TRADITIONAL AND INNOVATIVE JOINTS IN BAMBOO CONSTRUCTION

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Abstract

The use of bamboo as building material has been ascending recently due to the rise in public environmental awareness. Bamboo is one of the most sustainable building materials. It is a renewable resource that grows quickly. As a low-energy building material in its natural form, bamboo is traditionally associated with the cultures of Asia and South America. Its strength, enormous availability, and easy workability have made it a dominant building material throughout much of the world, where it has grown natively for centuries. Its use in modern, mainstream construction, however, is rare. A few pioneering architects and engineers in South America and South East Asia have demonstrated bamboo's potential for high-end buildings, but they remain the exceptions.

Despite this progress, using bamboo as a structural material remains difficult, especially as a tension element. Although bamboo has extremely high tensile strength, the lack of a joining system to accommodate its strength makes the application uneasy. The characteristics of the bamboo itself generate the difficulties in bamboo joinery. The round shape and cavities inside the bamboo are two of those characteristics. Therefore, it is a special task to develop tension loadable joints to expand the range of structural applications of anisotropic bamboo pole.

The main objective of this phenomenological and experimental research was to propose new tension loadable bamboo joints. The secondary objective was to classify bamboo constructions and bamboo joints to put the proposed bamboo joints in a context. The development of new bamboo joints classification was based on the classification by Janssen (2000).

Three types of tensile loadable bamboo joints were proposed: utilizing the hollowness of bamboo; using the outer part of bamboo by enlacing a steel wire; and employing the shear and the bearing strength of bamboo by attaching perpendicular elements. After a comparison study, the chosen lashing-based bamboo joints were developed in an experimental research. A loop of steel wire using a kind of lasso knot was twined around the bamboo in such way that it will tighten by pulling the wire. Tension force induced in the steel wire by an element inserted inside the cavity of the

bamboo was converted to radial compression perpendicular to the fibers to the center of the pole causing a circumferential stress in bamboo.

Preliminary tests were conducted to determine the radial compression strength of the bamboo. There were two types of winding: one and three hemispherical-windings. The result of these tests was used to calculate the load capacity of the joint under radial compression.

After calculating the strength of the joint in each component against its corresponding load, three samples of lashing joints with eye-bolts were tested. Two types of failures happened: the wire sliced the bamboo after the rings slipped into the holes; and the wire broke off. The average strength of the joints of 34.09 kN almost passed the ultimate strength of the used steel wire.

Based on the results above, the joint was improved by replacing the eye-bolt with a rod and some cross-dowels in such a way that similar lashing technique can be multiplied in every joint. As a result, it spread the force over a wider surface area of bamboo, and it was called bamboo joint with multi knots.

The tension tests on the bamboo joints with multi knots showed an expected result, as the failures of three samples happened in the rods when they broke off. The average tensile strength was 77.91 kN, beyond the ultimate strength of the used M16 rod. This type of failure is very important, because the user can predict the strength of this joint more precisely. After using a bamboo with approximately similar diameter and wall thickness, the strength of bamboo joint with multi knots can be customized. After the rod with certain tensile strength is chosen, the number of knots in accordance with the strength of each wire can be determined.

Developed from traditional lashing techniques, this bamboo joint with multi knots provides a relatively cheap and easy joint, which can be made even by an unskilled worker. Therefore, this joint can bolster the utilization of bamboo pole as a tension element in vernacular bamboo construction. Furthermore, the capability to transfer both tensile and compression force without eccentricity makes this joint also suitable for space structures.

Kurzzusammenfassung

Die Verwendung von Bambus als Baustoff ist in letzter Zeit mit zunehmendem Umweltbewusstsein gestiegen. Bambus ist einer der tragfähigsten Baustoffe überhaupt. Zudem ist er ein nachwachsender Baustoff, der schnell wächst. Bambus als energiearmer Baustoff in seiner natürlichen Form wird traditionell mit den asiatischen und südamerikanischen Kulturen in Zusammenhang gebracht. Durch seine Beanspruchbarkeit, enorme Verfügbarkeit und einfache Verarbeitung wurde er zu einem vorherrschenden Baustoff in weiten Teilen der Welt, in denen er schon seit Jahrhunderten natürlich vorkommt. Seine Verwendung in modernen, tragenden Konstruktionen ist jedoch selten. Einige bahnbrechende Architekten aus Südamerika und Südostasien haben bereits das Potential von Bambus für hochwertige Gebäude demonstriert.

Trotz dieses Fortschritts gestaltet sich die Verwendung von Bambus als Baustoff schwierig, besonders beim Einsatz als Zugelement. Obwohl Bambus eine extrem hohe Zugefestigkeit aufweist, erschwert das Fehlen geeigneter Verbindungssysteme, die Anwendung. Es sind zum Teil die besonderen Eigenschaften von Bambus, welche die Schwierigkeiten hervorrufen. Dazu gehören die runde Querschnittsform und der innere Hohlraum. Deswegen ist es eine besondere Aufgabe zugbeanspruchte Verbindungen zu entwickeln, um die konstruktive Anwendung von Bambusstäben weiter auszubauen.

Das Hauptziel dieser phänomenologischen und experimentellen Forschung war es, neue Bambusverbindungen zu erarbeiten, vor allem solche mit zugbeanspruchten Verbindungen. Ein weiteres Ziel war die Klassifizierung von Bambuskonstruktionen und Bambusverbindungen. Der Zweck dieser Klassifizierungen bestand darin, die entwickelten Bambusverbindungen in einen Zusammenhang setzen zu können. Diese neue Klassifizierung wurde weiterentwickelt aus einer früheren Klassifizierung nach Janssen (2000).

Es wurden drei Typen von zugbeanspruchten Bambusverbindungen entwickelt: unter Ausnutzung des Hohlraums des Bambus, der Inanspruchnahme des äußeren Teils des Bambus durch umlaufende Stahldrähte und unter Ausnutzung der Scher- und Tragfestigkeit des Bambus durch die Anbringung senkrechter Elemente. Nach einer

vergleichenden Studie wurden die ausgewählten drahtverspannten Bambusverbindungen in einer experimentellen Untersuchung weiterentwickelt. Es wurde eine Stahldrahtschlinge mit einer Art Lassoknoten so um den Bambusstab geschlungen, dass sie sich beim Ziehen des Drahtes verengt. Die in den Stahldraht eingeleitete Zugkraft wird so in umlaufenden Druck umgewandelt, der senkrecht zur Faserrichtung im Inneren des Bambusstabs verläuft. Dazu wurden Vorversuche durchgeführt, deren Ergebnisse zur Berechnung der umlaufenden Druckfestigkeit des Bambus dienten. Dabei wurden einfache und dreifache Umwicklungen untersucht.

Nach Berechnung der Druckfestigkeit der einzelnen Komponenten der Verbindung abhängig von ihrer Last werden drei Exemplare von drahtverspannten Verbindungen mit Augenbolzen untersucht. Es traten zwei Arten des Versagens der Verbindungen auf. Der Draht schnitt in den Bambus, nachdem die Ringe in die Löcher rutschten; oder der Draht riss. Dabei überschritt die durchschnittliche Festigkeit der Verbindung von 34.09 kN beinahe die höchste Zugfestigkeit des verwendeten Stahldrahtes.

Ausgehend von den vorigen Versuchsergebnissen wurde die Verbindung durch Ersetzen der Augenbolzen mit einer Gewindestande und einigen Kreuzdübeln so verbessert, dass eine ähnliche Verspannungstechnik vervielfacht werden konnte. Dies hatte den Effekt, dass die Kraft auf eine größere Bambusoberfläche übertragen werden konnte. Diese Ausführungsart wird Bambusverbindung mit Mehrfachknoten genannt.

Spannungsversuche an diesen Bambusverbindungen führten zum erwarteten Ergebnis, als die Verbindungen jeweils durch Brechen der Gewindestangen versagten. Die durchschnittliche Zugfestigkeit betrug 77.91 kN, was über die Festigkeit der benutzten M16-Stange hinausging. Diese Art des Versagens ist besonders hilfreich, da der Nutzer so die Festigkeit der Verbindung präziser vorhersagen kann. Durch Benutzung eines Bambusstabs mit ähnlichem Durchmesser und Wanddicke, kann die Festigkeit der Bambusverbindung mit Mehrfachknoten angepasst werden. Zuerst wird die Gewindestange mit einer bestimmten Zugfestigkeit ausgewählt/festgelegt, danach kann die Anzahl der notwendigen Knoten in Abhängigkeit von der Stärke der einzelnen Drähte bestimmt werden.

Entwickelt aus traditionellen Wickeltechniken, stellt diese Bambusverbindung mit Mehrfachknoten eine sehr einfache und günstige Verbindung dar, die sogar von unerfahrenen Arbeitern hergestellt werden kann. Somit kann diese Verbindung den Einsatz von Bambus als Zugelement in traditionellen Bambuskonstruktionen begünstigen. Zudem eignet sich diese Verbindung durch die Fähigkeit, sowohl Zug- als auch Druckspannung ohne Exzentrizität zu übertragen, auch für räumliche Tragwerke.

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I dedicate this dissertation to my beloved wife, Intan, my mother, and my family for their unconditional love and support in every way possible throughout the process of this course, this dissertation and beyond. Last but not least, I devote it to the world of bamboo with great hope that this research will give valuable contributions.

