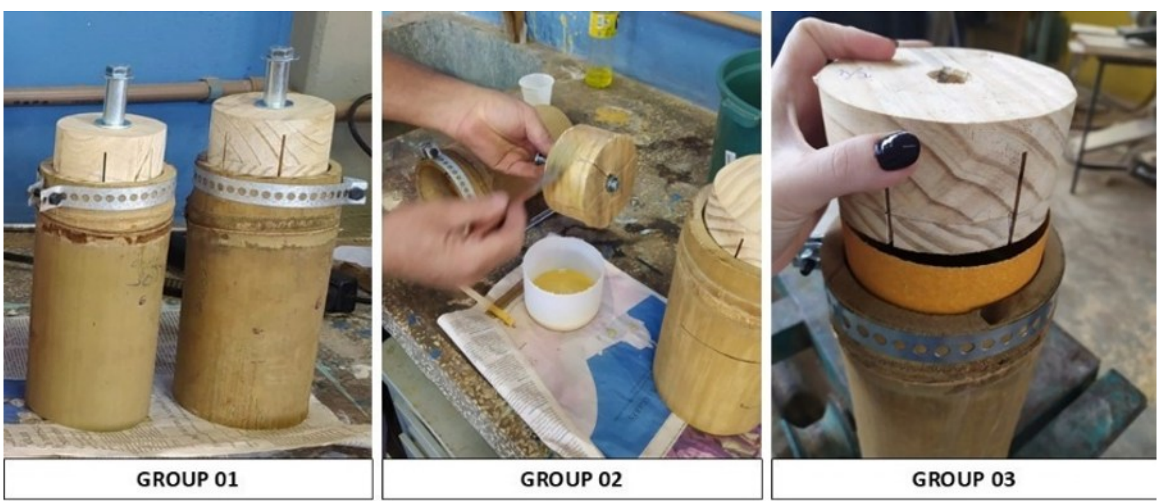

Fig. 7. Groups for comparative tests

Three models were developed for prototype fabrication of the expander piece (Fig. 7). Model 01 utilized a Pine wood expander with a 3/8” metallic anchor. Model 02 incorporated a commercially available bio-based polyurethane resin (IMPERVEG, Brazil), which has seen increasing use in recent years due to its sustainable characteristics. Model 03 added a No. 50 wall sandpaper layer glued to the main expander piece with the same bio-based polyurethane resin. These alternatives aimed to employ low-cost and widely available materials within the construction market.

A metal strap was installed around the end of each bamboo culm to maintain the stability of the cut section and to minimize the occurrence of cracking during specimen preparation and testing. Its function was solely to preserve the structural integrity of the culm throughout the experimental procedure and did not contribute to the mechanical performance of the proposed connection.

Assembly of Test Specimens

Simplified installation was considered a key requirement of this connection. This could be a key factor in promoting its acceptance among construction industry professionals and the market. In this study, since all culm collection, classification, and cutting were performed by students and technical personnel from UEL, the preparation of the culms prior to incorporation into the test specimens was carried out manually, as described previously.

The bamboo culms were sectioned into individual specimens, with each cut performed immediately above a node to preserve structural integrity and minimize the occurrence of cracking. Since one of the main objectives of the proposed connection is to accommodate bamboo culms with different diameters, specimens were prepared from the entire length of the culm, including the basal, middle, and upper sections. This approach also allowed potential adjustments required during the assembly of the test specimens to be identified and evaluated. The collected culms presented diameter variations between 100 and 146 mm, consistent with the expected morphological characteristics of *D. asper*.

Although nodes contribute significantly to bamboo stiffness, their removal was necessary in this preliminary investigation to enable insertion of the internal expander and evaluate the feasibility of the proposed mechanism. The initial attempt to remove the internal diaphragms was carried out using a hole saw with a diameter close to that of the culm.

However, the strength and thickness of the diaphragms, as well as their silica content, caused significant wear on the tool teeth, rendering the hole saw unusable. Since the hole saw proved inefficient, the diaphragms were removed using a tabletop jigsaw, commonly known as a "reciprocating saw" (Fig. 8, panel 1). After this procedure, small burs and remaining internal vascular bundle remnants were removed using a professional rasp (Fig. 8, panel 2).

