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UNLOCKING THE POTENTIAL OF EXISTING BAMBOO SCAFFOLD CONNECTIONS: A COMPREHENSIVE REVIEW ON REUSABILITY

Hintsa G. GEBREMARIAM[1*], Ermias A. AMEDE[2], Leule M. HAILEMARIAM[2]

[1] Addis Ababa Institute of Technology, Addis Ababa University, 1000, Addis Ababa, Ethiopia
[2] Ethiopian Institute of Architecture, Building Construction and City Development, Addis Ababa University, 1000 Addis Ababa, Ethiopia

Abstract

Bamboo scaffolding is a sustainable alternative to traditional scaffolding materials due to its low carbon footprint, renewability, and strength. Reusable connections are crucial to optimize its sustainability benefits. This review provides a comprehensive overview of the reusability potential of existing bamboo scaffold connections, exploring different connection types, factors influencing reusability, benefits and challenges, and current research and development efforts. Several factors influence the reusability of bamboo scaffold connections, including the design of connections to accommodate mid-culm attachment of secondary components, which is challenging for many existing connection types. Reusing bamboo scaffold connections offers significant sustainability and cost-effectiveness benefits, reducing the demand for new materials and minimizing construction waste. Friction-tight lashing, the most popular and adaptable bamboo scaffold connection method together with mechanical connectors to alleviate problems in traditional friction-tight lashing, offers high reusability potential. More advanced mechanical connections, such as notched and pierced connections, are also being explored for their reusability potential. Ongoing research and development efforts focus on innovative approaches such as three-dimensional printing, parametric software, and glue bonding for custom joint systems to improve the reusability of bamboo scaffold connections. By addressing the challenges and leveraging ongoing research and development efforts, reusable bamboo scaffold connections can play a crucial role in sustainable construction practices.

Keywords: *bamboo, reusability, scaffolding, bamboo connection, suitability, literature review*

Introduction

Bamboo is a strong, fast-growing, sustainable material with an anatomically distinct cylindrical shape, hollow shaft, and nodular structure [1–3]. The natural architecture of the culm contributes significantly to bamboo's high compressive strength; nodes are reinforced with diaphragms located at regular intervals within the cavity, which can brace against certain forms of buckling while remaining light and flexible. The culm's walls comprise long parenchyma cells surrounding vascular bundles that transport water and nutrients down the plant's length [4]. These axially oriented fiber bundles, which provide most of the mechanical strength, are denser and smaller in diameter toward the culm's exterior, where bending stresses are greatest. Tension strength perpendicular-to-grain is quite low due to the fibers' longitudinal orientation, which is an essential consideration in connection design. Because of the thin walls of the culm, bamboo has a low shear strength, making it easier to split and harvest than wood [5]. The cortex, the culm's outermost covering, is a protective, waxy, and resistant waterproofing membrane.

Bamboo is one of the world's few renewable non-wood products that can be used in various applications, including residential construction [6]. Bamboo has been used for thousands of years

*Corresponding author: hintsa.gebrezgiher@aait.edu.et

as a building material and has a long history. Bamboo was used to build buildings in ancient times due to its strength and flexibility. Bamboo is increasingly popular as a building material due to its natural texture and low-carbon environmental protection properties. Bamboo structures have the potential to coexist with the natural environment throughout their entire life cycle.

In the construction of bamboo scaffolding, connections are critical for structural load transfer. Due to hollow and slim-walled material characteristics of bamboo, the connecting of bamboo members has consistently been a significant challenge when utilizing bamboo. Nonetheless, researchers discovered that many connection forms are used in bamboo scaffoldings. Some existing connection types are not suited for bamboo scaffolding since it uses full-size bamboo parts, and the load transfer process uses a connector on the exterior of the culm to transfer force to the bamboo's firm outer surface via friction. The objective of this paper is to review existing bamboo connections, present an overview of existing bamboo connection technologies suited for bamboo scaffolding, and stimulate developments in the rapidly expanding field of bamboo engineering. Friction-tight lashing is the largest used connecting method in bamboo scaffolding because of its adaptability and inexpensive cost.. Future advances based on the features of bamboo scaffolding could include full, mid-culm scaffold connections, weight transfers via outer culm friction, and connections effective in reusable scaffolds.

Bamboo as scaffolding material

Scaffolding is a temporary framework that supports a work crew and materials during the construction, maintenance, and repair of buildings, bridges, and other man-made structures. Scaffolds are frequently used on construction sites to gain access to heights and areas that would otherwise be inaccessible [1, 2]. Bamboo scaffolding is a type of scaffolding that has been used in construction for centuries. Bamboo scaffolding was used to build several notable sites, including the Great Wall of China, and it is still used in some parts of the world today [7]. Bamboo scaffolding was first used in Hong Kong's construction industry in the 1800s, shortly after colonialism ended [8]. Bamboo has been considered a timber substitute scaffolding material due to its lightweight, versatility, and abundance. It is significantly lighter than steel and aluminum scaffolding and can be built and removed much more quickly. Bamboo is also one of the fastest-growing materials on the planet, making it easy to replenish and less expensive than other materials [1, 2].

