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Survey of Split Bamboo as a Primary Structural Material in Construction from 1970 to 2020 and Future Directions for Exploration

Sankalpa *

Srishti Manipal Institute of Art, Design, and Technology, India-560064

Abstract

This paper provides a comprehensive survey of research conducted between 1970 and 2022 on using split bamboo as a primary structural material in construction. Examining the existing gaps in the literature highlights the need for further investigation in order to expand the utilization of other forms of bamboo, e.g., splits, for construction purposes. Exploring its applications is a crucial step, particularly toward re-evaluating the global availability of construction-grade straight bamboo species, which is an inhibiting factor in expanding bamboo uses. Despite not possessing perfect straightness in various regions, these species can be a suitable alternative to poles locally in split form. The survey concluded that there is an immense amount of focus on works related to joineries in bamboo poles or engineered forms of bamboo, resulting in a gap regarding split bamboo structural and constructional possibilities. This study provides valuable insight into the future investigation that can be undertaken using the splits as a structural material.

Keywords Split bamboo; Structural system; Construction; Joineries

**Corresponding Author: Sankalpa, Srishti Manipal Institute of Art, Design, and Technology, 560064, India*

1. Introduction

A highly favourable market towards a few materials such as brick and RCC has resulted in loss in the diversity of construction materials, techniques and skill that were historically available in India. In urban centres the use of bamboo is almost negligible owing to many factors, including policy provision, social conventions, and for purely constructional reasons such as drudgery of bamboo work and customization of every joint at the site of construction. Nevertheless, Bamboo as a renewable material for construction has received considerable attention among the architects and engineers. It has been widely used in construction projects of all sizes, with splits and poles serving as secondary and tertiary structural components. With only a few exceptions, this trend is pervasive across the board. Notably, splits have received very little attention compared to how bamboo poles have been enhanced as a building material through structural and architectural modifications. Splits are not as prevalent in construction as they are in furniture and other items, making them seem misplaced or ignored. Splits, however, have tremendous potential for use as primary members in structures, particularly with good tensile strength. They display potential for standardization in form, allow for better packaging and shipping, and are usually simpler to handle. They also provide designers the freedom to develop organic shapes. Despite these benefits, little has been done to investigate these possibilities. The gap in knowledge and application of splits in construction is unintentionally widened by contemporary studies' focus on engineering bamboo into products similar to industrialized lumber or reinforcing materials for concrete. Furthermore, most studies on splits have only looked at how they function in compression, not tension, where they might be able to compete with steel. If splits' tensile capacities were also given additional consideration, a more comprehensive range of structural options could be revealed.

2. Literature Survey

2.1. General Introduction to Bamboo

The grasses that make up bamboo are part of the Poaceae family and Bambusoideae subfamily, includes 75 genera and 1250 species with varied characteristics and uses. Thriving in tropical and subtropical regions, bamboo rhizomes form sympodial or monopodial clumps. The young shoot, protected by sheaths, matures into fully grown culms. Harvested for construction after three years, distinct from trees, bamboo grows longitudinally, with no lateral or radial development (Negi, 2009).

Most species of bamboo are hollow, and some are solid. Hollow bamboo structure, resembles an elongated cone with interspersed diaphragms known as nodes. The region between two nodes is termed the internode, defining the bamboo culm. The culm comprises two epidermal layers: a thicker, more lignified inner layer and an outer layer covered by a cutinized wax coating. Culm cells provide transverse linkages in nodal areas and axial orientation in internodal regions. About 50% parenchyma, 40% fiber, and 10% conducting tissues make up the culm, with species-specific variations. The inner culm wall, richer in parenchyma and fewer vascular bundles, narrows vertically. In contrast to the basal section, which has a larger amount of parenchyma, the upper part of a culm includes equal to or more fibers per unit area than parenchyma. (Liese, 1987)

Bamboo is one of the major producers of biomass (Janssen, 2000), is valued as a building material for its rapid growth and abundant availability in its growth regions. Each species, however, matures at a different age to reach peak strength. Matured bamboo has low weight and high resistance to tension, compression, and deflection (Dunkelberg, 1985). Moisture content (7-18%), specific gravity (0.428-0.817), and various mechanical properties like fiber stress, modulus of rupture, modulus of elasticity, and compression strength parallel to grain vary in air-dried bamboo, depending on the species. As per (Bhalla, et al., 2008), species like *Dendrocallamus giganteus* typically have Young's modulus of 14 GPa, compressive strength of 55 MPa, and tensile strength of approximately 120 MPa. These numbers do not significantly differ from mild steel, which has Young's modulus of 20 GPa, yield strength of 250 MPa, and ultimate strength of 410 MPa.