With the diaphragms removed, the preparation of the wooden expanders began using a manual lathe. Two *Pinus* timber planks, each 45 mm thick, were bonded using the same bio-based polyurethane resin applied in Model 2, resulting in an expander with a final height of 9 cm. Subsequently, the six grooves were cut along the expander as specified in the design, and a central circular opening was made in the cylinder for installation of the 3/8" metallic anchor bolt. The number of grooves was determined according to the diameter of the pieces, ensuring adequate expansion without weakening the structural integrity of the expander.

With the connection components fabricated and the bamboo culms prepared without diaphragms, the installation process of the connection began. It should be noted that the bamboo bars to be connected could be prefabricated in the industry at the designed lengths, transported, and assembled on-site. This approach would allow for a single on-site assembly, resulting in a faster and more precise installation process.

The process for the assembly of the complete system starts with the wooden expander positioned inside the culm, with the grooves facing downward.

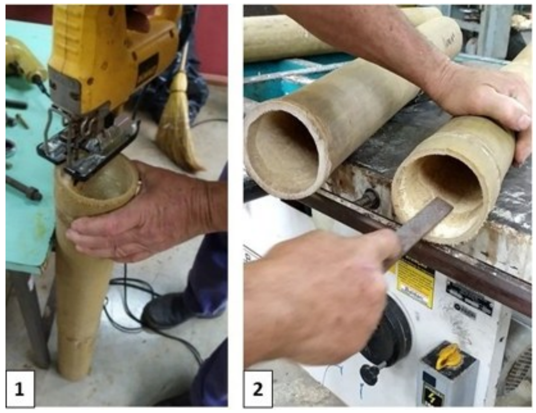

Fig. 8. Withdrawal of diaphragms

Then, the metallic anchor is inserted into the wooden expander and the structural adjustment of the metallic anchor is achieved by applying a specific, pre-determined torque to the screw. After expansion of the internal piece by the anchor, the screw is removed, and a threaded rod is inserted to simulate the connection with another bamboo element. The connection is concluded.

For a clearer visualization of the wooden expander opening, a section of the bamboo culm with the installed component was prepared (Fig. 9). The expansion of the grooves in the wooden piece can be observed, confirming the functionality of the expander. Preliminary expansion tests indicated that *Pinus* exhibited more suitable deformation behavior for this application compared with the alternative wood tested.

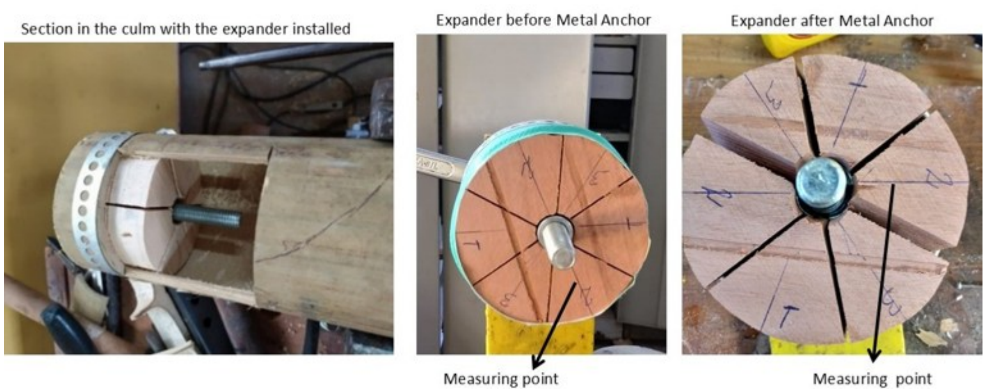

Fig. 9. Wood expansion test

This test confirmed previous research in which sacrificial tests were performed with expanders made from both types of wood, and at the end, Pine performed better.

It is important to emphasize that the assembly procedure adopted for the test specimens was intended solely to investigate the feasibility and mechanical performance of the proposed connection when applied to natural bamboo culms. One of the primary objectives of this invention is its industrial implementation within the construction sector, whereby the entire connection can be prefabricated and delivered to the construction site as a fully assembled unit. Under this approach, installation would require only the insertion of the connector into the bamboo culm followed by the application of torque to the anchor bolt, thereby activating the wooden expander. Another potential application is the industrial pre-installation of the connection into commercially available bamboo culms up to 3 m in length, consistent with the standard dimensions currently supplied and distributed by the bamboo industry.