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A	area
$A, B, C,...$	Point A, B, C,...
A_b, B_b	Point A, B at the bamboo
$A_{b,\perp}$	cross section area of bamboo
$A_{b,\parallel}$	longitudinal section area of bamboo
A_w, B_w	Point A, B at the wire
D_h	diameter of hole within bamboo perpendicular the fibers
D_i	inner diameter of bamboo
D_o	outer diameter of bamboo
D_r	diameter of ring
e	eccentricity; mathematical constant approximately equal to 2.72
E_b	modulus of elasticity of bamboo
F, F_1, F_2	force
$F_{1,w,t}, F_{2,w,t},...$	tension force in the wire at P_1, P_2,...
$F_{AB}, F_{BC}, F_{CD},...$	force in axis AB, BC, CD,...
$\Sigma F_{ARS}, \Sigma F_{BRS}$	total compression forces at Point R and S in Test A, Test B
ΣF_{BT}	total compression forces at Point T in Test B
$F_{c,\parallel}$	compression force parallel to bamboo fibers
$F_{c,\perp,D}$	diametric compression perpendicular to bamboo fibers
$f_{c,\perp,R}$	distributed radial compression perpendicular to bamboo fibers
$f_{f,\parallel}$	friction force parallel to bamboo fibers
$f_{f,\perp}$	friction force perpendicular to bamboo fibers
$f_{f,\perp,T}$	tangential friction force perpendicular to bamboo fibers
$F_{m,b,c,\perp,D}$	minimum tension force induced in the rod until the failure caused by diametric compression to the bamboo perpendicular to the fibers
$F_{m,b,c,\perp,R}$	minimum tension force induced in the rod until the failure caused by radial compression to the bamboo perpendicular to the fibers
$F_{m,w}$	minimum tension force induced in the rod until the wire break off
$F_{R0}, F_{R1},...$	tension force in R0, R1,...
$F_{r,c,\parallel}$	compression force by the ring parallel to bamboo fibers
$F_{r,c,\perp,D}$	diametric compression force by the ring perpendicular to bamboo fibers
$F.S.$	Factor of Safety
$F_{t,\parallel}$	tension force parallel to bamboo fibers
$F_{u,A,t}, F_{u,B,t},...$	ultimate-load capacity of Sample A, Sample B,...
$F_{u,ABC,t}$	average ultimate-load capacity of Sample A, B, C
$F_{u,DEF,t}$	average ultimate-load capacity of Sample D, E, F
$F_{u,b,c,\parallel}$	ultimate-load capacity of bamboo against bearing stress parallel to the fibers
$f_{u,b,c,\parallel}$	ultimate compression strength of bamboo parallel to the fibers
$f_{u,b,c,\perp,D}$	ultimate diametric compression strength of bamboo
$F_{u,b,c,\perp,R}$	ultimate-load capacity of bamboo against radial compression
$f_{u,b,c,\perp,T}$	ultimate tangential compression strength of bamboo
$f_{u,b,s,\parallel}$	ultimate shear strength of bamboo parallel to the fibers
$F_{u,b,s,\parallel}$	ultimate-load capacity of bamboo against shear stress parallel to the fibers
$f_{u,b,t,\parallel}$	ultimate tensile strength of bamboo parallel to the fibers

$F_{u,b,t\parallel}$	ultimate tensile load capacity of bamboo parallel to the fibers
$F_{u,k,t\parallel}$	ultimate-load capacity of a knot parallel to bamboo fibers
$F_{u,4k,t\parallel}$	ultimate-load capacity of 4 knots parallel to bamboo fibers
$f_{u,r}$	characteristic strength of rod
$F_{u,r}$	ultimate-load capacity of rod
$F_{u,tb}$	ultimate-load capacity of turnbuckle
$f_{u,w}$	characteristic strength of wire
$F_{w,c,\parallel}$	compression force by the wire parallel to bamboo fibers
$F_{w,c,\perp}$	compression force by the wire perpendicular to bamboo fibers
$f_{w,c,\perp,R}$	distributed radial compression force by wire perpendicular to bamboo fibers
$F_{w,t}$	tension force in the wire
$F_{w,t,45°}$	tension force in the wire directing 45º relative to the rod
$F_{w,t,\perp,T}$	tangential tension force in the wire perpendicular to bamboo fibers
ΣF_x, ΣF_y	total forces in axis x, y
h	height
H_A, V_A	horizontal, vertical reaction force in Point A
L	distance between holes and end of bamboo
ΔL	movement of lower table relative to the upper plank of test machine
ln	natural logarithm
M	moment
O	point of origin
P	load; pressure;
P_0, P_1,...	Point 0, Point 1,...
$r_{b,\perp}$	reaction force of bamboo perpendicular to the fibers
R_i	inner radius of bamboo
R_o	outer radius of bamboo
R'_o	outer radius of bamboo after radial deformation
ΔR_o	deformation of the tube in the radial direction
$r_{r,\perp}$	reaction force of ring perpendicular to bamboo fibers
$R_{w,t}$	resultant vector of the wire under tension
t_w	thickness of bamboo wall
W	weight; load
x, y, z	axis
$\beta, \theta, \alpha, \varepsilon$	angle in radians, angle
$\Delta\theta$	angle of deformation
μ_s	coefficient of static friction
π	mathematical constant approximately equal to 3.14
$\sigma_{b,c\parallel}$	bearing stress or compression stress in bamboo parallel to the fibers
$\sigma_{b,c,\perp}$	compression stress in bamboo perpendicular to the fibers
$\sigma_{b,c,\perp,T}$	tangential compression stress in bamboo perpendicular to the fibers
$\sigma_{b,t\parallel}$	tension stress in bamboo parallel to the fibers
$\sigma_{b,t,\perp}$	tension stress in bamboo perpendicular to the fibers
$\sigma_{b,t,\perp,T}$	tangential tension stress in bamboo perpendicular to the fibers
$\tau_{b,\parallel}$	shear stress in bamboo parallel to the fibers
$\tau_{b,\perp}$	shear stress in bamboo perpendicular to the fibers
$\tau_{b,\perp,T}$	rolling shear in bamboo perpendicular to the fibers

1 Introduction

1.1 Background

Bamboos are distributed worldwide in tropical and sub-tropical countries. In Asia-Pacific bamboo reaches the 42°S in New Zealand on south; the 51°N in Middle-Sakhalin on north; the Pacific Islands on east; and southwest of Indian Ocean on the west. The coverage of bamboo in America is relatively smaller. It grows from 47°S of Southern Argentina to 40°N of the Eastern United States. In Africa, it stretches starting from 22°S of Southern Mozambique to 16°N of Eastern Sudan. Those regions, in which bamboo grows, are also considered as regions with the highest population growth rates.

The history of bamboo as a housing material is probably as old as human civilization where bamboo is available. It has essential roles and is widely utilized to fulfill so many kinds of human needs including housing. The benefits of bamboo as a construction material do not end with its availability. Amongst the easiest materials to work with, bamboo provides all needs to build the house, from the frames (bamboo pole, split), building covers (bamboo mat, split), floors (flatten bamboo), roofs (bamboo shingles) or even the connectors (bamboo pin, rope).

A major disadvantage of bamboo as a building material is its low resistance against insects (beetles, borers or termites), fungi and degrading bacteria. According to Janssen (2000), it can be in service only 10 to 15 years in an ideal state without preservatives. Therefore, it is inferior to other materials such as wood, brick and concrete, and its social status is extremely low. In the region where it grows, bamboo is regarded a "poor man's timber" and it is a temporary solution for low-cost self-help housing, until the people are economically capable to replace with other durable material.

This lack of durability leads to the lack of evidence of traditional bamboo construction in the field, and further more leads to the limitation of developments in jointing techniques in the community that are transmitted from generation to generation. In compare with more durable timber construction, there are only few traditional bamboo joints that can be found in the field today. Mostly the evidences are taken from the old literatures, like “Bamboo as Building Material” by Klaus Dunkelberg (1985), who described traditional construction in around 1970.

With new technology of preservation and construction, more durable or even lifetime bamboo constructions can be built with better performance. In complement with the rise of awareness of sustainability, bamboo is used extensively in recent years as the main building material of housing, bridges, public buildings. Among the aims of immense utilization of bamboo are maximizing the uses of self-regenerated natural resources, minimizing the uses of high energy-consuming materials, and as carbon-traps. Other than bamboo pole, the utilizations of bamboo as building material are escalated at least to laminated bamboo and bamboo composites.

In bamboo pole constructions, after the issue of durability has been solved, the major problems move to the connection. To connect bamboo among themselves or to other materials is the most difficult part in bamboo construction for several reasons, such as variations in its properties and dimensions, hollow cone shape. Bamboo has high tensile strength, but there is a lack of joints that can maximize the utilizations of this strength. Researches and developments on bamboo joint are urgently needed to widen the use of bamboo.

The adoption of bolted joints, which are used previously in timber constructions, leads the mass utilization of bamboo to bigger construction than those with traditional joints. With these modern connection systems, it is possible to connect many bamboo poles at once to create a bunch of poles as large columns, high beams or multilayer frames to serve wider span or higher structures. The characteristics of these connections bring forth to specific bamboo architecture with a specific aesthetical appearance.

Although the utilization is not so extensive like bolted joint, the other significant connections are the ones to be used in space frame structures after the rising of the idea to replace steel or timber members in space frame structures with bamboo. These connections should perform different with previous utilizations because the members of bamboo pole in space structures are under compressions or tensions.

Despite the fact that there are many variations in bamboo pole constructions, there are not any established classifications of these constructions. Sometime the constructions are differentiated according to the functions such as flooring or roofing, or according to the building typology such as building or bridge.

The quite similar situation happens in bamboo connections. There is only one classification made by Janssen (2000). Some improvements and adjustment should be made to this classification and be updated to the recent developments of bamboo joint.

1.2 Objectives

The primary objective of this research is to propose new bamboo joints, which have the capability to transfer both tension and compression force. However, more attention should be addressed to transfer tension force because it is the most difficult engineering work. Tests were conducted to verify the ultimate tensile load capacity of the proposed joint and to promote joint configurations, which exhibit ductile failure modes. Furthermore, the proposed joint should enable the user to predict its strength for safety reason.

The secondary objectives are to classify bamboo constructions and also bamboo joints. There are not any established bamboo constructions classifications to put the proposed joints in a context. Janssen (2000) made the only definite bamboo joints classification, but some improvements should be addressed to update this classification to the recent developments of bamboo joints.

