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Review

Advances in Connection Techniques for Raw Bamboo Structures—A Review

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Abstract: While bamboo's sustainability and impressive mechanical properties make it suitable for structural use, its application is hindered by challenges in connection systems. Bamboo's hollow, thin-walled nature, dimensional variations, and anisotropic properties complicate connection design. Despite numerous studies and proposed connection types, a consensus on preferred bamboo connections remains elusive. Ideal connections for raw bamboo structures should be robust, economical, practical, simple, and easy to assemble. This paper reviews 62 scientific papers from the Scopus database published between 2003 and 2024, along with additional relevant references. It identifies research gaps, recommending further studies on bamboo connections considering factors like species, harvest age, treatment type, and node location. The analysis of failure modes and long-term behavior is essential to anticipate and mitigate risks associated with bamboo connections, ensuring durability, and minimizing maintenance needs. Lastly, developing universally accepted standards and codes for bamboo and bamboo connections is crucial for enabling their widespread adoption in the construction industry.

Keywords: bamboo; raw bamboo; bamboo culms; connections; bamboo structures

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1. Introduction

With growing concerns about climate change, designers, engineers, and architects are increasingly seeking renewable and sustainable resources. A material is deemed sustainable if it is created, utilized, and disposed of in an environmentally responsible way that satisfies current needs without endangering the capacity of future generations to satisfy their own [1]. Bamboo, readily available locally and requiring minimal treatment, stands out as a renewable and sustainable material [2].

Bamboo is the fastest-growing woody plant in the world, beating most other species in growth rate, and earning its status as a renewable resource [3,4]. There are some bamboo species that grow as much as 7.5 to 40 cm a day; one notable record is 1.2 m in a single day recorded in Japan [5,6]. Some commercially used bamboo species have a relatively quick maturation period of 4 to 5 years [7]. Bamboo is regarded as a renewable resource since it can be harvested quickly and continues to grow new stems even after the culm or stem is removed [6]. Bamboo also has the ability to be carbon-negative since it absorbs carbon during growth and after harvest [8,9]. Moreover, because it can be grown without the use of fertilizers or pesticides, bamboo is regarded as a low-impact crop. Therefore, compared to conventional crops, bamboo farming lowers soil degradation and water pollution, making it a more ecologically sustainable option [10,11]. Since bamboo's roots are like those of coconut trees—albeit bamboo is in the grass class—it can also endure landslides better than other types of trees. Additionally, these factors may make bamboo a viable substitute for industrial forests [12]. In terms of its physical and mechanical properties, bamboo is lightweight and has better compressive strength than concrete and higher tensile strength than steel [12]. Singh et al. [13] investigated the mechanical characteristics of various bamboo species.

Their findings revealed that *Bambusa nutan* exhibited the highest compressive strength at 98.24 MPa and bending strength at 7.669 MPa. Additionally, *Bambusa tulda* displayed the highest tensile strength at 226.28 MPa, while *Dendrocalamus hamiltonii* demonstrated the highest shear strength at 19.5 MPa. Furthermore, bamboo exhibits a modulus of elasticity approximately 0.84 times higher than wood [14]. Additionally, bamboo density varies across species; *Phylostachys edulis* has a density of 796 kg/m^3 [14], *Bambusa balcoa* has a density of 685 kg/m^3 [15], while the density of *Bambusa vulgaris* ranges from 630 kg/m^3 to 680 kg/m^3 [16]. With the advancement of technology, bamboo can now be treated to prevent insect and fungal attacks [17]. Thus, bamboo has drawn a lot of interest as a viable and eco-friendly construction material.

Raw bamboo, also referred to as full-culm bamboo, original bamboo, round bamboo, or bamboo culm, exists in its natural state with minimal processing or treatment [18]. Widely distributed across Asia, Africa, and South America, raw bamboo serves as structural material forming the primary framework for small- to medium-sized structures such as truss structures for roofs and bridge, scaffolds, and houses due to its high strength-to-weight ratio [19–23].

However, its tension strength perpendicular to the grain is relatively low, given the longitudinal orientation of the fiber [24]. Additionally, its shear strength is relatively low due to the thin culm walls, making bamboo susceptible to splitting [25]. Furthermore, irregularities in its geometry, such as inconsistent straightness and varying diameters, present challenges in connection design for raw bamboo [23,26]. While numerous studies have explored innovative connection methods for raw bamboo, limited applicable standards, design codes, and construction costs hinder the establishment of practical and economical connection methods for raw bamboo structures. These limitations impede the broader utilization of bamboo in the construction industry [18,27–30].

This paper aims to review the current connection designs documented in the collected literature, highlighting the research gaps in raw bamboo connections to guide future studies and applications.

2. Methodology

The relevant literature was gathered to conduct a comprehensive literature review. Our methodology adhered to a systematic approach, as illustrated in Figure 1. Our primary data source was the Scopus database, renowned for its extensive collection of abstracts and citations across various academic fields [31]. Utilizing Scopus, we employed keyword searches with Boolean operators such as AND, AND NOT, and OR to refine our search results [32]. Moreover, Scopus offers advanced search functionalities, citation analysis tools, and author metrics, enabling in-depth investigations, assessments of prior research impact, and the identification of influential authors [33].

The first step in the process involved selecting a combination of general and specific keywords. The general keywords aimed to capture the core theme of the study, which revolved around the "connection of bamboo culms on building structures". Alongside these, specific keywords such as "connections", "bamboo", "bamboo culm", "building", and "structures" were chosen. Employing Boolean operators, these keywords were structured into a search string: connections AND "bamboo culm" OR bamboo AND building OR structures AND NOT engineered AND NOT scrimber AND NOT laminate AND NOT glubam AND NOT composite AND NOT glulam AND NOT "bamboo-based". This search string yielded 154 pertinent documents. To ensure the selection of only relevant studies, advanced search filters were implemented. Initially, the publication year range was limited to 2003 to 2023, resulting in 152 documents. Following this, the search was focused on specific subject areas including *Engineering*, *Material Science*, *Agricultural and Biological Science*, *Environmental Science*, and *Chemical Engineering*, further refining the results to 132 documents. Additionally, the document type filter was configured to encompass articles, conference papers, conference reviews, and review papers, ultimately resulting in 127 documents.

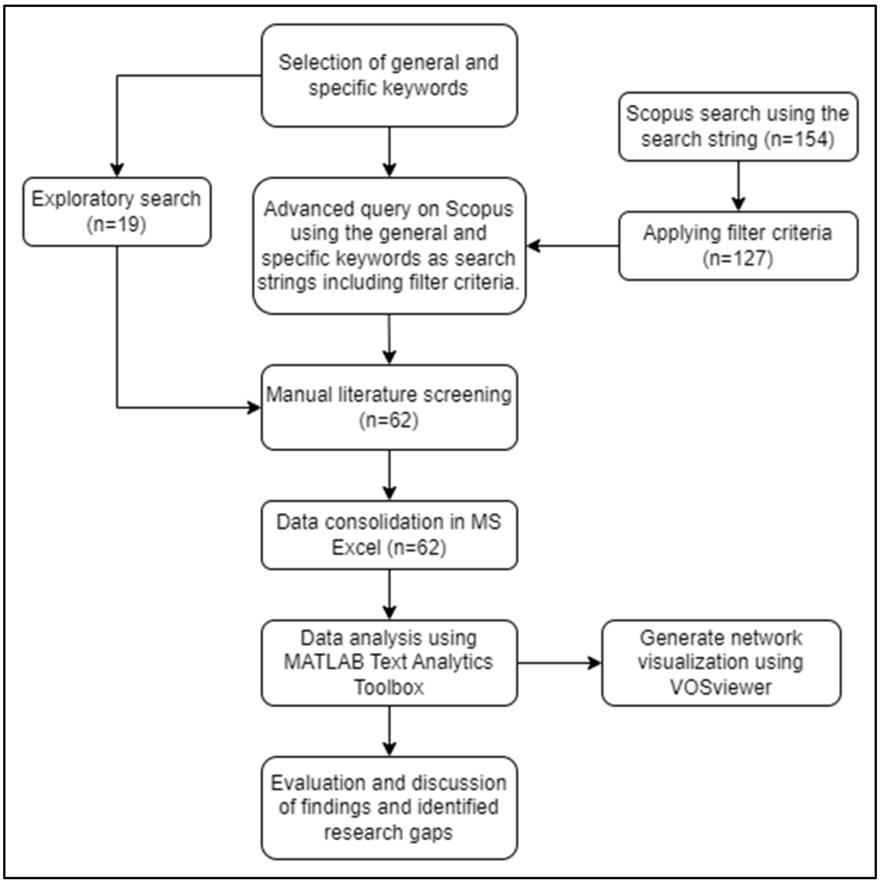


Figure 1. Methodology flowchart.

An exploratory search strategy was employed to locate additional pertinent documents beyond those initially identified through advanced searches. Diverse platforms such as Scopus [34], ResearchGate [35], and Google Scholar [36] were utilized for this purpose. The relevant cited studies in the initially selected documents were also included as part of the exploratory search conducted here. This yielded an additional 19 relevant documents, which were subsequently integrated into the research. Following this, a manual screening process was conducted to meticulously select documents explicitly addressing the connection of bamboo culms in building structures. Documents not discussing the connection of raw bamboo were omitted from the list. This meticulous approach resulted in the identification of 62 documents deemed suitable for systematic review and analysis, ensuring a comprehensive grasp of the subject matter.

