A Review of the Evolution of Research on Proposals for Bamboo Culms Connections in Structural Systems

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Structural systems built from raw bamboo have been used for years due to its highly renewable characteristics, versatility, and abundance in various countries, *e.g.*, China, Indonesia, all over South America, and especially Brazil. It is also considered a low specific weight material, which means it is easy to handle and transport. These characteristics make it a low-cost material for building construction. The objective of this systematic bibliometric review is to identify innovations in bamboo culms structural connections in order to contribute to the advancement of technology applied to civil construction by seeking joints that consider the use of industrialized or standardized products. This review revealed there is still no ideal connection capable of solving the great problem of this subject, which points out the need for more studies on the topic. This investigation also allows for the classification of the connections into 5 categories: Bolted connections; Steel member and Steel plate connections; Reinforced Connections with filler; Parameterized connections, and; Connections with the use of wooden dowels.

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INTRODUCTION

Bamboo is an ancient material, used in the construction industry because of its abundance in some countries, primarily Asian countries, *e.g.*, China and Indonesia, in addition to its highly renewable characteristics (Salzer *et al.* 2018; Lao 2021). This research analyzed publications issued in the last 5 years, according to a systematic review on connections, described in the Methods section.

One of the most prominent countries involved in the development of research with raw bamboo, as well as the international leader in this topic, is China (Qiu *et al.* 2019). In addition to proposals with traditional systems, *e.g.*, metal and screw connections, China has developed research focused on the use of innovative technologies for the development of connections. One example is the integration of a building information modelling (BIM) system for the design of connections. The use of parametric resources, *e.g.*, 3D printing, in the fabrication of connections has also been observed (Lorenzo *et al.* 2017). In other words, there is currently a great leap in the advancement of this type of research, especially in the association with updated technology.

As shown in Fig. 1, it is possible to identify those publications that are related to bamboo connections and focused on steel connections began appearing around 2005 and mostly focused on industrialization. However, it can be seen that the largest number of studies on the subject occurred in the last 5 years, with 2019 being the most prominent year with a total of 11 publications. Therefore, it is a developing field demanding research efforts.

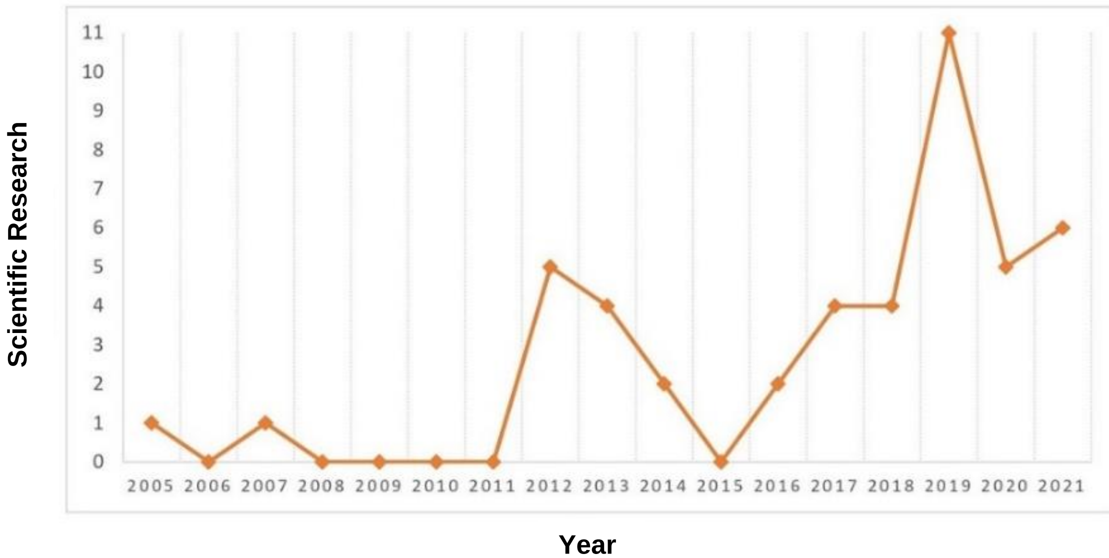

Fig. 1. Publications on bamboo structural connections (Source: Adapted from Scopus 2021)

The objective of this work was to search through connection designs within the mentioned profile, considering tools for contributing not only to scientific knowledge, but also as a means of inspiring new studies on the use of bamboo culms in civil construction.

METHODS AND APPROACH

This study was developed through a systematic and bibliometric literature review, with the use of online computer programs for categorizing readings. Initially, since the objective of this work was based on the search for innovative and original connections and the flow of publications is constant, it was decided to select only articles published in the last 5 years. Occasionally, some articles prior to this period were added, when it was detected that they were referential works for the others already selected.

Therefore, an exploratory search around the theme was conducted. This process enabled the identification of the main keywords, which later helped the formation and organization of the search strings presented below.

Table 1. Systematic Table of Search Strings Used

STAGE	DATABASES	STRING	HITS	SELECTED PAPERS	SEARCH DATE
Exploratory	Google Academics Scopus Web of Science Scielo	Busca aleatória: *bamboo; connections; raw material; joints; structural system; bamboo structures; bambu; conexões; sistemas estruturais.*	25 hits	12 papers	January - September 2021
Sistematic	SCOPUS	*bamboo* AND *"bamboo connections"* AND *bamboo structures* AND NOT *"engineered bamboo structures"* AND NOT *"laminated bamboo"* AND NOT *composite* AND PUBLYEAR > *2016*	17 hits	8 papers	11/03/2021
	Web Of Science	*bamboo* AND *connections* OR *joints* AND *bamboo structures* AND *design* NOT *laminated* NOT *composite* NOT *panel* NOT *"engineered bamboo"* NOT *wood* AND PUBLYEAR > *2016*	31 hits	6 papers	11/03/2021
		TOTAL	73 HITS	<u>26 PAPERS</u>	

In the exploratory searching stage, it was also observed that most of the works were published in the Scopus and Web of Science databases. The second step was the formation and definition of the search strings, and the ideal combination was defined, as shown in Table 1.