1.3 Research Framework

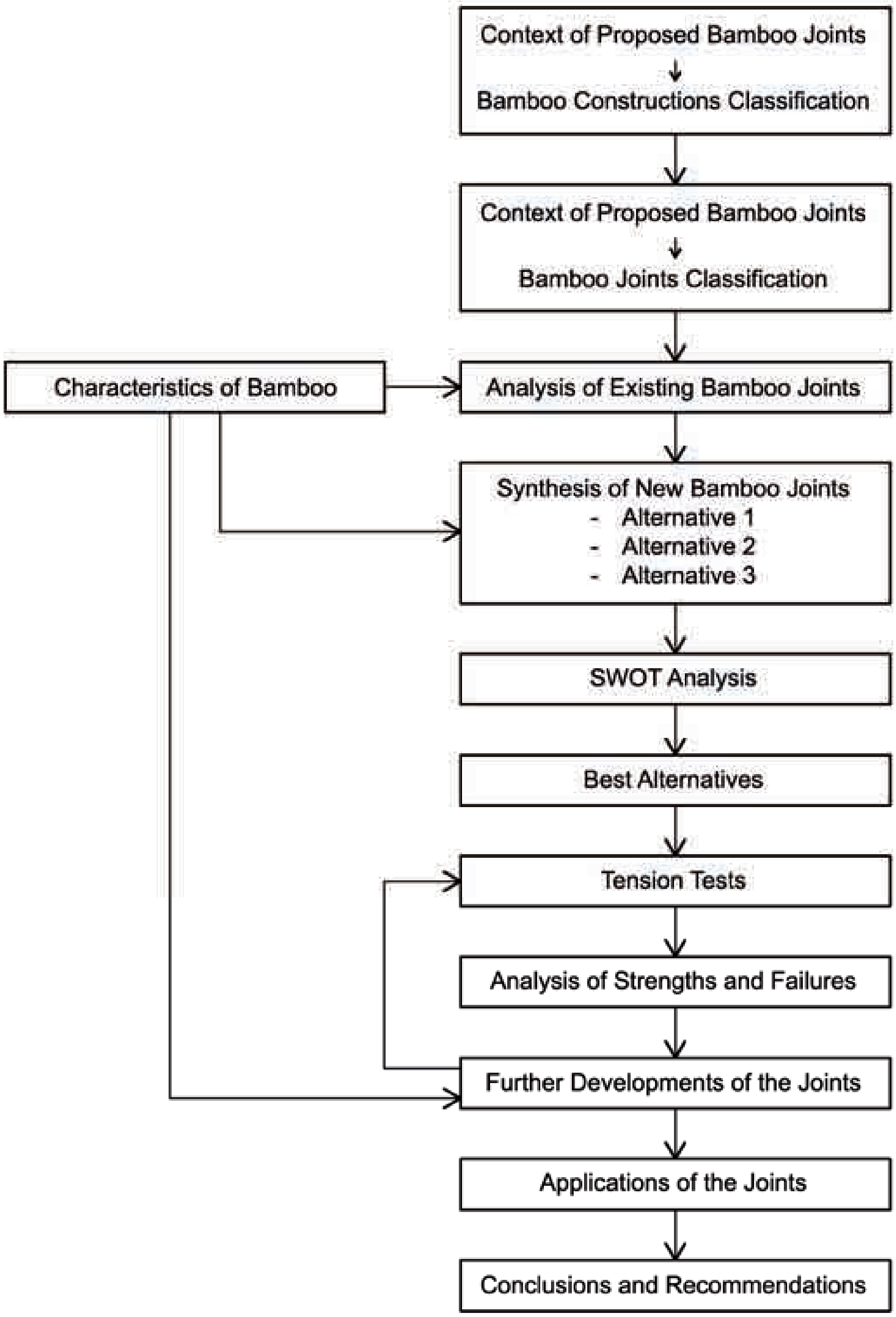


Figure 1-1: Research Framework

1.4 Dissertation Contribution

The expected contributions of this dissertation are as follows:

- Providing a comprehensive classification of bamboo pole constructions.
- Producing a new classification of bamboo joints, based on the place of connectors and induced forces. Further contribution of this classification is for the improvements of existing joints or even the inventions of new joints by using the same principles but in different details.
- Reviving the uses of lashing-based bamboo joints. Lashing is one of the ancient joints to connect round shape of bamboo, but has been long abandoned due to some problems. With modern approaches and materials, some of the problems can be solved, and at the same time, the advantages can be maintained.
- Giving alternatives for tension loadable bamboo joints, benefiting the high tensile strength bamboo fibers. Providing bamboo connections with high tensile strength will trigger further developments in wide span structures for buildings and bridges.
- Contributing alternatives for bamboo joints whose ultimate-load capacity can be calculated and customized more precisely. This breakthrough will bolster the uses of bamboo as tension elements and ensure the safety of the structures.
- Providing alternatives for simple bamboo joints with high tensile strength to promote the uses of bamboo as tension elements in vernacular bamboo constructions.

1.5 Dissertation Outline

Chapter 2 is theoretical chapter about the characteristics of bamboo. It reviews related basic researches to determine the properties and characteristics of bamboo that have significant effects to the joints.

Chapter 3 and 4 establish the classification of bamboo constructions and bamboo joints. These parts are very valuable to put the joints in the right context. Bamboo constructions can be found in remarkably different ways with huge variations of joints.

Chapter 5 presents the development of bamboo joints. These developments are both further improvements of existing designs of bamboo joints and new joints using the same principles, which have been mapped in Chapter 4.

Chapter 6 describes the tension tests of lashing based bamboo joints. Lashing joint is widely used in traditional bamboo constructions because it has so many advantages, but it is abandoned in modern constructions due to several problems.

Chapter 7 shows some possible applications of proposed lashing based bamboo joints. They had been used in a real tensegrity sculpture. The other possibilities are for joints in bamboo space structures and pedestrian bridge.

The study ends with Chapter 8 summarizing the findings and answering the general research questions. General contributions of the research are also outlined, followed by proposing future research.

2 Characteristics of Bamboo as Building Material

Bamboo is not a tree but a woody giant grass as part of family *Poaceae* or formerly known as *Gramineae* and sub-family Bambusoideae (Hidalgo-Lopez, 2003). These long-lived and woody-stemmed perennial grasses consist of approximately 87 genera and over 1500 species worldwide. There are two general types: clumper (*sympodial*) and runner (*monopodial*) bamboo.

Clumper or *sympodial* bamboos are typical native of tropical climate. It is called as clumper, because the new shoots grow very close to the respective parent plants; thus, they will form a clump of many stems or canes. These bamboos with *panchymorph rhizome* as reproducing root grow natively in America by genus *Guadua* and in tropical Asia by genera *Dendrocalamus* and *Bambusa* (Hidalgo-Lopez, 2003).

Runner or *monopodial* bamboos are temperate climate species, distributed mostly in Japan, China and Korea. They reproduce themselves with *leptomorph* rhizome system, which spread horizontally in a shallow depth of the soil to produce a new shoot in a relatively long distance from their parent plants. That is why this general type of bamboo is an invasive type. This group of bamboo is represented in Asia by the genera *Arundinaria* and *Phyllostachys*. Only three native species of bamboo in this group in America, and they belong to the Asiatic genus *Arundinaria* (Hidalgo-Lopez, 2003).

2.1 Anatomy of Bamboo Pole

Understanding the anatomy of bamboo is the key of successful design and construction of bamboo building because bamboo is unique, and the uniqueness belongs to individual pole. The characteristics and properties of individual pole are different from one pole to another, but of course, there are characteristics that belong to bamboo in general and to each bamboo species in more specific.

Amongst many literatures describing the properties and characteristics of bamboo, in this particular chapter, only the anatomy of bamboo pole is described in detail in regard to its constructions from a point of view of an architect. The discussion about the characteristics will be connected to the influences in bamboo constructions.

Growing Anatomy

As giant grass bamboo produce a large primary shoot within a short time of a few months without any later secondary growth of the culms in length and diameter (Liese & Kumar, 2003). Although naturally round and hollow this growing anatomy of bamboo can be utilized to produce square bamboo and even to bend bamboo in the growing process. Most of these rare techniques are used for craftsmanship or furniture. The methods to deform the culms or to make a square or rectangular cross section of the culms are described by Hidalgo-Lopez (2003).

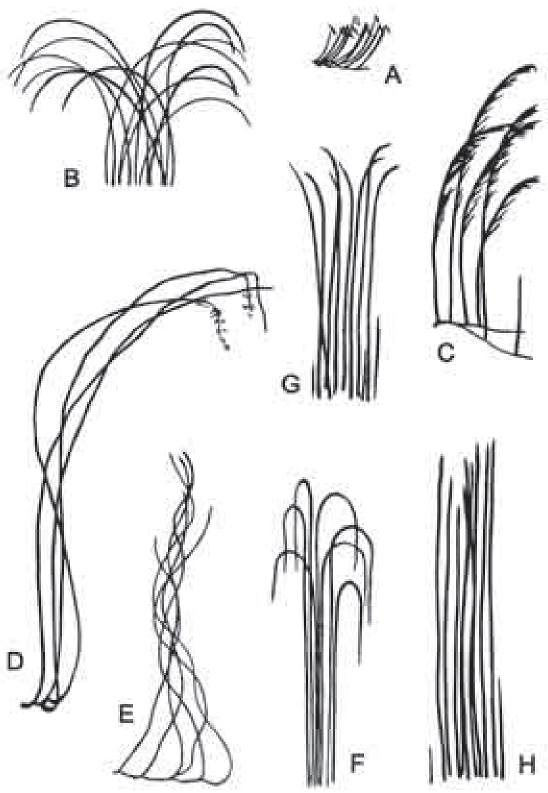


Figure 2-1: The upright habits of many bamboo species (courtesy of Dean Johnston)

Figure 2-2: The curve bamboo as an effect of growing environment (source: anonymous)

Some bamboo species naturally grow straight (Figure 2-1 H), and some grow severe twisted or even have to climb to other tree such as climbing bamboo or *Chusquea coronalis* (Figure 2-1 E). This growing anatomy is affected also by the growing condition. Bamboos growing on a river bank or close to a water source tend to have curve pole because they thrive but have less strong fibers than in normal environment (Figure 2-2).

Most bamboo structures use straight bamboo as raw material. Even some curve bamboos have to be straightened by bending in opposite bending direction above an open fire before used. Curve bamboo can be used for straight column using some techniques, but the curve should be in one direction. Three-dimensional curve bamboos are very difficult to use.

Regarding there are not any perfect straight bamboos, some architects use the uniqueness of natural curve material as curve building structure such as beam or column (Figure 2-3 and Figure 2-4).

Figure 2-3 (above): Curve bamboos as roof frame

Figure 2-4 (right): Curve bamboos as column (courtesy of Simon Velez)

Cylindrical Pole with Various Diameter

Figure 2-5: The extreme difference of the diameter and wall thickness between lower and upper part (courtesy of Arif Rabik)

Figure 2-6: Positive fitting joint in an easy made temporary bamboo structure

Naturally, bamboos have round cross section, and most of them are hollow. Only a few bamboos have solid culms, such as *Guadua affinis paraguayana Doll,* a species native to Brazil, *Chusquea spp.* and *Dinochloa spp*. The diameter differs between different species, between lower and upper part of a bamboo and even between individual poles (Figure 2-5). These characteristics are utilized in traditional bamboo construction for some unique joints. Positive fitting joint is one example of this as shown in Figure 2-6 (see also Figure 3-4). This joint consists of two bamboos; the smaller bamboo is driven through the bigger one in the perpendicular direction. Because of the hollowness and round shape of bamboo, it is easy to make a big hole to insert smaller one by making V-slicing in two opposite surfaces of the pole without cutting it off. It can be done even with very simple tools such as machete or saw. For a more precise joint, a special knife or chisel has to be used.