Experimental Phase: Tensile Capacity Tests

At the time of this experimental investigation, no specific standardized procedures for tensile testing of bamboo culm connections were identified in the available literature or technical standards.

First, it was established that, given the characteristics of the developed connection system, tensile capacity testing would be the most appropriate method to assess its structural potential. This is because the internal positioning of the connection within the culm, combined with the absence of wall perforations, may result in relative displacement between the wooden expander and the culm wall during tensile loading. Moreover, other published studies involving internal connection systems have employed tensile capacity tests, allowing for direct comparison with the system investigated herein.

Based on this rationale, the experimental phase was initially exploratory and aimed at defining appropriate testing parameters and procedures. From this point onward, the tests were conducted considering the load values recorded up to specimen failure, expander slippage behavior, and the performance of the metallic components coupled to the Universal Testing Machine. The specimens were tested using a DL-30000 Universal Testing Machine, with a 300 kN capacity, manufactured by EMIC.

The primary objective of this investigation and the corresponding experimental program was to determine the maximum load-carrying capacity and mechanical potential of the proposed bamboo culm connection configurations. Accordingly, the tests were conducted without imposing predetermined limits on either the loading level or the test duration, allowing each specimen to be loaded continuously until failure.

This testing approach was adopted to ensure that all relevant mechanical responses and experimental data could be recorded throughout the entire loading process, thereby enabling a comprehensive analysis based on the broadest possible range of variables associated with the structural behavior of the proposed connection.

For these initial tests, failure was defined as the point at which the connection could no longer sustain additional load according to the load-displacement response and/or when significant slippage or failure of the internal wooden connector was observed.

The Test specimens were assembled as previously described and divided into three groups:

- **Group 01:** Internal expander in *Pinus* wood and 3/8” anchor bolt;
- **Group 02:** Internal expander in *Pinus* wood, bonded to the internal culm wall with bio-based polyurethane resin (Brazilian brand “Imperveg”), and 3/8” anchor bolt;
- **Group 03:** Internal expander in *Pinus* wood, externally coated with No. 50 wall sandpaper bonded with bio-based polyurethane resin (Imperveg), and 3/8” anchor bolt.

During this initial stage, in some cases, displacement occurred with the wooden expander in an inclined position; in others, it displaced parallel to the culm axis. A third behavior involved displacement occurring exclusively in the metallic anchor and its component.

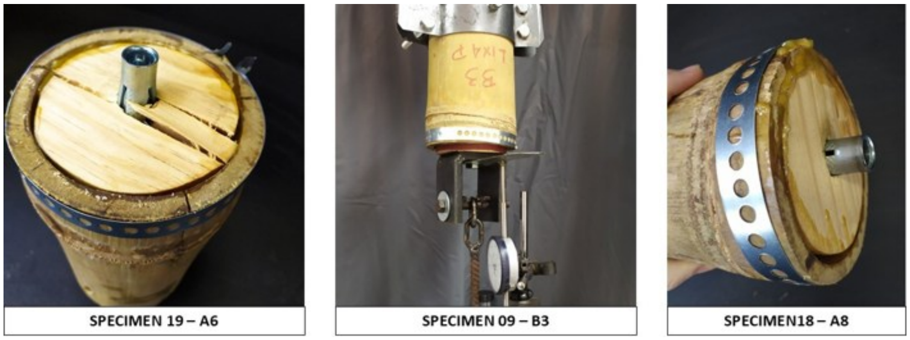

Fig. 10. Failure patterns in the initial stage

Specimen failure occurred according to three main patterns (Fig. 10); The first consisted of pull-out and detachment of the wooden expander A6; the second, observed primarily in Group 02, involved failure of the wooden expander along the groove alignment (shear parallel to the fibers), as illustrated in Fig. 10B3. Finally, slippage of the metallic anchor expansion mechanism within the wooden matrix was also observed A8.

Following this initial test, a method was developed to improve the standardization of the tensile capacity.