Common construction bamboo species in India include *Bambusa blacooa* (BB), *Bumbusa nutans, Bambusa tulda, Bambusa bambos, Dendrocallamus strictus,* and *Dendrocallamus stoksii*. BB exhibits favorable mechanical properties, with a better modulus of elasticity than *B. tulda* or *B. nutans*. The compressive strength of *B. balcooa* ranges from 39.4 to 50.6 N/mm2 in green and 51.0 to 57.3 N/mm2 in air-dry conditions. Modulus of rupture varies between 85.0-62.4 N/mm2 in green and 92.6-69.6 N/mm2 in air-dry conditions. The modulus of elasticity is 7.2-10.3 kN/mm2 in green and 9.3-12.7 kN/mm2 in dry air conditions (Kabir et al., 1991). BB, native to East and North-Eastern India, grows in Nagaland, Meghalaya, Tripura, Assam, West Bengal, Bihar, and Eastern Uttar Pradesh. It is cultivated in communities across several Indian states. While adaptable to various soil types, BB thrives in thick-textured soil with sufficient drainage, up to an altitude of 600 m. - shorten without loss of content

2.2. Traditional Uses of Bamboo All Over the World/India

Bamboo serves as a vital construction material in rural communities across South and Southeast Asia, including India, China, Vietnam, Indonesia, Philippines, Myanmar, and Bangladesh. Traditional bamboo construction employs prefabrication techniques, assembling walling and roofing elements over bamboo or bamboo-timber mixed frames. Notable structures, like the Toraja bamboo house in Indonesia with its distinctive saddled roof, attract global attention. In regions like Mindanao (Philippines), Majuli (Assam, India), and parts of Latin America (Colombia, Ecuador, Costa Rica), bamboo, especially the Guadua species, is employed for resilient lightweight constructions, like the durable bamboo bahareque houses that withstand weathering and earthquakes. (Gutiérrez, 2000)

In India, bamboo is extensively utilized in the northeast and eastern regions, with states like Mizoram, Nagaland, Tripura, Manipur, Arunachal, Assam, Bihar, Bengal, and Orissa actively engaging in bamboo construction. The Northeast excels in crafting everyday bamboo products, including furniture, baskets, trays, toys, mats, musical instruments, weapons, and fish traps. The *Riang* house (Tripura), *Mizo* house (Mizoram), *Adi Gallong* house (Arunachal Pradesh), and bamboo houses of Assam and Tripura are the most prominent of the houses (Ranjan, 1986). These houses are a mix of prefab construction with exquisite customized details. Bihar's bamboo houses in the *Kosi* region exhibit a similar approach to, however intricacies are most evident in Northeast India compared to other regions.

2.3. The Shift in Uses of Bamboo in India

In most parts of India, the use of bamboo is dwindling due to a shift towards reinforced concrete and bricks, driven by government housing schemes that classify bamboo constructions as "kutcha" or temporary. The 2011 Census indicates a decline in kutcha dwellings, with the percentage dropping from 27.44% in 1991 to 12% in 2011. The eastern and northeastern regions experienced significant reductions from 39% to 8% and 69% to 5%, respectively, between 1991 and 2018. Despite a surge in raw bamboo culm supply for horticulture (from 40% to 63% between 1980 and 2014), India's global bamboo product export share remains minimal at 0.04%, while China dominates with a 65% share (Tambe, et al., 2020).

The trends from the above data show Regardless of region and skill level, there is declining interest in using bamboo for construction. The Northeast, less transformed than other parts, faces challenges due to improved connectivity and increased use of industrial materials. Traditional thatch is replaced by galvanized sheets and pucca plinths, favoring durability over bamboo's climate limitations. Industrial materials offer standardized supply chains and performance advantages. While bamboo harvesting and treatment address some issues, social perceptions of status and durability persist. The shift from bamboo reflects a slow challenge to traditional norms, as the construction industry favors materials aligned with modern practices and demand

2.4. Modern Uses of Bamboo

In urban India, bamboo is relegated to temporary use as scaffolding or ornamental structures due to concerns about durability, vulnerability to fire, and the absence of contextually relevant building codes. Despite being accepted as a structural material in the National Building Code 2005, mainstreaming efforts face challenges. Various state governments, like Gujarat and Bihar, have issued guidelines for bamboo-based rural housing, especially in post-disaster reconstruction. Despite credible efforts at multiple levels, bamboo usage remains limited, falling short of achieving mainstream status akin to timber or steel.