Replicate papers were eliminated, as well as those for which complete access to the publication was not available. This selection was based on an analysis of the title, abstract, objectives, and images. Thus, a total of 26 articles diversified into state-of-the-art reviews and publications of connection proposals were selected. This selection was made by relevance and all the papers should have original connection proposals. Then, the selection was validated through the software RStudio, associated with the online software Bibliometrix. One of the results obtained was the word cloud (as shown in Fig. 2), which showed the words related to each other and direct to the chosen topic.

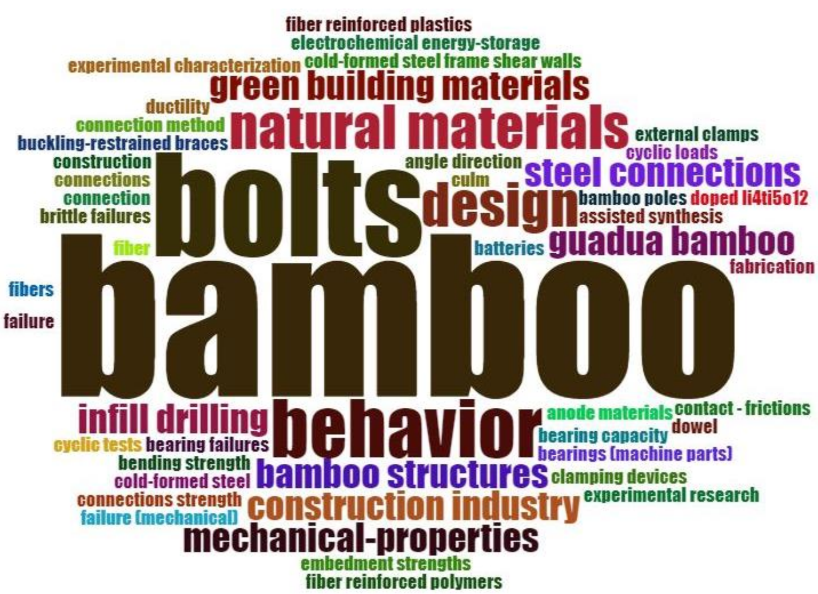

Fig. 2. Cloud word provided *via* Bibliometrix software analysis

CURRENT CONTEXT FOR BAMBOO CULM CONNECTIONS

The design of durable, secure, and systematically calculated connections has an important practical implication for encouraging the use of bamboo structures. They need to be well-designed, have an aesthetic quality, stability, and avoid structural performance.

From the point of view of comparing the structural strength x density of this material, Carbonari *et al.* (2017) named bamboo in its original form as "vegetable steel", comparing different bamboo species, steel, and concrete to determine various parameters, *e.g.*, the flexural, compressive, and shear strengths. The authors observed that bamboo, in most species, outperformed both concrete and steel in mechanical capacity, especially in terms of compressive strength.

According to Hong *et al.* (2019), although there is already research related to the connections between bamboo bars, the currently used connections are not completely satisfactory. This is not a single factor cause. There is a range of complexities in bamboo construction which the primary one is related to the physical/anatomical structure of the material. However, there are already some internationally relevant studies that investigate and/or propose connections based on new technologies addressed throughout this work.

The map in Fig. 3 was elaborated through an analysis performed with the Bibliometrix software, generating a world panorama of the main publications in the last 5 years. Thus, it can be seen that China, as well as other Asian countries have the largest number of studies and proposals published on the subject, leading the innovation and the use of technology, as Qiu *et al.* (2019) states. There are more than 500 species of bamboo in Chinese territory, accounting for one-third of the total area of bamboo forests in the whole world.

