

BUILDING WITH BAMBOO: A REVIEW OF CULM CONNECTION TECHNOLOGY

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ABSTRACT

Interest in the engineering performance of bamboo is on the rise primarily due to its rapid regenerative qualities and high strength-to-weight ratio. It has been a standard, sustainable building material for thousands of years in Asia and South America, where it grows naturally. Although there are many examples of magnificent bamboo structures, standards and documentation on safe and reliable bamboo design are scarce, particularly for connection design. Traditional connections involve friction-tight lashings (eg. ropes and cords of dried grasses) and pin-and-socket connections such as dowels and pegs, but more recent advances have involved integration with steel hardware and concrete. This paper presents bamboo as a feasible alternative building material and presents a review of past, current and emerging technologies to join hollow bamboo culms in structural applications. The paper's intent is to give an overview of the current state of bamboo connection technology and to promote developments in the emerging field of bamboo engineering. Recent technological advances and visionary architects have proven that it is possible to create safe structures that are not only sustainable but have tremendous potential for use in disaster relief and quick-build scenarios.

KEYWORDS

bamboo, structural connections, natural building material, mechanical properties

INTRODUCTION

Bamboo refers to a group of over a thousand tall, quick-growing grasses, notable anatomically for their cylindrical shape, hollow shaft, and nodular structure, as illustrated in Figure 1. The inherent design of the stem, known as the culm, contributes significantly to bamboo's high compressive strength; nodes are stiffened with diaphragms that are located at regular intervals within the cavity that can brace against certain modes of buckling, while maintaining lightness and flexibility. The walls of the culm consist of long parenchyma cells surrounding vascular bundles, which serve to transport water and nutrients along the length (Liese 1998). Axially oriented, these fiber bundles provide most of the mechanical strength and are denser and smaller in diameter toward the outside of the culm, where bending stresses are highest.

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Due to the longitudinal orientation of the fibers, tension strength perpendicular-to-grain is very low and an important factor to consider in connection design. Shear strength is also relatively low due to the thin walls of the culm, which makes bamboo easier to split and harvest than wood (Trujillo 2007). The culm's outermost layer, termed the *cortex*, is a protective, waxy and tough waterproofing membrane.

Bamboo is sustainable. In addition to its short maturation cycle and epic proliferation, bamboo also has carbon sequestration benefits in the same manner as wood, reducing over time the total amount of harmful chemicals in the planet's ozone layer. "According to the people at Zero Emissions Research and Initiatives (ZERI), a bamboo forest can sequester 17 times as much carbon as a typical tree forest" (qtd. in DeBoer 2012). Similar findings are reported in Muller and Rebelo (2010).

Bamboo has a broad tolerance for many environmental conditions which makes it a feasible crop for a wide variety of ecosystems. *Guadua angustifolia* Kunth (or Guadua bamboo) and *Phyllostachys edulis* (Carrière) J. Houz (or Moso bamboo) are two very popular variants often used for structural applications. Guadua bamboo grows naturally in tropical areas, most notably in South America. Moso bamboo grows in more temperate climate zones. Native to China, Moso has been successfully transplanted with hundreds of other species to North America, and currently is harvested everywhere from Louisiana to Oregon. Within these highly varied climates, bamboo has natural beneficial interactions with its surrounding environment as well as nearby societies (Farrelly 1984). For instance, its complex root system provides soil stabilization, preventing potentially dangerous erosion of dam walls and riverbanks, and absorbing excess rainwater from saturated soil. Its relatively speedy maturation process makes bamboo an investment crop with fast capital return; Guadua culms reach economic maturity in 4 years, as opposed to 30 to 40 years for a stand of pine trees. In multiple cases, small rural economies have been successfully restructured or bolstered through the introduction of bamboo harvesting (Muller and Rebelo 2010). The plant itself is highly multi-useful once cut, and has been used historically both inside and outside the home as structural framing, furniture, fencing, utensils, fiber webbing, paper, cloth, food, and modern technology: in 1880 Thomas Edison took out a patent to use carbonized bamboo fibers as light bulb filaments (Houston 1905).

Code-related guidelines and product standards for bamboo as a construction material are limited but are emerging to enable bamboo to be readily used in construction in the United States. In the year 2000, the International Code Council (ICC) approved the standard AC162 (ICC 2012) *Acceptance Criteria for Structural Bamboo*. Following this, a Hawaiian residential building company, Bamboo Technologies LLC, commissioned the first evaluation report for *Bambusa Stenostachya* - a Vietnamese species of bamboo (ICC-ES 2011). Then, in the year 2004, the International Network of Bamboo and Rattans (INBAR) spearheaded the development of two International Standard Organization (ISO) standards: ISO 22156 - Bamboo structural design and ISO 22157 - Determination of physical and mechanical properties.