In the absence of specific standards addressing tensile capacity tests for internally expanding connectors, the standard ABNT NBR 7190-5 (2022) was adopted as a reference. This standard defines test methods for determining the strength and stiffness of joints with mechanical connectors. Although primarily focused on timber elements and dowel-type fasteners, the procedures described were considered suitable for addressing the behaviors observed.

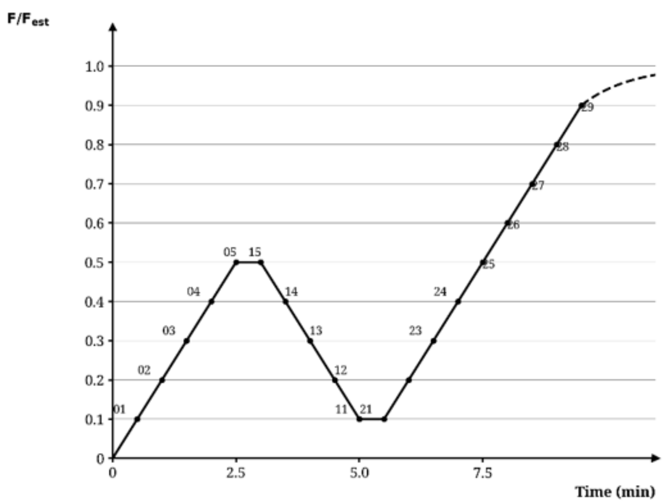

Fig. 11. Loading method, according to ABNT NBR 7190-5 (2022)

The standard recommends a minimum of 12 specimens for each connection configuration. As illustrated in Fig. 13, the procedure begins with the application of an initial load up to 0.5 F_{est} (50% of the estimated ultimate load), maintained for 30 seconds. The load is then reduced to 0.1 F_{est} and maintained for an additional 30 seconds to allow accommodation of the joint components. Subsequently, loading is applied to reach the ultimate load or a maximum slip of 15 mm, up to a limit of 0.7 F_{est}. The loading rate should correspond to 0.2 F_{est} per minute (± 25%). A subsequent adjustment in loading rate is recommended so that the total test duration ranges between 3 and 5 minutes (Fig. 11).

Due to limitations of the equipment, adaptation of the standard's recommendations was necessary. Therefore, the loading rate was maintained constant throughout the tests, and only the load levels required for the loading-unloading cycle were adjusted.

This approach enabled a more robust comparison of the results both across experimental groups and between testing phases. Although some variability in absolute connection resistance values was observed when using this procedure, the proportional performance trends among the groups were preserved. In Table 1, the letters in the second column identify the original bamboo culm from which each test specimen was obtained.

Table 1. Tensile Capacity Test Results

Group	Culm	Specimen	Ultimate Strength (kN)
Group 01	G	CP17	1.67
	G	CP18	2.63
	H	CP19	2.08
	I	CP20	1.30
	H	CP23	2.04
	G	CP24	3.39
	G	CP25	2.74
	E	CP26	1.66
	J	CP27	1.05
	G	CP28	3.09
	Average Result		**2.16**
	Standard Deviation		**0.77**
	CV (%)		**35.76**
Group 02	D	CPA	3.31
	H	CPB	5.03
	D	CPC	2.91
	J	CP1	4.66
	I	CP2	5.76
	H	CP3	3.24
	J	CP4	3.46
	H	CP5	4.22
	I	CP7	6.53
	J	CP8	5.57
	Average Result		**4.47**
	Standard Deviation		**1.24**
	CV (%)		**27.77**
Group 03	J	CP7	4.48
	H	CP8	3.54
	J	CP9	2.61
	C	CP10	2.50
	I	CP11	3.00
	H	CP12	3.93
	D	CP13	2.74
	G	CP14	3.88
	G	CP15	4.59
	I	CP16	2.21
	Average Result		**3.04**
	Standard Deviation		**0,85**
	CV (%)		**27.95**

Since one of the objectives of this study was to evaluate the proposed connection using culms with naturally varying diameters, the specimens obtained from each culm were randomly distributed among Groups 01, 02, and 03. This experimental design was adopted to minimize any potential bias associated with culm diameter and to ensure that no connection configuration benefited from a particular diameter range. The numbering presented in the third column identifies the individual test specimens and corresponds to the chronological order in which each specimen was tested.