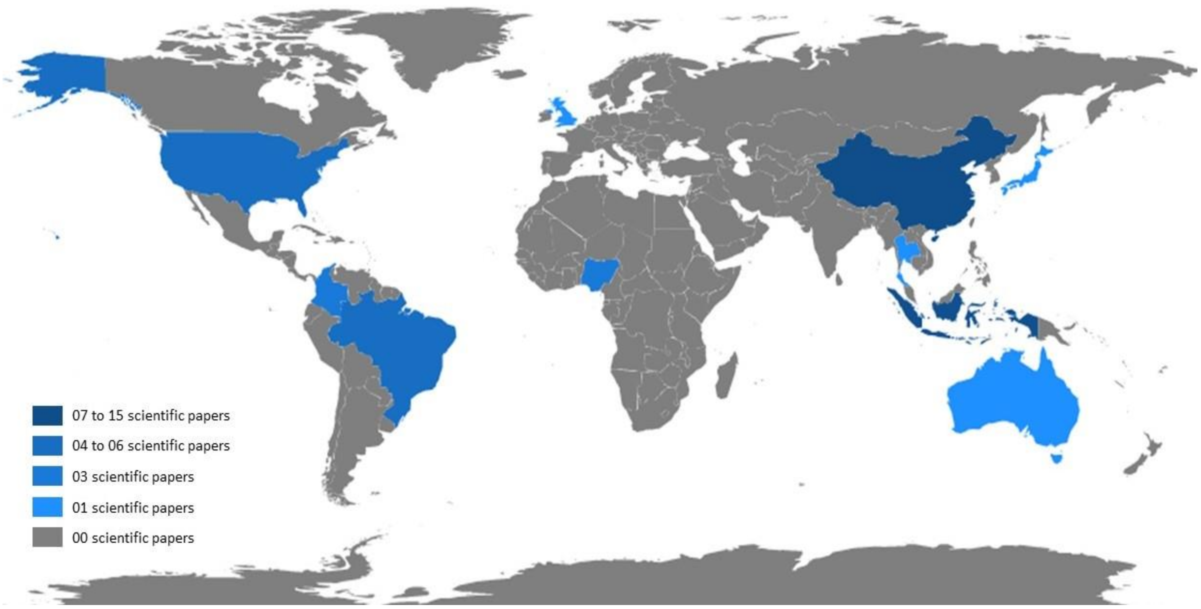

Fig. 3. The world scientific publications on bamboo connections in the last 5 years (Note: Developed by Bibliometrix (2021))

The use of Bibliometrix also allowed for the identification of the authors with the highest number of citations, classified by country. Chinese authors are the most cited (as shown in Fig. 4), due to both the importance of their research and the greater number of international publications compared to most countries. Within the systematized literature review, the countries responsible for the main studies and the authors related to the subject were compiled (as shown in Fig. 4).

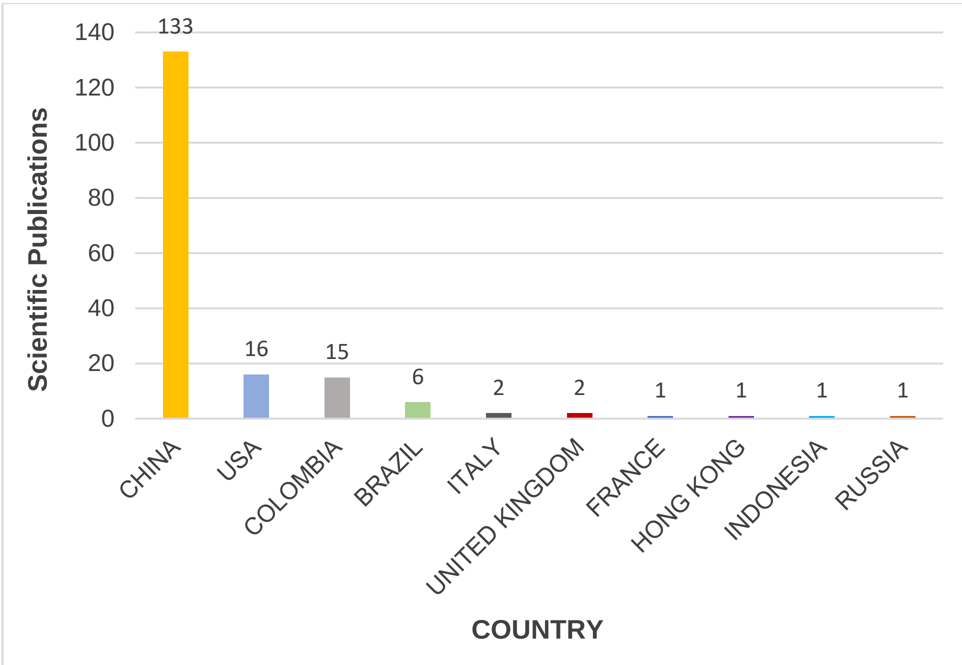

Fig. 4. Classification of the authors according to citations from databases (Source: Adapted from Bibliometrix (2021))

Colombian authors have an important place in this framework as well. They occupy 3rd place when it comes to publications on bamboo connections. Therefore, although the number of publications by country is not high, they have great relevance to this specific topic investigated. This is because all the works found propose a connection design and investigate its functionality under laboratory-controlled conditions.

In the process of reviewing the publications, the key role of Chinese researchers and innovations through the use of technology is always highlighted. It is noted that a large part of the works published by authors from this country approach the topic using a parameterization process in the manufacturing of connection parts.

Use of Metal Connections Today

Metal connections for raw bamboo structural systems have been widely used, and in some countries even on a large scale, *e.g.*, in Colombia. In that country, the standard instruction NSR-10 even provides the parameters for this type of joint. Hong *et al.* (2019) classify metal connections into three main categories, as outlined below.

Bolted joints

Bolted joints (as shown in Fig. 5) are those in which bolts form the connection of two or more bamboo culms. According to Hong *et al.* (2019), they are easy to produce and require little amounts of material and technology involved. However, they require a high shear strength, which usually causes the bamboo culm to break or crack during their installation, considerably decreasing their strength and reliability.

Fig. 5. Bolted joints examples from Hong *et al.* (2019); CC BY 4.0

This systematic review shows that the proposals for connections have evolved a lot from the technological point of view. Therefore, the most recent research connection proposals increasingly seek to use other metal elements associated with the bolted connections.

Steel member connections and steel plate connections

Steel member and steel plate connections have a complexity and a greater number of metal parts, and they are able to connect more than two culms at the same time. This connection enables its use in very specific projects, primarily in geodesic compositions/shapes, which usually implies some limitation to their application (Hong *et al.* 2019).

Rittironk (2021) developed a connection with a configuration different from those found so far. The proposal is a metal system of male (nozzles) and female connectors (receivers) snapped together, as seen in Fig. 6. The goal is to design more durable connections and speed up the construction process.