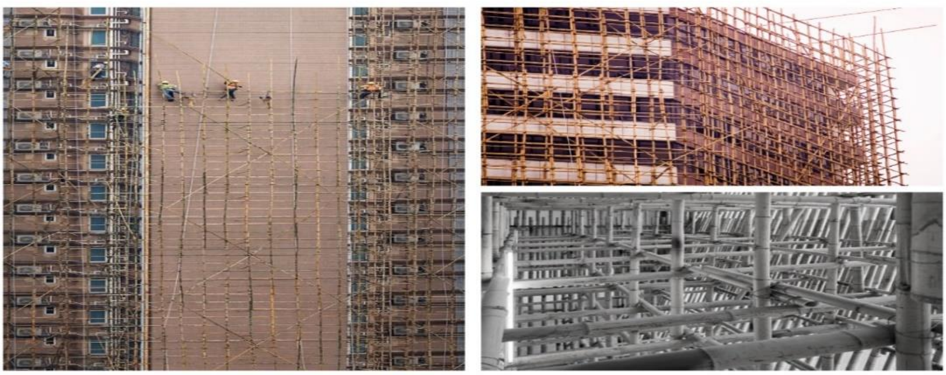


Fig. 1. Bamboo scaffolding from Hong Kong skyscrapers [9]

General overview of bamboo connections

So far, various difficulties have been observed while joining bamboo culms. It is difficult to make good and aesthetically acceptable bamboo joints because bamboo is hollow, tapered, has nodes at varying distances, is not precisely circular, fibers only develop in one direction longitudinally, there is no substance in the center of the cane to tighten the bamboo, and it is unsuitable for cross-directional loading: All these constraints must be considered while constructing a bamboo joint. Keeping all these constraints in mind, researchers discovered numerous forms of connections to be employed in the bamboo building. Establishing a system and categorization is necessary to understand the classification of bamboo joints. This would allow for the restoration of order across the board. In this case, the following categorization principles are employed [10]:1. A joint between two complete bamboo culms can be formed by contacting the whole cross-sections or collecting pressures from the cross-section and transferring them to a joining element. 2. The forces can be collected from the inside, cross-sections, or the outside. 3. The connecting element can be perpendicular or parallel to the fibers.

Factors influencing reusability of bamboo scaffold connections

Connections between the materials used in bamboo scaffolding should be planned and assessed differently from structural applications. For bamboo scaffolding, for example, secondary component attachment at the mid-culm is required (figure 2b), which presents a challenge for many accessible connection types. Furthermore, in the bamboo scaffolds life cycle (figure 2a), when a bamboo scaffolding project is completed, the dismantled bamboo scaffolds must be reused for future bamboo scaffolding projects. Some connection methods involve drilling holes in the culms of reusable scaffolds and bolting them together. On the other hand, bamboo scaffold members may become tired and degraded after repeated use of these connections. Furthermore, because of the substance's thin walls and voided behavior, raw bamboo can break during hole opening and service, and Bamboo culm fracturing or localized deformation is a common cause of connections failing. Scaffolding also uses full-size, uncut bamboo pieces, and the load transfer mechanism is accomplished by using connections on the culm's exterior to transfer force to the bamboo's sturdy outer surface via friction. As a result, numerous commonly used connection types are incompatible with bamboo scaffolding. This study looks at prevalent bamboo connections that might be used for reusable bamboo scaffoldings.

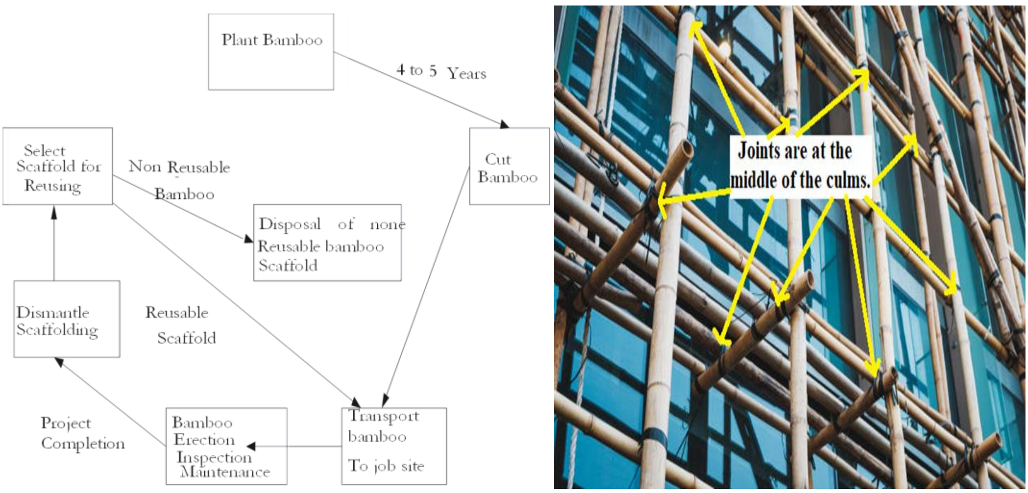
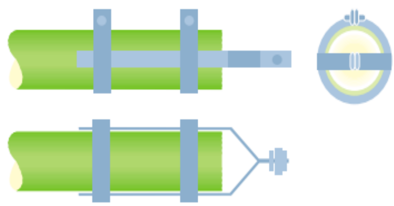
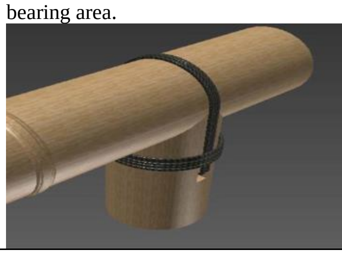