The recent upswing in urban interest in bamboo is predominantly fuelled by environmental concerns, particularly its potential for surface articulation like woven mats. Globally, bamboo addresses climate change and provides a medium for innovative architectural expression. Projects such as the Madrid Airport's roof and Castaway Island Resorts showcase bamboo's structural versatility. In India, the Kempegowda International Airport, designed by SOM, pioneers the use of engineered bamboo in public interiors and structural projects, signifying a shift from traditional bamboo applications. The increased global attention and research highlight bamboo as an eco-friendly, renewable resource with high tensile strength, carbon sequestration capabilities, and potential as a timber substitute in engineered products.

2.5. Challenges that Bamboo poses in Construction and how they are addressed

2.5.1. Anisotropy Behaviour:

The anatomy of the bamboo section comprises different parts, such as fibers, cells, and a lignin matrix which forms a layered structure with a specific pattern. Because of this arrangement, how the different parts of bamboo are connected can significantly impact its overall mechanical properties (Wegst & Ashby, 2004). The fibers are particularly important because they help to strengthen the lignin matrix. These fibers are denser towards the periphery of the bamboo and less dense towards the center (Lakkad & Patel, 1981) (Murphy & Alvin, 1992) (Ray, et al., 2004) (Zou, et al., 2009) (Wahab, et al., 2010) (Kaur, et al., 2016). This fiber distribution enhances mechanical properties at the outer edge. The linear arrangement of cellulose fibers within the parenchyma makes bamboo significantly stronger longitudinally along the culm than transversely. Bamboo exhibits strong anisotropic behavior, meaning it displays different mechanical properties in various directions. This contrasts with isotropic materials, which have consistent properties in all directions, making bamboo's strength dependent on loading direction.

Bamboo, prized for lightweight construction, falls short in tensile strength compared to steel, limiting its use in heavy construction. Tensile tests show bamboo has significantly lower strength and breaking points under stress. Its low breaking force renders it unsuitable as a primary load-bearing member for buildings (Ogunbiyi, 2015). Bamboo's anisotropic behavior, with weak bonding in the transverse direction, poses challenges in developing structural joinery. Unlike bamboo, steel exhibits strong isotropic behavior under mechanical stress. Various strategies have been adopted to overcome this weakness.

2.5.2. Bamboo Polymer Matrix Composite

One of the most effective ways to overcome the anisotropic limitations of bamboo as a material, is to engineer it with the aid of other materials. Engineered Bamboo involves modifying bamboo to create uniform construction materials. This process breaks down the entire culm into smaller sections, gluing them together into composite panels or dimensioned lumber using modern adhesives (Liu, et al., 2016). Common products in this category include bamboo scrimber and laminated bamboo. In India, only a few companies produce commercial bamboo scrimber. The bamboo scrimbers are crushed fiber bundles saturated with resin compressed into a dense block (Sharma, et al., 2015). Laminated bamboo is created by slicing bamboo into thin strips and bonding them with a waterproof adhesive, like phenol-formaldehyde. The strips are arranged to have fibers in adjacent layers oriented in opposite directions, resulting in a more uniform, isotropic, and predictable material with board-like products.

Laminated bamboo, achieved by bending wet bamboo into desired shapes, offers benefits like producing larger and intricate shapes. It is easily drillable and cut with standard woodworking tools, enhancing joinery accuracy and facilitating mechanical fastener installation. These advantages help address challenges in bamboo's structural use, making it a viable substitute for conventional materials.

2.5.3. Mechanical fastening

From the strategy perspective to overcome anisotropic properties, the experiment on connectors for bamboo culms is typical of two types. The first type relies on nuts, bolts, or equivalents for force transmission, while the second type utilizes surface grip. Materials like steel or fiber-reinforced polymers (FRP) are commonly used. For the former, strapping may enhance performance against longitudinal splitting, while the latter benefits from bolting to improve force transmission.

In the case of connectors involving nuts, bolts, or equivalents, piercing the bamboo disrupts its continuity, relying on the bamboo pole's sectional form and the shear strength of the bonding material for stress transfer. This connection optimally engages with the non-uniform bamboo pole section through point contact, with nuts and bolts securing the join for efficient force distribution. Curved washers have been explored to improve grip and enhance load transfer efficiency under transverse stress.