The widespread uses of lashing joint in traditional and vernacular bamboo construction are also because of the characteristic of round shape of bamboo cross section. This shape makes the friction between rope and bamboo more effective. Lashing joint is also widely used for bamboo scaffolding construction in Hong Kong and other part of Asia.

Wall Thickness

Regarding that bamboo is hollow; the material between the cavity and outer surface of bamboo is called as bamboo wall. The thickness of bamboo wall differs between species, between upper and lower part (see also Figure 2-5) and even between individual poles; however it remains almost constant in the internode with thickening near the nodes.

Wall thickness does not play an important role in the construction process of bamboo pole, except a thicker wall will increase the strength of the bamboo. The presence of more fibers in a thicker wall bamboo will reduce the possibility of splitting and buckling. For example, minimal 10 mm wall thickness is mentioned in the specific requirement of bamboo for scaffolding in Hong Kong, including minimal diameter of 75 mm (Occupational Safety and Health Branch of the Labor Department Hong Kong, 2009).

Wall thickness brings a big influence to bamboo split construction. Thicker wall gives the split more strength and rigidity; although in the other hand, it reduces its bending or weaving flexibility. That is the reason that the utilizations of split bamboo in Asia, especially for woven mat, are more advanced compared to those in South America. One of the reasons is the availability of many bamboo species with thinner wall in Asia in comparison with average thicker wall bamboo species in South America.

Node and Internode

Bamboo pole is strongly characterized by the presence of node along its conical culms, both visually and structurally. Internode is part of bamboo between two nodes. Node is an important center of morphogenetic activity and intercalary growth, where the roots and branches emerge (Hidalgo-Lopez, 2003). The important elements in the node regarding bamboo as building material are nodal ridge on the outside and diaphragm in the inside.

The outer diameter of a nodal ridge in some species of bamboo is significant bigger than the outer diameter of an internode. In this case, *Guadua* is one of the examples, but in some other species, the difference is not so significant, for example, *Gigantochloa atroviolacea* or *Gigantochloa pseudoarundinacea.* This characteristic is important to be exploited in traditional lashing joint because it gives a better friction between the rope and the bamboo. Most of the lashing joints are tightened at an internode before a node that acts as a stopper for further movement of the bamboo relative to the lashing joint after the tension force is induced.

Bamboo has only longitudinal fiber, which is prone to splitting. However, these fibers are rather twisted in the node. On one hand, this characteristic prevents the bamboo from that problem much better, but on the other hand, this phenomenon reduces tensile strength. Therefore, the failure by tension almost always happens in the node.

Diaphragms of bamboo in the nodes unify the bamboo wall, in such a way, the whole bamboo pole acts together as one. The function is similar with a diaphragm in building structure that transfers lateral loads to shear wall or frames and joins all vertical structural elements together.

The diaphragms also prevent bamboo from flattering and make it much better as beam. The buckling failure of bamboo column under compression always happens in the internode and never happens in the node because of the presence of diaphragm. Diaphragms divide the cavity of the bamboo into many parts. In some joints with mortar injection, the division of the cavity will restrain the injection into some necessary chambers.

The area between two nodes is an internode. The lengths of internodes vary in a culm. Some research shows that the longest internode is in the middle part of a culm. The length of internode of *Mellocanna baccifera* increases from basal part until 15th internode, then decreases gradually until the 45th internode, after which a slight increase is again noticed (Pattanaik et al., 2004). The similar pattern that shows the longest internode in the middle part is also reported happening in the species of *Dendrocalamus giganteus* (Ghavami, 2008).

The length of internode plays valuable role in the perspective of bamboo constructors, because in the construction phase, the joints should be placed as close as possible to a node. The node should be presented in the end of used pole to prevent splitting. Two holes cannot be made in a line in the same internode. It has to be done in a different line or alternated with at least a node. As beam, the bearing point should be placed on the node because diaphragm prevents bamboo from crushing. All these requirements regarding the presence of node have a close correlation with the average length of the internode in a bamboo pole. The closer distance between two consecutive nodes or the shorter internode means also the easier to place the joints or bearing point close to the node. The shorter internode in average will make the choice to present a node in the end of the used pole much easier.

2.2 Mechanical Properties of Bamboo

The mechanical properties of bamboo describe how the bamboo will react to physical forces. Bamboo is an anisotropic material. The properties of bamboo depend on the direction relative to the fibers. The fibers go in the longitudinal direction; although in the node area, they are rather twisted. Tensile strength of bamboo is much stronger in this direction than in the perpendicular to the fibers.

As already mentioned before, bamboo is a natural material. As a plant, the growing of the bamboo is subject to many constantly changing influences, such as soil, water, micro and macro climate. Therefore variability or variation in properties is quite typical for bamboo.

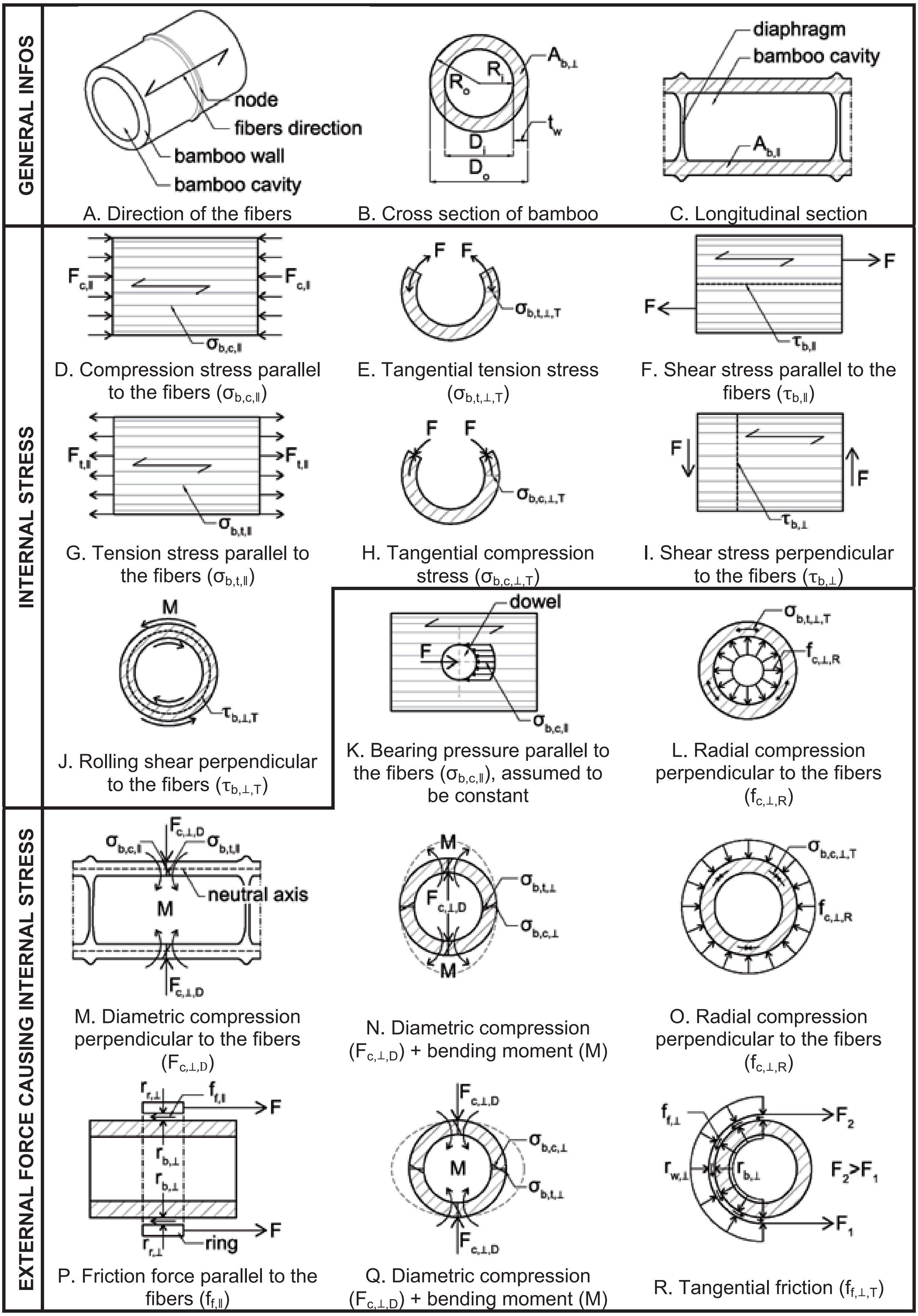


Table 2-1: Mechanical phenomena of bamboo pole in relation to loadings due to the design of mechanical joints

Table 2-1 shows the factors that influence the strength of bamboo and bamboo joints, completed with symbols. It demonstrates also the mechanical phenomena of bamboo pole under different loading effects.

In general bamboo has a high strength against tension parallel to the fibers ($\sigma_{\parallel,t}$) as shown in Table 2-1 C. If the strength-to-weight ratio is considered, bamboo's tensile strength is astonishingly high. Because of this property, bamboo earns the name of "vegetable steel" (Trujillo, 2009). Tensile strength of bamboo relies on the presence of the fibers. In bamboo culm, the fibers cover approximately 40%. The others are 10% vessels and 50% parenchyma (Janssen, 2000; Liese, 2004). The vessels to transport the nutrition are covered with a bundle of fibers, which is connected to other bundles by parenchyma. The fibers are not evenly distributed; the outer part of bamboo wall consist more fibers than inner part. Therefore, the outer part of bamboo has considerably higher tensile strength than inner part.

According to Arce (1993) there is too much information about tensile strength of the bamboo, although often very little account is given on the procedure followed to measure this quality, nor enough data included in reports or textbooks on the matter. Nevertheless, ultimate tensile strengths of bamboo ($f_{u,b,t,\parallel}$) reported from many sources are listed in Table 2-2.