It is important to note that the specimens within each experimental group exhibited highly consistent mechanical behavior throughout the tensile tests. This observation indicates that the testing configuration adopted in the present study provided reliable experimental results and suggests that the limitations of the testing equipment did not significantly influence the evaluation and interpretation of the mechanical behavior of the proposed connection.

In this phase, an additional 36 tests were performed, comprising 12 specimens per group. Due to irregularities identified in certain specimens, such as premature failure, some tests were excluded from the final comparative analysis. After excluding specimens affected by premature failures unrelated to the connection mechanism, approximately 10 valid specimens per group were considered for comparative analysis. The corresponding results are presented in Table 1. According to the adopted standard, the acceptable coefficient of variation for connection resistance values ranges between 18% and 28%.

RESULTS AND DISCUSSION

Overall, the incorporation of interface-enhancing additives into the original expander configuration increased the measured tensile capacity of the investigated connection. As shown in Fig. 12, the comparison of mean values indicates that the two groups incorporating additives in their configuration (Group 02 and Group 03) exhibited superior performance.

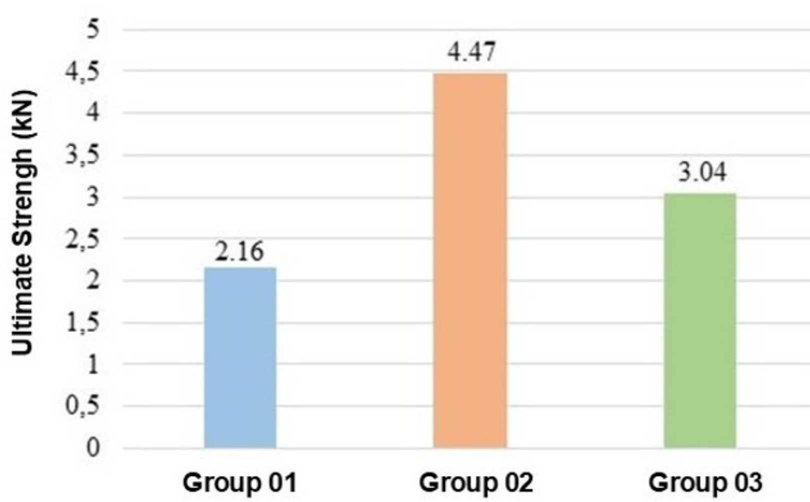

Fig. 12. Comparison between groups tested: Group 01 (*Pinus* wood internal expander), Group 02 (bio-based polyurethane-bonded pinus wood internal expander), Group 03 (sandpaper-coated pinus wood internal expander)

Figure 13 presents the graph representing the evolution trend of the Applied Load *versus* Displacement behavior observed in the majority of the Specimen. Periods of load reduction followed by partial recovery of load-carrying capacity can be observed. After reaching the maximum load, the connection progressively loses load-carrying capacity until failure occurs. However, certain exceptions were observed, particularly among the specimens of Group 02.

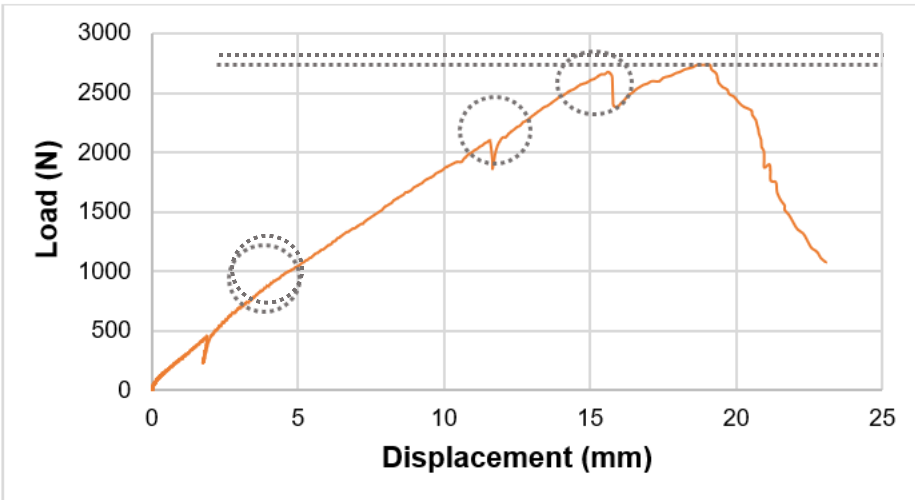

Fig. 13. Loading *vs*. displacement behavior on G7 specimen (25)