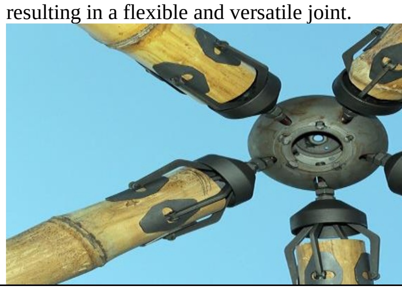
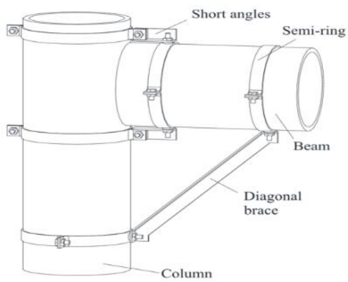
Fig. 2. A) Life cycle of bamboo scaffold [11]; b) Mid-culm joints in bamboo scaffolding

Friction tight rope connections, double butt bent joints, plugin/bolt connections, positive fitting joints, steel plate and steel member junctions, filler reinforced joints, scaffold clamps, and swage clamp connections are among the previously established bamboo connection types. Table 1 summarizes the extant bamboo connections discovered by scientists.

Table 1. General summary of existing bamboo connections

Joint types	Reference	Research focus	Description of study
Lashing joints	[12]) [13]	Traditional lashing.	Bamboos are lashed together using thin bamboo-skin thongs, ideally suited to this function. The thongs are soaked in water to increase their strength and elasticity and shrink after drying to form a very tight lashing."
	[14])	Joint with rattan lashing	
	[15])	Alternative lashing materials	Wires, metal straps, polyester plastic ropes, and bio-composite dressings have all been used to improve joint strength.
	[13]	Delft wire lacing tool	Delft University created a smart gadget called the "Delft wire lacing tool" for bamboo lashing with steel wires. This tool wraps the steel wire neatly around the bamboo to form a strong and stiff joint.
	[16]	A Note on Dome Structures Constructed from Short Bamboo and Timber Elements	Sonti offers another proposal in which bamboo components are fastened to a steel plate. The design can take advantage of the plate's stiffness while minimizing injury to the culms.
	[10], [17][18] [19]	Lashing with metal parts	Das, R.N. has tested and confirmed the effectiveness of these joints. 
	[14],[10]]	Plug in joints	Two bamboo pins cut from the culm connect the lower (vertical) and upper (horizontal) parts. These pins handle horizontal forces. For vertical (upward) stresses, a rope has been placed on both sides, with a pin through the bottom member. 
	[58 [14],19] [20]	Lashed fish-mouth joint with dowels.	Pinning (or engaging massive node protrusions) or using fish mouth lashed joints improves lashed joint efficacy.

			
	[15 [21]]	pierced connections with natural lashing	Allow the culm cross-arched section's shape to accept weight while retaining strength and bearing capacity and increasing joint stability by limiting slippage by creating a specific bearing area. 
Positive fitting	[14] [22]	Mortise-Tenon Joints /Positive fitting	Positive-fitting connections can be used to build plane frames in which a small diameter culm serves as a 'beam' attached to a larger diameter culm. 
Bolted joints.	[23]	Single and double bolted bamboo joints.	Under axial tension, the mechanical properties of single and double-bolted bamboo member joints were investigated. The findings revealed that end distance and bolt diameter influenced the final bearing capacity of the joints.
	[24]	Analysis of limit states for bamboo pin connectors	Taking into account the anisotropy and heterogeneity of the mechanically evaluated material, they used finite element simulation and experimentation to study the nonlinear stress patterns at the point of contact of a bolt in a circular bamboo hole. Given the magnitude of the local stress, it was suggested to utilize local reinforcing, like straps made of natural fiber attached next to the hole.
	[25]	Determinant of critical distance of bolt on bamboo connection.	Experiments were carried out to estimate the critical value of a bolt's end distance on a bamboo connection, considering the two principal failure mechanisms of shear and compression failure. The critical distance between the bolt and the end of the bamboo culms when both failure modes occur at the same time is 4-5 times the diameter of the bamboo.
	[26]	Examination of fastened bamboo joints with no void-filled substance through experimentation and theory.	The impact of bolt diameter, specific gravity, and bamboo thickness on lateral strength for shear single and double connections without void-filled material was investigated.
	[27]	Mechanical properties of bolted joints in prefabricated round bamboo structures.	The mechanical characteristics of a reinforced bolted junction made with high-strength mortar were studied. The study discovered that, under specific connection configurations, the joints could successfully prevent brittle failure and completely leverage the plastic performance of bolts, as well as that employing a doubly bolted joint could significantly increase bearing capacity.
	[28]	Empirically derived connection design properties for Guadua Bamboo.	Experiments with fastener diameter, density, and bamboo wall thickness resulted in prediction equations for three connection design parameters (dowel embedment strength, slip modulus, and screw withdrawal capacity). The results of the computation showed that predictive formulas were