The development of Mechanical fastening in bamboo construction addresses a prevalent failure mode—splitting, particularly under bending or tension forces. When a tensile force surpasses a bamboo culm's strength, fibers in the weakest region separate, causing failure. Splitting can occur across the culm's diameter and length. Common preventive measures include using resin and securing joint holes through lashing. Splitting represents the primary limit state for bamboo in structural applications, emphasizing its significance (Janssen, 1981) (Arce-Villalobos, 1993). To overcome bamboo's anisotropic limitations, orienting mechanical fasteners, such as bolts, parallel to the bamboo fibers proves effective. This orientation leverages the stronger bonding in this direction, resulting in a joint superior to one with perpendicular fasteners. Further enhancement involves infilling joints with materials like timber or cement mortar to boost grip. Architect Simon Velez employs cement mortar-reinforced joints to address this challenge, filling the bamboo's hollow part and connecting pieces with bolts and metal connections. This approach maintains joint rigidity and stability without compromising overall bamboo integrity. Strengthened bolted joints with high-strength mortar show significantly improved bearing capacity (Hu, 2018).

Mechanical fasteners, like bolts or screws, offer versatile options for joining bamboo elements, forming robust joints for resisting bending and shear loads. Yet, using them poses challenges, including the risk of splitting or cracking bamboo if not installed properly. Techniques like pre-drilling holes and using sharp drill bits can mitigate these issues. Another concern is the potential corrosion of fasteners over time, affecting joint strength. Choosing corrosion-resistant materials, such as stainless or galvanized steel, addresses this challenge. To enhance bamboo's structural performance, studies examine the relationship between mechanical properties and the critical distance from the bamboo end where bolts are applied. The table below summarizes research on bolted connections in raw bamboo pole structures, considering variables like end distance and bolt diameter.

2.6. Advantages and Disadvantages of Using Bamboo as a Construction Material in Buildings

Like any other building material, bamboo comes with its own challenges in construction. Here are some advantages and disadvantages of bamboo as a construction material.

Table 1. Advantages and Disadvantages of Bamboo as a Construction Material

Sr	Factors	Advantage	Disadvantage
1	Constructability	It is extremely light to handle compared to dominant linear materials like steel and timber for construction	It needs careful application of tools as it is susceptible to splitting
2	Maintenance	Being lightweight, it is easy to repair or disassemble	In comparison to similar materials like wood, its maintenance cycle is shorter
3	Detailing	The available inventory of connections for construction in bamboo is limited because of its morphology constraints. This makes it easy to expand the skill to handle it	Inability to develop a joinery because of deterioration in strength of the joint due to removal of material, limits most inter lockable mechanical joints
4	Finishes	Its surface offers almost all types of finishes similar to timber	Sanding is often used as a pre-step to polishing. But sanding should be avoided as the removal of the hard outer water-repellent and mechanically performing layer makes it more vulnerable to borers attack
5	Unforgiving Details	Its strong anisotropic behaviour has led to the development of new joineries	It gives up very easily in the transverse direction if considerable care is not taken while drilling in it
6	Dimensional Tolerance	Its high dimensional variability paves the way for the grading of bamboo based on straightness	Unlike other natural materials like timber, it is not necessarily straight or has the same cross-

		and cross-sectional area. This helps to use different grades of it for different purposes. A straight bamboo with more diameter is used for posts, whereas a smaller diameter straight bamboo is usually selected for rafters for a sloping roof.	sectional area along its longitudinal axis. This demands a certain degree of tolerance for built-in dimensions beyond materials like timber or steel while detailing to handle deviations in geometry.
7	Resource Utilisation	Every part of the bamboo can be utilized for some or other repurposed construction, e.g., pins, slats, slivers, and splits.	The entire utilization of bamboo needs a variety of skill sets to convert each part into its desired utility. This requires customization, which impacts the time of construction.
8	Fire	Bamboo's fire response values are within acceptable ranges for structural timbers, but its fire resistance is better than that of plywood (Mena, et al., 2011)	Because of its vulnerability to fire; it has been one of the reasons of not accepting it has a *pucca* material.
9	Prefabrication	Bamboo splits and slivers are converted into standardized engineered products	Non-standard form of bamboo in terms of dimensional and shape variations discourages standardization and prefabrication
10	Resource Availability	India is one of the largest producers of bamboo. It is fast growing and renewable	Poor supply chain of construction-grade mature treated bamboo
11	Durability	10-15 years in good condition (Negi, 2009). But there are examples of bamboo lasting more than 50 years.	Bamboo needs to be kept dry with unrestricted airflow to make it durable (Janssen, 2000). Hence, structural bamboo should be designed to keep free from water. It is also vulnerable when it comes to direct contact with the Earth.
12	Line and Levels	It works with a higher level of installation	Accuracy of the level in the bamboo being managed rather than achieved since the longitudinal diameter variation disables to achieve it

3. Split Bamboo: What is it?

Split refers to larger segments, thick sections, or thin strips of culm (Liu, et al., 2016). Splits have found their use more for a secondary structure role, like bedding for tiles, prestressed infill or flattened panels in pedestrian bridges, and walls instead of primary structural members. Woven bamboo poles have been the most typical way of creating an enclosure. In bridges, it is woven to create a pre-stressed form that can transfer the load onto the primary structural member. The pre-stressing of bamboo is also common in the walling system in India. There are examples of uses of splits in early versions of temporary structures made out of bending the splits to get a vaulted or umbrella form. Indian hand-drawn rickshaws used bend split over which textile fabric was reinforced to create shade and protection from the rain.

