Structural use of bamboo. Part 1: Introduction to bamboo

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Technical Note Series: Structural Use of Bamboo

Technical Note 1: Introduction to Bamboo

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Synopsis

Bamboo is a strong, fast growing and very sustainable material, having been used structurally for thousands of years in many parts of the world. In modern times it has the potential to be an aesthetically-pleasing and low-cost alternative to more conventional materials such as timber, as demonstrated by some visually impressive recent structures.

This Technical Note Series brings together current knowledge and best practice on the structural use of bamboo, covering:

1. Introduction to bamboo
2. Durability and preservation
3. Design values
4. Element design equations
5. Connections

The series is aimed at both developed and developing world contexts. This first Technical Note 1 provides an introduction to bamboo and the physical characteristics that are relevant to structural design. Basic properties along with a selection of suitable structural species are presented, and fire resistance and specification of bamboo are discussed, along with other considerations as to whether bamboo is suitable for a particular project.

Introduction

Bamboo is widely used across the world for everything from food and medicine to furniture and scaffolding. It tends to grow in a “belt” running through tropical, subtropical and temperate climates around the globe, and up to 3500m altitude. There are more than 1000 species of bamboo in total, broken into two “tribes”: herbaceous and woody. The former tend to be very small-diameter and resemble grasses, while the latter are the more familiar large diameter ones that can be used for construction and will be the focus of this Technical Note Series. Woody bamboos can be broadly divided into two groups: clumping and running[1,2]. Clumping species sprout their new shoots close to the base of the existing culm, while running species may send their shoots as far out as 30m from an existing culm. Woody bamboo diameters vary from 10mm to 200mm, wall thicknesses from <10% of the external diameter to completely solid, and culm heights can exceed 30m[3].

Bamboo is a form of grass and can grow up to 25m in six months[2]. Each culm emerges from the ground at its final diameter (i.e. its girth does not expand during its life), tapering as it increases in height, and growing vertically through cell-division “telescopically” between the nodes (i.e., the distance between nodes increases as it grows). Once fully grown, culms typically take three to five years to mature to full strength, during which they experience silification and lignification. After a period of five to six years, the culm’s strength begins to deteriorate.

Worldwide there are around 100 so-called “woody” species suitable for construction. Clumps (a group of culms growing together) of the larger woody species normally reach peak production after about seven years and can maintain regular cropping of around 20-25% throughout their productive lifecycle. Figure 1 shows a bamboo plantation in Ecuador.

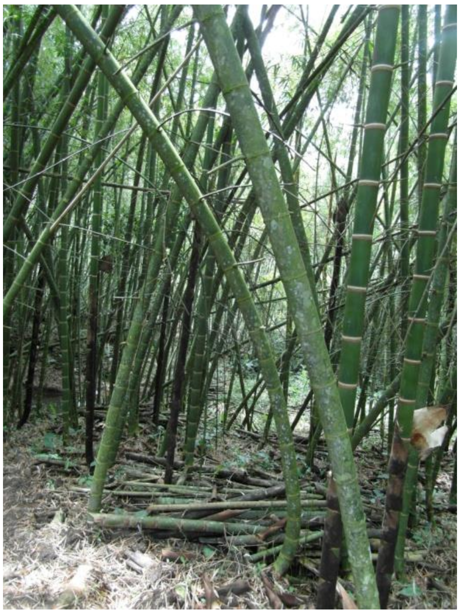

Figure 1: *Dendrocalamus asper* plantation in Ecuador[5]

The stem, or culm, is segmented by nodes, the bands at regular intervals. The node manifests as a diaphragm to the interior of the culm which helps to prevent buckling of the walls. The space between nodes is known as the internode (Figure 2); the internodal spacing varies along the culm and between species. Within the internodes, cellulose fibres and vascular bundles run parallel to the length of the culm[4], while at the nodes they intersect, with some of them crossing into the nodal diaphragm[2]. For natural efficiency, these fibres are roughly six times more numerous on the outside of the culm compared to the inside (Figure 3) making it both denser and stronger towards the outside[3]. As in timber, a weak matrix called parenchyma (which is primarily made of lignin) holds these strong fibres transversely together[4], and it is this material which normally governs the strength of a bamboo culm, especially in tension perpendicular to the fibres and in shear. Providing a protective shell around the cellulose is a tough silica layer about 0.25mm thick, which is relatively impermeable[3]. The dry density of bamboo is typically about 500-800kg/m^3, although this can vary both along the length of the culm and as noted through the thickness of the wall.