			suitable for bamboo when compared to analogous equations in Eurocode 5.
	[29]	Production of a bolt-connected bamboo-tube truss member.	A raw bamboo jointing procedure that made the end flat was proposed. The joint is made by removing a portion of the bamboo's end and inner skin, then using glue to bind the bamboo to The piece of wood and pressing the bamboo with heat treatment into a regular entire.
	[30]	Bamboo joints fastened with fiber reinforcement.	Natural fiber and fiber-reinforced plastic joints were examined in terms of mechanical properties. Joints' capacity for bearing and slip stiffness, reinforced with FRP sheet were dramatically improved.
Mechanical connectors	[15]	Clamp connectors	To join bamboo, the connection employs a clamp action. The clamp has four prongs, allowing it to be used with varied sizes of bamboo and overcoming the issue of non-standard diameter and taper. The design was created after thorough prototyping of many choices. The final design compromises utility and weight, resulting in a flexible and versatile joint. 
	[31]	Robust swage clamp connector	Force is transferred to the culm's outer surface.
	[20]	Conventional scaffold clamps.	These are intended to clamp and engage friction on a single culm, frequently necessitating a neoprene rubber (or similar) interface layer and producing a more complicated mechanical union.
Steel Plate and Steel Section connections	[32]	Bamboo connections that convey a moment equipped with steel clamps.	Three different forms of bamboo joints capable of conveying moments have been shown. Using steel clamps on bamboo members efficiently prevents early fracturing at the connections, according to linear, periodic, and static assessments 
	[33]	Monotonic loading testing and characterization of new multi-full-culm bamboo to steel connections	The joint's influence on end distance and hose clamp limitation was evaluated. The results of the tests indicate that by providing transverse confinement, hose clamps may successfully limit fragile tearing property at the junction.
Filler Reinforced Joints	[34]	Design of bamboo connections.	Arce developed and researched joints that fill the bamboo's open extremity using a spherical piece of wood kept in place by wood glue.
	[35]	Dowel-bearing strength behavior of bamboo.	Experiments were carried out to evaluate the integration capacity and strength of mortar-injected joints. It was discovered that cement mortar's compressive strength significantly impacts joints' bearing capacity.

	[36]	Experimental study of mechanical properties of bamboo's connections considering tension and compression load	A prefabricated steel cuff was initially put into a natural raw bamboo cavity, then mortar was filled between the cuffs and the bamboo wall, and steel rings eventually restrained the joint.
	[37]	Evaluating the structural reaction of a steel eyebolt bamboo connector filled with cement under periodic and bending stresses.	Under bending, periodic and shear loads, a fish-mouth cut orthogonal mortar-infilled steel eyebolt connection was constructed and tested. Despite more than tripling the mass of the joints, the outputs showed that cement mortar infilling boosted shear capacity and prevented the local splitting failure of the bamboo.
	[38]	Development of a connecting method for natural round bamboo. Proceeding of World Conference on Timber Engineering	A junction packed with strands of bamboo and linked with a bamboo connection was proposed. The tests revealed that the joint was stiff until near the peak of force and that the bamboo connector finally destroyed the joint due to adhesive failure. He also advocated a steel ring and plaster cup joint. The test findings showed that the gap hindered the proper application of friction between the steel ring and the culm, which ultimately caused the joint to be damaged by the steel ring's displacement from the bamboo surface.
	[39]	New construction technology of bamboo houses node	Plaster and chemicals are used to fill the empty spaces in raw bamboo. In terms of toughness and machinability, plaster-filled joints are comparable to solid wood components, according to research.
Other new connections.	[40]	The experimental research and analysis on the mechanical properties of reinforced bamboo.	Raw bamboo connections strengthened with CFRP (carbon fiber reinforced plastics/polymer) underwent a shear test. The results indicate that there may be an 18.4% increase in the shear capacity of joints reinforced using single-layer sheets.
	[25]	The study of wooden clamps for strengthening of connection on the bamboo truss structure	A lightweight coupling made of bolts, innovative wooden clamps, and wooden gusset plates was proposed for the raw bamboo truss connection. According to the test findings, the load-bearing capability of joints with wooden clamps increases roughly 40% compared to connections without clumps.
	[41]	A novel technique to connect bamboo culms.	It was proposed to use a bamboo culm-to-culm connection made of a custom-machined hardwood and metal clamps. Bamboo can be linked to wooden blocks by inserting machined pegs into the culms and attaching them with hose clamps. This connection is affordable and straightforward to construct, but each must be tailored to the bamboo culms used.
	[42]	A parametric investigation on a specially designed joint mechanism for bamboo.	A custom joint system was created using three-dimensional printing. Parametric software is utilized to adjust quickly to the irregularity of the bamboo. According to the program, the joints connecting bamboo of varying diameters are built individually, assuring the secure connection of each specific connection at each junction and eliminating construction waste.