In several parts of the world, split bamboo instead of bamboo poles is also used for construction. Sometimes bamboo acts as a skeleton frame on which splits are woven to get the form. The Dorse tribe hut of southern-Ethiopia uses splits to make curved-shaped hut (Dunkelberg, 1985). In India, the splits make granaries and contribute as secondary structures for roofs, walls, and bridges. Most of the structure uses bamboo poles or splits under flexure or compression. There isn't much evidence of the use of bamboo in tension, although it has good tensile strength. Bamboo has been used under tension in some parts of India and China, but in these cases, it is treated like cables. In China, bamboo cables have been used for shipyards and ships for making suspension bridges and towing ropes. The bamboo poles were cut into thin strips and used to make rope. The strips from the inside of the pole were chosen for the cable core due to their lower tensile strength. This core was covered with a layer of tightly plaited bamboo strips that were taken from the bamboo's outer layer, covering about half of the cross-sectional area. The Chinese also used the tensile bamboo structure to reinforce river banks. (Dunkelberg, 1985).

4. What are the Advantages of Using Split-Over Bamboo Poles?

The world of exploration of bamboo as a construction material has moved into two pre-dominant areas. The first area focuses on working with bamboo poles and exploring it to achieve an architecture accommodating its morphological limitation of it through careful detailing and new joineries. This includes works of architects like Simon Velez, Nilam Manjunath, Nripal Adhikari, Vo Trong Nghia, Elora Hardy, and Anna Heringer, to name a few. The second type of work has moved towards engineered bamboo, similar to industrial timber products. The products are primarily being used for secondary structures or infill materials though some structural forms of engineered bamboo have already undergone successful structural tests. In between these two explorations; limited and only intermittent attention has been paid to split bamboo and its potential. The table below compares the advantage of using split bamboo over bamboo poles.

Table 2. Advantage of using split bamboo over bamboo poles

Sr	Category	Comparison	
		Bamboo Poles	**Splits**
1	Straightness	Indian bamboo, e.g., *Bambusa balcooa*, for construction purposes, is not as straight as species like *Dendrocalaums asper, Guadua angustifolia*.	It is possible to derive straighter splits from non-straight bamboo. Within a limited deviation for straightness, there are more available samples of two-dimensional bent bamboo poles instead of three dimensions.
2	Standardization	Bamboo poles are not of a uniform cross-sectional area or sectional profile, which makes standardization of poles untenable.	It is possible to machine the split to get standard sections to overcome the morphological variability of bamboo poles.
3	Packaging	Currently, bamboo poles are transported on carriers based on their length. The maximum length of bamboo available in the market is usually twenty-four feet length.	With the standardization of split, the packaging for transport is accessible and readily achievable, unlike bamboo poles because of their morphological variability.
4	Structural form	Bamboo poles have limited ability to offer curvilinear structural elements.	Unlike bamboo poles, it is highly flexible to offer curvilinear elements potentially.
5	Prefabrication	The morphological variability of bamboo poles limits their potential to be prefabricated. However, evidence of prefabricated roofing elements is available at a smaller scale where it is possible to lift and erect manually.	The splits can get packed better because they can be standardized. This opens up the potential for prefabrication of components and elements compared to bamboo poles. Element-level prefabrication is common, like making fences or roofs.
6	Constructability	Bamboo poles, unlike splits, have more weight and need a strength-based tool to handle them.	The splits are lighter, flexible, safe, and easy to handle for construction.
7	Lightness	Unlike split, its use makes the	It can be used to construct light-

		spanning structure heavy.	spanning structures like open web joists (Villegas, et al., 2015)
8	Node Handling	Joints near the nodes are preferable, but getting such conditions everywhere is nearly impossible. Therefore, it's better to design a joint without considering its added advantage initially.	Such conditions of joint handling don't arise in the case of split bamboo for making joineries.
9	Line & Level	Being an elongated cone, the level is impossible to maintain if the line is maintained.	Such issues do not arise with a split, as it is possible to maintain both straightness and an approximate cross-sectional area.
10	Dimensional tolerance	It has high dimensional variability from top to bottom.	It can be standardized to get minimum variability from top to bottom.

