Bamboo material characterisation

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Bamboo material characterisation 13

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13.1 Introduction

According to the Food and Agriculture Organisation of the United Nations (FAO, 2007), it is estimated that over one billion people worldwide live in traditional bamboo housing, and 2.5 billion people depend economically on bamboo. It has also been demonstrated that bamboo is a more sustainable material than steel, concrete and timber (Van Der Lugt et al., 2003) even when imported into Western Europe. Murphy et al. (2004) state that housing made with bamboo is both less expensive and more sustainable than reinforced masonry alternatives. As this chapter will demonstrate, some of bamboo's mechanical properties are remarkable. Yet engineers throughout the world very rarely consider using this structural material. This chapter aims to briefly explain some of the characteristics of bamboo, with the hope of contributing to its wider adoption. The chapter will start by explaining what bamboo is, and then it will present some of the efforts that have been made to characterise bamboo as a structural material. It will then move onto explaining the tests that are currently used to determine its physical and mechanical properties, and thereafter it will explain some of the current procedures used to establish design values from test data. The chapter concludes by listing a series of tasks that bamboo researchers should consider when working in future characterisation of bamboo.

Although characterisation can have a broad range of meanings in material science, in the context of this chapter, characterisation is assumed to refer to the process of studying geometric, physical, mechanical and elastic properties of bamboo at a macroscopic level, and mainly with the view of adopting it for structural applications. Examples from a range of authors' work are used to make observations about general trends in bamboo characterisation.

13.2 Bamboo as a plant

Bamboo is a giant grass (Liese, 1998), native to all continents except Europe and Antarctica. There are in excess of 1250 species worldwide, although fewer than 100 species have potential for structural use. The term bamboo as used throughout this chapter is a generalisation for those species having structural use with which the

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authors are familiar. These include the following: *Guadua angustifolia* Kunth; (the most valuable commercial species in South America), *Dendrocalamus asper*, *Phyllostachys edulis* (Moso; the most valuable commercial species in China) and *Bambusa blumeana*.

Bamboos, unlike trees, only exhibit primary growth and not secondary growth (Liese, 1998); this means they emerge from the ground having the diameter they will have throughout their life and will only grow vertically, not broaden, over the years. The culm, or aerial part, is hollow (though there are a few solid species), tapered and segmented. The anatomy of the culm can be divided into nodes and internodes. The internodes are fundamentally hollow tubes, with axially oriented cells. To the interior of the node a diaphragm is formed, and from the exterior the culm-sheath and branches form, as seen in Fig. 13.1.

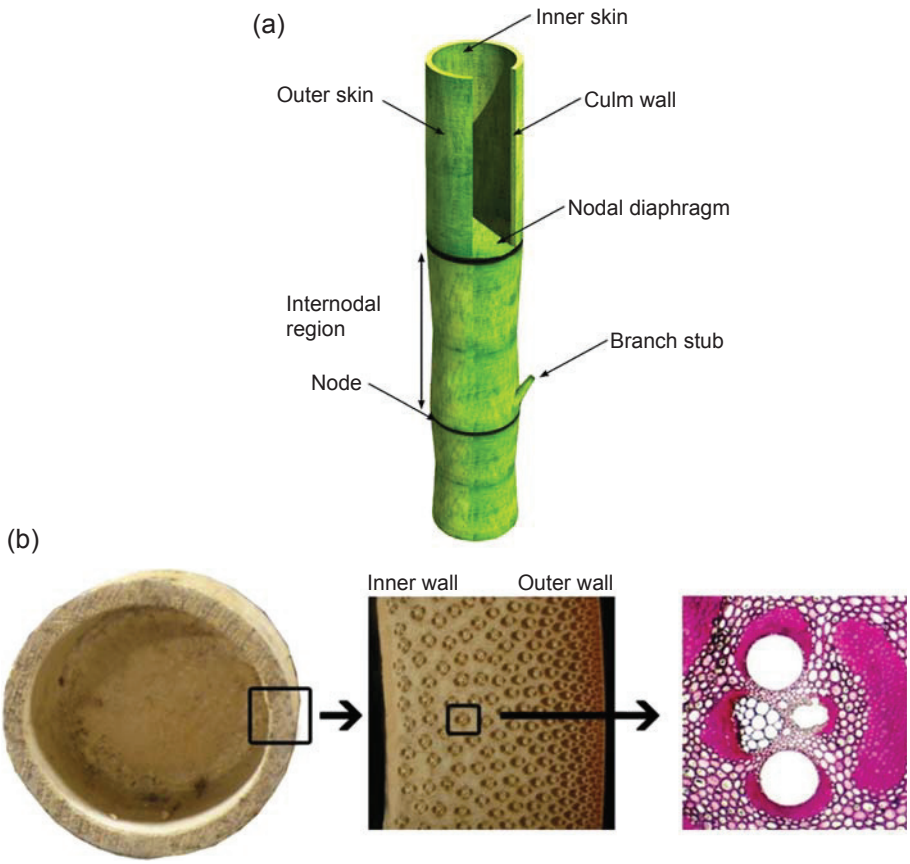

Figure 13.1 Anatomy of a bamboo culm: (a) schematic view of a culm segment, © Sebastian Kaminski, David Trujillo and Andrew Lawrence, (b) section of culm wall showing grading of vascular bundles (Gottron et al., 2014).

The wall of the culm is composed of a hard, shiny outer skin layer (the epidermis); a soft, light-coloured matrix material (the parenchyma) and the stronger and darker vascular bundles. The vascular bundles in turn are composed of metaxylem vessels, phloem and fibre sheaths (Liese, 1998) and impart the strength of the culm as fibres in a fibre-reinforced matrix. Vascular bundles are smaller and more numerous towards the exterior of the culm and larger and fewer towards the interior. As the culm tapers towards the top, the walls of the internode reduce in thickness, the number of vascular bundles decreases, but their density increases (Liese, 1998). In this manner, bamboo, a functionally graded material, has evolved to resist its primary loading in nature: its own self-weight and the lateral loading effects of wind. Typically the culm is constituted of approximately 52% parenchyma, 40% fibres and 8% vessels. A typical chemical constitution for bamboo would be 45% cellulose, 21% lignin, 32% soluble matters, 2% ash and less than 1% nitrogen (Amada et al., 1996).