To demonstrate how *Bambusa Stenostachya* compares structurally to other common engineering materials, Table 1 lists the materials' allowable stress design values. Fifth percentile

FIGURE 1. Bamboo Culm Anatomy.

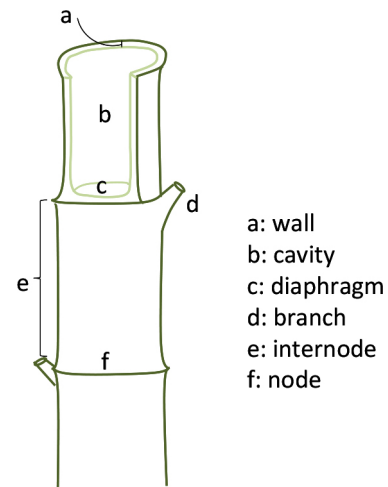


TABLE 1. Mechanical Properties for Selected Engineering Materials

Material	Specific Gravity	Modulus of Elasticity (GPa)	Tension (parallel-to-grain) (MPa)	Compression (parallel-to-grain) (MPa)	Bending (MPa)	Shear (MPa)
Concrete ¹	2.4	21	0.7	9.3	-	0.7
Hem-Fir joists ¹	0.5	10	5.5	7.2	7.9	0.5
A-36 Steel ¹	7.8	200	151.7	151.7	151.7	100.0
Parallel Strand Lumber ¹	0.7	14	13.8	20.0	20.0	2.0
Bambusa Stenostachya ²	0.7	12	7.6	4.1	10.3	1.3
Guadua angustifolia ³	0.6	12	35*	28 -38	46	2.3

* higher values have been reported

¹ values are Allowable Stresses. Source: Onouye and Kane, 2002

² values are Allowable Stresses. Source: ICC Report ESR-1636

³ values are 5th percentile values. Source: Trujillo, 2009

values are also provided (in lieu of having allowable stress values) for *Guadua angustifolia*, to give a sense of other bamboo species' properties and its general capability. Bamboo's specific gravity and low stiffness is similar to wood. Low stiffness results in flexible structures which are able to absorb energy and thus fare well in earthquakes. In compression, bamboo culms have a tendency to buckle due to their lack of straightness. As with wood, the shear strength is low and splitting can be a problem. Related to this is one of the main design concerns for bamboo structures: how to connect round hollow elements that are of varying diameters.

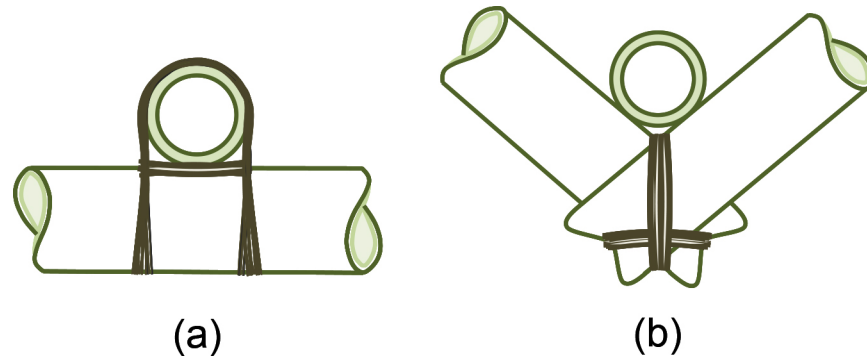
TRADITIONAL BAMBOO CONNECTIONS

Friction-tight lashing

For structures made entirely of bamboo, there has been a distinct historical evolution in the types and method of connection between culms. The earliest known bamboo connection technology utilizes a friction-fit technique with braided or multi-strand cords made from indigenous grasses like jute, hemp, rattan, and dried bamboo pith. Requiring very few tools, this low-technology approach does not require highly skilled labor to execute. If the natural fibers are installed while green, the connection tends to tighten around the joint in service. Unfortunately, in most of the United States, seasonal moisture changes could cause the bamboo to expand and contract by as much as 6% across the diameter (Dunkelberg 1985), which would cause a slackening of the joint.