5. Modern Structural Uses of Splits in Construction

The experiment in modern uses of split bamboo can be traced back to work done in Latin America and India during the 1980s. Between 1976-84, Eda Schaur experimented with split bamboo in School of Architecture, Ahmedabad, India to incorporate it into the fold of lightweight structures through experiments on grid shells and some preliminary tensile structures. These experiments primarily used bamboo under axial compression or bending instead of tension. No literature study is available to conclude why the grid shell project could not make it beyond some experimental buildings or demonstration level.

Table 3. Modern structure and experiments using split bamboo

Sr	Institution/ Firm	Year	Form of Bamboo	Structural Form	Joinery
1	Schaur, Eda	1976-84	Split	Grid shell	Lashed nodal joints in jute
2	Studio Cardenas	2009	Split	Geodesic	Clamped neoprene joint with steel bolt
3	the Weak Architects	2009	Split	Shell	Woven
4	Albert, Heinz	2015	Split	Surface structure	Lashing

5	Villegas et al.	2015	Split	Truss	Metal curved washer with through bolts
6	Mehta, Yash	2018	Split	Doubly-curved	Pinned nodal joints; metal clamped bolted end joints (Figure1)
7	Setia, Abhimanyu	2019	Split	Doubly-curved (Figure2)	Metal clamped friction nodal joint; metal clamped bolted end joint
8	CO-Lab Design Office	2019	Bundled splits	Shell	Screwed and strapped
9	Pounamu	2019	Bundled split	Arch	Arched and bundled splits under compression
10	Villegas et al.	2019	Bamboo pole and splits	Truss	Metal connectors with through bolts

The above table shows that very few work has happened when bamboo splits are under tension instead of compression. All the attempts with splits under tension are experimental structures and elements.

Figure 1. Pinned nodal joints; metal clamped bolted end joints

Source: (Mehta, 2018)

Figure 2. Doubly-curved Shell with square grid

Source: (Setia, 2019)

Figure 3. Clamp connector

Source: (Mehta, 2018)

6. Challenges of Using Split Bamboo and How the Existing Literature Addresses

6.1. Morphological Standardizations

Sourced from the bamboo poles, split bamboo instead of an elongated cone converts into a section whose cross-sectional area change along the longitudinal axis. In this conversion, the splits lose some advantage of strength induced through the closed form of the pole. With the assumption that standardization has led to ease of construction and widened the use of materials like timber or steel, there is no reason that would not be the case for the splits. In fact, engineered bamboo, particularly laminated bamboo, used bamboo strips for making boards. The standardization of split eventually leads to ease of assembly. The ease of assembly reduces the construction time and offers wider accessibility for exploring this material for building elements.

Splits taken out from the culm are not perfectly regular in its cross-sectional area along the length, and neither it has a predictable, regular geometry. To make the section uniform, either the material is sanded out of the split after splitting or planned using planer machines to get the same width across the length. There are two, three and four-sided planar machines available in the market. Gaining uniform width through the above two cases or uniform wall thickness is possible; the biggest dilemma lies while managing the mechanical properties of the bamboo. Whereas the outer layer of bamboo is most suitable for the mechanical property, removing it to get a uniform section reduces its structural purpose and wider applicability in construction. Not only is the structural performance of bamboo not uniform for all species, nor is the ability to take mechanical stress the same everywhere along the length of the same bamboo. This makes standardization challenging for two reasons. Firstly, even if the form is standardized, the mechanical performance will vary widely. There is no evidence of how people have overcome stress conditions other than primarily using the splits under compression. There are very few documented examples of experiments with splits under tension. Secondly, removing the outer performing layer isn't the best choice when mechanical performance is a criterion. Currently, there are no commercially available standards for the availability of the splits, nor there are any international standards available to standardize it for market use.

If the purpose of the split is to be used for a screen as compared to its purpose to be used for its structural application, both call a very different way of looking at standardization. Unlike basketry or other smaller objects of everyday use made out of bamboo slivers, the structural use of bamboo in building demands mechanically the most suitable part to be used. Standardizing fasteners for splits seem illogical without the standardization of the split itself.

6.2. Standardization of Fastener

The possibility of standardization of splits for structural purposes should include the most mechanically performing part of it as a contributor. Thus, the prospect for standardization of the section based on the previous discussion is possible within the constraints of the non-removal of the outer layer of bamboo. Morphologically, this creates constraints over the development of those fasteners in which the outer layer participates in its design. This constraint owing to the non-uniform curvature of the top layer that needs to be engaged, also potentially demands a suitable way to design fasteners and integrate the split section with a balance between the standardization of the split and its mechanical performance. The only alternative way to standardization and mechanical performance work is to use engineered bamboo with the standardized possibility of solid sections in various desired geometry like squares and rectangles. Standardizing splits is necessary to standardize the fastener system, which may lead to ease of construction.