Bamboo grows as a system of roots (technically, rhizomes) that produce culms. Regular extraction of some of the mature culms does not affect the health of the overall root network. Culms can reach full height (up to 20 m) in as little as 3 months. For some species, this is a rate of growth of 1 m a day (Kuehl and Yiping, 2012). However, culms will require a period of maturation before they have optimal strength for structural applications. This period ranges from 3 to 6 years. Their fast rate of growth signifies that they potentially can act as very effective carbon sinks, especially if regular, selective extraction is used (Kuehl and Yiping, 2012). If the extracted culms are used for durable products, such as housing, bamboo can act as a very sustainable and environmentally friendly material, sequestering on the order of 5 tonnes of carbon per hectare per year (Chinese Moso reported by Song et al., 2011).

13.3 Material properties of bamboos

Although bamboo has been used for millennia throughout the world for structural purposes, research into the determination of its structural properties is fairly recent and sparse. Although engineers identified the need to research the mechanical properties of bamboo from the late 19th century, for example Azuola-Guerra (1887), the oldest known published paper on mechanical properties of bamboo is Meyer and Ekelund (1923). Since then, numerous authors have contributed to the body of knowledge, many of which were compiled by Janssen (1991). In the last 20 years a vast contribution to the body of knowledge has been made, and yet, work into characterisation of bamboo species still needs to be furthered greatly. The following sections identify trends observed by diverse authors, which can be helpful in the process of characterisation of a bamboo species. They do not intend to be an exhaustive literature review or a summary of the state of the art.

13.3.1 Effect of density on mechanical properties

In a similar manner to other materials, in particular timber, the strength of bamboo correlates well with its density. This correlation has been observed to be linear and

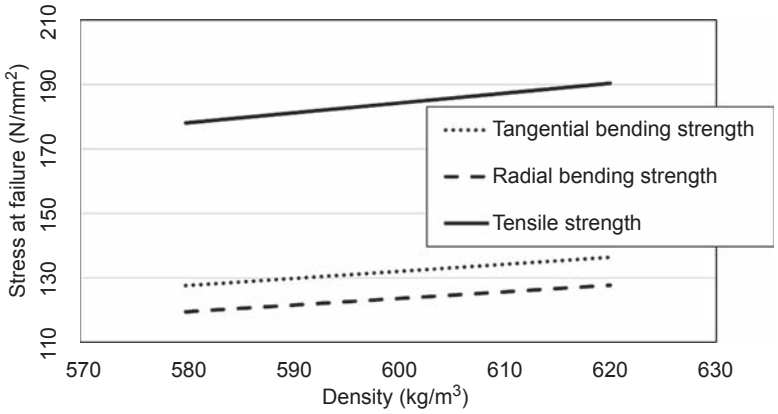

Figure 13.2 Relationship between density and ultimate stress (Zhou, 1981). Bending tests were carried out using strips cut tangentially or radially. Tensile tests were parallel to the fibres.

has been acknowledged for some time, for example, Ota (1950), Sekhar et al. (1962) and Zhou (1981) (see Figs. 13.2 and 13.3). Density values correlate well with compressive, bending and tensile strength; this is likely to be because denser samples have a higher content of cellulose. Janssen (1981) quotes Meyer and Ekelund (1923) by observing that shear strength also correlates to density, the explanation for this being related to the thickness of cell walls. However, observing other authors' results (eg, Abdul Latif et al., 1990), a clear correlation between density and shear strength is not discernible.

13.3.2 Variation of density and other properties in the culm

It has been observed that density increases from the bottom of the culm towards the top (eg, Zhou (1981), Fig. 13.4), and that density increases from the inside towards the outside of the culm wall at the internode (eg, Ota, 1950). Similarly the ratio of fibre

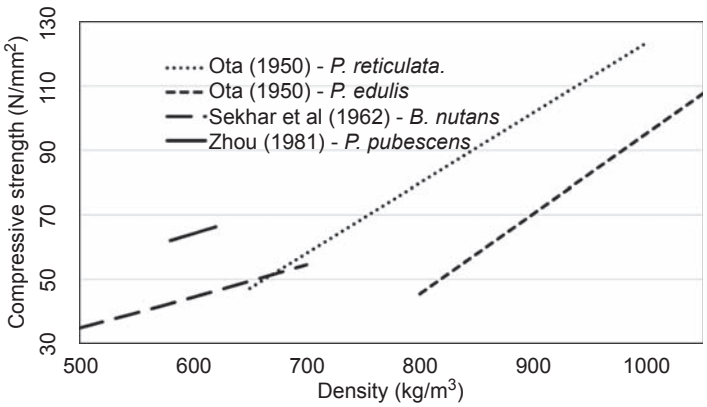

Figure 13.3 Relationship between compressive strength and density, several authors.

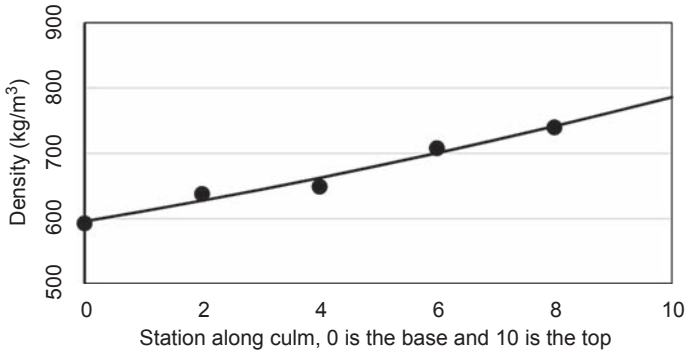

Figure 13.4 Variation of density along the culm, Zhou (1981).

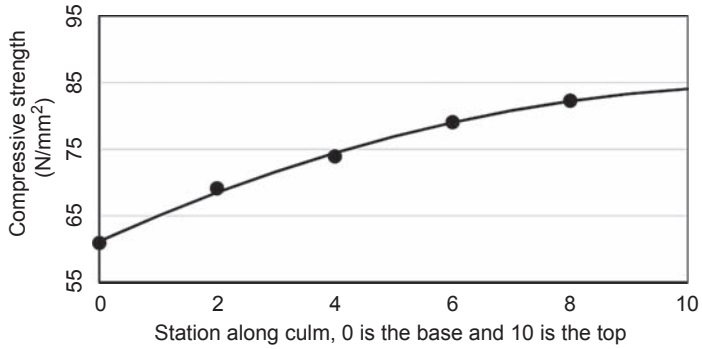

Figure 13.5 Variation of compressive strength along the culm, Zhou (1981).

to matrix material increases from the inside to the outside of the wall, and from the bottom of the culm to the top (eg, Amada et al., 1996). The increase in density from the bottom to the top of the culm is accompanied by an increase in compressive strength, as shown in Fig. 13.5 (eg, Ota (1950), Zhou (1981), Abdul Latif et al. (1990)) and an increase in tensile strength (eg, Amada et al., 1996). Zhou (1981) observed that the moisture content at harvest reduced from the bottom towards the top of the culm (Fig. 13.6); this trend was also observed by Abdul Latif et al. (1990).