The compiled set of 62 documents was organized using MS Excel and then imported into Matlab software (R2023b) for text analysis purposes [37]. Leveraging the Matlab Text Analytics Toolbox facilitated the extraction of textual data from the documents and provided insightful visualizations. These visual representations included word clouds, topic mixtures, and graphical displays illustrating the yearly and country-wise distribution of published papers [33]. Figure 2 illustrates a word cloud generated from the imported documents, prominently featuring the term “bamboo”, underscoring its pivotal role as a sustainable construction material. Furthermore, noteworthy terms such as “connection”, “material”, “structure”, “structural”, and “design” were prevalent in the word cloud, indicating a predominant focus on the structural design of connection material in bamboo structures. This observation is precisely in line with the study’s chosen general keywords.

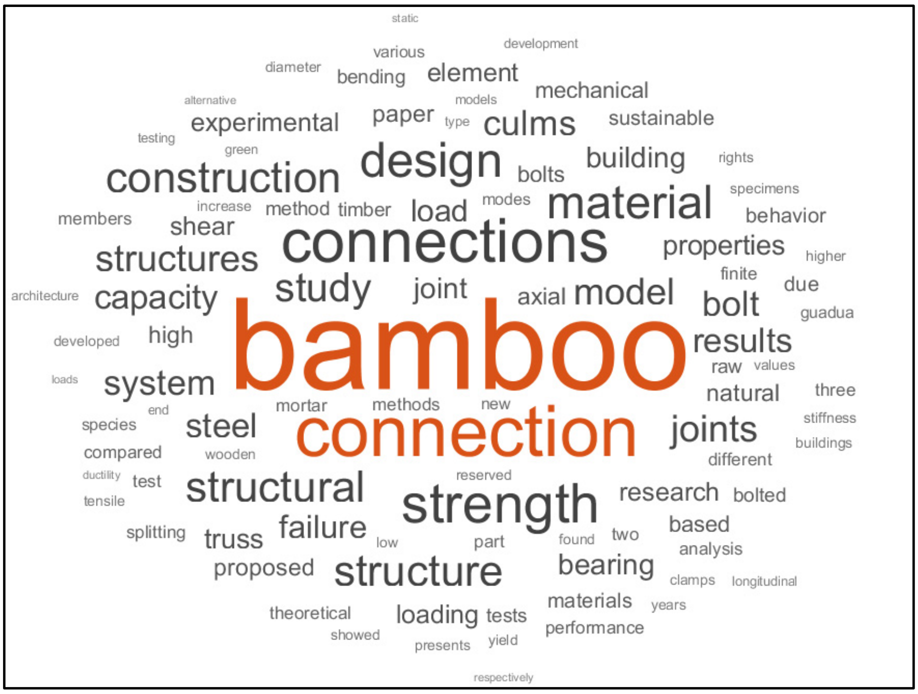


Figure 2. Word cloud.

In this study, we utilized Latent Dirichlet Allocation (LDA), an algorithm designed for topic modeling purposes. Topic modeling serves as a technique to represent each document as a blend of various topics, with each topic comprising a mixture of words [38]. The primary aim is to uncover the underlying themes embedded within each document. LDA, functioning as an unsupervised topic model, possesses the capability to autonomously discern the optimal number of themes or topics [38]. Hence, the process of determining the most suitable number of themes or topics involved evaluating the goodness-of-fit of LDA models with different quantities of themes or topics. Initially, we opted for eight themes or topics. To gauge the effectiveness of the LDA model, we assessed its performance using perplexity, a metric that gauges how effectively the model describes a collection of documents [39]. Lower perplexity values signify a superior fit, indicating that models with lower perplexity are more favorable [32]. Consequently, four (4) themes or topics were selected in this study, as this demonstrated the lowest perplexity, as depicted in Figure 3. Figure 4 shows the word clouds corresponding to each topic, while Figure 5 presents the topic mixtures and probabilities of 62 documents. Additionally, the primary topics identified from these 62 documents are enumerated and visually depicted in Figure 5. Topic 1 (color blue) centers around the study of connections for bamboo construction through modeling, while Topic 2 (color red) delves into the study of the structural load capacity of bamboo joints using a finite element model. Topic 3 (color yellow) investigates the strength of bolt connections through failure analysis of the bolt material, and Topic 4 (color purple) concerns the design of buildings or structures made of bamboo. These four primary topics are discussed qualitatively in this document.

Figure 6 illustrates the distribution of the obtained documents over the years, revealing a clear upward trajectory in publications concerning this subject matter. This trend suggests the topic's timeliness and relevance, possibly indicating a growing interest in sustainable materials within the construction industry. It reflects a response to mounting concerns about climate change and the environmental impact of conventional construction materials like steel and concrete. Figure 7 depicts the distribution of documents by country, highlighting China as the foremost contributor to publications on this subject. With the most abundant bamboo resource globally and expansive bamboo plantations [40], it is no surprise that China leads in bamboo research.

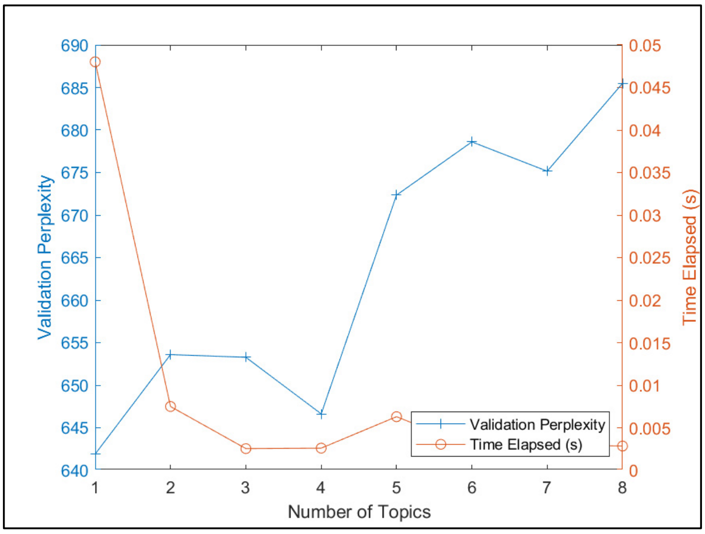


Figure 3. The number of topics.

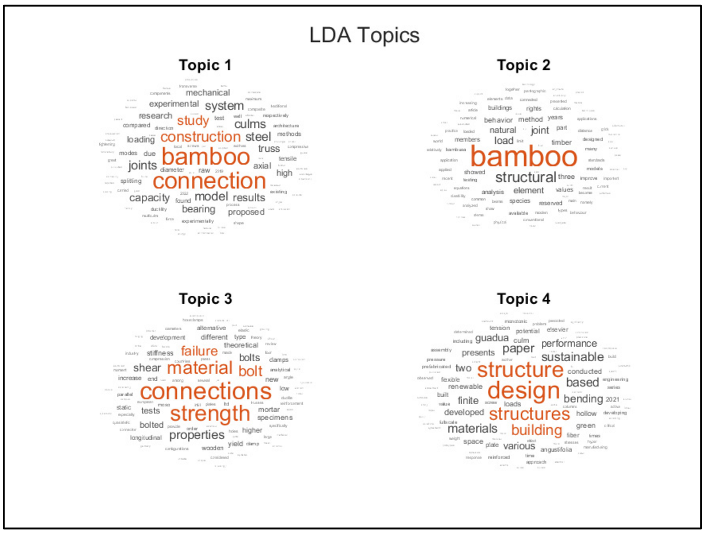


Figure 4. Word cloud of each topic.

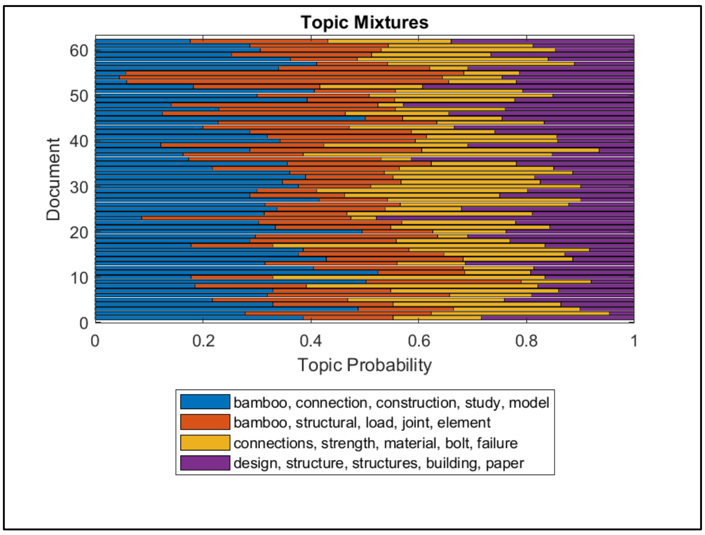


Figure 5. Topic mixtures.