Fig. 6. Parts from a system of male and female connectors (Source: Rittironk 2021); CC BY-NC-ND 4.0

These prototypes were built and fitted into the bamboo culms, but no structural tests were performed to validate the strength capacity of these pieces, which allows for further investigations. The focus of this research was to validate the compatibility of the metal parts with the culms.

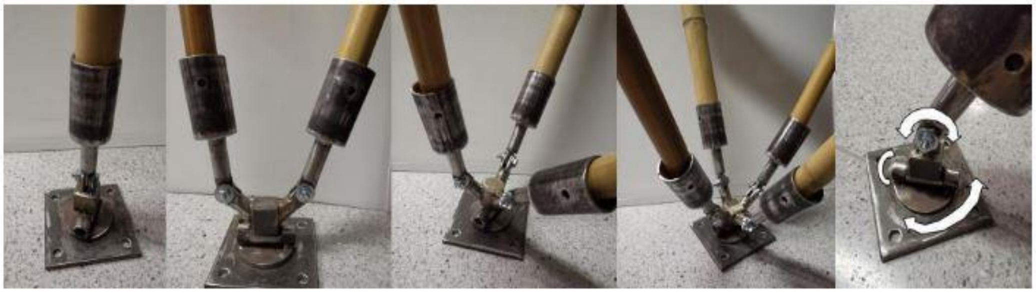

Fig. 7. Fit test between the metal and bamboo parts(Source: Rittironk 2021); CC BY-NC-ND 4.0

A recent proposal of a metal connections presented loading capacity tests. This study showed satisfactory results for this category and proved to be more resistant than traditional bolted connections. The test was performed with 3 types of metal connections for the manufacturing of a spatial truss, using the *Bambusa pervariabilis* culm species (Paraskeva *et al.* 2019).

These authors present a connection joint in different bamboo culms through screws and metal plates. Through this system, it is possible to build complex structures such as the lattice beam presented.

For the above-mentioned connection, an investigation was carried out using the foundation zone technique, with the possibility of minimizing the pecking and cracking of the bamboo bars. The idea was to create a zone below the insertion of the bolts with a softer material, *e.g.*, fibers. Using this method, a reduction in stiffness was observed when embedding the parts (Mouka and Dimitrakopoulos, 2021).

The method used by Paraskeva *et al.* (2019) used the culm that was already pre-drilled for the installation of the bolts and other thatches drilled during the installation of the connection. In this way, it was concluded that due to the installation of metal hose clamps, the pre-drilled samples did not suffer disruption in the embedment area.

The use of these metal clamps has been quite common in bamboo connections. For example, Moran and García (2019) addressed not only the proposal itself, but also performed a series of laboratory experiments to obtain the resistance parameters. The goal of the authors was to develop a lightweight connection that would resist shear, transmit moment, simple manufacture, and more important, to be easily adopted by the industry. Three prototypes with different configurations were tested, including one with internal mortar filling, a simple direct solution, however it made the structure too heavy.

The results obtained in the tests were compared to bolted connections, ranging from 30% to 250% in stiffness. However, they are handmade, and it is not possible to know if it can adapt when applied to a different bamboo species than the one used in the experiments (Moran and García 2019).

Villegas *et al.* (2019) constructed a bamboo truss from the *Guadua angustifolia* species in 3 m modules in combination with metal parts. The purpose of this structure was to replace traditional trusses to support floors and roofs in prefabricated housing. The connections were formed by metal clamps screwed in two points, *i.e.*, a screw that adjusts the clamps around the bamboo culm, and another screw that connects the metallic clamp to the bamboo slat. It is these slats that connect the two main culms and structure the truss.

For the strength tests, both traditional screws and drywall screws were used. The authors realized that it would be necessary to use two screws in each clamp. This installation is easily performed, even in a prefabrication process, preventing the compression on the circumference of the part to be reduced, which consequently prevents longitudinal failure (Villegas *et al*. 2019). At the end of all experimentation stages and tests of the 4 different prototypes with different screws, it is suggested that further investigation is still needed from the strength standpoint. In addition to the installation of the two mentioned screws, it was also necessary to insert additional bamboo slats to achieve an even greater resistance of the component.

Another way to connect bamboo culms is through the use of only metal clamps, as shown Fig. 8. This type of connection can easily be incorporated into a structural system. However, it is necessary that these clamps be installed and adjusted individually in each one of the bamboo culms.

Fig. 8. Proposal connection by Hu *et al.* (2021); CC BY

This type of connection was investigated by other researchers to improve the proposal, but an ideal final result has not yet been obtained. In some cases, the metal clamp was not present in the initial proposal of a connection, but after the strength tests, it was incorporated as a solution to avoid the appearance of cracks in the bamboo culms (Padovan 2010; Barnet and Jabrane 2019; Mouka and Dimitrakopoulos 2021; Lao 2021).

Reinforced connections with filler

The third classification is reinforced connections with filler. These are characterized by bolted connections, but the bamboo culms are internally filled with some expansive material, *e.g.*, mortar. This way, the joints become very resistant and durable, especially in terms of their shear and tensile properties. The negative point of its use is the fact that the bamboo culms, as a result of being formed by internal fibers, can "detach" from the filling, losing its resistance properties. Caution is also needed when filling the culms so that there is not an obstruction in the holes drilled in the culms (Hong *et al.* 2019).