13.3.3 *Effect of age on other properties*

Many properties of bamboo have been observed to be affected by the age of the culm at harvesting; these include density (eg, Fig. 13.7), moisture content at harvest (Fig. 13.8), strength (Fig. 13.9) and modulus of elasticity. Zhou (1981) and Lu et al. (1985) observed that many of these properties would peak at a particular age and then decrease again if the culms are not harvested. The optimal age for harvesting varies among species and location of the plantation. Correal and Arbeláez (2010) found a significant correlation between age and density, and age and compressive

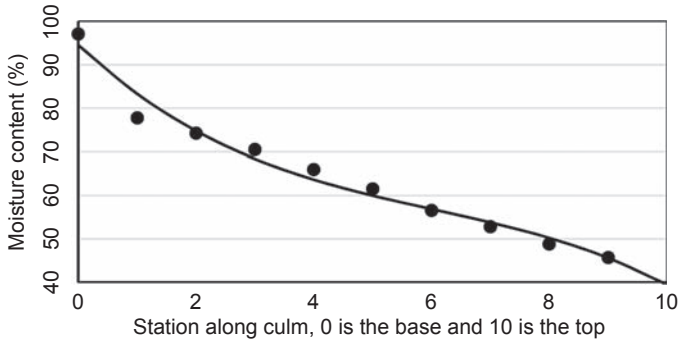

Figure 13.6 Variation of moisture content along the culm, Zhou (1981).

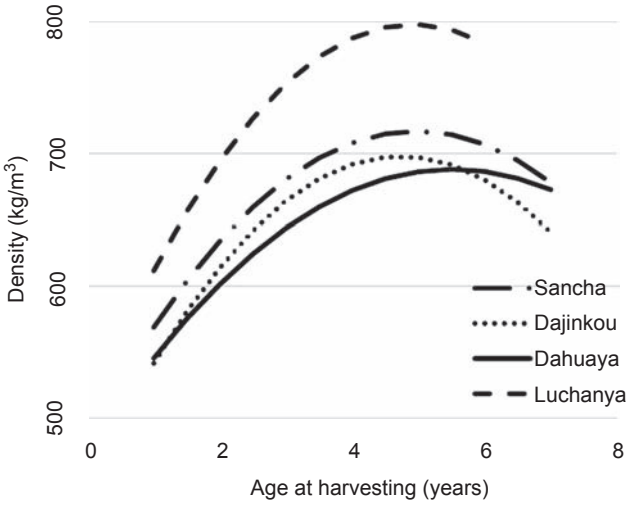

Figure 13.7 Effect of age at harvesting on density for *Phyllostachys glauca* from four different regions of Shandong province, Lu et al. (1985).

strength, but no relationship between shear strength and age or position along the culm. Increase in strength and stiffness has been associated with the thickening of the cell walls of fibre and parenchyma (Liese, 1998) which occurs with age.

Limaye (1952) also observed that the modulus of elasticity varied with age. The age range adopted in this study is quite limited. The variation to the modulus of elasticity is quite significant for green bamboo, but relatively small for dry bamboo in comparison to variations observed for other properties (Fig. 13.10). However, other authors arrive at conflicting conclusions. Low et al. (2006) find that both modulus of elasticity and strength are higher in *Sinocalamus affinis* in young specimens (1 year old) than in mature specimens (5 years old), although this could be explained by the rise and fall of these properties (ie, an optimal age between 1 and 5 years) as seen in Fig. 13.9.

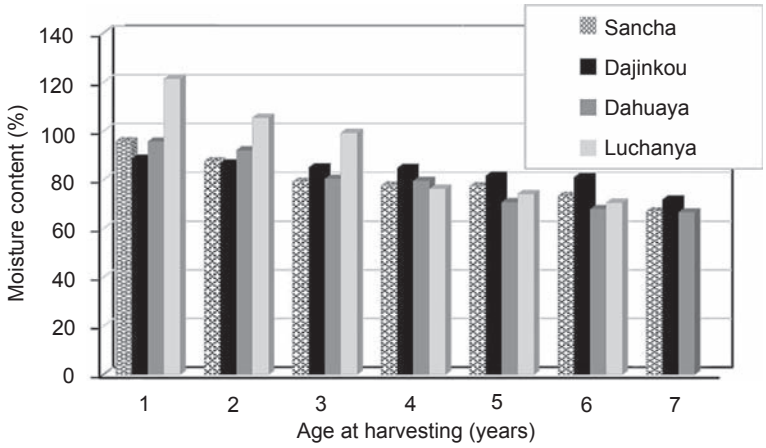

Figure 13.8 Effect of age at harvesting on moisture content for *Phyllostachys glauca* from four different regions of Shangdong province, Lu et al. (1985).

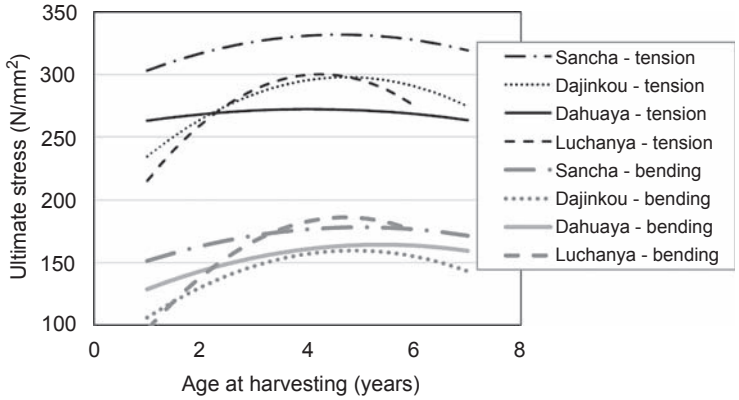

Figure 13.9 Effect of age at harvesting on strength for *Phyllostachys glauca* from four different regions of Shandong province, Lu et al. (1985).

Correal and Arbealáez (2010) found no significant correlation between modulus of elasticity in bending or compression and age for *G. angustifolia*.