Depending on the specific context, Group 01 may achieve satisfactory tensile resistance without the use of additives. Further investigation is required to better understand the factors that led specific specimens to reach ultimate tensile loads ranging from 3.00 to 6.00 kN. One possible explanation is the occurrence of improved contact conditions between the expander and the inner culm wall in certain specimens, potentially associated with the naturally more regular geometry of some culms. Group 02, in which the expander was bonded to the culm wall, achieved the highest average tensile capacity among the evaluated groups. The results for this group ranged from 4.46 to 6.52 kN.

Although Group 02 exhibited the highest resistance, this increase was accompanied by a more abrupt failure mechanism. In this case, failure exhibited a more abrupt behavior, characterized by sudden withdrawal of the expander after reaching the maximum load. This behavior was exclusive to Group 02. It is therefore assumed that the use of adhesive enabled higher load levels to be attained; however, it also restricted the plastic deformation capacity of the wooden expander, ultimately resulting in sudden specimen failure.

For the other two groups, failure occurred in a more ductile manner, characterized by significant displacement of the wooden expander prior to reaching the ultimate load, thereby exhibiting a more progressive failure mechanism (Fig. 14).

From the standpoint of tensile resistance, Group 03 ranked second, with average values of approximately 3.04 kN in Phase 02, respectively. The third position was occupied by Group 01, in which failure generally occurred due to relative slip between the wooden expander and the inner surface of the culm wall.

For both Group 01 and Group 03, failure was characterized by slow and controlled sliding of the wooden expander. This feature is considered advantageous as a safety aspect. Such behavior may allow the impending collapse of the connection to be anticipated.

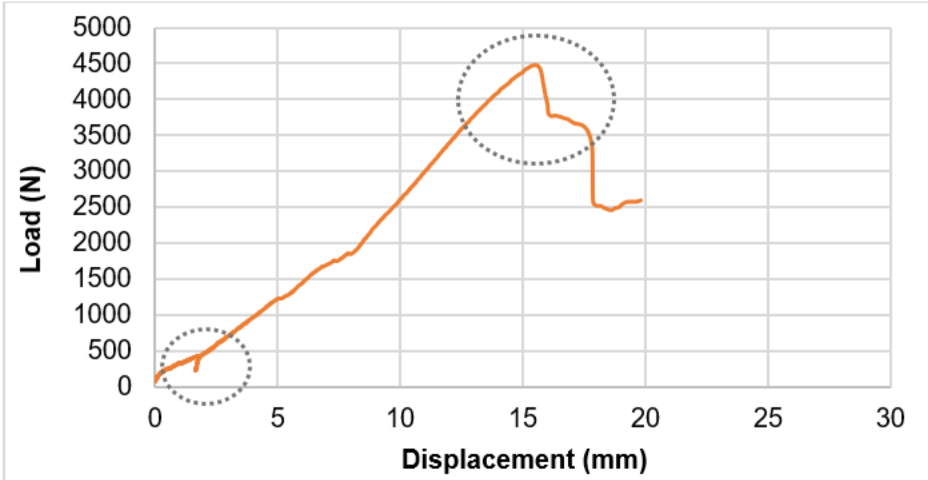

Fig. 14. Loading displacement behavior on J7 specimen

Group 1 presented a coefficient of variation of 35.8%, which exceeds the range recommended by the adopted standard. Based on the observations made during the experimental program, one possible factor contributing to this result was the inherent heterogeneity of the bamboo culms. Variations in the geometry and diameter of the culms promoted greater slippage of the *Pinus* wooden expander.

Failure Mechanisms

In some cases (Fig. 15), delamination occurred within the laminated wooden expander itself. The lower portion of the expander, which contains grooves, detached from the upper portion, which has no grooves and is responsible for providing stability.