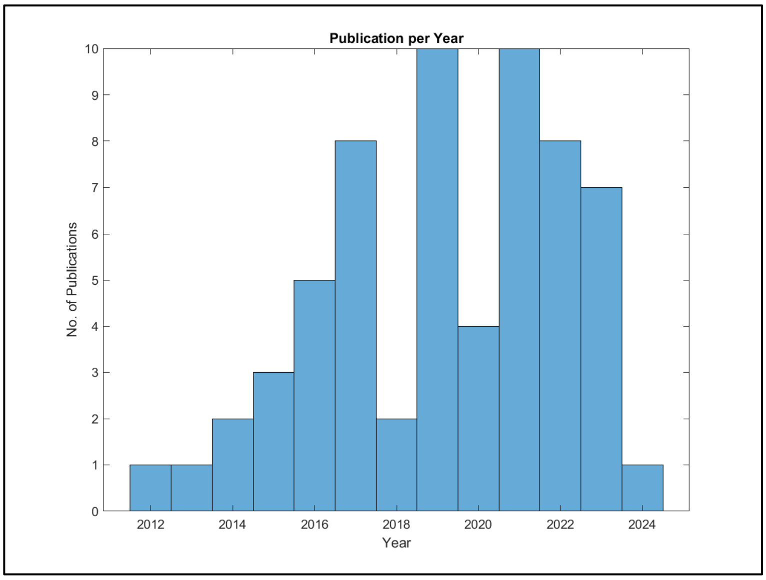


Figure 6. Yearly distribution of published papers.

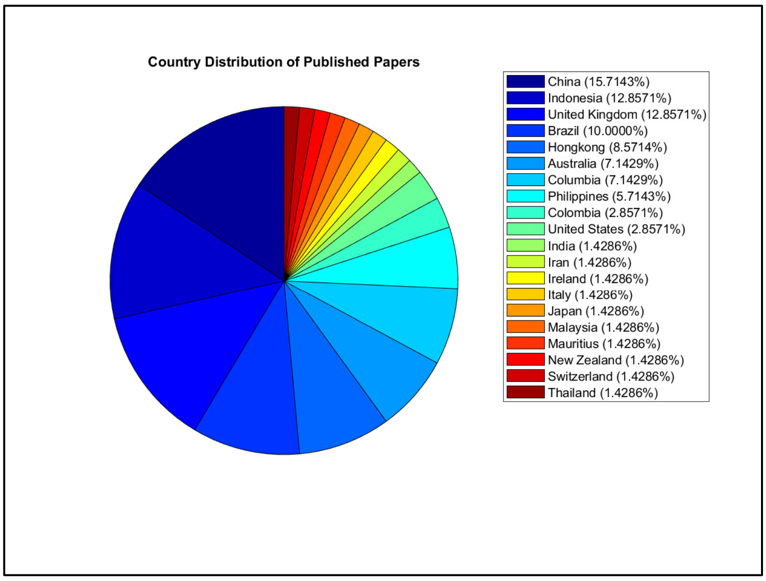


Figure 7. Distribution of published papers per country.

VOSviewer [41] was utilized to create a network visualization, depicted in Figure 8, which illustrates the connections among elements within the dataset, composed of consolidated literature. In this paper, the elements correspond to keywords, represented as nodes, while the connections between nodes are depicted as links. In the visualization, the keyword "bamboo" emerges as prominent, echoing the prominence observed in the word cloud generated by Matlab. Figure 8 illustrates that "bamboo" is linked to various keywords such as "sustainable materials", "bamboo structures", "connection", "design", "joints", "buildings", "building materials", and "natural materials". This suggests that the literature obtained emphasizes bamboo as a natural and sustainable building material suitable for constructing bamboo structures, with particular emphasis on designing the joints and connections within these structures.

The visualization tools presented thus far offer a convenient way to quickly grasp the subject matter discussed in the acquired documents. Integrating these interpretations can help identify knowledge gaps and support assertions about trends, gaps, and the necessity of conducting this study.

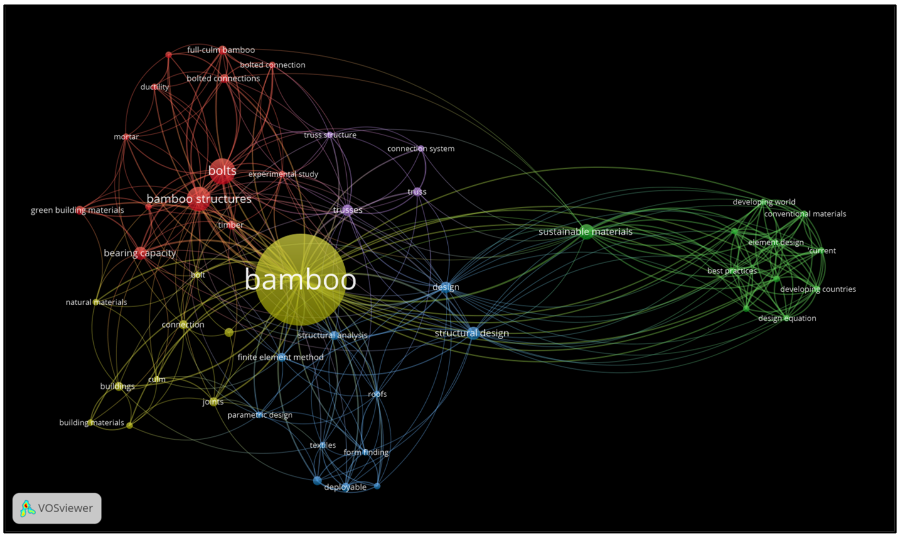


Figure 8. Network visualization generated by VOSviewer on 10 March 2024.

3. Results and Discussion

The objective of this paper is to review the current connection designs documented in the collected literature, which encompasses the various bamboo species used by researchers in studying different bamboo connections, the classification of raw bamboo connections, and the standards and codes applied in raw bamboo connections. Additionally, this paper presents the research gaps in raw bamboo connections identified by reviewing the collected literature, aiming to provide guidance for future studies and applications.

3.1. Bamboo Species

Bamboo is widely utilized due to its versatile applications. In regions such as Asia, bamboo shoots are highly valued as a food source, while the culm serves various purposes. Young, flexible culms are crafted into woven items like baskets, trays, and wall coverings, while mature culms are employed in constructing affordable housing, tool handles, and furniture [42]. Renowned as the world's fastest-growing woody plant, bamboo outpaces most other species in growth rate, earning recognition as a renewable resource [3,4]. Consequently, there is growing interest in exploring bamboo as a structural material for construction, providing an alternative to timber, which requires a longer harvesting period, and conventional materials like steel and concrete, known contributors to carbon emissions.

Bamboo exhibits a broad geographical distribution, with native habitats spanning Africa, Asia, and the Americas, thriving in humid tropical and subtropical regions. Remarkably adaptable, bamboo species also thrive in colder temperate climates across Europe, Asia, and North America. There are approximately 1200 to over 1600 bamboo species present in the world [42]. Traditionally, bamboo species favored for construction possess attributes such as abundant local growth; robustness, with diameters typically ranging from 50 mm to 200 mm; relatively straight growth patterns; rapid maturation within 3 to 5 years; moderate resistance to pests and fungi; and reduced susceptibility to splitting [43]. Table 1 presents a list of bamboo species commonly used as structural construction materials worldwide.

Table 2 displays the various bamboo species utilized by researchers identified in this study. This paper employed species identification, as depicted in Table 2. In the 62 documents collected, a total of 15 bamboo species were utilized. As depicted in Figure 8, Moso bamboo (S-12) emerged as the most frequently utilized bamboo species by researchers. These researchers were from Colombia, China, Hong Kong, Ireland, and the United Kingdom, as outlined in Table 3. While there is no explicit mention of bamboo growth in Ireland and the United Kingdom, it was sourced from a bamboo supplier. Notably, Moso bamboo is extensively cultivated in China, which represents the primary contributor to publications on this subject, as depicted in Figure 9.

Table 1. List of bamboo species commonly used in construction as structural material. Data adapted from [43].

Scientific Name (Local Name)	Areas Found	Diameter (mm)
Guadua angustifolia Kunth	South America	120–160
Dendrocalamus strictus (Calcutta)	Asia	25–80
Bambusa vulgaris	Africa, Asia, South America	80–150
Phyllostachys edulis (Moso)	Asia	120–180
Dendrocalamus asper (Petung)	Asia, South America	80–200
Bambusa blumeana (Spiny/ThornyBamboo)	Asia, Asia–Pacific	60–150
Gigantochloa apus	Asia	40–100

Table 2. Bamboo species used by researchers identified in this study.

Species ID	Scientific Name (Local Name)	Reference
S-1	*Bambusa blumeana* (*Spiny/Thorny/Ori bamboo*)	[44,45]
S-2	*Bambusa pervariabilis* (*Kao Jue*)	[21,22,29,46–48]
S-3	*Bambusa multiplex* (*Cendani bamboo*)	[49,50]
S-4	*Bambusa ssp*	[51]
S-5	*Bambusa vulgaris*	[44]
S-6	*Dendrocalamus asper* (*Petung*)	[44]
S-7	*Dendrocalamus merrillianus Elmer*	[44]
S-8	*Gigantochloa atroviolacea* (*Wulung*)	[19,26–28,45,52–54]
S-9	*Guadua angustifolia Kunth*	[20,23,55–60]
S-10	*Phyllostachys aurea*	[61–65]
S-11	*Phyllostachys bambusoides* (*Madake*)	[30]
S-12	*Phyllostachys edulis/Phyllostachys pubescens* (*Moso*)	[21,56,61,63–73]
S-13	*Phyllostachys iridescens* (*Hong*)	[74]
S-14	*Phyllostachys nigra Boryana*	[75]
S-15	*Phyllostachys vivax* (*Kara*)	[76]

Table 3. Distribution of bamboo species across the countries identified in this study.