13.3.4 Effect of moisture content

In a similar manner as timber, the strength of bamboo is affected by the moisture content of the specimen. Specimens exhibiting a moisture content greater than the fibre saturation point (FSP; the moisture content corresponding to no free water – only bound water – being present in the culm) exhibit fairly stable strengths, and those with moisture contents less than the FSP exhibit an increase in strength inversely proportional to the moisture content (Fig. 13.11). Ota (1953) established that the ratio between oven-dry and water-saturated (FSP) compression strengths is about 2.2. It would

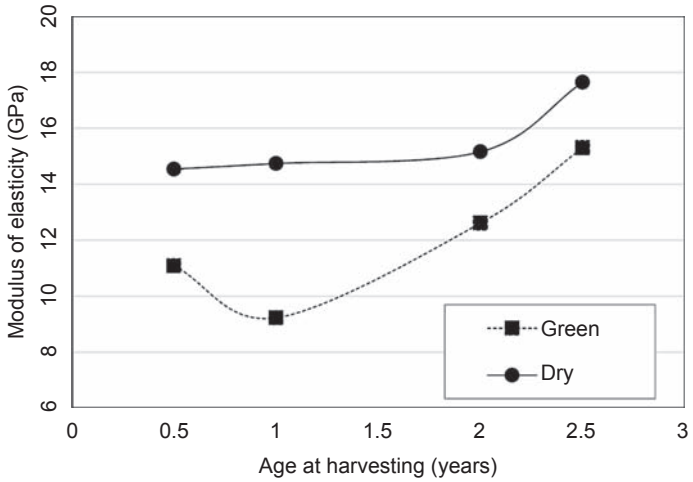

Figure 13.10 Effect of age on modulus of elasticity for *Dendrocalamus strictus* in green and dry condition, Limaye (1952).

seem that a ratio of around 2 is probably valid for shear strengths (Fig. 13.11). The effect of moisture content can be seen in the data presented by Limaye (1952) who tested both dry bamboo (typically at an MC = 12%) and green bamboo (with a moisture content greater than the FSP) (Fig. 13.12).

13.3.5 Dimensional properties of the culm

If bamboo is to be characterised with the aim to use it in its round form, ie, as a pole, its dimensional characteristics should also be considered in the process of

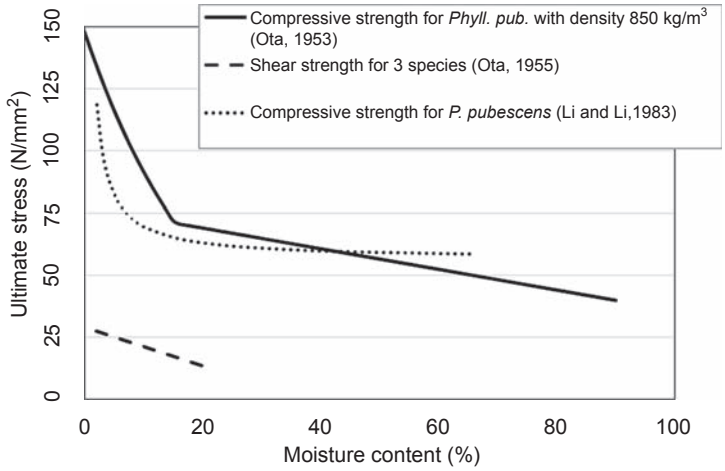

Figure 13.11 Effect of moisture content on strength, several authors.

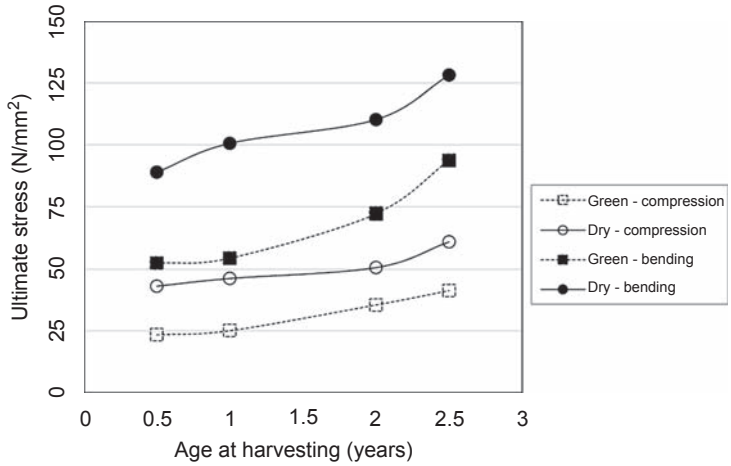

Figure 13.12 Effect of age on strength for *Dendrocalamus strictus* in green and dry condition, Limaye (1952).

characterisation. It is important to establish the typical diameters and wall thicknesses for a given species, although reporting of this data is less common. Length of internodes and taper also vary considerably among species. To this effect, the work of Shigematsu (1958), who studied the form of the culm of 15 different Japanese species, provides an excellent example of what can be achieved (Fig. 13.13). Shigematsu (1958) introduces the 'wall thickness index', which is a percentage of 2 times the wall thickness over the diameter to normalise dimensions. As Fig. 13.13 represents the dimensional characteristics of 15 species, it is possible to assume, in the opinion of the authors of this chapter, that some observations are fairly universal: (1) the length

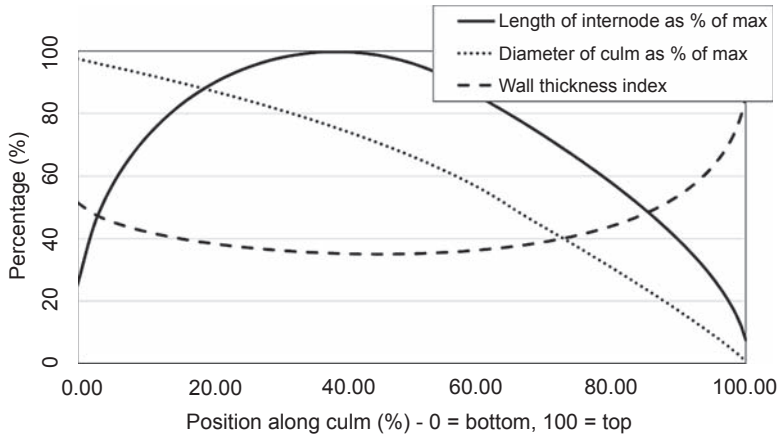

Figure 13.13 Dimensional properties of the culm for 15 Japanese species. Adapted from Shigematsu (1958).

of the internode peaks somewhere between a third and the middle of the culm; (2) the form of the taper of the culm is not linear; and (3) for a given species, a single wall thickness index is likely to be representative for the lower 70% of the culm (the part of most structural interest).