Nevertheless, analysis of the Load versus Displacement curve (Fig. 14) indicates that a similar sliding and adjustment process occurred, as observed for specimen J7, albeit at a different scale. In this case, the tensile resistance capacity reached approximately 2.80 kN. This is a noteworthy result, as even with the occurrence of internal delamination in the wooden expander, the specimen still achieved an above-average resistance and the third-highest load value within Group 01 (Table 1).

Fig. 15. J7 specimen, after failure

In Group 03, some specimens exhibiting low resistance experienced failure of the wall sandpaper layer either during testing or even during installation (Fig. 16). These bonding failures may be mitigated by employing a different type of adhesive, as well as by refining the specimen assembly procedure. This group demonstrated satisfactory overall performance, with tensile resistance values approaching those achieved by Group 02, in addition to a resilient behavior characterized by gradual loss of load-carrying capacity.

The detachment of the sandpaper from the wooden expander contributed to the results obtained for Group 03. However, this failure is likely attributable to the adhesive used to bond the abrasive layer rather than to the friction-enhancement concept itself. Future studies may investigate alternative adhesives with greater bonding strength to prevent this type of failure. Such investigations may also determine whether this modification can further improve the tensile capacity of the connection while supporting the industrial production of this connection configuration.

Fig. 16. Test specimen after failure

Some cases also exhibited atypical behavior within the same group. Specimen CP24 (G1) from Group 01, for example, showed higher resistance compared to the other specimens in the same group and achieved values comparable to those observed in Groups 02 and 03. Despite not incorporating any additional treatment—such as bonding of the expander or the application of sandpaper to the wooden expander—it reached a final resistance of 3.38 kN, whereas the mean value of Group 02 was 4.47 kN.

As previously mentioned, some specimens from Group 01 achieved results comparable to those of the other two groups; however, these cases represented exceptions to the general trend. Overall, from Group 01 to Groups 02 and 03, a considerable increase in resistance was observed with the incorporation of additives into the original expander, thereby improving its structural performance. The lack of effective contact between the lateral surface of the expander and the culm—resulting from the natural irregularity of bamboo culm walls—compromised the connection strength. Both the use of adhesive and the application of sandpaper compensate for local geometric irregularities, increasing the contact area and friction between the interacting surfaces. It is assumed that the internal machining of bamboo culms may contribute to improving this interface condition and, consequently, further enhance the performance of the connections in Groups 02 and 03.

The observed failure mechanisms can be summarized into three distinct failure modes. The connection system investigated in this study is based on the principle of lateral friction resistance induced by the expansion of a grooved wooden component, referred to as the *expander*, against the inner surface of the bamboo culm. Load transfer occurs through the contact between the surfaces of the expander and the inner wall of the culm.

Mode 1: Expander Pull-out Failure

This was the most frequently observed failure mode. In this mechanism, after the elastic phase, a gradual withdrawal of the expander occurs, followed by progressive sliding until complete loss of load-carrying capacity.

Due to the natural geometric heterogeneity of bamboo, discontinuities in the effective contact between the expander (with a regularly machined cylindrical shape) and the inner surface of the culm are generated (Fig. 15b). This characteristic is considered the main cause of the variability observed in the experimental results, as the effective contact area between the components varies among specimens.

To mitigate this limitation, internal machining of the bamboo culm may be an effective approach to homogenize the inner surface and promote a more efficient fit between the expander and the culm. The development of equipment for this purpose is being considered as part of the continuation of this research.

Mode 2: Expander Delamination

Failure of the expander occurred through delamination, with the detachment of the upper un-grooved portion from the lower grooved portion.

In this failure mode, rupture occurred at the bonded interface between the wood laminates that compose the expander, indicating that the laminated configuration adopted for the expander represented a weaker interface than the surrounding materials. This issue could be addressed by using a solid (non-laminated) wooden expander or by implementing a more rigorous and reinforced lamination bonding process, including the use of internal metal clamps within the expander to provide greater resistance to tensile stresses.

However, for the specimens exhibiting this failure mode, the observed load-bearing capacity was comparable to that of the other specimens within the same group.