Country	Species ID														
	S-1	S-2	S-3	S-4	S-5	S-6	S-7	S-8	S-9	S-10	S-11	S-12	S-13	S-14	S-15
Australia		✓													
Brazil										✓					
Colombia									✓			✓			
China												✓	✓		
Hong Kong		✓										✓			
Indonesia	✓		✓					✓							
India															
Iran															✓
Ireland												✓			
Mauritius				✓							✓				
Philippines	✓				✓	✓	✓								

Table 3. *Cont.*

Country	**Species ID**														
	S-1	**S-2**	**S-3**	**S-4**	**S-5**	**S-6**	**S-7**	**S-8**	**S-9**	**S-10**	**S-11**	**S-12**	**S-13**	**S-14**	**S-15**
Switzerland														✓	
Thailand			✓												
United Kingdom									✓			✓			
United States									✓						

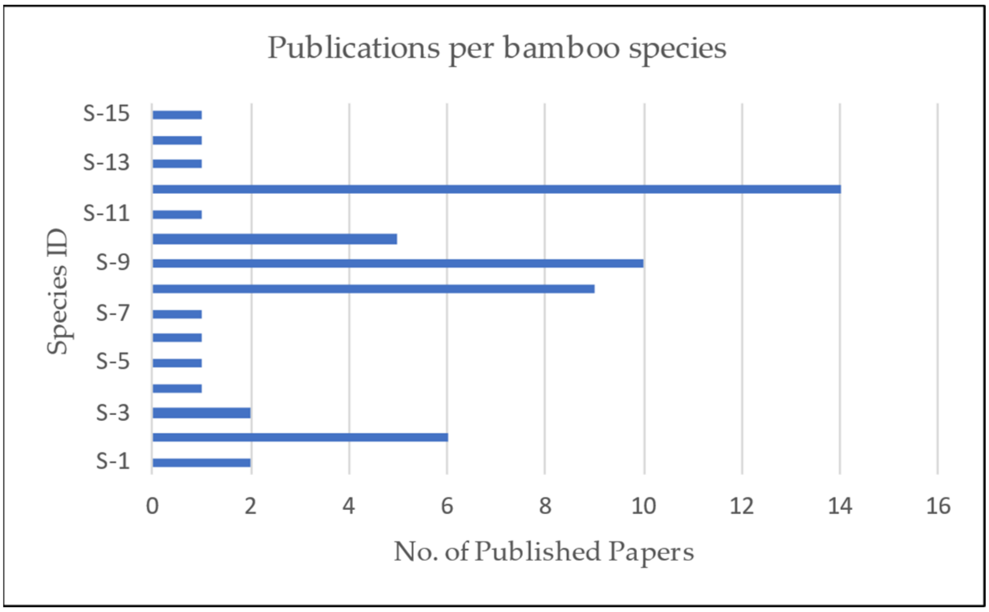


Figure 9. Publications per bamboo species.

3.2. Classification of Raw Bamboo Connections

The emergence of modern bamboo structures is not only attributed to their aesthetic appeal, but also to bamboo's exceptional strength-to-weight ratio and natural flexibility, rendering it suitable for structural applications. However, the overall performance of bamboo structures is significantly influenced by their connection systems [19]. Joint failure jeopardizes the safety and stability of the entire bamboo structure and may result in collapse [70]. Therefore, the design of joints or connections is integral to structural integrity.

The joining or connection of raw bamboo structures has perennially posed a significant challenge in the advancement of modern bamboo architecture [26,74,77]. Raw bamboo's hollow, thin-walled composition, dimensional variations, and anisotropic material properties exacerbate the complexity of designing bamboo connections [23,74,77]. While studies have been conducted on raw bamboo connections, and various connection types have been proposed by researchers, a consensus on the preferred bamboo connection remains elusive. A suitable connection for raw bamboo structures must be not only robust, but also economical, practical, simple, and easy to assemble.

Based on the gathered documents, researchers have categorized raw bamboo connections primarily based on the connector material and the method of connection. Table 4 illustrates the classification of raw bamboo connections, revealing two main categories: traditional and modern connections. Bamboo, being a traditional building material, was historically employed in ancient structures, typically utilizing ropes or mortise-and-tenon joints as connectors, akin to those utilized in timber structures. However, with the advent of modern bamboo construction, there has been a notable shift towards the integration of engineering hardware.

Table 4. Classification of raw bamboo connections according to researchers identified in this study.

Reference	Classification of Raw Bamboo Connections
[24]	1. Traditional Bamboo Connections 1.1. Friction-tight Lashing 1.2. Notched and Pierced Connections 2. Modern Bamboo Connections 2.1. Pierced with Metal Connections 2.2. Concrete-filled Connections 2.3. Capped Connections 3. Emerging Technologies
[77]	1. Traditional Connection Joints 1.1. Lashing Joints 1.2. Mortise–tenon Joints 2. Modern Connection Joints 2.1. Bolted Joints 2.2. Steel Member and Steel Plate Joints 2.3. Filler-Reinforced Joints 3. Other Types of Joints
[78]	1. Traditional Bamboo Connections 1.1. Friction-tight Lashing 1.2. Mortise–tenon Joints 1.3. Other Traditional Bamboo Joints 2. Modern Bamboo Connections 2.1. Bolt Joints 2.2. Clamp Joints 2.3. Other Modern Bamboo Joints
[79]	1. Use of Metal Connections 1.1. Bolted Joints 1.2. Steel Member Connections and Steel Plate Connections 1.3. Reinforced Connections with Fillers 2. Parameterized Connections 3. Connections with the use of Wooden Dowels

In this paper, the authors proposed a slight modification to existing classifications. Bamboo connections are presently categorized into three types: traditional, modern, and hybrid connections. Each of these classifications will be further elucidated in the subsequent section. One addition made by the authors is the introduction of hybrid connections. The recently proposed raw bamboo connections combine elements from traditional and modern connections [57], integrate multiple modern connections [20,23,26,50,80–82], or blend modern connections with supplementary connection components [29,46–48,50,55,68–71,74]. Hence, they are termed hybrid connections. Supplementary connection components, such as sleeves, gussets, and fillers, are components incorporated into modern connections to overcome limitations and bolster overall structural integrity. Referred to as supplementary connections, they cannot function independently as connectors; instead, they must be paired with modern or even with traditional connections, although such partnerships have not been explicitly documented.

Figure 10 delineates the classification of raw bamboo connections according to the authors' framework, while Table 5 provides a description of these connections based on the reviewed literature. Each raw bamboo connection (RBC) is assigned an identification code (RBC ID), with letters denoting its classification: TC for traditional connections, MC for modern connections, and HC for hybrid connections. The numerical component of the RBC ID signifies the specific type of connection within its designated classification, as outlined in Table 6. Table 5 also includes information about the type of structure in which the connection was employed. Additionally, it indicates whether the connector can join two or more culms.

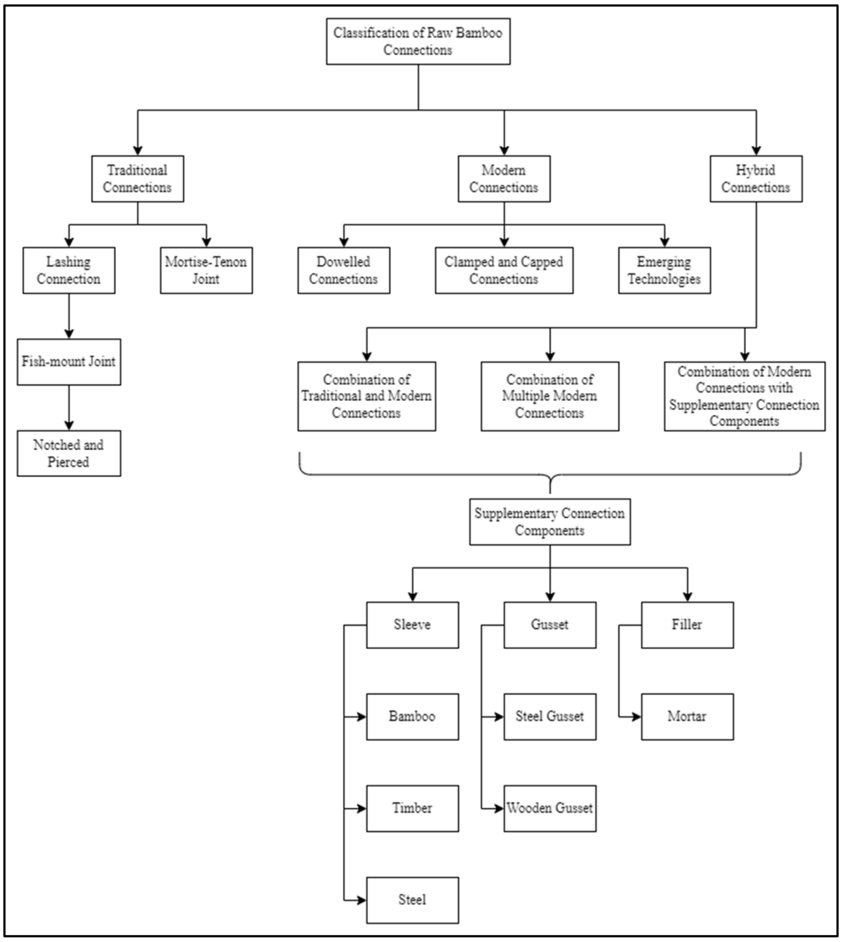


Figure 10. Classification of raw bamboo connections according to the authors of this study.