Amada et al. (1996) carried out a similar analysis for the geometric characteristics of *P. edulis*. They observed that diameter and wall thickness decreased along the culm in nearly a linear manner, provided the reference for position along the culm was not stated in units of length, but as node number. They also observed that the elastic section modulus varied along the length of the culm in a proportional manner to the bending moment caused by wind.

13.3.6 Functionally graded material

Amada et al. (1996) concluded that bamboos have evolved to be highly efficient composite materials or 'smart structures'. For example, the reduction in both the diameter and wall thickness along the culm also closely matches the reduction in bending moment along the culm. This results in bamboo having an almost constant maximum surface stress along its length when subjected to wind forces. Another interesting result is the near constant radius of gyration throughout the culm, which ensures the buckling capacity of the culm does not vary significantly over the height of the culm. Similarly, the percentage of area occupied by vascular bundles – a term the authors call volume fraction of the [vascular] bundle sheaths – increases with height to compensate for the loss of stiffness resultant from the loss of diameter and wall thickness. The distribution of the vascular bundles across the wall thickness mirrors the bending stresses caused by wind, ie, the more highly stressed perimeter has a greater concentration of vascular bundle sheaths and therefore fibre.

Though many of the observations made by Amada et al. (1996) were known, the elegance of their analysis was novel at the time. The authors did not attempt to separate strength and stiffness properties from the geometrical characteristics of the section or the location in the culm, this approach of considering both geometric and material properties and their variation along the culm is an important lesson provided by this paper for anyone intending to characterise bamboo.

13.4 Tests for material and physical property determination

As mentioned earlier, research into the physical and mechanical properties of bamboo has a history in excess of 90 years. During this period, different approaches have been used, sometimes with not entirely satisfactory results. Tests depend, to an extent, on the intended end use of the material. Tests carried out on laminated bamboo products (also referred to as engineered bamboo) can, in most instances, adopt timber standards (eg, Correal and López, 2008). Some specific differences do exist between engineered timber and engineered bamboo, but these are beyond

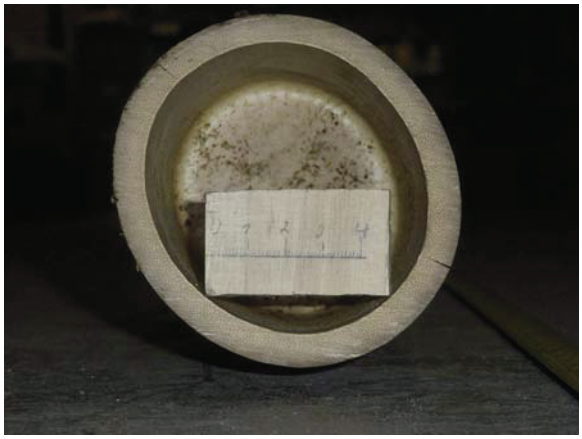

Figure 13.14 Bamboo rarely is absolutely round. *Note also the fissures at the southeast quadrant and northwest quadrant* (scale shown is in cm).

the scope of this chapter. However, when the intention is to understand the properties of pole or round culms, simple adoption of timber testing procedures is not appropriate in most instances. Bamboo is hollow, round (though frequently more oval shaped, refer to Fig. 13.14) and tapered. All tests present some difficulty, and a direct extrapolation from timber, or other construction materials for that matter, is not possible.

For instance, in bending tests for *G. angustifolia*, Gnanaharan et al. (1994) determined that short specimens (using midpoint flexure specimens having a span of 700 mm and a shear span-to-culm diameter ratio of approximately 4.4D) do not provide reliable bending strength values as failure will occur through either shear or crushing prior to bending. A similar conclusion was arrived at, independently, by Sánchez and Prieto (2001). Gnanaharan et al. (1994) also observed that using strips of bamboo in lieu of whole round sections is not a reliable alternative. Their conclusion was that long specimens (in this instance, tested in third-point flexure (ie, four-point bending) over a span of 3000 mm, resulting in shear span-to-culm diameter ratio of approximately 12.5D) should be used. Load was applied by means of wooden saddles similar to the ones in Fig. 13.15(a). A variation to the wooden saddle system was presented by Correal and Arbeláez (2010) using straps; this allows for a more even distribution of loads, avoiding localised crushing, and permits rotation of the individual load point. An adaptation to the strap system was developed at Coventry University (Fig. 13.15(b)). Nugroho and Bahtiar (2013) observe that to obtain accurate values for the modulus of rupture in a four-point bending tests (such as that for ISO 22157-1 (ISO, 2004a)), culm taper should also be considered.

Round bamboo members can present a whole range of failure modes when subject to bending tests, which can affect interpretation of results. ISO 22157-1 (ISO, 2004a) recommends using specimens of a length at least equal to 30 times the diameter in a third-point flexure arrangement. This ratio was determined by Vaessen and

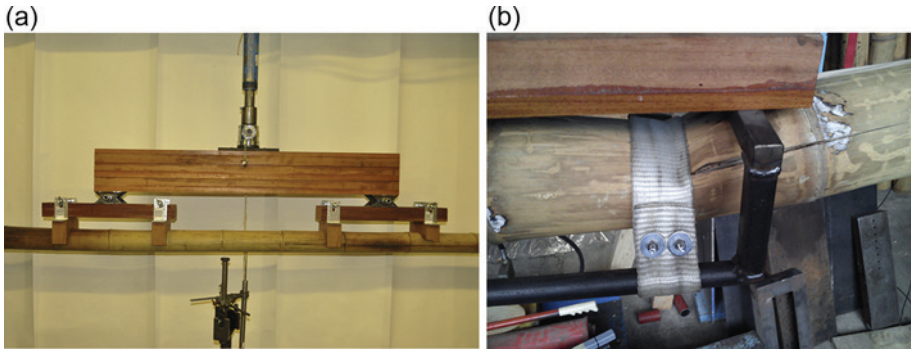

Figure 13.15 (a) Wooden saddle for bending test, (b) straps allow a more even distribution of stress at the supports or points of load application.
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Janssen (1997) to be in fact 26.3, which results in a shear span-to-diameter ratio of 10. If an alternative four-point bending arrangement is used, the shear span-to-diameter must still be observed, and even then, shear failures may still be observed. These occur in one of the shear spans between a point of load application and the nearest support. Failures that occur between the central points of load application are undoubtedly bending failures, but these failures occur in a range of manners, ranging from crushing of fibres in compression to collapse of culm in the compression side of the culm (as seen in Fig. 13.16).