Richard *et al.* (2017) developed a connection adopting this typology. It makes use of filling the hollow parts of the bamboo culms with concrete grout. The purpose of this solution was the reconstruction of buildings in a Filipino community after an earthquake in 2013. Because it represented a real need for installation in a community, the authors realized the need to perform a virtual simulation for structural analysis. To this purpose, the software RISA - 3D was used, which presents the entire designed, which shows the recommendations for foundations points.

Awaludin and Andriani (2014) presented an investigation into the various proposals identified for bamboo joints, including the one shown in Fig. 9. This illustrates one of the ways of making the concrete filling inside the culms. In this example, the authors used cement mortar. In addition to this material, steel plates and threaded bars were also used to ensure the connection between two different culms.

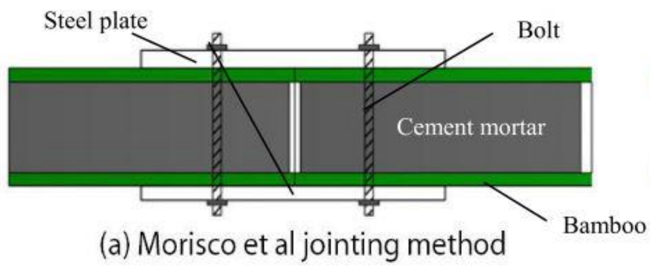

Fig. 9. Reinforced connection with cement mortar filler analised by Awaludin and Andriani (2014); CC BY-NC-ND 3.0

Even though investigations on this connection category are needed, it is still a widespread model, especially in South American countries, *e.g.*, Colombia. According to Correal *et al.* (2021), this type of connection can be imprecise, since it depends on the interaction between the bamboo parts, the filler, and the metal parts. This factor is not fully understood.

These same authors developed a model that, within the analyses of the prototypes in laboratories, generated results within the recommendations of the Colombian National Code NSR-10. The tests performed sought to analyze the behavior of the connection in relation to the shear planes/stresses. This connection is composed of bamboo culms, filled with mortar and connected by metal bolts, being tested in several positions to assess the strength of the entire structure.

The authors observed that the prototypes performed with the parts coming from the base of the bamboo culms presented a higher strength than those built with parts from the middle and top. The capacity of the connection increases with lower inclinations, *i.e.*, the loads applied parallel to the longitudinal direction (a 0° loading) were considerably higher than when perpendicular (a 90° loading). This variation was also attributed to the fact that the material was raw, and some variation was already expected (Correal *et al.* 2021).

In this research, the influence of the screw diameter was also analyzed. Two different diameters were studied: 9.5 mm and 15.9 mm. It was possible to see that with larger screws there were better results in terms of the strength compared to the smaller screws. The exception was with the screws installed parallel to the bamboo fibers. In this last case, the result was not affected neither by the diameter of the screw nor by the distance between the nodes (Correal *et al.* 2021).

Another experiment proposed by Wang and Yang (2020) showed an investigation of a metal connection formed by bolts, with and without internal concrete filling, seeking to understand the influence of this filling on the connective system. The connection is based on the composition with metal plates.

The authors presented how the prototypes were analyzed and tested. Three different patterns were developed, the first with one bolt, the second with two bolts, and the third with two bolts plus internal concrete filling. Then the authors showed an elevation of the drawings design.

In the prototypes without filling, the authors observed that the distance between the bolts determined the deformation of the part. The rupture of the part initially occurs internally, *i.e.*, not visible, and after that, the bar breaks without warning. The failure always occurred vertically in relation to the bamboo piece and from the center of the bolt installation. With this knowledge, the author proposes a 4th model, now with the installation of a metal washer aiming to prevent this failure, that was also not effective in solving this issue. (Wang and Yang 2020).

As final conclusions, the authors state that the application of concrete filler was effective in terms of improving the results and the strength capacity of the connection. This can postpone the observed bolt hole from failing and increase the ultimate load by up to 82%. However, there were some differences between the simulation results and the ones observed experimentally, being either higher or lower in relation to each model. The authors attribute this to the fact that the material is natural and has organic variations in its composition, suggesting further analysis before any of these connections can be effectively used (Wang and Yang 2020).

Technology Associated with Parameterized Connections

In building construction, the use of technology and computerized models has already offered many benefits. In this review, it was observed that for bamboo connections in structural systems, there are already some proposals based on technology that seek to make construction with this material more feasible.

The first research found with this technology was entitled BIM Bamboo, from 2017 (Lorenzo *et al.* 2017). Although a formal proposal for a connection is not presented, a scan of the parts was developed through the use of the building information modelling (BIM) system. In this way, one has the digitization of both the geometric physical composition and the mechanical properties. Therefore, with this digital information, it is possible to associate it with other computer software to develop a more efficient design based on real data (Lorenzo *et al.* 2017).

This research gave rise to another work that shows and analyzes all the properties and information that was possible to obtain using the same process as above for the scanning of 25 bamboo culms. The conclusion was that it is possible to design with these pieces and propose new connections in a more technical and targeted way with the use of these technologies (Lorenzo *et al.* 2019). Even so, no research studied in this paper presented results for a definitive connection.

An example is the research developed by Wu *et al.* (2020), in which the use of augmented reality, associated with 3D printing and the BIM modeling system, was proposed. The researchers tested numerous scanning equipment and developed an application for use on cell phones (machine learning) that allows for the reorganization of some aspects of the bamboo culms. This research was also inspired by the application developed by Lorenzo *et al.* (2017).