Types of Bamboo Scaffold Connections and Reusability Potential

Friction tight rope connections/lashing

Lashing is joining two bamboo culms to form a more extended portion. More than two internodes connect the culms, overlapped or lapped at any angle. The lashing's friction contacts the joint, which 'self-tightens' owing to the wedge action of the engaging culms. Finally, node contact offers mechanical layer protection against catastrophic slides [43]. A connector put on the exterior of the culm at the joints in the friction-tight rope connection identifies the joints. The common joining materials for lashing are bamboo rind strips, rattan, and lianas. Before use, lashing materials are soaked to make them more flexible. The strands shrink, and the bamboo poles' connections tighten as they dry. The connections are also composed of organic material, guaranteeing optimal compatibility among the various components of the building system.

Distinct rope material choices are available in various places. People picked materials in the early days primarily because they were more convenient. Palm rope was used in some households in warm climates, such as southern China, to attach bamboo items, but hemp rope was commonly used in dry climates, such as northern China. Wires, metal straps, and even polyester plastic ropes and bio-composite bandages [15] have all been used to increase joint strength over time. Bamboo ropes composed of twisted bamboo fibers may reach up to 350 meters. Lashing connections should be made with two- or three-fold nylon or vegetable fiber strips of the same length. If the canes were green and not adequately cured, there might be a volume shift in the bamboo and drooping at the junction, both of which are problems with lashing connections.

Lashing was the most used connection method in prior bamboo scaffolding (Figure. 3), and it has a benefit of being easily adjustable and inexpensive. However, lashing is inefficient and time-consuming to build, and joint performance is heavily impacted by human operation. Because cutting and creating holes in raw bamboo poles damages the cross-section, a flexible bamboo connection through rope is employed instead. Ancient cultures developed a range of traditional lashing knots via long-term expertise and application.

Fig. 3. Lashing joint [44]

Methods of lashing

According to girl scouts of California central coast, 2016, there are several techniques of strapping bamboo together, each with its specific use for building the most lasting product. The categories are as follows:

• Square lashing: This is the most popular type of lashing. It is used to connect two bamboo poles that are at a 90° angle or highly close to perpendicular. This method of lashing will keep the two poles from slipping together.

• Tripod lashing: This method connects three poles to form a tripod. The same style of lashing may be used to connect four poles to form a sturdier quad pod.

• Diagonal lashing: Used when the poles are at an angle other than 90 degrees and must be brought together or are prone to springing apart.

• Sheer lashing: This method links two poles to form a scissor shape, typically used to connect two bamboos.

• Round lashing: This method connects two poles to generate a longer length.

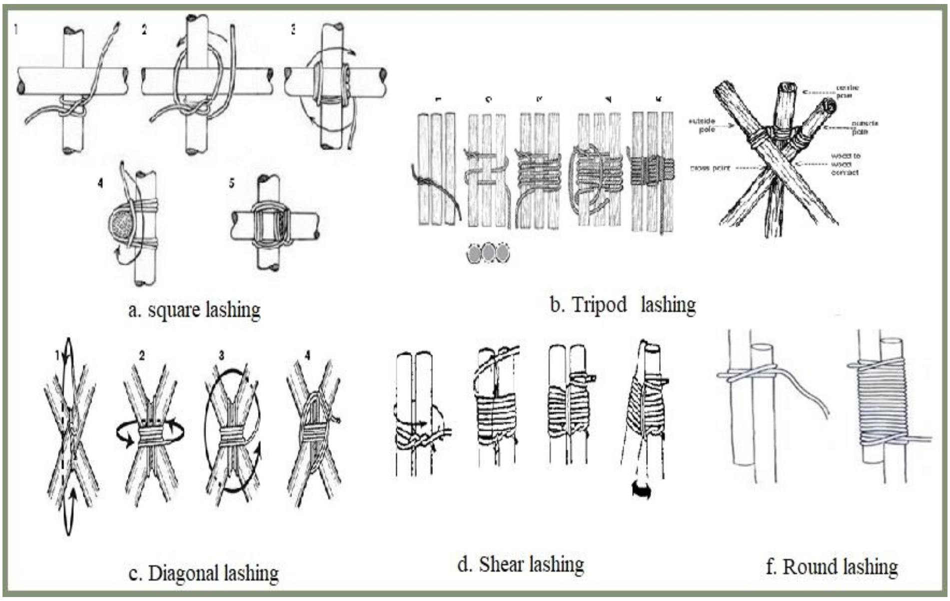


Fig. 4. Types of lashing (Girl Scouts of California's Central coast, 2016)

Because of its round form and rough, slippery exterior cover, attaching a connection to the outside of a bamboo culm is challenging. Lashing is the best effective way of attaching external connections since it adapts readily to the culm and increases the contact area for friction. According to, lashing has various disadvantages [34]. Although tying culms together with natural or synthetic rope typically results in minor harm to the culms, the force that may be imparted is restricted. Some lashing materials are weak, with a low friction coefficient between the rope and the bamboo skin. As the bamboo dries, it shrinks, reducing friction. In most lashing joints, slip is unavoidable. Stronger, regularly prestressed lashing with cables (for example) might produce culm cracking and diameter crushing at the culm ends, according to Arce [34].