No.	Reported by	Bamboo Species	$f_{u,b,t,\parallel}$ (N/mm^2)	Note
1	Von R. Bauman (1923)	*Phyllostachys nigra*	301	Outer layer
			156	Inner layer
			203	Entire thickness of the wall
		Arundinaria amabilis	377	Outer layer
			133	Inner layer
2	Meyer & Ekelund (1923)	Not known	100	Maximum
			70	Maximum, bamboo rope from outer layer, twisted, plaited
3	Uno (1930)	*Phyllostachys bambusoides*	178	Average, inner layer
			378	Average, outer layer

No.	Reported by	Bamboo Species	$f_{u,b,t,\parallel}$ (N/mm^2)	Note
3	Uno (1930)	*Phyllostachys nigra var. Henonis*	124	Average, inner layer
			234	Average, outer layer
		Phyllostachys pubescens	88	Average, inner layer
			291	Average, outer layer
		Phyllostachys lithophila	144	Average, inner layer
			304	Average, outer layer
		Dendrocalamus latiforus	84	Average, inner layer
			299	Average, outer layer
		Bambusa oldhamii	205	Average, inner layer
			452	Average, outer layer
		Bambusa stenostachya	187	Average, inner layer
			301	Average, outer layer
		Bambusa vulgaris var. vittata	197	Average, inner layer
			403	Average, outer layer
4	Duff (1941)	*Phyllostachys pubescens*	54	Average, inner layer
			342	Average, outer layer
5	Karamchandani (1959)	*Dendrocalamus strictus*	150	Minimum, inner layer
			160	Maximum, inner layer
			100	Minimum, outer layer
			335	Maximum, outer layer
6	Cox & Geymayer (1969)	*Arundinaria tecta*	110	Average
7	Atrops (1969)	Not known	153	Average, inner layer
			290	Average, outer layer (skin)
8	Hidalgo (1978)	*Guadua angustifolia*	315	Maximum, upper part of bamboo, a half year old culm

No.	Reported by	Bamboo Species	$f_{u,b,t,II}$ (N/mm^2)	Note
8	Hidalgo (1978)	*Guadua angustifolia*	100	Minimum, 5 years old culm
			296-314	1 year old culm
9	Sjafii (1984)	*Dendrocalamus giganteus*	187	Average, internode including 2 nodes
		Dendrocalamus asper	209	Average, internode including 2 nodes
		Gigantochloa robusta	188	Average, internode including 2 nodes
		Bambusa vulgaris var. striata	130	Average, internode including 2 nodes
10	Soeprayitno et al. (1988)	*Gigantochloa pseudoarundinacea*	178	Average, bamboo from slope hill
			149	Average, bamboo from valley bottom
11	Prawirohatmodjo (1988)	*Bambusa arundinacea* *Bambusa vulgaris* *Dendrocalamus asper*	297	Average, green bamboo
		Gigantochloa apus *Gigantochloa ater* *Gigantochloa verticillata*	315	Average, dry bamboo
12	Sharma (1988)	*Bambusa vulgaris*	145	Average, bamboo with nodes
			200	Average, bamboo in the internode (without nodes)
13	Bodig et al. (1993)	*Phyllostachys edulis*	610	Fiber
			50	Matrix
			140-230	Composite
14	Zhou (1994)	*Phyllostachys pubescens*	263	Average, without node
			213	Average, with node

No.	Reported by	Bamboo Species	$f_{u,b,t,II}$ (N/mm²)	Note
15	Li et al. (1995)	*Phyllostachys edulis*	34-220	
16	Ghavami & Moreira (1996)	*Dendrocalamus giganteus*	150	Average
17	Lopez & Silva (2000)	*Guadua angustifolia*	35	Average
18	Steffens (2000) Zhang (2001)	*Phyllostachys pubescens*	196	
		Guadua angustifolia	140	
19	Ghavami (2004)	*Guadua angustifolia*	83	Average, bamboo with nodes
			96	Average, bamboo in the internode (without nodes)

Table 2-2: List of reports on the tensile strength of many bamboo species

The modulus of elasticity of bamboo compared to timber is also quite high particularly that of the pure fiber. The different elaborated values of this property are listed in Table 2-3 below.

No.	Reported by	Bamboo Species	Modulus of Elasticity E_b (N/mm²)	Note
1	Uno (1930)	*Phyllostachys bambusoides*	21975	Average, inner layer
			51345	Average, outer layer
		Phyllostachys nigra var. Henonis	20391	Average, inner layer
			53926	Average, outer layer
		Phyllostachys pubescens	8367	Average, inner layer
			33067	Average, outer layer
		Phyllostachys lithophila	22615	Average, inner layer
			42092	Average, outer layer
		Dendrocalamus latiforus	12833	Average, inner layer
			50116	Average, outer layer

No.	Reported by	Bamboo Species	Modulus of Elasticity E_b (N/mm^2)	Note
1	Uno (1930)	*Bambusa oldhamii*	28148	Average, inner layer
			66416	Average, outer layer
		Bambusa stenostachya	26804	Average, inner layer
			41984	Average, outer layer
		Bambusa vulgaris var. vittata	19339	Average, inner layer
			65811	Average, outer layer
2	Cox & Geymayer (1969)	*Arundinaria tecta*	18670	
3	Soeprayitno et al. (1988)	*Gigantochloa pseudoarundinacea*	27631	Average, bamboo from slope hill
			19643	Average, bamboo from valley bottom
4	Sjafii (1984)	*Dendrocalamus giganteus*	14044	Average, internode including 2 nodes
		Dendrocalamus asper	12875	Average, internode including 2 nodes
		Gigantochloa robusta	9639	Average, internode including 2 nodes
		Bambusa vulgaris var. striata	7473	Average, internode including 2 nodes
5	Bodig et al. (1993)	*Phyllostachys edulis*	46000	Fiber
			2000	Matrix
			11000-7000	Composite
6	Ghavami & Moreira (1996)	*Dendrocalamus giganteus*	15000	Average
7	Steffens (2000) Zhang (2001)	*Phyllostachys pubescens*	10500	
		Guadua angustifolia	19000	

No.	Reported by	Bamboo Species	Modulus of Elasticity E_b (N/mm^2)	Note
8	Torres et al. (2007)	*Phyllostachys pubescens*	1685±132	Circumferential moduli
		Guadua angustifolia	485±172	Circumferential moduli

Table 2-3: List of reports on the modulus of elasticity of many bamboo species

Compression strength parallel to the fibers is the capacity of bamboo fibers and matrix within the wall to resist longitudinal pressure or compression parallel to the fibers (see Table 2-1 D). According to Hidalgo (1978), the compression strength of the culm increases with the age of the bamboo and with its height. A study on the mechanical properties of the internodes by Sjafii (1984) concluded that each internode of a culm has different mechanical properties. In some species, the compression strength does not increase progressively. For example, the compression strength of the 1st internode of *Dendrocalamus asper* is 63 N/mm^2, and 7th internode is 56 N/mm^2 (Hidalgo-Lopez, 2003).

The values of ultimate compression strength of bamboo parallel to the fibers ($f_{u,b,c,II}$) are listed in Table 2-4 below.

No.	Reported by	Bamboo Species	$f_{u,b,c,II}$ (N/mm^2)	Note
1	Uno (1930)	*Phyllostachys bambusoides*	53	Average
		Phyllostachys nigra var. Henonis	40	Average
		Phyllostachys pubescens	60	Average
		Phyllostachys lithophila	85	Average
		Dendrocalamus latiforus	35	Average
		Bambusa oldhamii	31	Average
		Bambusa stenostachya	33	Average
		Bambusa vulgaris var. vittata	52	Average

No.	Reported by	Bamboo Species	$f_{u,b,c,\parallel}$ (N/mm^2)	Note
2	Sjafii (1984)	*Dendrocalamus giganteus*	61	Average, internode including 2 nodes
		Dendrocalamus asper	59	Average, internode including 2 nodes
		Gigantochloa robusta	51	Average, internode including 2 nodes
		Bambusa vulgaris var. striata	45	Average, internode including 2 nodes
3	Zhou (1994)	*Phyllostachys pubescens*	63	Average, without node
			59	Average, with node
4	Martin et al. (1981)	*Guadua angustifolia*	31	Average, internode, lower section, 1-3 years old
			38	Average, internode, middle section, 1-3 years old
			44	Average, internode, lower section, 3-5 years old
			48	Average, internode, middle section, 3-5 years old
			40	Average, internode, lower section, ≥5 years old
			43	Average, internode, middle section, ≥5 years old
5	Steffens (2000) Zhang (2001)	*Phyllostachys pubescens*	56	
		Guadua angustifolia	56	

Table 2-4: List of reports on compression strength of many bamboo species

3 Classification of Bamboo Pole Constructions

In the area where bamboo grows naturally, it always plays an important role. The utilization of bamboo grows side by side with the civilization; thus, makes many activities unable to be separated from the existence of this giant grass.

One of the most important uses of bamboo is for building construction. Bamboo is believed to have been the first choice as building materials as people began to occupy the areas where bamboo grows naturally. The common reasons were its availability and workability. Due to its lack of durability, most people replaced the use of bamboo with more resistant materials, such as timber and brick after a short period of time. According to Hidalgo (2003), due to the low durability of most giant bamboo species of Southeast Asia, at present most of the countries in this area do not use bamboo for the construction of the main structure of their houses.

In recent years, with the issue of sustainability the use of bamboo regains a new value. Bamboo offers many advantages that fulfill most of the criteria of a sustainable material, especially as a substitute for timber to reduce deforestation. This awareness has been followed by a massive amount of bamboo research and utilizations. Bamboo has been used directly with minimum preparation or after being transformed with high-tech methods. Great bamboo buildings made of preserved bamboo-poles can be found at the present time, as well as luxurious interiors made of bamboo lamination or ply-bamboo. Vernacular bamboo constructions are also still prevalent in suburban or rural areas.

In the hands of artists, architects and engineers, bamboo becomes a promising material to create a wide variety of building typologies. Bamboo can be used in all parts of the building, either as structural or architectural elements. It can stand alone or in combination with other materials. Bamboo also can be simply transformed or high-tech-transformed to form new materials. With their specific characteristics and properties, these materials can be constructed in different ways.

Obviously, these circumstances drove many authors to classify bamboo constructions in many different ways, based on building typology, building element, time frame or bamboo based material.

In this dissertation, bamboo constructions will be classified, based on the way bamboo is constructed, to put bamboo joints in a context of the whole bamboo pole construction. It does not depend on where the bamboo construction will be placed or what it is for, but how it will be constructed. This differs from other publications that distinguish the constructions based on the building elements such as footings or roofing construction, or based on building types, such as housing or bridge construction.

This classification of bamboo pole constructions is part of the classification of the entire bamboo based constructions. According to this classification, bamboo constructions are divided into two main categories: conventional and substitutive bamboo constructions (Widyowijatnoko & Trautz, 2009) as indicated in the following diagram in Figure 3-1. Conventional bamboo constructions are divided into two categories: traditional or vernacular and engineered conventional.