In this way, the authors created a building system based on two modular pieces that generated a connection. An important feature of this design is that it allows adjustments on the sides, so it is possible to fit to different diameter bamboo culms. In addition, a 3D printer is used to print the two parts separately and then one is connected to the other with metal screws. Each has a different color for easy assembly, *i.e.*, red or white (as shown in Fig. 10).

Fig. 10. 3D connections proposal by Wu *et al.* (2020) CC BY 4.0

Another interesting aspect of this research was that, through the development of a mobile application, it is possible to assemble and organize a structure. Moreover, through this cell phone application, it is also possible to understand the step-by-step procedure of the assembly, in order to facilitate even more of the whole construction process. This process is presented in Fig. 11, and the last image is the final result of this construction as an example of the possibilities.

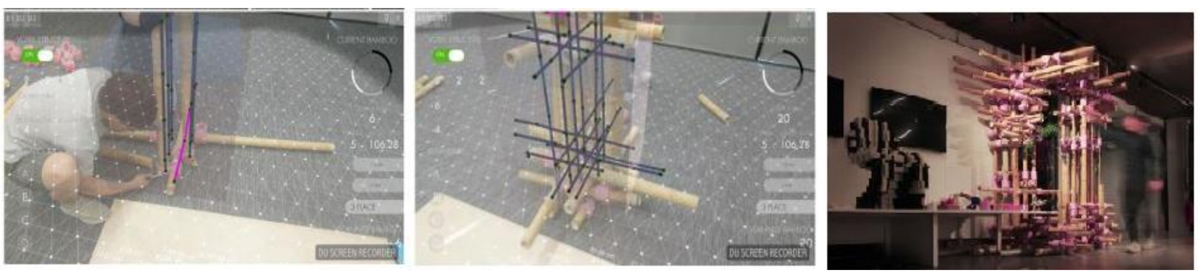

Fig. 11. Assembly method using augmented reality and the finished prototype (Source: Wu *et al.* (2020) CC BY 4.0)

Initially a single node was worked on so that the connection could be adapted and disseminated in other structural compositions. After the design, through the use of a specific software, an analysis was made to determine the stresses acting on the nodes. For the printing of the prototype, a biodegradable filament of polymers originating from vegetables was adopted.

For the manufacturing, the authors proposed the association of the connection with metal parts and screws. A small-scale model was assembled, using a small diameter bamboo species, but physical strength tests and the fabrication of a large scale structural were not performed.

The most recent experience found was a publication in the 2021 *Composite Structures* journal, under a partnership between the University of Brussels and the Composite Construction Laboratory (CCLab) of the Federal Polytechnic School of Lausanne, Switzerland. This model was composed of a removable clip connection, which made it highly standardizable and adaptable, to be integrated into the European construction market (Wassenhove *et al.* 2021).

According to the authors, this connection was developed to assemble pyramidal structures from bamboo culms that are 30 mm to 60 mm and have a wall thickness up to 4 mm. Each clip can be printed in a specific way for each culm selected for the structure and is adaptable to distinct species.

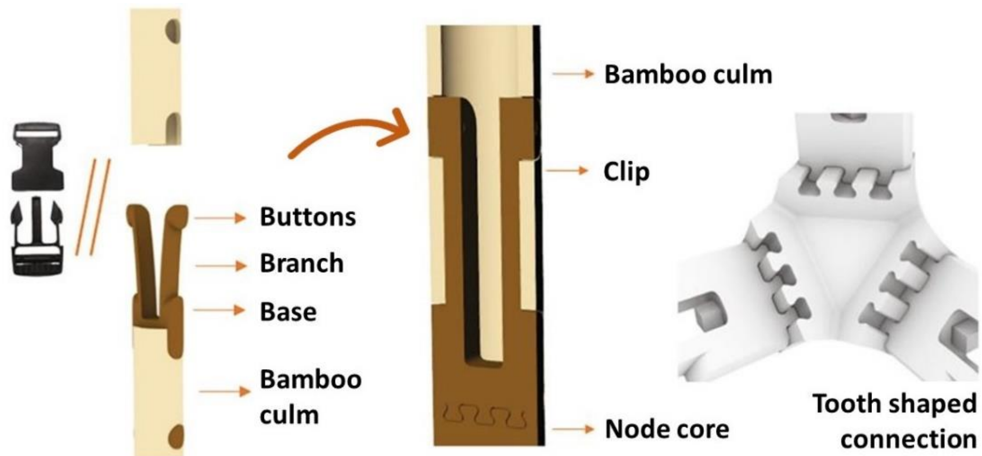

Fig. 12. Clipping mechanism of the proposal developed by Wassenhove *et al.* (2021), CC BY-NC-ND 4.0

The interest of this proposal is the materials as well as the utilization of a parametric software for its manufacture. For the printed connection, besides 3D printers, a biocomposite of filaments of continuous charcoal fibers was also used. The inspiration came from quick release buckles (as shown in Fig. 12). The buttons are attached to holes drilled directly into the bamboo culms; the branches connect the buttons to the base, which in turn is attached to the end of the second bamboo culm.

Since the bars are just fitted into the culms, it is not necessary to remove any material, and the same piece can be reused as long as the new culms have a compatible dimension, allowing a clearance of 0.4 mm. However, this error rate depends directly on the precision of the equipment to be used for printing.

In the resistance test stage, 8 different samples were tested, and the last one had the best result, *i.e.*, was more resistant than the others. This result was due to minor modifications in the clip. The difference between this clip and the others is the association of bolts and metal clamps to the buttons of the connections. A greater fragility of the connection at failure was observed, since the internal configuration of the bamboo culm is formed by longitudinal fibers.