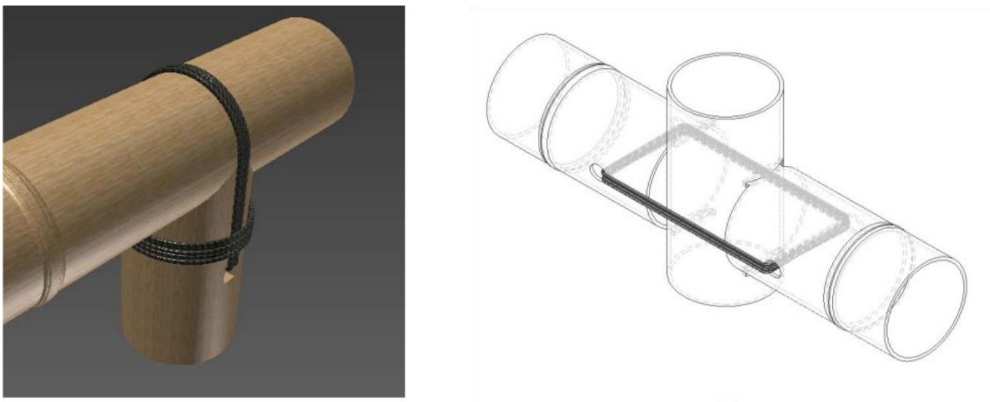
Furthermore, the endurance of lashed joints is questionable, mainly when natural fiber lashing materials are utilized. Conversely, though, lashing joints offer various benefits, the most prominent of which is that they are very straightforward to build regardless of culm diameter variation. Lashed joints also play an essential function in avoiding longitudinal culm splitting and are usually applied with combination with other connections. Despite the constraints noted above, connecting the complete bamboo culm cross sections of scaffolds by bearing with bamboo strips, rattan, iron wire, and plastic strips is the preferred method of jointing for bamboo scaffolding.

Connections with notches and piercings

Full-culm lashed joints, which require mid-culm attachment of secondary components and are challenging to fabricate, rely on the lashing material's load-carrying capabilities, as opposed to corner connections, which depend on the weight-bearing capacity of the typical bamboo. Because of this structural fault, notched and pierced connections were developed to leverage the natural load-bearing capability of bamboo culms into multilevel or pass-through connections (Figure 4). Notched connections, which require slightly more sophisticated equipment than pure lashing, allow the arched shape of the culm cross-section to accept weight while retaining strength and bearing capacity and increasing joint stability by limiting slippage by creating a specific bearing area [21].

Pierced connections employ a peg as an anchor point for lashing or the threading of lashing material through the punctured hole. Mid-culm connections and angled two-dimensional connectors are the most prevalent uses for pierced and notched junctions. Cut-culm connections, like full-culm and lashed connections, can be braced or unbraced depending on the direction and degree of joint stress. Because of the increased complexity potential, cut-culm linkages are discovered with many more culms integrated. The chance of failure increased as the complexity of the execution increased because puncturing the culms weakens them.

Conversely, cut-culm lashed connections were adequate for everyday or residential usage and were often utilized. Traditional bamboo constructions are usually secured using Lashing connections and mortise-Tenon joints. Rope binding makes mortise-Tenon joints more challenging to split and loosen, enhancing joint dependability and making load distribution at joints more tolerable. However, the end outcome of this combo is still disappointing. It is inevitable that raw bamboo has hollow material properties, and tie rope has poor strength and durability. The joints' components are prone to slipping and coming off when in use, which weakens the structural system as a whole or maybe destroys it [21]. Pierced connections are more rigid and stiff, whereas drilled holes might diminish calm strength. They are more effective on scaffold corners and edges.



(a) **(b)**

Fig. 5. Pierced connections with natural lashing: (a) two culms (b) three culms [21]

Bolted connections

Bolts are the most extensively utilized metal connectors because of their excellent economic performance, high construction efficiency, and simple and trustworthy force transfer. The most direct bolt connection is to drill holes large enough for the bolt diameter in the bamboo rod and then join the bamboo components with matching bolts and nuts. Other sorts of bolt connections are optimized and developed on this basis. This connection has the advantage of addressing a difficult connection problem with a simple construction technique, but it also has certain downsides, such as inadequate joint strength and easy bending hook shedding. Raw bamboo with high shear and splitting resistance is required for bolted connections. Due of the material's thin walls and hollow interior, raw bamboo can break during hole opening and in service, and joints commonly fail to owe to fracture or locally vertical displacement of bamboo culms [10]. As a result, bolted connections are rarely employed in bamboo scaffolding.

Mechanical connectors

Many simple mechanical connections appear as lashing connections; they frequently employ pipe clamps or similar devices to induce pre-tensioning (Figure 7 (a)). Bamboo has also been studied for use with swaged or clamp connections of varying complexity. These are intended to clamp and engage friction on a single culm, frequently needing a neoprene rubber (or similar) interface layer, and produce a more complicated mechanical union (Andry Widyowijatnoko [20]). Scaffold clamps are a straightforward form of this connection (Figure 7(b)), whereas [31] presented a more robust swaged clamp (Figure 7(c)). Because they overcome the limits of tight rope connections, these sorts of connectors are perfect for bamboo scaffolding.