Lashing techniques of the past few hundred years have historically been shown to create connections of 2-4 culms utilizing full or end-notched culms, without the use of puncturing or adhesives (See Figure 2). Simple connections rely solely on the tensile capacity of the lashing material to take joint load. For more complicated connections, additional compression members are sometimes added as cross-bracing. As size and frequency of building increased, housing structures began to be built flat and assembled as large pieces. Different cultures, whose independent aesthetic and traditional practices dictated differing structural shapes,

FIGURE 2. Lashed Connections: (a) 2 culms (b) 3 culms.



built them using either two-dimensional/flat style connections (built flat and raised to create quadrilateral forms, with each element contained unilaterally within the X, Y, or Z plane) or three-dimensional/bunched style connections (often used to create circular or modular floor plans, or triangular sections over quadrilateral bases). In mixed-style construction, two-dimensional/flat lashed connections were generally used for walls, while three-dimensional/bunched connections were used for roofs (Farrelly 1984; Janssen 2005).

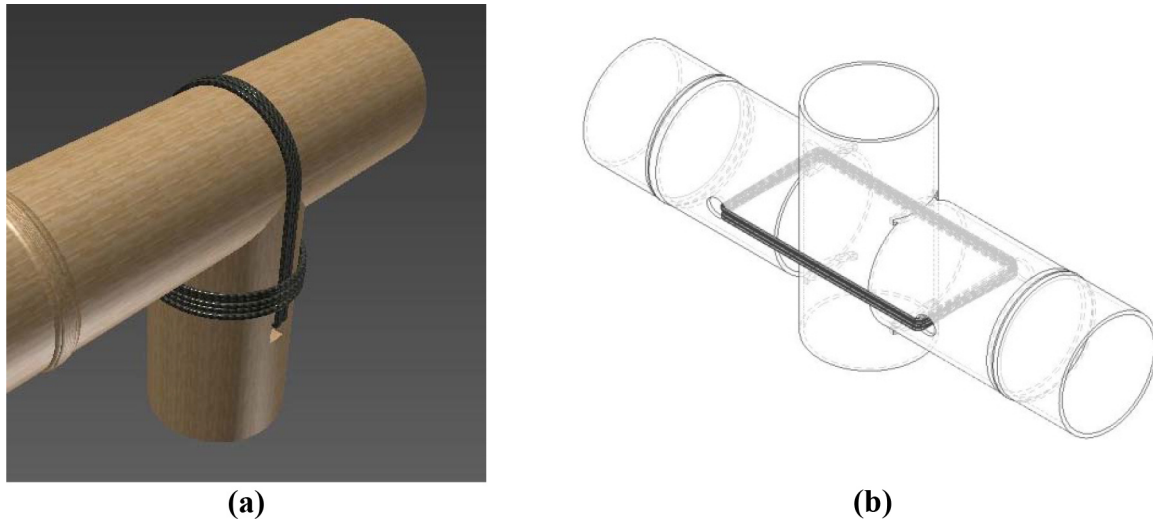
Notched and Pierced connections

As opposed to corner connections, which utilize the load bearing capacity of the bamboo itself, full-culm lashed joints which require mid-culm attachment of secondary members, depend on the load bearing capacity of the lashing material and are difficult to construct. Because of this structural shortcoming, notched and pierced connections were developed to integrate the inherent load bearing capacity of bamboo culms within multilevel or pass-through connections (Figure 3).

Requiring slightly more sophisticated tools than pure lashing, notched connections allow for the arched shape of the culm cross-section to take weight, maintaining strength and bearing capacity while increasing joint stability by reducing slippage through the creation of a specified bearing area. Pierced connections either make use of a peg as anchor point for lashing, or use the punctured opening to thread lashing material through. Mid-culm connections and angled two-dimensional connections are the most often seen uses of pierced and notched joints. Like full-culm lashed connections, cut-culm connections are seen braced as well as unbraced, depending on direction and severity of force acting on the joint. Because of the increased complexity potential, cut-culm connections are seen with many more culms included. With increased complexity of execution came increased potential for failure, as puncturing the culms can weaken them. For everyday or residential use, however, cut-culm lashed connections were sufficient and widely utilized.