Numerous types of shear tests have been proposed over the years as summarised by Janssen (1981), who proposes the currently widespread 'bow-tie' test method (as presented in Fig. 13.17), which has been incorporated into ISO 22157-1 (ISO, 2004a). This test places a segment of culm into longitudinal compression between two 90 degree quadrant plates (arranged like a bow-tie). The plates are rotated 90 degrees relative to each other at the ends of the specimens, resulting in four longitudinal shear planes along the length of the specimen along which failure occurs. Once again, adoption of timber test methods for round bamboo is not possible. Mitch (2009) suggests that a relationship between tension perpendicular to fibres and shear resistance may be derived, since both values are a function of the matrix material.

Compression parallel to the fibre tests also require consideration, as interaction with the loading platens may occur affecting results, a phenomenon identified by Arce (1993). Essentially, the friction between the culm plates effectively restrains the lateral expansion of the culm at the platen. Janssen (2000) recommends the use of Teflon plates or some other means to minimise friction between the platens and the culm segment. This recommendation has been incorporated in to ISO 22157-1 (ISO, 2004a). Harries et al. (2012) found that using sulphur capping compound (as is done for concrete cylinders) works well and has the additional advantage of ensuring that the culm ends are parallel and uniformly loaded.

Testing the tensile strength of the whole round culm is not easily achieved, and as such is not covered in standards. Instead the tensile strength of strips extracted from the

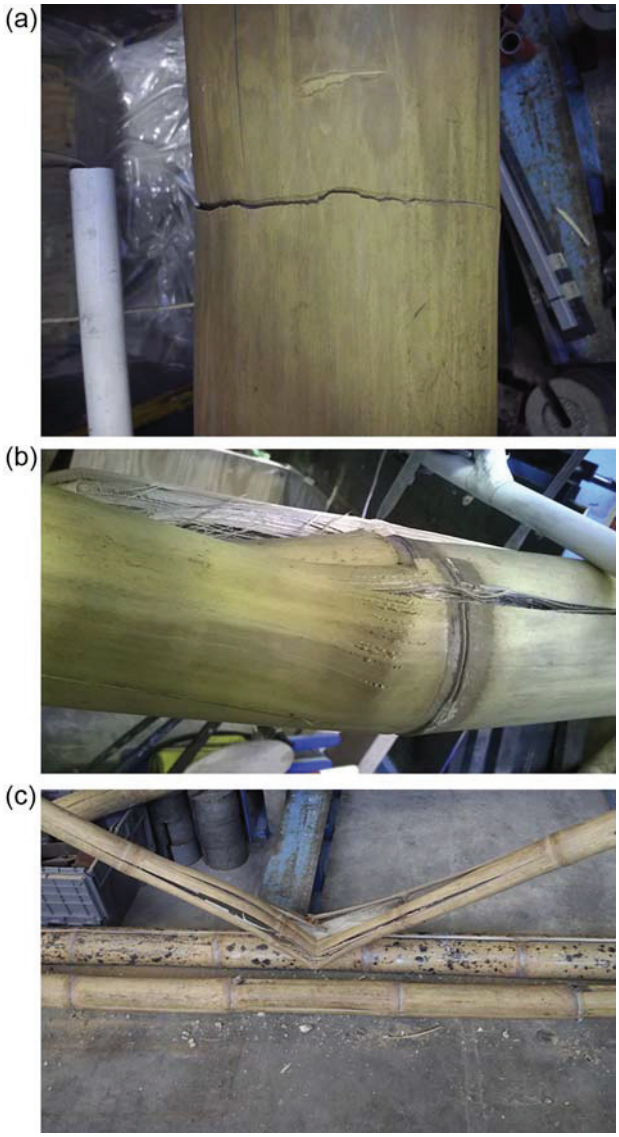

Figure 13.16 Bending failure modes in bamboo: (a) crushing of fibres in compression, (b) collapse and buckling of fibres in compression, and (c) collapse of culm.

culm wall are the conventional way to calculate the strength of bamboo in tension. The strip is tabbed or cut as a 'dog bone' to ensure failure does not occur at the grips (in a manner similar to steel). Richard and Harries (2015) observed a range of failure modes for this test; these involved failure at the clamps, splitting, 'brooming' and pure tensile rupture. Reported tensile strength values for radially oriented *Bambusa stenostachya*

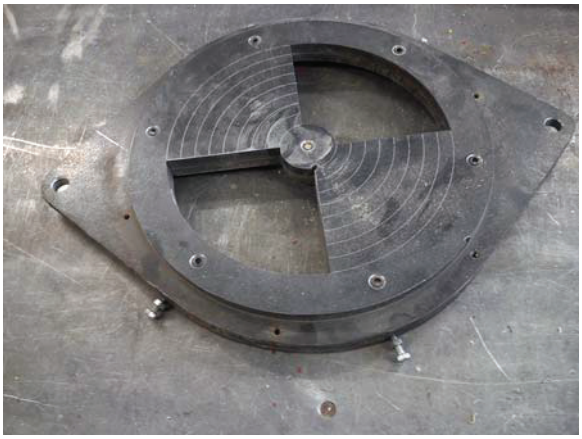

Figure 13.17 Bow-tie-shaped platens used in shear tests for bamboo.
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specimens ranging from 132 N/mm^2 to 141 N/mm^2, dependent on the fixity conditions of the tension grips used. They reported that testing tangentially oriented specimens extracted from near the middle of the culm wall resulted in slightly more uniform characteristic values. Tension tests that include nodal regions exhibit capacities approximately half of those that do not.

A test that is even less common is that for the determination of the tensile strength perpendicular to the fibres. The first reported attempt was by Arce (1993), with fairly unsatisfactory results; yet he rightly identified the importance of this property when he stated *Bamboo culms do not fail in compression, in bending or shear, but do fail when a maximum tangential tensile stress is reached*. A different test procedure was proposed by Castrillón and Malaver (2004) and later used by Pacheco (2006), consisting in pulling a length of internode transversely apart in direct tension. Mitch (2009) critiques this method, pointing out that although it requires a simple calculation, it is impractical, as the two semicircular wedges that are placed inside the culm need to fit exactly inside the section of culm, and as every culm is of a different size and shape, a range of wedges would be needed to achieve a tight fit. If a perfect fit is not achieved, this will result in bending stresses perpendicular to the fibre being exerted with the tensile stresses. Mitch (2009) instead proposed a test procedure using a split pin (Fig. 13.18), which has the benefit of determining both the tensile strength perpendicular to the fibre and the mode I stress intensity factor, K_1. This procedure can accommodate diverse diameters of specimens without major difficulty, although preparation of the test specimen is laborious. This test procedure has the disadvantage of inducing a failure mode more akin with prying than pure tension, although this results in a lower-bound solution that may be appropriate for establishing parameters for design.