Table 5. Description of raw bamboo connections.

RBC ID	Description	Structure	Number of Culms Connected		Reference
			Only 2	**2 or More**	
TC-1.1	Bamboo culms, polyester ropes, and bio-composite rings termed Hinged Flexible Connections (HFCs)	Pantographic bamboo space structure, self-supporting bamboo structure		✓	[61,62,83]
TC-1.2	Bamboo culms and flexible hinged lashed joints with textile-based techniques (HFC)	Pantographic hybrid amphitheater structure		✓	[64]
TC-1.3	Bamboo culms and textile moorings	Mobile self-stabilizing structure		✓	[63,65]
MC-1.1	Bamboo culms and steel bolts	*	*	*	[27,30]
MC-1.2	Bamboo culms and metal pins	*	*	*	[56,84]
MC-1.3	Bamboo culms and bolts	*		✓	[54]
MC-1.4	Bamboo culms and dowels	*	*	*	[60]
MC-2.1	Bamboo culms and steel hose-clamps	Temporary bamboo structure	*	*	[76]
MC-2.2	Bamboo culms and steel hose-clamps (termed clamp-culm)	Bamboo truss		✓	[23]
MC-2.3	Bamboo culms and steel clamps	Beam–column		✓	[20,58,59]
MC-2.4	Bamboo culms, steel hoops, steel bolts, and NBR pads	*	*	*	[82]

Table 5. *Cont.*

RBC ID	Description	Structure	Number of Culms Connected		Reference
			Only 2	2 or More	
MC-3.1	Bamboo culms and 3D-printed biocomposite removable connection system	Temporary bamboo structure, furniture		✓	[75]
HC-1.1	Bamboo culms, fish-mounts, and steel bolts	Hypar roof	✓		[57]
HC-2.1	Bamboo culms, steel bolts, and GFRP	*	*	*	[80]
HC-2.2	Bamboo culms, steel bolts and nuts, and steel caps	Frame–ground		✓	[50]
HC-2.3	Bamboo culms, steel hose-clamps (termed clamp-culm), and screws	Bamboo truss		✓	[23]
HC-2.4	Bamboo culms, steel hose-clamps (termed clamp-culm), and steel through-bolts	Bamboo truss		✓	[23]
HC-2.5	Bamboo culms, steel clamps, and drywall screws	Beam–column		✓	[20]
HC-2.6	Bambo culms, steel clamps, and steel through-bolts	Beam–column		✓	[20]
HC-2.7	Bamboo culms, steel bolts, and FRP	*		✓	[26]
HC-2.8	Bamboo culms, steel bolts, and natural fiber (ijuk)	*		✓	[26]
HC-2.9	Bamboo culms, steel bolts, and steel hose-clamps	*	*	*	[81]
HC-2.10	Bamboo culms, steel bolts, and GFRP	*	*	*	[81]
HC-3.1	Bamboo culms, bamboo sleeves, steel bolts, and nails	Column		✓	[57]
HC-3.2	Bamboo culms, steel sleeves, steel bolts, screws, and mortar	Slab–wall		✓	[69]
HC-3.3	Bamboo culms, steel bolts, and mortar	Footbridge		✓	[55]
HC-3.4	Bamboo culms, steel bolts, steel gusset plates, and steel hose-clamps	Truss structure for footbridge		✓	[22,46,48]
HC-3.5	Bamboo culms, steel bolts, and steel sleeves	Frame		✓	[50]
HC-3.6	Bamboo culms, bamboo sleeves, steel bolts, and nails	Beams		✓	[74]
HC-3.7	Bamboo culms, steel plates as sleeves, steel bolts, and mortar	*	✓		[70]
HC-3.8	Bamboo culms, steel bolts, and steel plates	*	*	*	[71]
HC-3.9	Bamboo culms, steel bolts, and mortar	*		✓	[85]
HC-3.10	Bamboo culms, steel bolts, and steel gusset plates	*	✓		[22]
HC-3.11	Bamboo culms, steel bolts, steel gusset plates, and steel hose-clamps	*	✓		[47]
HC-3.12	Bamboo culms, steel bolts, steel gusset plates, steel hose-clamps, and mortar	*	✓		[47]
HC-3.13	Bamboo culms, steel bolts, and mortar	*		✓	[49]
HC-3.14	Bamboo culms, Cendani bamboo bolts (as shear connectors), and mortar	*		✓	[49]
HC-3.15	Bamboo culms, steel bolts, nuts, washers, and steel gusset plates	Footbridge		✓	[29]
HC-3.16	Bamboo culms, steel bolts, wooden clamps, and wooden gussets	*	*	*	[19,28,52,53]
HC-3.17	Bamboo culms, steel sleeves, and riveted joints	*	✓		[51]

Table 5. *Cont.*

RBC ID	Description	Structure	Number of Culms Connected		Reference
			Only 2	2 or More	
HC-3.18	Bamboo culms, steel sleeves, and self-drilling metal screws	*	✓		[51]
HC-3.19	Bamboo culms, Ori bamboo bolts (as connector), and mortar	*		✓	[45]
HC-3.20	Bamboo culms, screws, and steel plates	*	*	*	[66]
HC-3.21	Bamboo culms, wood pegs (sleeves), and steel hose-clamps	One-storey frame structure	✓		[72]
HC-3.22	Bamboo culms, steel sleeves, mortar, and steel rings	*	✓		[73]
HC-3.23	Bamboo culms, steel bolts, and steel sleeves	*	✓		[73]
HC-3.24	Bamboo culms, steel bolts, and steel plates (as sleeves)	*	✓		[73]

* Not indicated.

Table 6. Description of RBC ID.

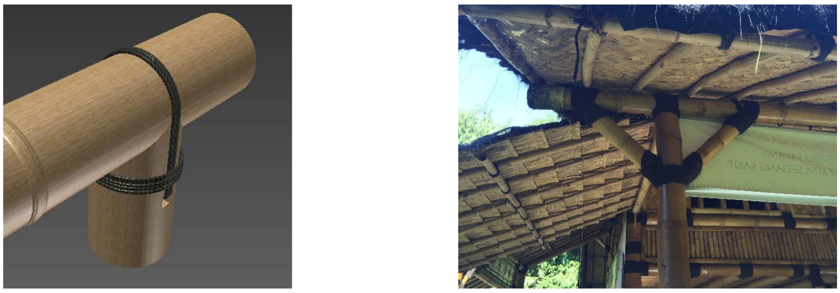
RBC ID	Classification of Raw Bamboo Connection	Description
TC-1	Traditional	Lashing connection
TC-2	Traditional	Mortise–tenon joint
MC-1	Modern	Dowelled connection
MC-2	Modern	Clamped and capped connection
MC-3	Modern	Emerging technologies
HC-1	Hybrid	Combination of traditional and modern connections
HC-2	Hybrid	Combination of multiple modern connections
HC-3	Hybrid	Combination of modern connections and supports

3.2.1. Traditional Connections

Lashing Connections

Lashing stands as one of the earliest methods employed for connecting bamboo, predominantly observed in traditional residential constructions of the past [24,77]. As the term suggests, it involves binding bamboo culms together utilizing an array of materials, including jute, hemp, rattan, dried bamboo pith or strips, palm rope, sisal, and coconut, and has evolved to include wires, metal straps, textile polyester rope, and bio-composite bandages [24,77,78]. This technique facilitates the connection of two or more bamboo culms, regardless of whether they possess nodes at their ends, without piercing the culm, which could lead to splitting or weakening. Numerous lashing knots have been practiced over time, although the effectiveness of this connection largely depends on the tensile strength of the lashing material and the friction between the ropes and bamboo [24,78]. However, due to bamboo's natural properties, such as expansion and contraction in response to varying humidity and temperature, as well as the potential loosening of natural fiber lashing materials under these conditions, joints may become slackened over time. Additionally, prolonged exposure to natural elements can cause natural fiber lashing materials to become brittle, necessitating timely replacement to ensure proper functionality. To enhance joint performance, ropes are often treated with oil immersion before use to increase their toughness and strength, while repeated lashing can also improve joint strength [77,78]. To enhance the contact area between bamboo culms, they are cut in a fish-mouth shape and then tied together, giving rise to the term "fish-mouth support". Alternatively, the notched and pierced method was devised to bolster joint stability by minimizing slippage [24].

This technique employs pegs as anchor points for lashing or utilizes punctured openings through which lashing material is threaded, as depicted in Figure 11.



(a) (b)

Figure 11. Lashing joints: (**a**) notched and pierced with lashing [24]; (**b**) lashing joint using palm rope [77].