In 2020, Brazilian researchers developed a proposal for connecting structural systems of lightweight steel bars and a non-orthogonal 3D design. More than one software was used in the whole process from analysis to modeling and parameterization. The idea was that it could be customizable for the structure shape and tubular bars. The connection was divided into 2 parts: first, the global definition of the contact surfaces, supports, and fitting angles; and second, the definition of the geometry of the parts (Oliveira *et al.* 2020).

Although the system proposed by the Brazilian researchers was not specific to bamboo, it follows the same principle of connecting tubular hollow structural systems. Therefore, there is a possibility of adaptation and/or inspiration to bring the proposal to the universe of bamboo construction. In this case, the researchers also made use of parameterization and software that has also been mentioned in international research, *e.g.*, Rhinoceros 3D (for modeling and parameterization) and the Karamba plug-in (for structural analysis).

The Use of Wood Members as Connections of Bamboo Culms

Through this same review it was also possible to identify one more classification of connections: Connection with the use of wooden dowels. A Brazilian example of this type of connection was proposed by Pinto (2019). The objective of this proposal was the construction of a structure of vacant beam, associated with the development of a metal connection for the construction of a nursery.

The washer is welded onto the end of the threaded bar and then a hole of the same gauge is made in the center of the octagonal pieces. All the beams were assembled on the ground, so that the structural system could then be composed. During this process, it was necessary that some adjustments were made in relation to the dowel so that the structure did not break.

At the end of the tests carried out by the author, he found that there was difficulty in assembling the structure, since it requires the installation of many parts. It was also needed that each one of the connections systems were made individually for each culm. At the same time, an advantage of this proposal is the fact that it is not an expensive proposal to produce, although the cost of producing the whole system was higher than expected by Pinto (2019). Therefore, the author proposed that improvements are still needed to be associated with this design.

Another proposal that can be classified in this way was developed by researchers in Peru (Barnet and Jabrane 2019; Barnet *et al.* 2020). These authors proposed a pre-molded piece of eucalyptus wood, which fits internally to the bamboo culms. Thus, it is possible to assemble the entire connection on the floor before composing the structural system. Two ways of using eucalyptus wood as a connector are described. The first is by inserting a long piece of round wood inside the culms and connecting them in parallel (Fig. 13). This technique requires the use of intermediate screws to assist in anchoring the culms. It is important that the bamboo culms selected for this structure are cut close to the nodes. This helps prevents the disruption of the fibers from the bamboo culms.

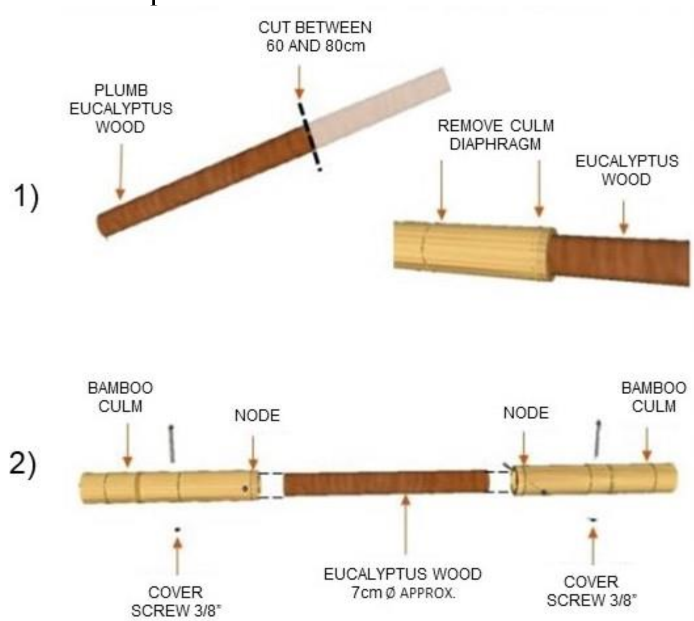

Fig. 13. Connector using plumb eucalyptus wood in parallel presented by Barnet *et al.* 2020, CC BY-NC-ND 4.0; edited by the authors, 2023.

The construction of these connections is divided into two main parts. First, it is necessary to make a cut in the selected plumb eucalyptus wood, so it is possible to verify that it has the necessary diameter to fit into the culms.

Subsequently, two bamboo culms are fitted parallel to the end of the plumb wood and fixed with 3/8 screws, transversely across its diameter. Therefore, it is possible to guarantee the locking of this internal connector. Since this model of connection involves few parts and is made from easily available materials, the authors claim that it is a cheap and easy way to assemble the connection (Barnet *et al.* 2020).

Another connection proposal presented by the authors connects a bamboo culm perpendicularly (Fig. 14). This connection allows the culm to be fixed to wooden beams or other concrete structures in order to form a structure. The assembly is made in three stages. First, the eucalyptus wood has to be cut as shown in the previous one. Then, a rectangular piece of OSB wood is attached to the plumb wood using a 15-cm long metal bar. This is the main design of the connector shown. Then, this part is installed inside the bamboo culm and secured using drilling screws, preventing slippage between the pieces. The third step is to install the joint on the desired structure, which could be a beam or a slab, for example (Barnet *et al.* 2020).

The interesting thing about this system is that it allows the bamboo culm to be connected perpendicularly to a structural system, unlike other proposals presented. According to Barnet *et al.* (2020), this has also proved to be a cheap and easy-to-assemble connection. A few precautions are necessary, such as ensuring that the eucalyptus wood fits snugly into the culm. This is a major challenge for all research on this subject, given the main irregularities that bamboo culms naturally present.