There are three types of exploration on joinery similar to bamboo poles. The first is a friction-lashing joint using metal or natural fibers. This is the most prevalent way of connection used for bundling splits to increase strength. The second type of joinery uses through bolts with washers to transfer force. The washer, in this case, has been experimented with flat and curved profiles. The curved profile transmits more forces by inducing radial compression to counteract shear failure (Villegas, et al., 2015). The third type of joint usually houses or clamps (Figure3), splits, and secures it using through bolts. The table below documents the type of joints tested using metal and bolts for splits.

Table 4. **Type of joints tested using metal and bolts for splits**

Sr	Author	Year	Form of Bamboo	Investigation	Findings
1	Sonar et al.	2009	Split (*Dandarcalamous Strictus*)	Studied the mechanical properties using half-split bamboo as structural members and joints with a mild steel plate gusset for single- and double-bolted bamboo joints under axial tension.	Different end distances and bolt diameters would influence the joint's ultimate bearing capacity. Double-bolt joints had a higher ultimate failure stress than single-bolt joints.
2	Villegas et al.	2015	Splits (*Guadua angustifolia*)	Studied the efficacy of a new joint developed to tackle the ductile behavior of bamboo split under compression along the thickness of the culm or radial	There is a significant increase in joint strength without radial compression when tested for truss.

				direction. The joint connects two splits using two curved steel plates, a bolt, and a nut.	
3	Villegas et al.	2019	Splits (*Guadua angustifolia*)	Studied the structural performance of trusses made out of bamboo poles and splits using steel clamps.	The clamp design performed better to counter the longitudinal splitting in bamboo poles or splits and accommodated morphological variations in them.

Different end distances and bolt diameters would influence the joint's ultimate bearing capacity (Sonar & Siddhaye, 2009). The work on the relationship between bolt diameter and end distance is done with variable thickness of the split bamboo for axial tension test. The study doesn't establish the impact of change in width on stress. The end condition uses two splits instead of one as a connector that sandwiches a metal plate. The species chosen for this study was *Dandrocalmus strictus*.

7. Constraints of the Split as a Form-giver

Constraints imposed by splits towards bending and rotation limit the possibility of those forms that require it to rotate along its axial axis to achieve the desired form. Therefore, any form possible by bending in one direction of the split is readily possible compared to the one in which it requires bending in two directions or a combination of bending and rotation. An inbuilt tolerance towards bending or twisting in other directions or along the axis needs study. Tolerance in the degree of rotation needs to be found with respect to the length of the split. Further tests must be conducted to determine its overall effect in giving shape while maintaining the desired structural performance of any form. Early work with split bamboo in grid shells (Dunkelberg, 1985) was carried out by the Institute of Lightweight Structures in Ahmedabad with the collaboration of the School of Architecture (1976-77). The principle of this form finding was based on reversing the catenary chain. The reversal in form led to the reversal in the force from axial compression to axial tension. The joineries in these structures were primarily based on lashing. Although this example is based on transforming an orthogonal grid to a parallelogram, the grid members simultaneously bend along with nodal joint rotation to make the shell. Experiments were also conducted on doubly curved surfaces with splits showing a certain degree of rotation to achieve the form (Mehta, 2018) (Figure 4), (Setia, 2019) (Figure 5), (Bagul, 2020) No study is available to show the relationship between the degree of axial rotation in split bamboo as a determinant in deriving the type of such forms.

Figure 4. Doubly curved shell with diagonal grid
Source: (Mehta, 2018)

Figure 5. Doubly curved shell with square grid
Source: (Setia, 2019)

Bamboo as a renewable material for construction has received considerable attention among the architects and engineers. It has been widely used in construction projects of all sizes, with splits and poles serving as secondary and tertiary structural components. With only a few exceptions, this trend is pervasive across the board. Notably, splits have received very little attention compared to how bamboo poles have been enhanced as a building material through structural and architectural modifications. Splits are not as prevalent in construction as they are in furniture and other items, making them seem misplaced or ignored. Splits, however, have tremendous potential for use as primary members in structures, particularly with good tensile strength. They display potential for standardization in form, allow for better packaging and shipping, and are usually simpler to handle. They also provide designers the freedom to develop organic shapes. Despite these benefits, little has been done to investigate these possibilities. The gap in knowledge and application of splits in construction is unintentionally widened by contemporary studies' focus on engineering bamboo into products similar to industrialized lumber or reinforcing materials for concrete. Furthermore, most studies on splits have only looked at how they function in compression, not tension, where they might be able to compete with steel. If splits' tensile capacities were given more consideration, a more comprehensive range of structural options could be revealed by this focus.