While this concept has ancient roots, it remains relevant today. The development of a flexible joint known as a Hinged Flexible Connection (HFC) was aimed at lightweight structures, enabling deployable motion at the joint's center, and facilitating mobile assembly procedures [83]. In this connection system, polyester rope is wrapped around the circumference of bamboo culms and secured by bio-composite rings affixed to the outer wall. This approach avoids the use of steel as the primary material for the joint, suggesting sustainable alternatives. However, the long-term performance of lashed joints requires further consideration and examination [83].

Mortise–Tenon Joints

This joint mirrors the ancient connections prevalent in timber structures, where structural elements are bound without the use of nails or bolts. In a bamboo structure, one end of a bamboo culm is carved into a tenon, which is then inserted into a notch on another bamboo column created by drilling a hole, as shown in Figure 12. Bamboo, being an anisotropic material, exhibits relatively low tensile strength perpendicular to the grain. Additionally, due to its hollow nature, drilling into bamboo to create a mortise can adversely affect its structural performance, potentially leading to splitting and cracking [77,78]. Therefore, integrating mortise–tenon joints with supplementary connection components such as lashing is a viable solution.

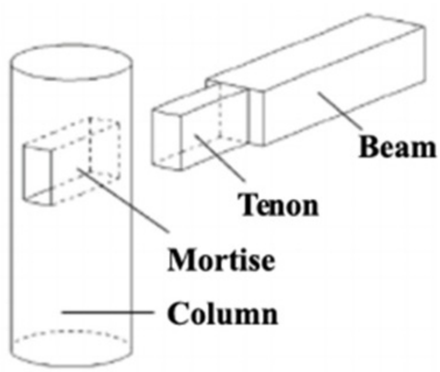


Figure 12. Mortise–tenon joints [78].

3.2.2. Modern Connections

Modern bamboo structures are adopting modern bamboo connections with growing preference for engineering hardware [24]. These modern connections are essential for meeting the higher demands of modern bamboo structures [77]. Unlike traditional joints, which directly transmit force through overlapping bamboo, modern connections utilize metal and other joint materials to effectively address issues such as poor durability and slippage [77]. By integrating these, designers and researchers have enhanced joint stiffness [78], leading to a range of modern raw bamboo connections, including dowelled connections, clamped and capped connections, and some emerging technologies used in raw bamboo connections, which will be discussed in later sections.

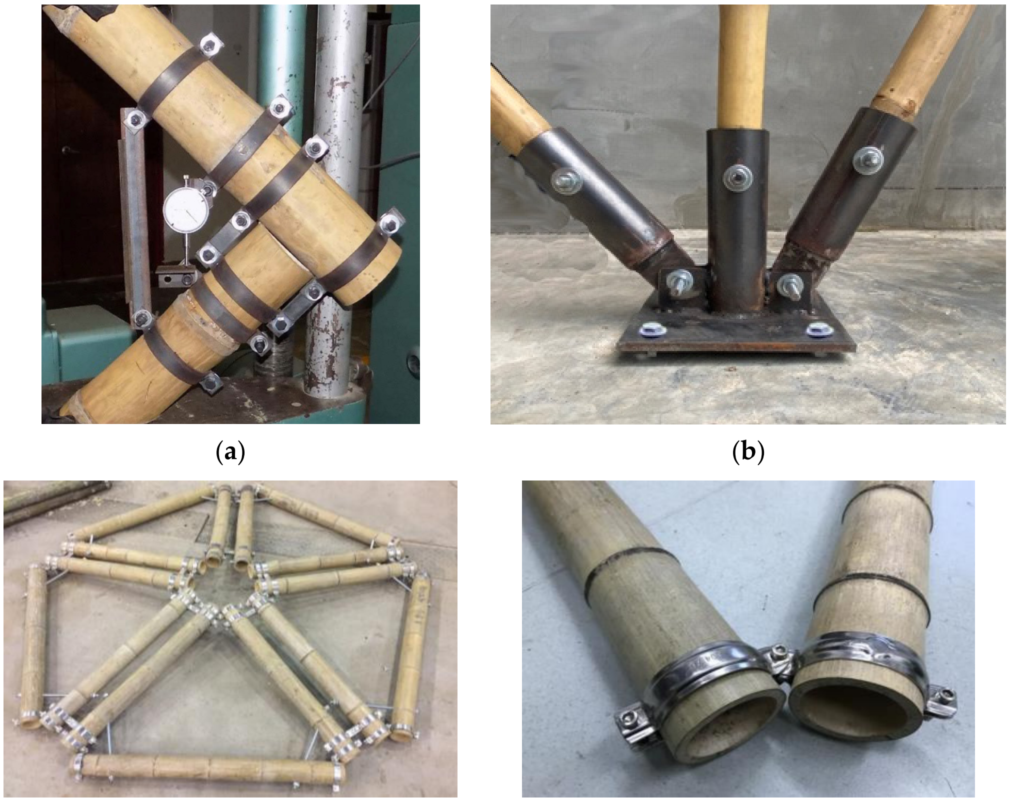
Dowelled Connections

Dowelled connections encompass a variety of fasteners, including dowels, bolts, screws, nails, and similar hardware mainly made of metal, but occasionally, bamboo or timber, as defined by Malkowska et al. [66]. These connections are favored for their ease of construction, yet they pose challenges such as insufficient joint strength and the risk of splitting or cracking when punching into bamboo culms [78,79]. Consequently, researchers have conducted experimental and theoretical studies to enhance the performance and widespread adoption of dowelled connections [27,30,54,60,66,84]. For instance, Masdar et al. [27] established the minimum distance between bolts and the end of bamboo culms without nodes, crucial for designing bolted connections under real-world conditions. Oka et al. [54] investigated factors affecting lateral strength in bolted bamboo connections, while Trujillo and Malkowska [60] developed bamboo-specific design approaches using various metal fasteners. Their work yielded predictive equations for connection properties, highlighting the inadequacy of Eurocode 5 [86] equations for bamboo. Ramful [30] analyzed failure modes in bamboo bolt connections under tension, identifying shear-out failure as dominant due to bamboo's high axial strength but weak radial and tangential strength. Additionally, Malkowska et al. [84] derived equations to predict splitting capacity and provided insights into the mechanics of laterally loaded dowelled connections in bamboo, offering valuable guidance for designers [56]. This study aimed to enhance designers' confidence to implement dowelled bamboo connections in practice. Figure 13 illustrates a bolted bamboo structure.

Figure 13. Bolted connections [78].

Clamped and Capped Connections

Due to the limitations posed by dowelled connections, such as weakening the bamboo through drilling or cutting, clamped connections were developed as an alternative. Clamped connections involve joining two or more bamboo culms using two semi-circular steel hoops fastened with high-strength bolts. The sliding friction is controlled by the interfacial pressure, which is adjustable by tightening the bolts [82]. The tightening of bolts is carried out periodically to accommodate any changes in the bamboo's dimensions due to natural factors such as shrinkage. Unlike dowelled connections, clamped connections do not require drilling into the bamboo culms, making them easy to install and disassemble. They are also suitable for use in spatial bamboo structures, as shown in Figure 14. Capped connections, also typically made of steel, involve attaching metal caps to the end of bamboo culms with bolts or adhesives, enhancing joint performance by integrating the components of bamboo structures. However, a challenge with capped connections arises from the fixed size of the metal caps or hubs, requiring the raw bamboo to be cut to match their inner diameter.



(a) (b) (c) (d)

Figure 14. Clamped and capped connections: (**a**) steel clamp (reproduced with permission from Ref. [20]; copyright 2019 Elsevier.); (**b**) prefabricated steel connector attached at the end of bamboo culm (capped connection) [50]; (**c**) spatial structure of raw bamboo connected by BHC [82]; (**d**) bamboo connected by steel hoops [82].

Garcia et al. [59] explored the use of two thin steel semi-rings for connecting bamboo culms. Due to their thinness, they can conform to the diameter size irregularities of bamboo culm when tightened. While their study confirmed the feasibility of this clamped connection, issues such as the connection system's behavior after adjustments over time need further investigation [59].

Moran and Garcia [20] confirmed in their study that steel clamps capable of transmitting moment can effectively improve the structural performance and versatility of bamboo structures. Their study concluded that steel clamps can provide sufficient confinement to prevent premature splitting failures, thus establishing them as a viable option for bamboo connections.

Villegas et al. [23] utilized steel clamps as connectors for constructing trusses supporting floors and roofs in low-cost, prefabricated housing projects, though further experimental studies are needed to validate their use under construction codes. Their study also revealed that providing two drywall screws, one on each semi-ring, can enhance joint redundancy.

Hu et al. [82] introduced the term BHC, standing for bamboo connections using hoops, and investigated the frictional properties of the composite interface between raw bamboo and steel hoops to establish proper methods for calculating sliding friction force and provide design details for BHC.

Emerging Technologies

Emerging technologies in bamboo connections encompass innovative techniques, materials, and design methods that are driving advancements in bamboo construction. These advancements include, but are not limited to, the use of parametric software to create connectors suitable for varying the diameters of bamboo culms, employing 3D printing for connector fabrication, and integrating fiber-reinforced plastic (FRP) sheets.