In cultures where bamboo made up a large part of the economy and therefore building material, the techniques used to build complex bamboo connections were passed down from generation to generation, leading to cultural individuation through an intertwining of natural material and manual techniques. This technological knowledge was more or less insular within each community until the advent of intercontinental trading and colonization in the 16th century - inspired heavily by Marco Polo's 13th-century journey between Italy and China (Farrelly 1984). As more and more European countries in particular brought back artifacts and

FIGURE 3. Pierced Connections with natural lashing: (a) 2 culm (b) 3 culms.



customs from the Far East, so too came aesthetics and building techniques utilizing bamboo. After the Japanese trade embargo ended in 1853, influence of the bamboo-building culture spread worldwide with even greater speed via Worlds Fairs and International Exhibitions, which at the time were the main thoroughfare for the global dissemination of culture and aesthetics. The 1862 International Exhibition in Paris featured a section on Japan which, according to scholars at the University of Oxford's Pitt-Rivers Museum (2010), "was highly influential in introducing the British general public to the Japanese aesthetic and material culture."

Between conquering nations and naval trade, the visual aesthetic of indigenous bamboo architecture of Southeast and East Asia was increasingly mimicked in Europe and their colonies for centuries, eventually leading to the adoption of bamboo connection technology for residential and commercial aesthetic constructions and then residential and commercial building in areas where bamboo was grown or imported. The Aesthetic Movement in England during the late 1800s was based largely on the "Oriental aesthetic" brought into vogue by high society. This presented a large problem, however, as connections using natural materials could not withstand large commercial loads. The introduction and integration of modern materials with indigenous bamboo connection techniques in the past 80 years has increased the load-bearing capacity of culm-to-culm connections.

MODERN BAMBOO CONNECTIONS

New buildings are still being erected using traditional connection techniques; however, the use of engineering hardware, similar to that used in wood connections, is growing in popularity. In general, modern bamboo connections can be categorized into three types: pierced-with-metal connections, concrete-filled connections, and capped connections.

Pierced-with-Metal Connections

Stemming from the technical base of traditional notched and pierced connections, using metal to join bamboo culms has the added benefit of reliability and ductility. In some systems, such as those used by famed Italian architect Renzo Piano, metal plates are inserted into the

FIGURE 4. Light-metal plate connection.

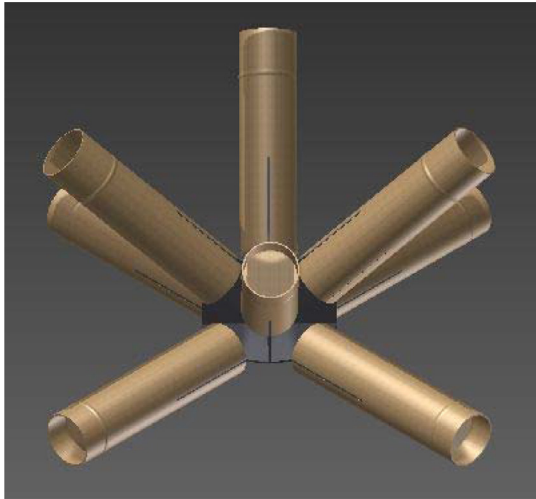
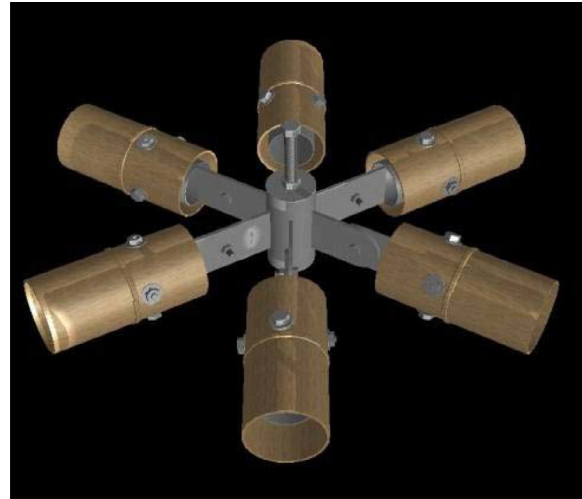


FIGURE 5. Bolted connection system.



end cavity of the bamboo to form a hub or structural node (Vélez et al. 2000). An illustration is shown in Figure 4. Light metal components used in this way can provide concentric compression and/or tension capacity for a sophisticated bamboo space frame. In a similar three dimensional node system, architect Shoei Yoh of Japan used an interior metal tube system with uniaxial bolts inserted into the culm cavity, as shown in Figure 5. Even with the increased stability from sandwiched metal connections, however, piercing the culm still makes it vulnerable to splitting and tensile failure due to reduced cross sections.