Mode 3: Sandpaper detachment

In this mode, failure occurred in the sandpaper layer applied to the surface of the expander, mainly observed in Group 03.

In these cases, the sandpaper layer was detached from the wooden surface during the test. The strength of the wood/sandpaper bonded interface was insufficient to withstand the tensile stresses generated during the experiment (Fig. 15).

Nevertheless, this group exhibited satisfactory average structural performance, with an average resistance value close to that obtained for Group 02, as well as resilient behavior characterized by a gradual loss of load-bearing capacity of the connection.

This issue can be addressed by adopting a higher-strength adhesive and improving the bonding procedures during the fabrication of the expander. Ongoing research results support this hypothesis.

LIMITATIONS AND IMPROVEMENT OPPORTUNITIES

Although the expansion mechanism was successfully activated, small gaps between the inner wall of the bamboo culms and the wooden expander were observed reducing the effective contact area responsible for friction transfer. Consequently, the incorporation of an additional interface-enhancing element should be considered, not only to increase the tensile capacity of the proposed connection, but also to improve the consistency and standardization of the experimental results.

No failure was observed in the bamboo culm, indicating that, for the proposed connection design, the critical aspects are related to the conception, geometry, and composition of the expander. Therefore, improving the overall performance of the connection ultimately requires preventing relative sliding between the components, which is currently being investigated in the ongoing research.

The manual fabrication process and the use of adapted laboratory equipment represent limitations of the present study, potentially contributing to variability in specimen geometry and interface conditions. Although a unified protocol was adopted for the fabrication of the connections, the entire process was conducted manually in the laboratory, using adapted equipment and subject to inherent uncertainties in dimensional precision.

Surface treatment using sandpaper bonded to the wooden expander also presents demonstrated advantages, as it significantly increases the load-bearing capacity of the connection. This configuration is suitable for prefabrication or systematic large-scale production and can be delivered to the construction site in a finished state.

The proposed connection successfully transferred tensile loads through friction mobilized by internal expansion, without causing damage to the bamboo culm. The main limitations identified were associated with interface standardization rather than with the structural integrity of the bamboo element itself.

CONCLUSIONS

1. The literature review demonstrated that structural connections for natural bamboo culms remain an unresolved research challenge. Existing connection systems frequently present limitations related to fabrication complexity, structural performance, and scalability.
2. The proposed connection system avoids metallic fasteners penetrating the bamboo culm wall, providing an alternative approach based on a simple assembly procedure and components suitable for industrial prefabrication.
3. One of the central concerns of this research is the quantitative assessment of connection efficiency. Across the three groups, comprising two different surface treatments, reduced variability in the results was observed, with performance levels meeting standard requirements and achieving a structurally satisfactory level of tensile resistance.
4. The experimental phase confirmed the feasibility of the proposed connection concept and provided relevant information for subsequent development stages, as the construction of a full-scale prototype for evaluation of its integrated structural performance.
5. An increase in tensile load capacity of the proposed connection was observed when additional surface treatments were applied to the wooden expander.
6. Considering that the research envisions prefabricated components being delivered to the construction site with the connections pre-assembled, the use of resin is highly feasible, since the curing time (24 hours) can be accommodated within the prefabrication facility.

7. The natural irregularity of the internal bamboo culm geometry was identified as the main factor affecting connection consistency, both in terms of load capacity and variability of results. Laboratory observations indicate that preparation of the internal culm surface is essential to increase load-bearing capacity and reduce result dispersion.
8. Further development of manufacturing procedures and prefabrication strategies may contribute to improving reproducibility and scalability.
9. The experimental technical approach enabled the determination of connection resistance values, as well as the identification of the potentialities and limitations of this connection typology, thereby supporting designers and builders in informed structural decision-making.

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Conflict of Interest

The authors declare no conflicts of interest.

Use of Generative AI

The authors declare that artificial intelligence (AI)-based tool (ChatGPT) were used exclusively to improve the final translation of the manuscript, following the suggestion provided by Reviewer B, after the entire manuscript had been completed and revised by the authors. ChatGPT was used solely to improve the translation into the journal's language, without modifying the authors' original ideas, interpretations, images, figures, graphs, or data presented in the manuscript.

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