Awaludin and Andriani [26] experimented with FRP sheets and natural fiber "ijuk" to wrap bolted bamboo connections, aiming to delay bamboo splitting failure. Their findings demonstrated a notable increase in both the joint slip modulus and lateral load capacity of bolted bamboo connections when wrapped with FRP sheets.

Meng et al. [81] utilized glass-fiber-reinforced polymer (GFRP) to enhance the deformation and bearing capacity of bolted bamboo connections. Shear tests were conducted to examine the impact of GFRP reinforcement on failure mode, bearing capacity, and deformation performance. Prior to the shear test, a laser 3D scanner was employed to accurately capture the point cloud data of bamboo node parameters, such as loaded area, height, and wall thickness—a novel approach in the field.

Li et al. [80] also employed GFRP to wrap bolted bamboo connections, aiming to boost the shear capacity and prevent brittle splitting failure. Their approach was validated through numerical simulations using finite element models.

A notable innovation in bamboo connections is the introduction of a 3D-printed bio-composite removable connection system for bamboo space structures, as depicted in Figure 15 [75]. van Wassenhove et al. [75] utilized parametric design and 3D printing, allowing for customized design and production processes adaptable to varying bamboo culm dimensions while maintaining standardization. Experimental validation has confirmed the efficiency of this innovative connection system.

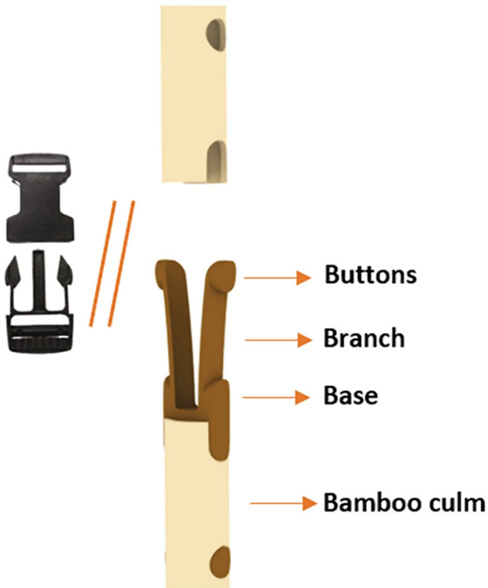


Figure 15. 3D-printed removable connection [75].

3.2.3. Hybrid Connections

Hybrid connections involve blending features from various types of connections to leverage their respective strengths, resulting in robust and adaptable connections tailored to bamboo's distinctive properties. They are categorized into three main types: the combination of traditional and modern connections, the combination of multiple modern connections, and the combination of modern connections with supplementary connection (SC) components. The identification codes for each type of supplementary connection component are as follows: SC-1.1 for a bamboo sleeve, SC-1.2 for a sleeve made of timber or wood, SC-1.3 for a steel sleeve, SC-2.1 for a steel gusset, SC-2.2 for a wooden gusset, and SC-3.1 for bamboo filler made of mortar. These classifications will be elaborated upon in the subsequent section. Details of the combinations of different connection types utilized by the researchers identified in this study are provided in Table 7.

Table 7. Matrix for Hybrid raw bamboo connections.

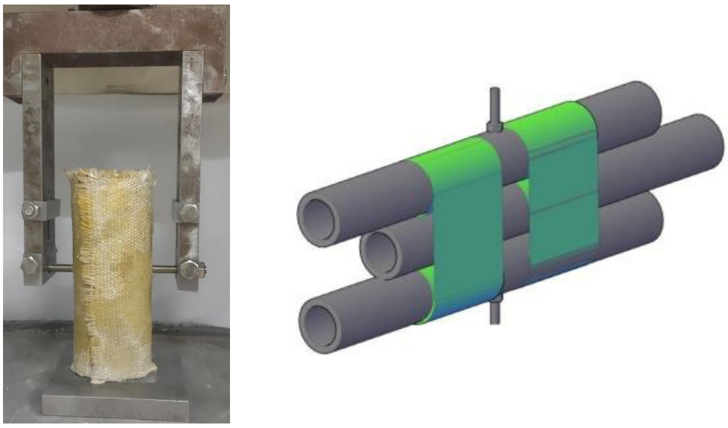
RBC ID	Combinations of Raw Bamboo Connections										
	TC-1	**TC-2**	**MC-1**	**MC-2**	**MC-3**	**SC-1.1**	**SC-1.2**	**SC-1.3**	**SC-2.1**	**SC-2.2**	**SC-3.1**
HC-1.1	✓		✓								
HC-2.1			✓		✓						
HC-2.2			✓	✓							
HC-2.3			✓	✓							
HC-2.4			✓	✓							
HC-2.5			✓	✓							
HC-2.6			✓	✓							
HC-2.7			✓		✓						
HC-2.8			✓		✓						
HC-2.9			✓	✓							
HC-2.10			✓		✓						
HC-3.1			✓			✓					
HC-3.2			✓					✓			✓
HC-3.3			✓								✓
HC-3.4			✓	✓					✓		
HC-3.5			✓					✓			
HC-3.6			✓			✓					
HC-3.7			✓					✓			✓
HC-3.8			✓						✓		
HC-3.9			✓								✓
HC-3.10			✓						✓		
HC-3.11			✓	✓					✓		
HC-3.12			✓	✓					✓		✓
HC-3.13			✓								✓
HC-3.14			✓								✓
HC-3.15			✓						✓		
HC-3.16			✓	✓						✓	
HC-3.17			✓					✓			
HC-3.18			✓					✓			
HC-3.19			✓								✓
HC-3.20			✓						✓		
HC-3.21				✓			✓				
HC-3.22				✓				✓			✓
HC-3.23				✓				✓			
HC-3.24				✓				✓			

Combination of Traditional and Modern Connections

Michiels et al. [57] integrated traditional and modern connection methods by adapting the fish-mouth connection, historically paired with lashing, to incorporate bolted connections instead. This modified connection was utilized in hyperbolic paraboloid bamboo grid roofs and subjected to laboratory testing. Their results indicated that the joint reaction within the fish-mouth joints did not surpass the joint's ultimate load capacity in compression or tension.

Combination of Multiple Modern Connections

As mentioned in the section Emerging Technologies, FRP sheets are employed together with bolted bamboo connections, as shown in Figure 16, to boost shear capacity and prevent brittle splitting failure [26,80,81]. This connection is a combination of two modern connections used to leverage the strength of both connection types.



(**a**) (**b**)

Figure 16. Combination of bolted connection and emerging technologies in bamboo connection: (**a**) bolted connection wrapped in GFRP [80]; (**b**) bolted connection wrapped in natural fiber "ijuk" [26].

Moran and Garcia [20] investigated the performance of steel hoops combined with through screws and drywall screws for beam–column bamboo connections. The results show that these connections have better average stiffness and moment strength compared with the corresponding values reported for traditional bolted and mortar-injected connections.

Rittironk [50] introduced prefabricated steel connectors, depicted in Figure 14b, which combine elements of capped and bolted connections. These steel connectors were designed to enhance the efficiency of raw bamboo connections and shorten the construction time. Through real-world simulations, this research investigated whether the prefabricated steel connector could effectively reduce construction time for building raw bamboo frames. The findings of their study confirmed a notable reduction in construction duration.

Combination of Modern Connections with Supplementary Connection Components

Supplementary connection components include sleeves, gussets, and fillers, each serving distinct purposes in reinforcing bamboo joints. Sleeves, which can be made from smaller-diameter bamboo, timber, or steel, act as splices between two bamboo culms. Gussets, or gusset plates, typically made of metal or wood, are bolted to bamboo culms to augment support and rigidity at the joint. Fillers, on the other hand, are materials used to occupy the internode or hollow section of bamboo culms such as mortar. Fillers are strategically placed within the internode where bolts penetrate to bolster joint strength and prevent splitting. Incorporating mortar filler adds weight to the structures, which can pose challenges as the materials may not effectively accommodate each other due to the varying shrinkage-swelling rates between cement mortar and bamboo. Consequently, this disparity can result in the development of cracks within the structure. [55]. Figure 17 depicts various connections integrating modern techniques with supplementary components for improved structural integrity.