Work investigating compression perpendicular to the axis dates back to Atrops (1969), who reported resistance values in units of force and not in terms of stress. Presumably, this was done because the researcher acknowledged the complexity of

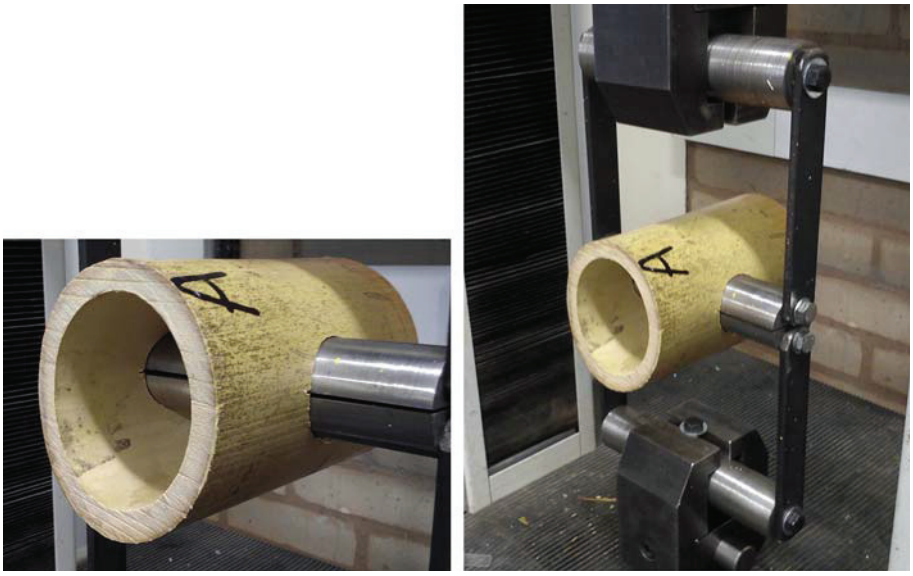

Figure 13.18 Split-pin test as proposed by Mitch (2009).
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the induced stresses, as round bamboo specimens that are loaded perpendicular to their axis crush in a 'three-pinned arch' failure mode that induces flexural stresses (tension and compression) through the culm wall thickness (refer to Trujillo (2007) and Sharma et al. (2013)). Other authors (eg, Lozano (2010)) have mistakenly called this failure mode compression perpendicular to the fibre. Sharma et al. (2013) provide a rigorous analysis of the stresses induced in a more correctly termed 'edge-bearing test' (Fig. 13.19), and they suggest that results would be of value to derive a correlation between tension strength perpendicular to the fibre and bending strength (modulus of rupture) perpendicular to the fibre. This correlation has yet to be established, but it is worthwhile noting that these values vary by an order of magnitude. Mitch (2009)

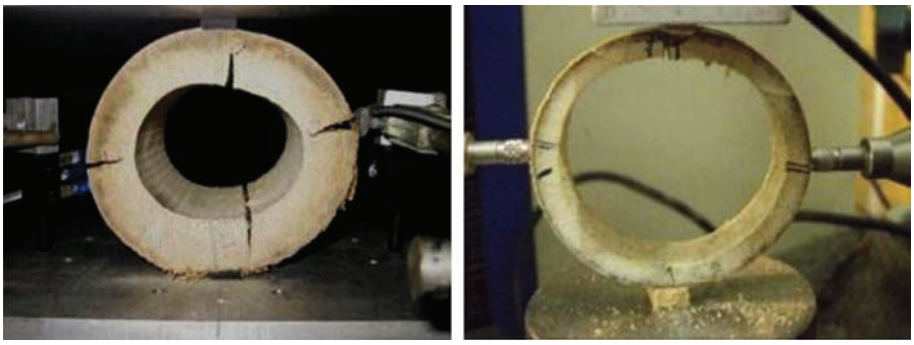

Figure 13.19 Edge-bearing test.
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reported an average ultimate stress in tension perpendicular to the fibres using the split-pin method of 1.0 N/mm^2 for *B. stenostachya*. Whereas, Sharma et al. (2013) obtain values ranging from 3.3 to 5.8 N/mm^2 for bending perpendicular to the fibres (dependent on whether the wall was bending inwards or outwards) for the same species. Due to the nature of the edge-bearing test, the behaviour varies for thin- and thick-walled specimens. A *D/t* ratio of 10 is proposed as the threshold between behaviours (Sharma et al., 2013).

13.4.1 Development of test standards

The first bamboo testing standard in the world was introduced in 1973 by the Bureau of Indian Standards (BIS, 1973) under the name 'IS:6874 – Methods of tests for round bamboos'. From the late 1990s, Dr Jules Janssen, through the International Network for Bamboo and Rattan (INBAR), led an initiative to develop international standards for bamboo. This effort culminated in 2004 with the publication by the International Standards Organisation (ISO) of 'ISO 22157-1: Bamboo – Determination of physical and mechanical properties – Part 1: requirements' (ISO, 2004a), 'ISO 22157-2: Bamboo – Determination of physical and mechanical properties – Part 2: laboratory manual' (ISO, 2004b) and 'ISO 22156: Bamboo – Structural design' (ISO, 2004c). ISO 22157-1 (ISO, 2004a) contains the following test procedures: moisture content, mass by volume (ie, density), shrinkage, compression [parallel to fibres], bending, shear and tension [parallel to fibres]. ISO 22157-2 (ISO, 2004b) explains how to use these standards and provides useful advice for those undertaking experimental work. ISO 22156 (ISO, 2004c) presents, in the form of a model code, a design philosophy for bamboo and some outline guidance for structural design, although it contains little of the practical guidance that would be expected in a design standard. It does, however, contain guidance with regards to the derivation of characteristic and allowable stresses. This particular aspect will be discussed in greater depth later.

ISO 22157-1 (ISO, 2004a) has been widely adopted throughout the world; countries that have either directly adopted or adapted this standard include Colombia, Ecuador, Peru, Jamaica, Ethiopia and India. As such, they have proven invaluable as a basis to ensure that test results between researchers are comparable. They have also created a basis upon which to develop further standardisation. However, these standards are not without fault, as will be discussed hereafter.