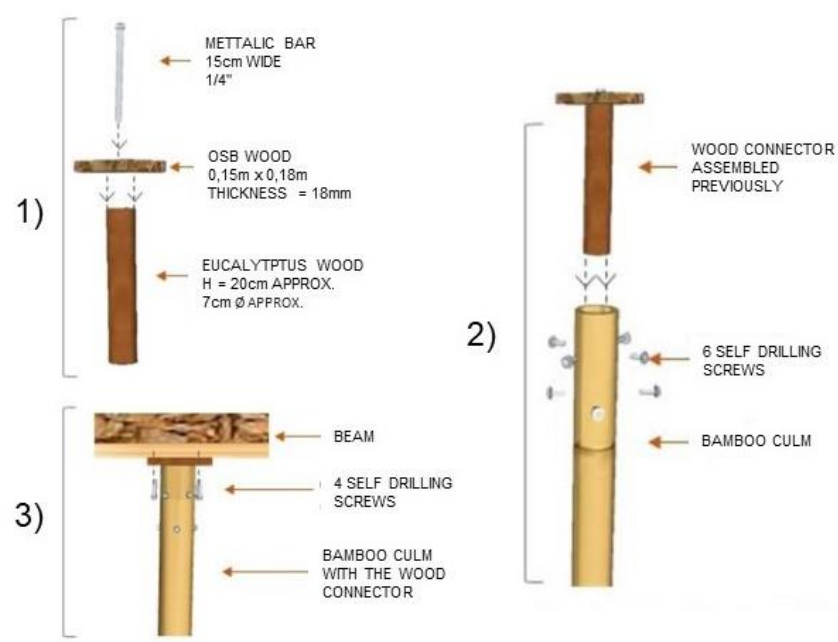

Fig. 14. Wooden connector perpendicular to the bamboo culm presented by Barnet *et al.* 2020, CC BY-NC-ND 4.0; edited by the authors, 2023.

Barnet *et al.* (2020) also presented other forms of bamboo joints using wooden connectors, but these two models were selected to exemplify this category. They are examples that can be found more commonly in architecture that uses this material as the structural system, especially in South and Central America.

DISCUSSION

An interesting contribution of this systematic review was the understanding of connections of raw bamboo structural systems as categories. In other words, it is possible that the materials that are researched for this function are repeated, but it is the creativity of their combination and proposal that differentiates them. Most authors present solutions for traditional simple screwed connections. This type of joint has already proved to be fragile. It is possible to state that technology and the industrialization process allow for new proposals.

Even if there is no irrefutable solution, it is interesting to note that there are joint proposals more suitable depending on the demanding type of structure. Trusses and geodesic structures, for example, require connections that allow different angulations and a more complex joint. Some even are composed of more pieces, as in the case of the proposal elaborated by Wassenhove *et al.* (2021). Meanwhile, the traditional system, beams and columns, allows for a more simplified angulation.

Recent studies have been concerned with the parameterization of these connections. Through the use of 3D printing, parts can be produced and also considered in the designs from their beginning. The development of these structures associated with BIM, could represent a diffusion in the use of such systems in civil construction.

None of the authors presented a conclusive result of the effectiveness of their proposal. However, all of them have potential to be developed and function properly for is purpose. Even so, among all the works presented, it is possible to notice that there are connections more expensive in production than others. This may also depend on the type of bamboo culm structure it is intended to build. The greater the number of metal parts involved, as in the case of metal plates and clamps, the higher the cost would be. Another impact factor in this matter is the ability of the joint to adapt to the variety of diameters of bamboo culms found within the same species.

FINAL CONSIDERATIONS

The heterogeneity of bamboo members in relation to their diameter and central axis is the primary problem to be raised on this topic. There is great difficulty in connecting these elements, primarily due to their organic nature and the heterogeneity of the internal thickness of the walls. Another point observed by the authors is that there is low strength in terms of parallel-to-fibers splitting and thus, every structural member needs to be carefully analyzed before any drilling or alteration of its original shape can be undertaken. Therefore, it is possible to state that the subject is still open for research and proposals of connections for structural systems using bamboo as a raw material. So far, there is no satisfactory proposal easy to industrialize, that is flexible, and that can be widely adopted by the construction industry.

At the end of this investigation, it is possible to state that the connections between bamboo culms can be classified into 5 categories: Bolted connections; Steel member connections and Steel plate connections; Reinforced Connections with filler; Parameterized connections, and; Connections with the use of wooden dowels.

All the proposals discussed here have in their objectives the search to meet a demand, but the conclusion of the authors themselves is that more experimentation and research is still needed to more precisely determine their reliability and effectiveness. There is a great leap in the bamboo construction process with the incorporation of advanced software. This method is becoming more and more widespread in the daily use of projects in building construction, and thus seeks to spread its commercial use.

An original example brings a general new perspective on the way to connect bamboo hollow tubular members. Several aspects are taken into consideration, *e.g.*, the desired elimination of adhesive. The glue generally used is not necessarily an organic or unpolluting component.

Despite the available technology pointed out in this research, this does not represent a higher quality or a better strategy for the development of research related to bamboo culm connections. These connections are still under development and have been less tested in relation to the others, as wood, steel, and concrete. Even so, there is a common intention in all the research analyzed to disseminate the use of this type of connection in order to achieve numerous economic and environmental benefits, ease and speed of manufacture, and high quality and durability.

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