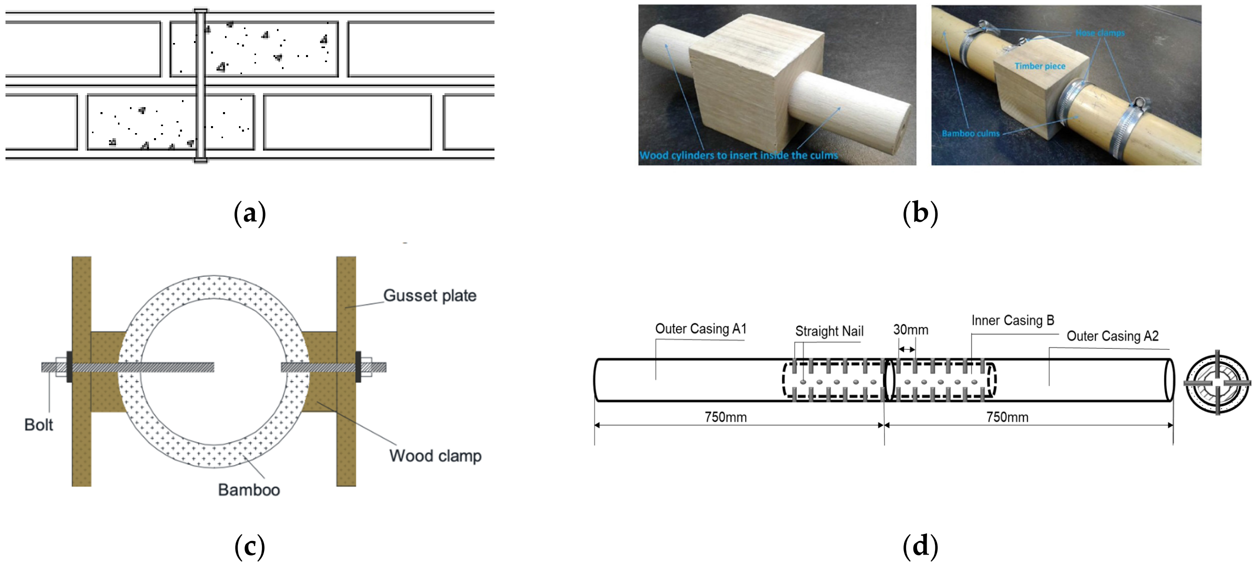


Figure 17. Combination of modern connections with supplementary connection components: (**a**) parallel bolted mortar infill connection [55]; (**b**) bamboo culms connected by wooden block (sleeve) and steel hose-clamp (reproduced with permission from Ref. [72]; copyright 2019 Elsevier.); (**c**) bamboo connected by wooden clamp, wooden gusset plate, and steel bolts [19]; (**d**) bamboo connected by bamboo sleeve and nails [74].

Zhou et al. [74] introduced a sleeve-nailed bamboo connection method involving three bamboo culms. This technique joins two bamboo culms of similar diameter longitudinally by inserting a shorter bamboo culm with a smaller diameter, which is then secured with nails.

Lefevre et al. [72] devised a custom-machined wooden block with cylindrical pegs that match the inner diameter of the bamboo culm. Metal hose-clamps are used to secure the pegs after insertion into the bamboo culm, making the connection relatively lightweight and suitable for use in developing countries due to its simplicity and the accessibility of materials.

Fu et al. [73] developed a novel sleeve–cement bamboo joint configuration, utilizing steel sleeves, rings, and mortar for adhesive purposes. They also investigated the performance of sleeve–bolt and groove–plate connections, finding that these joints exhibit brittleness under axial load, with the failure mode being governed by shearing-split. In contrast, the sleeve–cement joint demonstrated good ductility with relative slip between the bamboo and cement mortar.

Masdar et al. [52] studied the elastic behavior of a connection system consisting of wood clamps, wooden gusset plates, and steel bolts. The design of the wooden clamps was customized to match the shape and dimensions of the raw bamboo. Their experimental findings demonstrated that incorporating wooden clamps boosted the load-bearing capacity of the joints by approximately 40% compared to joints lacking such clamps.

Noverma et al. [49] compared the strength of steel bolts and Cendani bamboo as shear connectors, finding that bolted connections with mortar infill in the internode were stronger than those using Cendani bamboo alone.

Correal et al. [85] developed an analytical method to estimate the strength of bolted mortar infill (BMI) bamboo connections based on a modified European yield model (EYM) theory, showing promise for design applications.

Quintero et al. [55] analyzed the structural behavior of a bamboo bridge connected by bolted mortar infill (BMI), where the bamboo internode is filled with mortar to provide stiffness and then connected by bolts, as shown in Figure 17a.

Nie et al. [70] investigated the failure modes of bolted bamboo connections with embedded steel plates and grouting materials, finding that the diameter of the bolt significantly influences connector bearing capacity, and that filling with grouting material can enhance joint strength.

3.3. Codes and Standards for Bamboo

While bamboo boasts sustainability and impressive mechanical properties, making it viable for structural use, its application remains constrained. This limitation is largely attributed to the difficulties posed by its connection systems, worsened by the limited widely applicable standards and codes to aid in the design of structural elements. Consequently, bamboo's utilization as a structural material heavily depends on established practical methods [87].

In this study, we found that researchers utilized International Standards for bamboo, as outlined in Table 8. These include ISO 19624:2018 [88], ISO 22156:2021 [89], and ISO 22157-2019 [90]. It is worth mentioning that while other International Standards and many of the Standard Test Methods listed in Table 8 pertain to timber or wood, they were adapted for use with bamboo due to the limited, if not absence of, International Standards specifically tailored for bamboo. Furthermore, it is essential to mention that although bamboo shares some similarities with wood, it differs significantly in terms of both its physical and mechanical properties.

Table 8. Bamboo codes and standards used by researchers identified in this study.

Codes and Standards	Related Material	Subject	International	National	Country	Reference
JG/T 199-2007 [91]	Bamboo	Material testing		✓	China	[69–71,80,82]
GB/T 3098.1-2010 [92]	Fasteners	Material testing		✓	China	[71]
GB 50005-2017 [93]	Timber structures	Design		✓	China	[70,71]
EN 1993 [94]	Steel joints	Design		✓	Europe	[20,21,48,58]
EN 1995 [95]	Timber structures	Design		✓	Europe	[21,48,60,80]
EN 383:2007 [96]	Timber fasteners	Material testing		✓	Europe	[60]
EN 1382:2016 [97]	Timber fasteners	Material testing		✓	Europe	[60]
EN 12512:2005 [98]	Timber fasteners	Material testing		✓	Europe	[29]
EN 14358-2016 [99]	Timber structures	Material testing		✓	Europe	[60]
BIS 15912:2012 [100]	Bamboo	Design		✓	India	[47]
AWC-TR12 [101]	Dowels	Design		✓	United States	[29,48]
ASTM A240/A240M-12 [102]	Steel plates, sheets, and strips	Design	✓			[29]
ASTM D1761 [103]	Fasteners in wood	Material testing	✓			[85]
ASTM D5652 [104]	Bolt connections in wood	Material testing	✓			[71]
ASTM D5764-97a [105]	Wood	Material testing	✓			[27,28,48,53,60,66,85]
ASTM F1575-03 [106]	Nails	Material testing	✓			[29,45,48,54,66,85]
ISO 527-1:2019 [107]	Plastics	Material testing	✓			[75]
ISO 527-4:2023 [108]	Plastics	Material testing	✓			[75]
ISO 10984-2:2009 [109]	Timber fasteners	Material testing	✓			[60]
ISO 12122-1:2014 [110]	Timber structures	Material testing	✓			[66]
ISO 16670:2003 [111]	Timber fasteners	Material testing	✓			[20,22,26]
ISO 19624:2018 [88]	Bamboo	Material testing	✓			[48,66]
ISO/TR 21141:2022 [112]	Timber connections	Material testing	✓			[66]
ISO 22156:2021 [89]	Bamboo	Design	✓			[20,46,47,60,66,68,84,85]
ISO 22157:2019 [90]	Bamboo	Material testing	✓			[19,21–23,27–29,46,48, 49,53,60,66,68,69,74,76]
AC 162 [113]	Bamboo	Design	✓			[21]

As indicated in Table 8, certain countries, such as China, India, and Colombia, have developed their own codes and standards for bamboo. However, these codes primarily focus on determining the physical and mechanical properties of bamboo and do not address the design of raw bamboo connections. Consequently, there is a pressing need to develop comprehensive widely applicable standards for bamboo design and construction, including codes of practice for both bamboo and bamboo connections, to foster the wider adoption of bamboo in the construction industry.

4. Conclusions

While there have been studies conducted on bamboo connections, it is important to note that these studies examine various factors. The literature reviewed involves different bamboo species and considers factors such as the age at which specimens were harvested, type of bamboo treatment, diameter and wall thickness, and distance of nodes from the bamboo culm's end, among others. Therefore, it would be premature to conclude that the existing studies are comprehensive. Further research considering all relevant variables is necessary to enhance our understanding of bamboo connections.

Numerous bamboo connection methods have been proposed based on the obtained literature. While some exhibit promising performance, there should be criteria for selecting the most suitable type of bamboo connection. For instance, the promotion of raw bamboo structures is driven by their environmentally friendly, renewable, and sustainable nature. However, using mortar as filler and steel as connectors may contradict these objectives. Additionally, in developing countries where bamboo is abundant, promoting connectors that are readily available, affordable, and easy to install is crucial. Proposing connectors that are satisfactory but expensive would hinder the widespread adoption of raw bamboo structures in the construction industry.

The failure modes of the bamboo connections discussed in the literature obtained were examined. Failure modes should be further analyzed. Understanding how various bamboo connections fail assists designers and engineers in anticipating and mitigating the risks associated with bamboo connections, thereby enhancing the resilience of raw bamboo structures. Additionally, the long-term behavior of bamboo connections should be investigated to verify their durability. This analysis also helps determine the frequency of maintenance and, consequently, quantify the cost-effectiveness of bamboo connections.

Codes and standards play a crucial role in bamboo construction, particularly in ensuring the safety, quality, and resiliency of bamboo structures. They are also essential in boosting the confidence of designers and engineers in adopting raw bamboo as structural materials in the construction industry. The lack of International Standards for bamboo connections is considered to be a research gap. There is a need to develop a comprehensive widely practical code and standards for bamboo and bamboo connections.

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