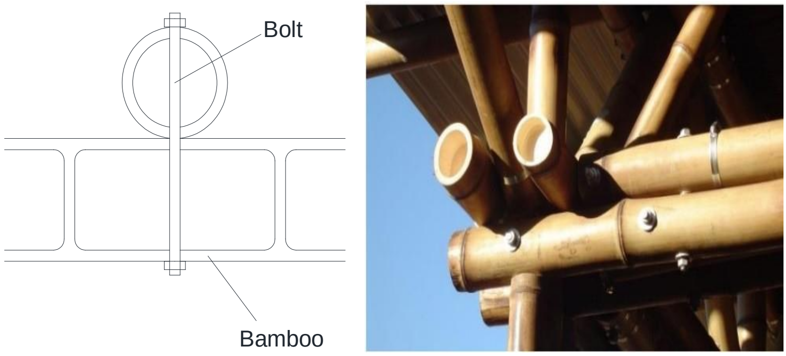
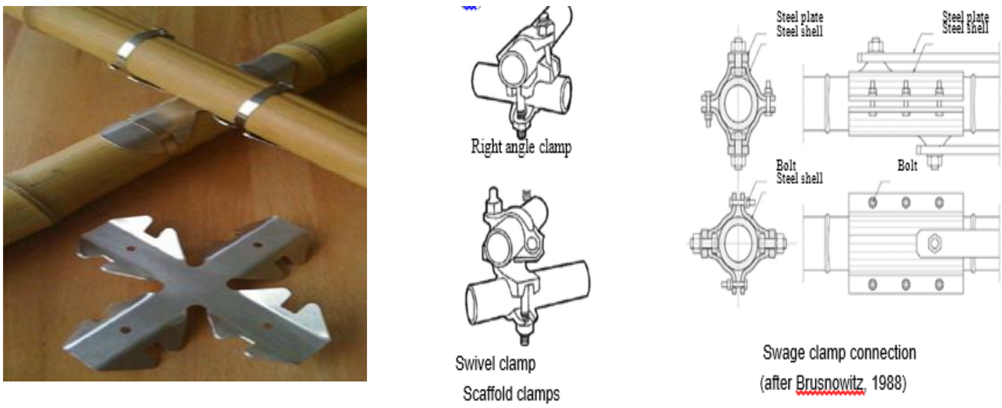


Fig. 6. Bolted connections [15]



a) b) c)

Fig. 7. Mechanical connectors: a) plate connector; b) swivel clamp; c) swage clamp (Andry Widyowijatnoko [20])

The bamboo clamp connector

Many people have used clamps to connect bamboo and build structures. The connectors, as the name implies, are in the shape of a clamp and attach to the outside of the bamboo poles. These clamps are usually constructed to order for a specific application. As an experiment, we constructed a Bamboo Greenhouse using ordinary fencing clamps to explore how difficult it would be to construct using standard connectors (Figure 8). Clamps offer much flexibility and ease in building, but bamboo has no clamping connectors. Because bamboo has a variable diameter and taper, typical steel clamping connections are inefficient [15].

The Bamboo Clamp Connector is a gadget that facilitates and speeds up bamboo manufacturing. It combines the best characteristics of the various types of connections described earlier. (Vahanvati [15]) created a four-prong clamp connection (Fig. 8) that can engage culms of varying diameter and ovality—tightening the center bolt forces the prongs towards the collar, clamping them to the culm and imparting force by friction on the culm’s outer surface, similar to wedge connections.

The connection is suitable for small to medium-sized projects and is primarily intended for Do It Yourself (DIY) applications. The connector joins bamboo by means of a clamping motion. The clamp's four prongs solve the problem of non-standard diameter and taper while enabling it to be utilized with a variety of bamboo sizes. After numerous iterations and considerable testing, the final design was chosen. The final design strikes a compromise between weight and usability to produce a universal joint appropriate for a range of uses. A multitude of design choices are possible due to the Bamboo Clamp Connector's modular and flexible nature. Different combinations of the parts might result in different types of joints [15]. According to my research, these connection styles are appropriate for bamboo end culm attachments in scaffolding.

Fig. 8. Clamp Connectors for bamboo [15]

Benefits of reusing bamboo scaffold connections

The reusability of bamboo scaffold connections offers significant benefits in terms of sustainability, cost-effectiveness, and contribution to the circular economy. Bamboo is a renewable resource with low carbon emissions, and it is strong and lightweight. Using bamboo scaffold connections can help to reduce the environmental impact of the construction sector by reducing the demand for new materials and minimizing construction waste. The reusability of bamboo scaffold connections can further extend the environmental benefits of bamboo scaffolding systems. By reusing connections, the lifespan of bamboo scaffolding systems can be increased, reducing the need to produce and dispose of new scaffolding systems. The reusability of bamboo scaffold connections can also lead to significant cost savings. The cost of bamboo scaffold connections is typically lower than the cost of traditional scaffolding materials, such as steel and wood. Additionally, reusing connections can reduce the overall cost of scaffolding projects by eliminating the need to purchase new connections for each project. The reuse of bamboo scaffold connections contributes to the circular economy by extending the lifespan of bamboo scaffolding systems and reducing the generation of waste. The circular economy is a manufacturing and consumption paradigm that seeks to maximize the value extracted from resources, extend their useful life, and reduce waste creation.