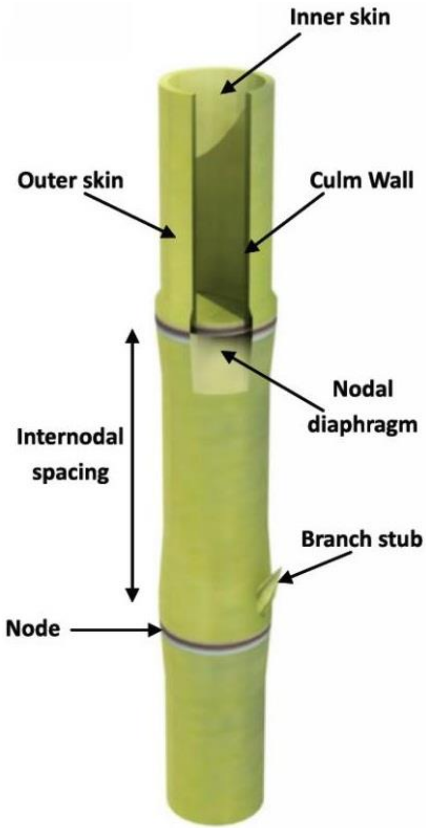

Figure 2: Structure of a bamboo culm

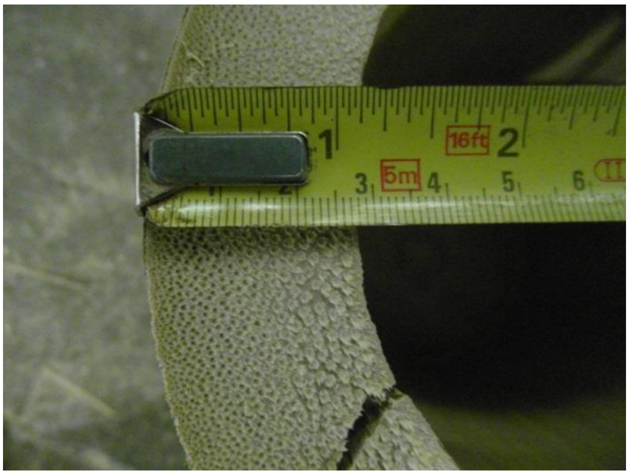
Figure 3: Section through the culm wall showing variation in fibre density[5]

Amongst non-engineers, it is a common misconception that bamboo is "as strong as steel" (see Technical Note 3). In fact, some of the stronger bamboo species possess strength properties similar to high grade (e.g. D40) hardwood, except in tension perpendicular to fibre where it is weaker. Bamboo generally has very good parallel-to-fibre structural properties, with allowable stresses in bending, tension and compression all around 15N/mm^2 for one of the main species of bamboo used structurally called *Guadua angustifolia Kunth*[2], and a wider range of between 10-20 for most species of bamboo[6]. Allowable shear stresses are relatively low at around 1.2N/mm^2, which is further accentuated by bamboo's tendency to split[7] due to the weak parenchyma matrix and the typically thin section walls – suggested characteristic tensile strengths perpendicular to the fibre are as low as 0.46N/mm^2 [8]. Because of these properties and the hollow nature of bamboo, joints are normally the most difficult aspect to design and also likely to be the weakest elements in the structure.

Beams should generally be limited to lightly loaded roofs and floors, heavily loaded beams should be avoided, as the hollow cross-section risks crushing or shear failure at the supports. It is therefore most efficient to use bamboo structural members mainly in axial tension or compression, however, for tension members connections will be the weakest link. Figures 4-8 show a few examples of buildings where bamboo is the primary structural material.

Starch content varies between different bamboos, making some more susceptible than others to insect attack[9]; however, bamboo still has less natural durability than most woods, owing to a shortage of some naturally occurring chemicals present in wood that enhance durability[3]. In addition, the hollow nature of bamboo means that any insect or fungal damage that does occur is likely to reduce the total section by a larger proportion than when compared to a solid section of timber. Therefore, permanent structures should always be chemically treated.

Suitable Structural Species

The bamboo species that have traditionally been used for construction tend to have the following characteristics:

- grow locally in abundance
- stronger than other local species
- large diameter (50mm–200mm)
- grow relatively straight.
- mature quickly (three to five years)
- slightly more resistant to insects and fungi (lower starch content).
- less susceptible to splitting

Table 1 presents a list of some commonly used structural species around the world.

Table 1. List of commonly used structural bamboo species around the world[9,10,11].

Scientific name (local name)	Areas found	Diameter (mm)	Solid/hollow
Guadua angustifolia Kunth	South America	120–160	Hollow
Dendrocalamus strictus (Calcutta)	Asia	25–80	Hollow
Bambusa vulgaris	Africa, Asia, South America	80–150	Hollow
Phyllostachys edulis (Moso)	Asia	120–180	Hollow
Dendrocalamus asper (Petung)	Asia, South America	80–200	Hollow
Bambusa blumeana (Spiny/Thorny Bamboo)	Asia, Asia-Pacific	60-150	Hollow
Gigantochloa apus	Asia	40–100	Hollow

Basic Properties

Basic properties of bamboos used structurally are as follows[2,3,9,12,13]:

- dry density: 500kg/m^3–800kg/m^3
- culm heights: 6m–25m
- nodal spacing 250mm–500mm
- diameters 50mm–200mm
- elastic modulus E ~7000N/mm^2–17 000N/mm^2
- wall thickness = 10% external diameter.