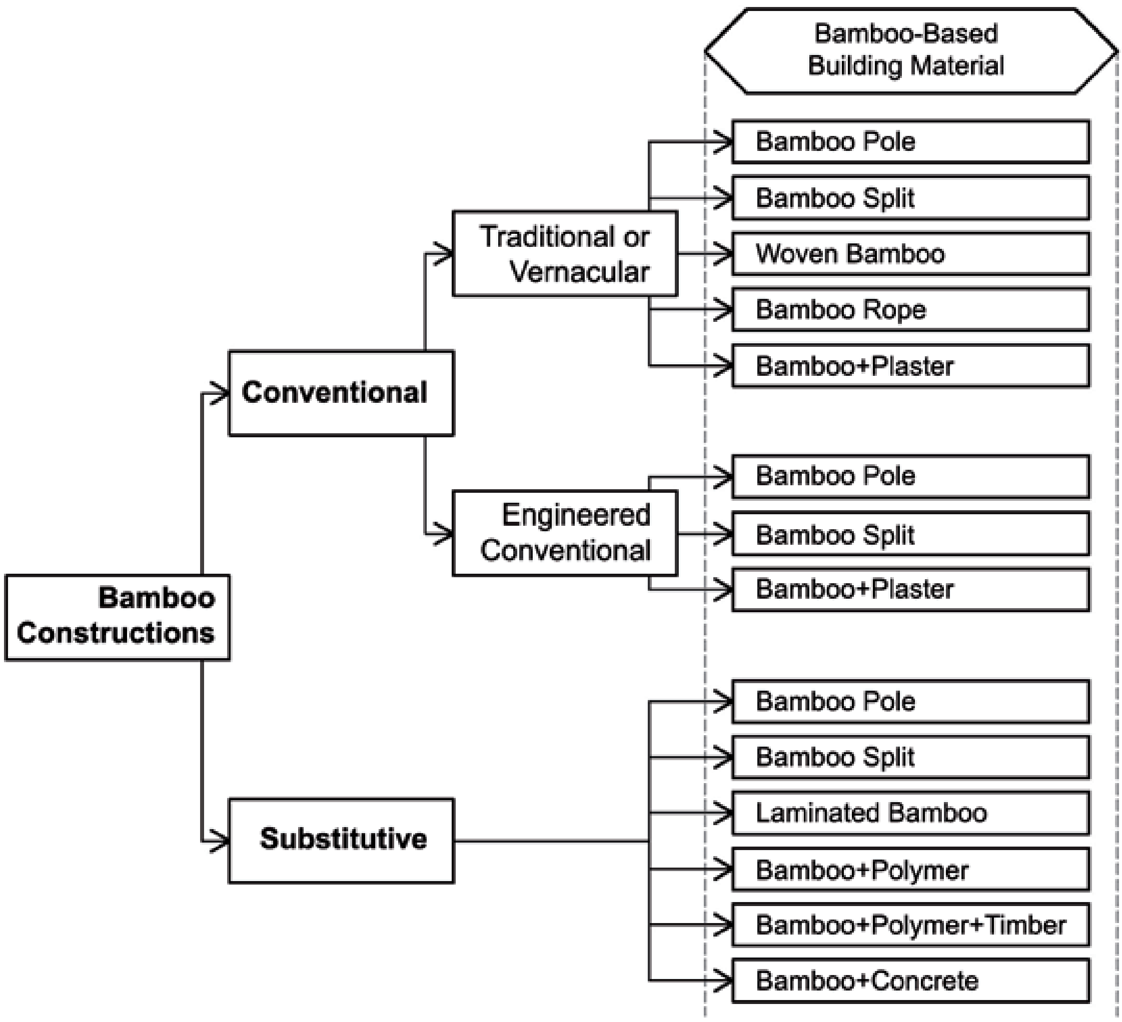


Figure 3-1: Diagram of bamboo constructions classification

‘Conventional’ bamboo construction is used to describe a construction of bamboo based on the specific characteristics of bamboo. A convention is a set of unwritten rules, a set of agreed, stipulated or generally accepted standards, norms, social norms or criteria. Conventional bamboo constructions stand for the constructions based on a convention of bamboo construction in the community. This convention is not only used in traditional or vernacular constructions, but also applied in the modern bamboo constructions with or without improvements.

On the other hand, bamboo is utilized to replace other material in an established structural system. Thus, these bamboo constructions will be classified as “substitutive bamboo construction”. The best examples of bamboo as a substitute for other materials are laminated bamboo and bamboo as concrete reinforcement. Laminated bamboo can absolutely replace wood construction. Bamboo is also utilized to replace steel rebars as concrete reinforcement. In the pole constructions, the uses of bamboo poles in this category are mostly bamboo construction with logic of steel construction in a space frame structure.

3.1 Traditional or Vernacular Bamboo Construction

Vernacular architecture is used to distinguish the buildings made by empirical builders in an informal way (Arboleda, 2006) from those designed by architects. Sometimes it is also called as traditional architecture, although some references distinguish these two terms. According to Brunskill (2000), although there are links between them, traditional architecture would not be included as part of vernacular architecture.

In bamboo architecture, the problem of durability of bamboo in the past reduced the utilization of bamboo mainly to vernacular architecture and to only a limited use in traditional architecture. In traditional architecture, it was mostly used as part of non-structural element in, such as roofing constructions, roof tiles, woven bamboo as building envelopes. In vernacular architecture, bamboos are used not only as architectural elements, but also as structural elements, although most of them are designed to be temporary constructions.

Traditional bamboo pole constructions are based on a long history of empirical experience, and it becomes a basic of conventional bamboo construction. In this construction, the specific characteristic of bamboo is highly benefited. Therefore, some specific connections are considered as 'original bamboo connections' that could not be applied to other materials. An example can be found in Figure 3-2. Basically, this is a fish-mouth joint. To ensure the stable seating of a bamboo, the end of another bamboo is cut to form a saddle or fish-mouth shape with a long tongue-shaped strap. This strap is bent right over the transverse bamboo and tied back.

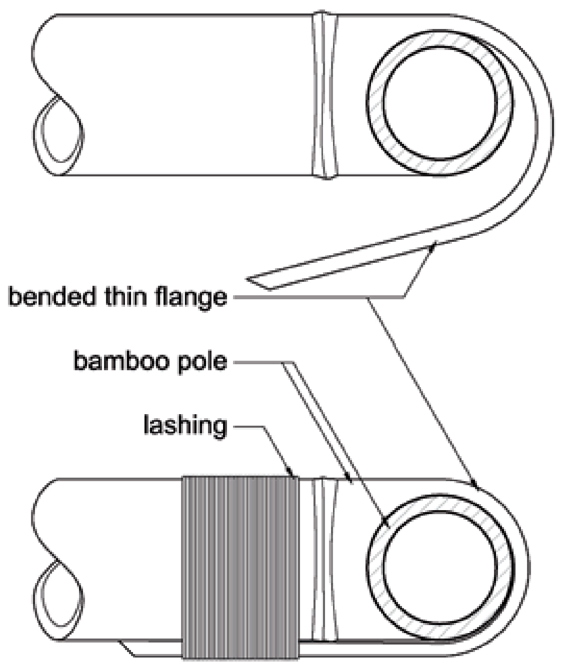


Figure 3-2: Fish-mouth joint with bended thin strap and lashing (after Dunkelberg, 1985)

Figure 3-3: Fish-mouth joint with two pinned flanges (courtesy of Benjamin Brown)

The most common connections in this category are fish-mouth joints (Figure 3-2 and Figure 3-3), lashings (with coco-fiber, bast, rattan or bamboo rope), plug-in joints, and positive-fitting connections (Figure 3-4). Lashing joints are deemed to be one of the most ancient kind of bamboo connections. Despite being a simple kind of joint, they are made with highly efficiency by using friction between the bamboo and the rope due to the circular cross section of bamboo. Bamboo has to be pinned, concaved or fish-mouth shaped to make a strong lashing joint in most cases. This is easy to do because of the hollow core of the bamboo, even with just a machete.

In most of the traditional bamboo buildings, the supporting structure is formed from straight full-section canes. They are almost always under compressive or bending stresses. Canes under tensile stress can rarely be found (Dunkelberg, 1985). Although bamboo has very high tensile strength, it is difficult to connect the bamboo poles to maximize the use of that strength, especially when the connector is made of traditional material that commonly out of natural resource.

Figure 3-4: Traditional bamboo gazebo in Indonesia with positive fitting and lashing joint

Figure 3-5: Planar frame in common vernacular bamboo construction (courtesy of AMURT)

Most of the traditional or vernacular bamboo buildings consist of planar frames (Figure 3-5 and Figure 3-6). Commonly, this two-dimensional frame is composed of one layer (Figure 3-7). In Asian culture, where bamboo in different culms diameter is easy to find, this planar and one layer frame is constructed with a positive-fitting connection. A bamboo with a small diameter serves as a beam and is connected by being placed through a bigger diameter bamboo as a column (see also Figure 3-4).The other specific characteristic of conventional bamboo construction is the existence of eccentricities of load transfer in the connection because of the difficulty connecting many poles at once in one point (see also Figure 3-7).

Figure 3-6: One layer frame of wall construction in Colombia (source: anonymous)

Figure 3-7: Eccentricity of force transfer and the effort placing the joints near to the node

3.2 Engineered Conventional Bamboo Construction

Based on traditional or conventional techniques of bamboo construction, many architects, artists and engineers develop the further uses of bamboo that are scientifically acceptable. Scientific approaches such as basic research and calculations are conducted to determine the strength and constructability of bamboo building. Therefore, this utilization is categorized as engineered conventional bamboo construction.

Engineered conventional bamboo poles construction is also part of conventional bamboo construction that is developed based on the uniqueness characteristics of bamboo. The greatest improvement from traditional to engineered conventional bamboo construction is the use of bolted joint with or without mortar injection, employing a modern tool electric drill machine. With an electric drill machine, two or more bamboo poles can be drilled at once to attach a long rod. After that, they can be tied and tightened together with the help of a pair of nuts. Without an electric drill machine and a long rod, the similar joining technique can be applied to connect maximal two bamboo poles using dowel out of bamboo or timber. It is difficult to join bamboo poles more than two layers with traditional methods.

Bolted joint provides an easy workability, high durability and capability to connect many bamboo poles at once because of the availability of long rods (Figure 3-8). The great impact is easier to make a building frame with more than two layers (Figure 3-9 and Figure 3-10). A column of four bamboo poles in three layers is widely used in engineered conventional bamboo construction. Different with traditional bamboo construction, three-dimensional frames are introduced in this category (Figure 3-11).