7. The Architectural Expression

Three important criteria influence how split bamboo aids in expression in architecture. To begin with, the material's intrinsic limitations, such as its tensile strength and flexibility, guide its use in design. Second, structural demands and material choices have an impact on joinery design because in designing joinery force distribution and material compatibility must be considered. Thirdly, the architectural programme influences how split bamboo can be integrated, taking into consideration specific qualities of bamboo and joinery on the one hand and on the other aesthetic objectives.

7.1. Restraint Imposed by Material

The choice of materials in architecture is influenced not only by structural requirements, such as span and system, but also by the unique properties that each material offers. Different materials possess distinct characteristics that make them suitable for specific architectural applications. For instance, in spanning thirty meters, a reinforced concrete (RCC) beam might not be the ideal choice due to limitations in its strength-to-weight ratio. In such cases, a truss system made of steel is often preferred as it provides a readily available solution with high strength and relatively low weight. Consequently, the architectural expression through RCC and steel stresses are radically different given the inherent qualities of the concrete and steel. Hence, we could argue that the structural necessities influence the choice of materials and the material qualities in turn drive the architectural expression. The ingenuity of the architects depends on her/his abilities to aesthetically combine the structural requirements and material choices and its qualities. Split bamboo, for instance, possesses inherent constraints in terms of flexibility and bendability, which restricts its morphological possibilities for synclastic or anticlastic systems. It also has to do with limited rotational possibility in order to give one form over another. Further, the material overlaid on the structural system its own chromatic, tactile, and aesthetic characteristics to give rise to architectural expression.

8. Influence of Structure and Choice of Material on Design of Joinery

The effectiveness of a mechanical connection in architecture hinges on its ability to fulfil structural requirements. The performance of joinery is a direct outcome of factors like material selection, joining mechanism, constructability, and the overall morphological design of the joint. These elements contribute to the joint's capacity to effectively transfer stress from one member or set of members to others. The process of exploring the formal nature of joints often involves conducting experiments to evaluate the strength, stability, and durability of various connection methods. These experiments are crucial in determining the most suitable approach for connecting two or more structural members. By subjecting joints to rigorous testing, architects and engineers can assess their load-bearing capabilities, resistance to external forces, and its long-term reliability. The choice of materials significantly impacts the performance of a joint. Different materials possess distinct mechanical properties, which directly influence the joint's overall structural integrity. The choice of materials within a joint is crucial to ensure optimal load transfer and prevent premature failure. The overall morphology and design of the joint are key considerations when addressing the transfer of stress between members. The joint's geometry, dimensions, and connection details need to be designed to optimize load distribution, minimize stress concentrations, and enhance overall stability. The forms of joinery, the materials used for the joinery in turn contribute to the architectural expression.

9. **Design Program**

The design program plays a crucial role in shaping architectural design and expression. Each program, whether it be a bus terminal or a hospital, has unique functional and spatial requirements that guide the design process. For example, a bus terminal demands a porous and transparent space to facilitate movement and enhance accessibility, while a hospital necessitates a healthy and controlled environment to ensure the well-being of patients. Consequently, the design choices and details are directly influenced by the program. The robustness and durability of joinery details differ between a bus terminal, where ease of maintenance and sanitization are essential, and a hospital, where hygiene and infection control are important. Therefore, the design of joinery and its joining mechanisms need to align with the specific requirements of the architectural project. Factors such as load distribution, anticipated stress levels, function, and desired aesthetics all contribute to the design considerations, ensuring that the joinery serves its purpose effectively within the overall architectural vision.

Conclusion

Existing literature on the use of bamboo, especially split bamboo, as a building material reveals a number of research gaps. First, the application of split bamboo as a tension member in construction projects is understudied. Second, there is a lack of emphasis on standardisation procedures for splintering bamboo in order to maximise its use in construction. Thirdly, while there has been extensive research on the design of joints with standard fasteners, including patents for bamboo poles, there is a notable lack of research on joints involving split bamboo. Fourthly, the research on split bamboo, particularly with different species, is limited and requires validation, particularly in light of regional variations. Finally, the building codes with respect to the structural use of split as a tension member needs to be looked into. In conclusion, despite a few experimental projects, there are no identified structures that utilise the tensile properties of split bamboo in their construction. It is crucial to address these research gaps in order to advance our understanding and application of split bamboo in construction. Eventually, the architectural expression can emerge once these gaps are scientifically filled in.

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Conflict of Interest

The authors declare there is no conflict of interest

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