Some typical design capacities of various bamboo diameters are provided in Table 2, based on the strengths and design equations proposed in the forthcoming papers. Its variability and the lack of proper grading methods mean that testing of members and connections will always be needed for all but the most modest structures.

Table 2. Typical indicative design capacities of different bamboo culm diameters in different failure modes based on a limit state approach using Technical Note 3 and 4, for Service Class 2 and Permanent loading.

Failure mechanism	**50mm ∅, 5mm wall thickness**	**100mm ∅, 10mm wall thickness**	**150mm ∅, 15mm wall thickness**
Flexure (kNm)	0.1	0.7	2.4
Shear (kN)	0.3	1.0	2.4
Axial (kN)	10	45	100

Fire considerations

Bamboo behaves in a similar way to timber in fire in that it chars at a slow and predictable rate and is also a poor conductor of heat, so that the bamboo behind the charred layer remains virtually undamaged. Though limited fire tests have been conducted[14], it is possible to assume charring rates similar to those for timber (e.g. 0.6mm/minute), and because the culm walls are so thin it is possible to conclude that after burning for only a few minutes the thin walls will start to lose strength rapidly. . This implies that a visually exposed bamboo structure would only be suitable for situations where there is no fire resistance requirement such as roofs and possibly the walls of single-storey buildings. It has occasionally been used for two-storey dwellings[15] but only in locations where fire regulations are not rigorously applied or where the bamboo is adequately protected by e.g. cement render.

Behaviour in earthquakes

It is a common misconception that bamboo as a material is somehow ‘miraculously’ good in earthquakes. In fact as an individual element it possess several brittle failure modes which could affect its seismic performance. Bamboo buildings have historically performed well in earthquakes primarily because of their lightweight nature (high strength-to-weight ratio), and secondarily because of their ability to absorb energy at connections, especially if using nails. This has been seen after earthquakes in vernacular buildings such as *bahareque*[15], which normally uses nailed connections. The flexible nature of some traditional bamboo constructions may also be favourable in earthquakes, but this is not a characteristic that can be easily exploited in modern constructions which tend to be heavier, have smaller movement tolerances and require a greater certainty of resistance to earthquakes than traditional buildings.

Modern bamboo structures generally require higher strength bolted connections with mortar, which are unfortunately relatively brittle. However, where good practice seismic design principles are applied in conjunction with more locally ductile connections such as nails, greater earthquake resistance and overall building ductility can be achieved[16].

Specification of bamboo

When specifying bamboo, it is important to ensure that it comes from a sustainable source and is harvested, procured and visually graded by a reputable and experienced organisation (note current visual grading is very limited in detail, mostly comes from experience, and has not yet been correlated with strength data). The following criteria should be included in a specification:

- exact species and origin (eg *guadua* is the name for many different sub-species, each with different properties, so, for example, *Guadua angustifolia Kunth* should be stated)
- acceptable age range (note that this is difficult to control for, and requires using reputable and trustworthy suppliers)
- culm length, minimum external diameter and minimum wall thickness
- taper
- straightness (1% out-of-straightness limit recommended)
- splitting (no splitting is acceptable) (this should be checked after the material has been dried)
- no insect and fungal damage
- treatment, fumigation and seasoning.
- moisture content (recommend it is delivered dry).

Culms which are split should not be used as they are significantly weaker (in shear, bending, axial and at the connections).

Considerations for whether bamboo is suitable for a project

Bamboo used in the round is a strong, lightweight, fast-growing material which also has a very low embodied energy[17]. The following questions will help decide if bamboo, used in the round, is a suitable material for a particular project:

- Does bamboo satisfy the architectural aesthetic?
- Will the bamboo be exposed to the rain or other sources of water?
- Is a suitable size and species of bamboo available locally?
- How demanding are the loads on the members and connections?

The next paper in this Technical Note Series will cover durability and preservation methods of bamboo, which is an essential consideration when designing with this material.

Figure 4: Prototype of ZERI bamboo pavilion used in the EXPO 2000 in Hannover, Colombia, by Simon Velez. Bamboo is Guadua[5]

Figure 5 and 6: Jenny Garzon Bridge, Colombia, by Simon Velez. Bamboo is guadua[5]

Figures 7 and 8: Low-cost bamboo housing in Costa Rica, part of the National Bamboo Project[5]

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