Concrete-filled Connections

To mitigate the weakening effect of punctured connections, other methods exist of injecting concrete into the hollow culms to act as a stabilizing anchor for the bolts and increases tension and compression strength. See Figure 6. The stiffening which occurs from filling the culm with concrete makes possible long compressive spans and large cantilevers which would otherwise be unstable due to the potential for buckling of the hollow section. Renowned Colombian architect, Simón Vélez, in his Alternative Cathedral as well as other structures, used an internal metal bolt system similar to that of Shoei Yoh, but with the added strength of threaded rods embedded in concrete/mortar injections (DeBoer and Bareis 2000). Marcelo Villegas is also known to utilize concrete-filled connections in his houses and pavilions (Villegas 2003).

Another critical connection occurs between the concrete and the bamboo at ground level. Because of bamboo's naturally porous internal structure and susceptibility to insect infestation and rot, it is necessary to avoid bamboo's contact with damp ground. Concrete and steel are useful in this way as a transitional element at every corner of a bamboo building particularly between bamboo columns and foundation slabs. A comprehensive experimental study was recently conducted on base connections of this type (specifically, single and four-culm grouted bar connections) at the University of Pittsburgh (Mitch 2010). It was found that longitudinal splitting of the culm and slip of the mortar plug was a distinct failure mechanism.

The largest commercial bamboo structure to date—Big Tree Farm’s Bamboo Chocolate Factory in Bali, Indonesia—was built in 2011 using traditional Indonesian construction techniques (*bigtreefarms.com*). It makes use of concrete for floors, retaining walls, and as bases for the bamboo columns. These reinforced connections and concrete integration techniques have increased bending and compression capacity of structural bamboo and enabled impressively long spans as found in the ZERI Pavilion at Expo 2000 in Hanover, Germany by Vélez. The structure is a ten-sided polygon, 40 meters in diameter with 7 meter long cantilevers (Rohrback and Gillmann 2001).

Another variation of this technology is utilizing concrete-filled culm connections with embedded threaded bolts and external clamps, instead of pierced bolts, as illustrated in Figures 7 (a) and 7(b). Extensive research was conducted to optimize the load carrying capability of this connector at the Technical University of Darmstadt, Germany under the auspices of Professor Garrecht (M. Diem, personal communication, June 20, 2012). One of the main issues was mitigating dimensional changes of the bamboo from moisture transport through the concrete during fabrication. For this, a sustainable high-proportion fly-ash concrete mixture was developed as well as a novel method to prepare the inner surfaces of the bamboo to make the bamboo less prone to taking on water from the fresh concrete. The bamboo-concrete-steel composite was realized by prominent architecture firm, MUDI Shanghai, in the impressive German-Chinese house at the 2010 Expo in Shanghai, China (Figure 8). The Expo building is an interesting mix of many different types of bamboo, including laminated beams as well as giant culms, 23 cm in diameter by 8 meters long.

FIGURE 6. Concrete/mortar injected bamboo connection.

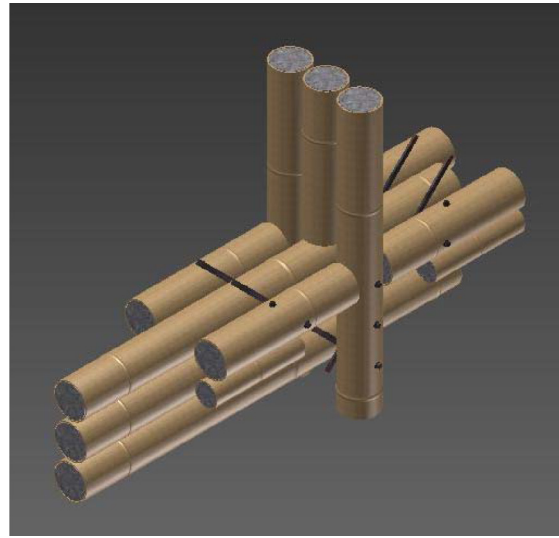


FIGURE 7. Concrete-filled bamboo culms with bolts and clamps. (a) roof level (b) foundation level (photos used with permission from MUDI architects, Shanghai).



(a)



(b)

FIGURE 8. German-Chinese house at 2010 Expo in Shanghai, China (photo used with permission from MUDI architects, Shanghai).