Current Research and Development on Reusable Bamboo Scaffold Connections

This section highlights ongoing research and development activities aimed at improving the reusability of bamboo scaffold connections. These efforts focus on innovative approaches in three key areas: One promising approach for improving the reusability of bamboo scaffold connections is the development of custom joint systems using three-dimensional printing, parametric software, and glue bonding. These systems can be designed to specifically address the challenges of connecting bamboo members, such as their hollow and thin-walled nature [32]. Three-dimensional printing allows for the creation of complex joint geometries that would be difficult or impossible to produce using traditional manufacturing methods. This flexibility enables the design of joints that are optimized for strength, reusability, and ease of assembly and disassembly.

Parametric software can be used to automate the design of custom joint systems, based on specific input parameters, such as the type of bamboo being used, the loads to be supported, and the desired reusability potential. This can help to streamline the design process and reduce the risk of human error. Glue bonding is a promising approach for connecting bamboo members without drilling holes, which can weaken the bamboo culm and lead to fatigue failure. Researchers are developing new adhesives that are specifically formulated for bamboo and that offer high strength and durability [43].

Another approach to improving the reusability of bamboo scaffold connections is to reinforce the connections with fibers, such as natural fiber or fiber-reinforced plastic. This can help to improve the shear and splitting resistance of connections, making them less susceptible to failure. Natural fibers, such as bamboo fiber, hemp fiber, and coconut fiber, are sustainable and renewable resources. They can be used to reinforce bamboo scaffold connections using a variety of methods, such as weaving, braiding, and pulping. Fiber-reinforced plastic (FRP) is a composite material that consists of fibers embedded in a polymer matrix. FRP is known for its high strength and durability, and it has been used to reinforce a variety of structures, including bridges, buildings, and aircraft. Researchers are exploring the use of FRP to reinforce bamboo scaffold connections at critical stress points. This can help to extend the lifespan of the connections and improve their reusability potential [43].

Conclusion

Bamboo has been used for thousands of years as a construction material and has a rich history. Bamboo was used to build houses and scaffoldings in ancient times because of its strength and flexibility. Bamboo is an increasingly popular construction material due to its natural texture and low-carbon environmental protection features. So far, several difficulties have been observed while combining bamboo culms. Because bamboo is hollow, tapered, has nodes at varying intervals, is not perfectly round, and fibers only develop longitudinally, creating sound and aesthetically pleasing bamboo joints is challenging. Keeping all of these constraints in mind, researchers discovered numerous forms of connections to be employed in the bamboo building.

In contrast, all contemporary bamboo connectors are unsuitable for reusable bamboo scaffolding. Bamboo scaffolding necessitates the attachment of secondary components mid-culm, which is inconvenient for several accessible connection types. After a bamboo scaffolding project is completed, the disassembled bamboo scaffolds must be reused for future bamboo scaffolding projects. Some connection options involve drilling holes in scaffold culms and bolting them together, which leads to fatigue and degradation after frequent usage. Because of its hollow and thin-walled material qualities, raw bamboo can break during hole opening and in service, and joints commonly fail to owe to cracking or local deformation of bamboo culms. Scaffolding also uses full-size, uncut bamboo parts, and the load transfer mechanism is performed by employing connections on the culm's exterior to transfer force to the bamboo's firm outer surface via friction. As a result, several readily available connection types are incompatible with bamboo scaffolding. This research examines existing bamboo connections suitable for reusable bamboo scaffolding. Following a thorough review of the literature, the following connectors suited for reusable bamboo scaffolding are recommended.

With some constraints in mind, the favored way among the many methods of connections in bamboo scaffolding is binding the complete bamboo culm cross sections of scaffolds through bearing with bamboo strips, rattan, iron wire, plastic strips, and so on. The load-bearing capabilities of the lashing materials are critical in full-culm lashed joints, which require mid-culm attachment of secondary components and are challenging to fabricate.

In the case of scaffold corner connections, which rely on the bamboo's weight-bearing ability, notched and pierced connections were developed to combine the inherent load-bearing capacity of bamboo culms into multilevel or pass-through connections. Notched connections, which need slightly more sophisticated equipment than pure lashing, allow the arched shape of the culm cross-section to absorb weight while keeping strength and bearing capacity and increasing joint stability by preventing slippage by providing a particular bearing region. Because of the technical foundation of conventional notched and pierced connections, using metal to join bamboo culms has the added benefit of dependability and ductility.

Raw bamboo with high shear and splitting resistance is required for bolted connections. Because of its hollow and thin-walled material qualities, raw bamboo can break during hole opening and in service, and joints commonly fail to owe to cracking or local deformation of bamboo culms. Drilling holes in scaffold culms and bolting them together are necessary for bolted connections, resulting in culm fatigue and degradation after continuous usage with these connections. As a result, bolted connections are rarely employed in bamboo scaffolding. Several simple mechanical connections appear to be lashing connections; these frequently employ pipe clamps or similar devices to induce pre-tensioning. Because they overcome the limits of tight rope connections, these sorts of connectors are perfect for reusable bamboo scaffolding. There are also recently created Clamp connectors for making bamboo buildings quicker, faster, more flexible, and more convenient. These connection styles are appropriate for bamboo scaffolding to end culm attachments.

Future advances based on the features of bamboo scaffolding might include complete, mid-culm scaffold connections, weight transfers via outer culm friction and effective reusable scaffolds.

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