Like in most traditional bamboo constructions, in this category, bamboos are almost always under compressive or bending stresses. Bamboo poles under tensile stress are also rarely found. There are also eccentricities of load transfer in this type of construction because of the difficulty making a connection in one point (see also Figure 3-9).

An example of bamboo construction in this category that was recently built is 'Great Hall OBI' designed by author (Figure 3-11). The bamboo hall has an oval plan with the minimal span of 20 m and maximal of 31 m without any column in the middle.

Figure 3-8: The capability of bolted joint to connect three big bamboos at once

Figure 3-9: Eccentricity of load transfer in a joint (courtesy of Jörg Stamm)

Figure 3-10: Two-dimensional frame with many layers (courtesy of Jörg Stamm)

Figure 3-11: Three-dimensional frame and the beauty of the rhythm of repetitive frame in the Great Hall OBI by architect Andry Widyowijatnoko (courtesy of Eko Purwono)

The main structures of Great Hall OBI are double layer and double deck frame in the perimeter with an additional floating roof structure in the middle. This rigid frame provides a corridor and a mezzanine floor in the perimeter. Bolted joints are used in combination with fish-mouth joint, strengthened by lashing in some parts.

The buildings of this particular construction type are mostly single buildings with a relatively simple form, because their beauty lies in the details and the rhythm of repetitive frames (see Figure 3-11). So if the building has a complicated form, the structure or the detail will be overcrowded.

3.3 Substitutive Bamboo Constructions

Beyond the conventionality, bamboo is utilized to replace other established material in building construction. Many types of construction with many kinds of building material exist today. Parts of these materials are produced with the high cost, endangered the sustainable development or not available in some places. Therefore, the new idea comes to replace those materials with bamboo. For that reason, this type of bamboo construction is called 'substitutive bamboo construction'.

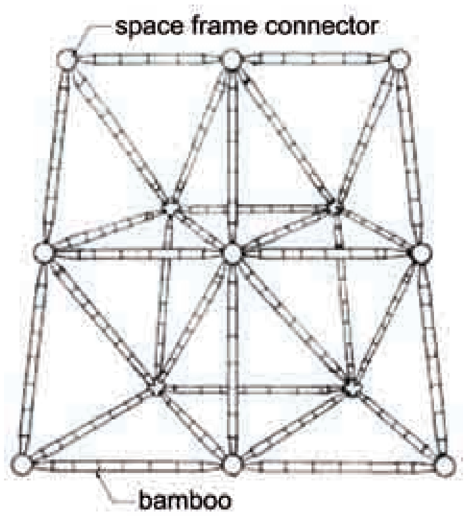


Figure 3-12: The idea of using bamboo as space structure member to replace common steel or timber (Hidalgo, 2003)

Figure 3-13: The development of bamboo connection to avoid eccentricity of load transfer with a space frame connector (courtesy of Chair of Structures and Structural Design, RWTH Aachen)

In this category, a bamboo pole is used to replace other materials in its type of construction, although sometimes, the construction is foreign to the nature of what bamboo wants to be. Therefore, bamboo is sorted or treated to fit in with the requirements. Most of the utilizations of bamboo in this division are replacing steel or wood member in space frame structures (Figure 3-12). Most space frame structures use circular or square hollow tube members because of their better performance in resisting forces, which normally pure axial tension or compression, with only secondary bending effects. Tubular members are also considered having a superior aesthetic appearance (Chilton, 2000). For that reason, the natural circular hollow tube of bamboo becomes very attractive to be used. Hidalgo (2003) described the construction of bamboo for spatial structure in a special section in his book, Bamboo: The Gift of the Gods, although it covers all kinds of bamboo-based material, not only bamboo pole.

Space structures feature the best strength of geometric properties for covering large areas with a few columns (Ghavami & Moreira, 1993). Space structures are the answer to the demand for efficient and adaptable long-span structures. Mainly the structures are composed of double layers in that a top and a bottom layer consisted of linear bars, interconnected by vertical or inclined, equally linear, member (Sebestyen, 2003). Double layers space grids are one of the most efficient and lightweight structural systems due to their ability to share the task of load carrying through the whole structure (Chilton, 2000). Space structures are developed to have high efficiency by using its members purely as tension or compression members and avoiding eccentricities of load transfer. Although there is not a big leap concerning the design of bamboo space frame structures, the great achievement lies in the development of the joints to accommodate these requirements (Figure 3-13). The design of the joints between bamboo and nodal joints of space structure is more of a challenge than the design of the structures. It is widely known that the connection constitutes the most difficult problem in bamboo construction. In some specific joints, which node has a vital role, the process of sorting becomes very crucial to find a number of poles in a certain length of the pole and certain length of internode in the end of bamboo pole.

Compared to the widely used conventional bamboo construction, the limited amount of examples of bamboo space structures are due to the difficulties and the high cost of bamboo joints for space structures. It is in contrary with ease to work and low cost bamboo. One example is a building designed by Leiko Motomura in Cotia, Sao Paulo, Brasil. This summer classroom uses bamboo space truss for roofing structure (Figure 3-14).

Part of this group is the use of bamboo as compression members in combination with other materials, mostly steel as tension members. As an example, Simon Hosie designed a toll gate in Colombia in Figure 3-15. In this building bamboo is used also as the main structural element for the very long cantilever. Thus, not only compression is induced in the bamboo, but also bending stress.

Figure 3-14: Bamboo space structure by architect Leiko Motomura (source: Amima)

Another example of building in this category is German-Chinese House in Shanghai Expo 2010 (Figure 3-16). Markus Heinsdorff designed this 330 square meter building. The stability of the structure relies on the trusses or triangle configurations. Bamboos are used mainly as compression members, while the tension is transferred through steel elements.

Figure 3-15: Bamboo as compression element in combination with steel as connector and tension wire

Figure 3-16: German-Chinese House in Shanghai Expo 2010 (source: Thom, 2010)

4 Classification of Bamboo Joints

The classification of bamboo constructions shows strong hints to the differences of bamboo joints used in the three categories of bamboo constructions. In traditional or vernacular bamboo construction most of the connectors are made of natural material. Lashing joint with natural fiber such as bamboo, bast, rattan, coco-palm, is utilized very often with or without dowel made of bamboo or timber. On one hand, some joints are made with high skill craftsmanship, and on the other hand they can be made very easy even by an unskilled worker. Some joints can be considered as 'original bamboo joint' because the uniqueness of the joint cannot be replicated even adapted to any other material. They are made with high considerations to the specific characteristics of the bamboo, such as the hollowness of the pole and the high flexibility of the fiber.

In modernized conventional bamboo construction, the joints are dominated by bolted joint. Some traditional bamboo joints are also used widely. The development of the joint in this category from traditional bamboo construction is relatively not so sophisticated, compared to the development of the structural design.

Since the effectiveness of space structure for wide span building attracts architects and engineers to adapt bamboo construction for this structural system, the development of the joints becomes more crucial. More attention is addressed to provide a suitable joint, which accommodates the requirements of the structural system that have significant differences with the joints in conventional bamboo construction.

The connectors are mapped as the first step of bamboo joints classification, as shown in Figure 4-1. The mapping is based on how or where the connectors are attached to the bamboo, which can be divided into three ways: on the outside, in the inside of the cavity, or perpendicular to the fibers. Despite of the easiness to handle the assembling process, attaching connector on the outside faces the problem connecting to round surface and hard skin of bamboo. Some of the connectors attached on the outside are gusset plate, steel plate, hose-clamp, and rope. Most of these connectors can only be attached to the bamboo with help of other connectors attached perpendicular.

It is very common to employ perpendicular elements for fixing parallel connectors attached on the outside or inserted inside and transferring the force from them to the bamboo by shear and bearing stress. An example is the use of bamboo or wooden pin or dowel to fix the position of the rope in traditional lashing joints. The most popular joining element in modern bamboo construction is the bolt. Bolted joints play a key role in modernized conventional bamboo construction.

Inserting connectors inside is very favorable because bamboo is naturally hollow and it can hide them to have a visually clean joint. They can be for instance a piece of wood, steel tube or another bamboo with smaller diameter. The prevalent well-known element is mortar injection. It can be used to prevent crushing against perpendicular force or to fix a bolt or a steel plate inside the bamboo.

Although there are many existing bamboo joints and it is widely known that the connections play a key role in bamboo constructions, the classification of bamboo joints is out of attention. Although some publications try to differentiate in simplest categories as traditional and modern bamboo joints, there is only one clear classification made by Janssen (2000). He made the classification of bamboo joints in regard to the following criteria:

- A joint between two whole bamboo culms can be made either by contact between the full cross-sections, or by collecting forces from the cross-section to a joining element.
- Collecting the forces may occur from the inside, the cross-section or the outside.
- The joining element can run parallel with the fibers or perpendicular to them.

Based on those criteria, Janssen (2000) classified bamboo joints into 8 Groups:

- Group 1: full cross section
- Group 2: from inside to an element parallel
- Group 3: from inside to an element perpendicular
- Group 4: from cross-section to element parallel
- Group 5: from cross-section to element perpendicular
- Group 6: from outside to element parallel
- Group 7: from outside to element perpendicular
- Group 8: for split bamboo.