Capped Connections

The third category is capped connections in which metal caps are attached over the end of the culm with adhesive or bolts, as shown in Figure 9. These connections can be standardized, and require less labor to install than bolted connections. Without relying solely on culm-to-culm connections, capped connections have the potential to be modular, leading to a simplified plug-and-build construction process with hub joints. The German Bambutec system (patented in 2002) comprises a set of inflexible standardized hubs which can be combined to create a variety of structures (Rottke 2003). Culms are pre-grooved and held in place with adhesive.

F. Albermani et al. (2007) at the University of Queensland and Hong Kong Polytechnic University, developed a PVC joint-hub system which is not only standardized, but also positionable. By utilizing a planar rotating bolt connection between the cap and multi-port hub, up to 8 culms can be attached at various angles to a single joint.

Emerging Technologies

Emerging technologies which are adaptations of the three aforementioned connection types combine hub-style modular connections with adjustable or sizable caps to accommodate a wide range of culm diameters and structural styles. The Guadua Tech system, which was patented in 2005 (Lodoño 2005; Durant and

FIGURE 9. Guadua Tech Hub connection.



Prichard 1989), uses steel wrapped cable to grip the terminal end of each culm, attaching it to a steel end piece which is then able to connect with any number of variable hubs, depending on project or load direction. This system is enormously valuable as a whole because it makes use of variable culm sizes by standardizing them via engineered terminal assemblies. Another is the QuaDror relief housing system (*quadrdror.com*). Patented in 2011, it comprises an established structural program with swappable members (as opposed to established members with swappable structural program - the pattern most often present in connection design). Developed for smaller noncommercial projects but with structural potential for modular application, the QuaDror “elbows” are designed to accommodate a variety of materials by screwing into the side of any long rigid form (bamboo culms, fallen sticks or saplings) at established angles to create quick-build, stable structures.

With modular and simple connections making use of a range of culm diameters, a greater number of projects can be completed with a minimum discrepancy of parts or labor. This has strong implications for refugee housing and disaster relief, as connections which do not require a standard culm diameter could be implemented using found materials, without the need to sort exhaustively by size.

DISCUSSION AND CONCLUSIONS

In order to continue formulating effective and efficient connections using bamboo, basic lessons of building can be taken from both new and old techniques. Firstly, base stability is required and must be engineered for any structure made exclusively of bamboo culms. These base members must also be isolated from damp ground, which can be done in a variety of innovative and sustainable ways. Simón Vélez experimented with glass Perrier bottles filled with cement mortar as bamboo column footings. Secondly, protection against racking must be taken into account, which can be achieved by paying attention to structure shape and connection angles. Arches and polyhedral shapes have historically been proven to maximize the efficacy of bamboo’s flexibility without introducing a dangerous factor of instability. Thirdly, using the most accessible methods possible to build in a wide variety of environments, sizable and/or modular connections are the most efficient for accommodating the largest variety of material diameter. It seems likely that, although modern standardized connections are efficient, the most accessible solution will be one that is technique-based, rather than product-based.

We know what is possible with high technology, and how beneficial the use of bamboo can be as a residential and commercial building material. Incorporating modern materials does increase the building potential of bamboo, but it also increases the technology required to complete projects, which moves its availability up and away from the rural neighborhood or relief setting which could most benefit from the introduction of a set of safe, sustainable building methods that make use of what’s already on hand.

What would be useful in modern research and development is a modular connection that does not require technologically sophisticated materials. This may be in the form of adapting existing technologies for construction on-site, or in developing a set of technique manuals which make use of existing knowledge of shape- and connection-building to create potentially complex structures from a simplified set of connections. Using connections which can be modified to accommodate cuboid or polyhedral shapes will likely increase the size of possible dwellings from bamboo, and combining framework with multi-culm connections could create a modular structure requiring few construction elements. Cuboid, or even prismatic

shapes, being space efficient, may be better suited to developing world conditions which require density of structures due to high population density. In areas where bamboo structures are created from locally-harvested materials, the structures themselves act as a connection to the surrounding natural environment. Buildings such as the Big Tree Farms chocolate factory in Bali act as visual connection as well. By leaving structural bamboo culms exposed, this factory is somewhat camouflaged within the surrounding forest.

As research progresses in both high- and low-technology approaches to bamboo construction and design, interdisciplinary integration of new knowledge with existing skill sets will continue to produce the most innovative solutions to both commercial and domestic application of bamboo connection technology.

ACKNOWLEDGMENTS

Gratitude is extended to research assistant Bonnie (Zhuo) Yang for her help with preparing CAD images on this project.

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