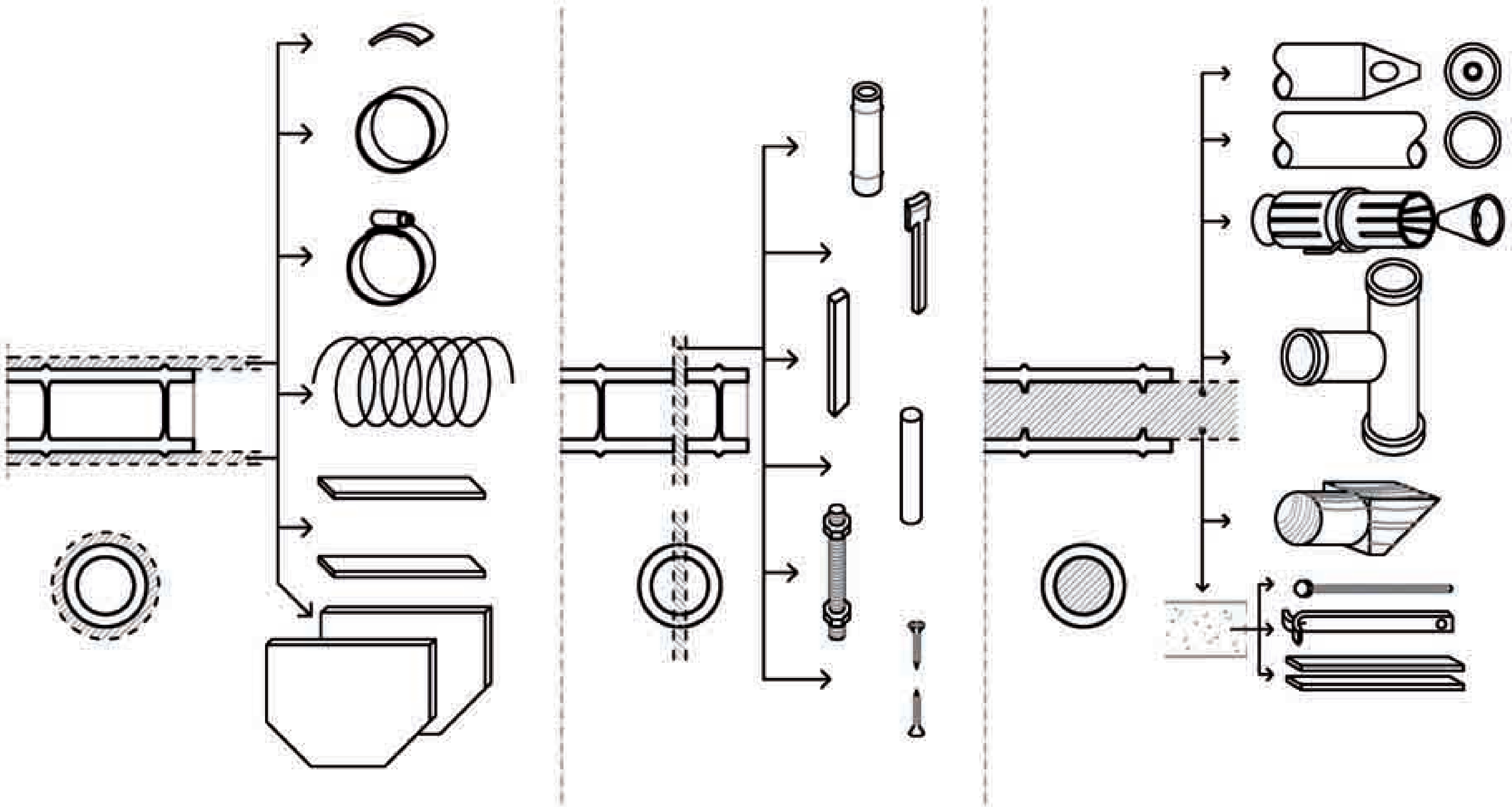
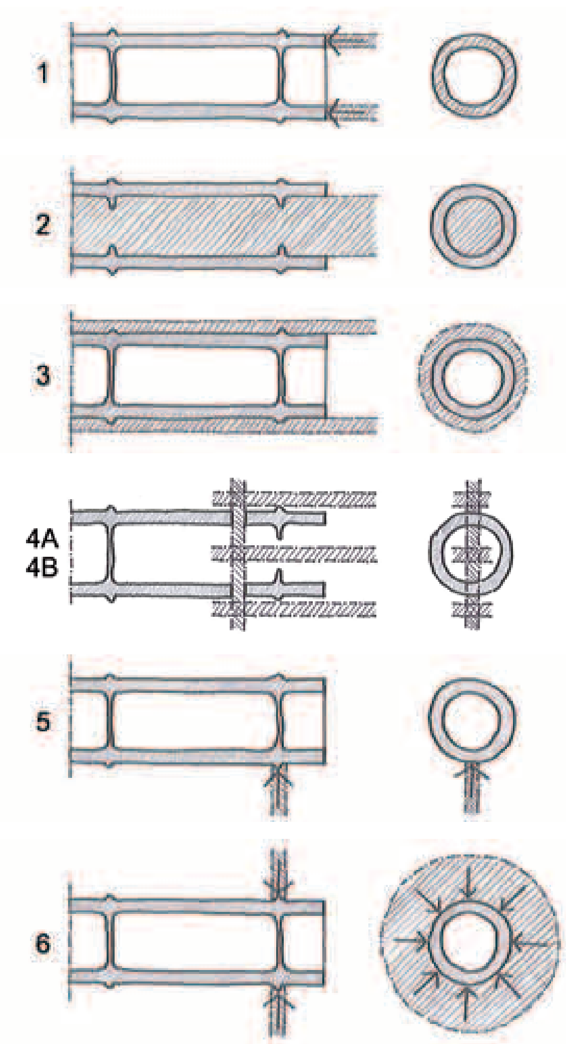


Figure 4-1: Connectors mapping, connected on the outside (left), perpendicular to the fibers (middle) and inserted inside (right)

Considering that according to this classification Group 3 and 7 have hardly any practical application and Group 8 is not relevant to the pole construction, an improved classification is proposed. This classification is based on the following principles (Widyowijatnoko & Trautz, 2011):

- Distinction of the ways of force transfer: compression along the fibers or perpendicular to the fibers; tension; friction on inner surface or on the outside; shear; or bearing stress
- Distinction of the position of the connector: attached in the inside or on the outside of the poles, and attached parallel or perpendicular to the fibers
- A type of connection is considered as a connection between one bamboo and its connector or supporting base. For example, a joint between two bamboos can consist of one or two types of joint. It is different with the classification by Janssen, which mostly define a joint as connection between two bamboos.



Group 1 – Transferring compression through contact to the whole section

Group 2 – Transferring force through friction on the inner surface or compression to the diaphragm

Group 3 – Transferring force through friction on the outer surface

Group 4 – Transferring force through bearing stress and shear to the bamboo wall from perpendicular element connected from inside (4A) or outside (4B)

Group 5 – Transferring force perpendicular to the fibers

Group 6 – Transferring radial compression to the center of the pole through shear and circumferential stress perpendicular to the fibers

Figure 4-2: Main categories of bamboo joints classification

According to the principles above, bamboo connections can be divided into 6 main groups as shown in Figure 4-2. Most bamboo joints use a combination of these basic principles, and mostly use Group 1 to transfer compression and Group 2, 3 or 4 to transfer tension. In the following sub-chapter, the main categories will be described, followed by the joints with the combination of those principles.

4.1 Group 1: Transferring compression through contact to the whole section

This group belongs to the connections, which transfer compression through contact to the whole section of bamboo pole along the fibers. In this group, only compression is taken into account, because practically there is not any glue, which can be used on the surface of the cross section of bamboo in order to hold the bamboo against tension. However, glue cannot be used for tensile loads, because the joints with glue will fail without any indications of overload.

Figure 4-3: Simplest joint of the bamboo column on a stone

Figure 4-4: Fish-mouth joint, bamboo at the right side belongs to Group 1, but at the left side belongs to Group 5

Most bamboo columns use this principle, because of its workability and strength. It is the strongest connection against compression. Sometimes, half part of a steel anchor is planted to the foundation, and another part is placed inside the cavity of the bamboo. Occasionally, a mortar injection is used to stabilize the position of the bamboo horizontally, because it fills the gap between the anchor and bamboo wall. In Figure 4-3, the columns are placed on a natural stone after a hole is made through the stones to put a steel rebar. This steel rebar acts as an anchor to fix the position of the column.

Fish-mouth or butt or saddle joint in Figure 4-4 connects two bamboos in a perpendicular direction or a certain angle. This is a T-joint, which one bamboo has to be round carved to fit with round shape of bamboo, which resembles a fish mouth. Principally, this bamboo transfers the weight of another bamboo to its whole section and is classified in this group, while the other is part of Group 5. Typical examples of T-joint are roof eaves beams or floor beams on posts. There are many variations of these joints as shown in Figure 3-2 and Figure 3-3 to improve their capability to transfer force or to fix the position of the beam on the saddle, but the simplest form belongs to this group.

Considered as the strongest and the most effective joint to transfer compression, this principle is employed in most of the combinations of bamboo joints.

4.2 Group 2: Transferring force through friction on the inner surface or compression to the diaphragm

Bamboo is naturally hollow, although some species have an almost solid wall. This characteristic is highly utilized mostly in the substitutive bamboo constructions to put the connector inside, and leave a steel or timber connector in the end of the bamboo pole. As a result, it can be connected to other steel or timber connectors by means of common connection systems in steel or timber construction. Only few joints use plastic as connector.

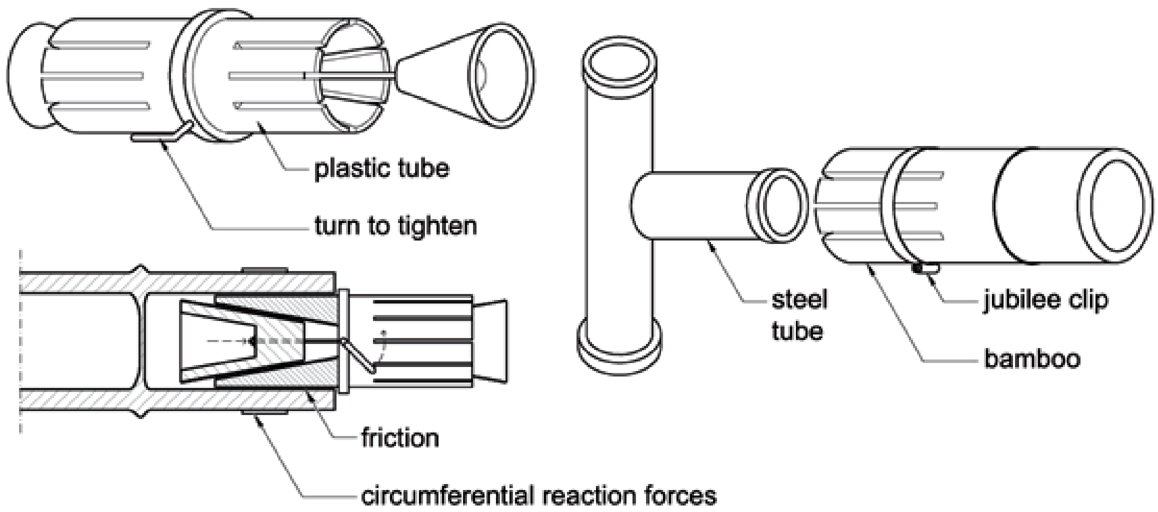


Figure 4-5: Expandable joint (left) and steel tube joint (right) proposed by Nienhuys (after Nienhuys, 1976)