ISO 22157-1 (ISO, 2004a) does not include tests to determine tensile strength perpendicular to the fibre. Because, as has been argued, this is such an important property in bamboo, this seems to the authors of this chapter a serious omission. The shear test contained in ISO 22157-1 (ISO, 2004a) has also been critiqued. Mitch (2009) points out that it rarely triggers more than one, and at the most three, shear planes (this is also the experience of the authors), yet ISO 22157-1 (ISO, 2004a) requires the derivation of shear strength to be based on the assumption that four planes will be triggered. This is not necessarily a problem from the design point of view, as assuming four shear planes results in a lower-bound value for shear capacity, but can be unhelpful if the desire is to determine the real shear strength. Deriving the shear strength based on only the shear planes that were triggered, ie, dividing the total force

by the area of the triggered shear planes, is a common error that violates the principles of equilibrium. Mitch (2009) also points out that the requirement that ends of the culm specimen be cut perfectly parallel is very difficult to achieve (particularly in the field). Janssen (1981) also noted that shear strengths obtained through the bow-tie test seem to be larger than those derived from shear failures in bending tests. This calls into question the utility of this test, although it can be explained: the bow-tie test results in pure mode II shear failures. Flexural tests introduce a component of mode I behaviour whose interaction naturally 'weakens' the mode II capacity (Richard, 2013).

As previously discussed, bending tests require further adaptations such as straps to avoid crushing. Richard and Harries (2015) have identified a number of practical issues associated with testing tension parallel to the fibres that can result in inconsistent results (including grip fixity, specimen orientation). Thus, while a good basis, the ISO 22157 documents are presently being considered for revision to account for advances made since they were first approved.

13.4.2 *Case study:* Guadua angustifolia

Guadua angustifolia Kunth is one of the most studied bamboo species in the world. Work investigating this South American species dates back from the 1980s under the tutelage of Oscar Hidalgo López. Most characterisation discussed in this section will relate to the physical and mechanical properties observed, although it is worth noting that many other authors (eg, Londoño et al. (2002)) have characterised other aspects of the anatomy of its culm including its fibre content, cellular structure, etc. Londoño et al. (2002) also report average geometric properties, listed in Table 13.1. Interestingly, these results do not seem to fit into the equations derived by Shigematsu (1958), with the exception of length of internode, which warrants further research for this species.

As mentioned, determination of the mechanical properties of *G. angustifolia* date back to the 1980s. The resulting large database of test results (an example of the then extant database is shown in Fig. 13.20, adapted from López and Trujillo (2002)), alongside the broad spectrum of structural experience (Trujillo, 2007, Trujillo et al., 2013) has built considerable confidence in the properties of *G. angustifolia*, which has resulted in arguably the most comprehensive code for structural use of bamboo in the world: the Colombian Seismic Standard NSR-10 (AIS, 2010).

Table 13.1 Average dimensions for the culms in study, Londoño et al. (2002)

	Average diameter (mm)	Average wall thickness (mm)	Length of internode
Bottom segment (node 0–16)	111.5	18.2	200 (min)
Middle segment (node 16–40)	110.5	13.2	350 (max)
Top segment (node 40–72)	58.4	8.9	Not reported

Table 13.2 **Mechanical properties parallel to the fibres for *Guadua angustifolia* for three distinct regions of Colombia, Lozano (2010)**

	Bending				Compression					Shear					Tension			
Condition	**Green**				**Green**				**Dry[a]**	**Green**				**Dry[a]**	**Green**			
Region	A	B	C	Mean	A	B	C	Mean		A	B	C	Mean		A	B	C	Mean
Sample size (*n*)	61	12	11	84	76	70	74	220		91	75	80	246		61	49	51	161
Mean (N/mm^2)	69.0	65.0	68.8	68.4	33.9	32.3	32.4	32.87	54.8–56.2	5.66	5.52	6.44	5.87	7.10–7.47	61.5	55.5	66.9	61.4
Coefficient of variation (%)	26.0	39.1	48.2	31.1	30.0	27.0	17.6	25.6		24.3	18.9	17.0	21.3		21.7	18.5	22.2	22.3
Moisture content (%)				71				87					98					93

[a]Dry values are quoted by Lozano (2010), but correspond to other researchers.

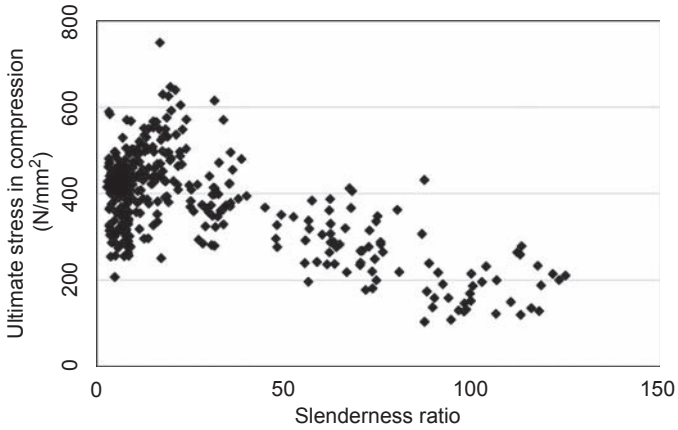

Figure 13.20 Stress at failure versus slenderness for *Guadua angustifolia.* Adapted from López and Trujillo (2002).

One very extensive investigation into the properties of *G. angustifolia* is Lozano (2010). This report compiles data from 246 samples from three distinct regions of Colombia: Quindío, Cundinamarca and Valle del Cauca (Tables 13.2−13.4). Note that results are reported under the generic names of zone A, B and C to avoid generating the perception that a certain region produces better bamboo. The value of this work is that it provides insight into intraspecies variability. It is interesting to note that variation between regions is not remarkably large. Another very valuable investigation into the properties of *G. angustifolia* is that by Correal and Arbeláez (2010), which studied the effect of age at harvesting on several mechanical properties. It is interesting to note that both aforementioned studies tested bamboo in green conditions

Table 13.3 Mechanical properties perpendicular to the fibres for Colombian *Guadua angustifolia*, several authors

	Mechanical properties perpendicular to fibres		
	Bending[a]	**Tension**	**Compression**[b]
Source	Lozano (2010)	Pacheco (2006)	Correal and López (2008)
Condition	Green	Green and dry	Dry
Sample size (*n*)	150		29
Mean (N/mm^2)	6.59	0.73	5.4
Coefficient of variation	43.65%		14.66%
Moisture content	81%		10%

[a]Lozano (2010) calls this failure mode compression perpendicular to fibres.
[b]These values were obtained for laminated bamboo; however, they are quoted here for reference.

Table 13.4 Average elastic properties for *Guadua angustifolia* for three distinct regions of Colombia, Lozano (2010)

	Modulus of elasticity				Modulus of rigidity	Poisson's ratio
	Bending	Compression parallel to fibres	Tension parallel to fibres	Circumferential		
	Green	Green	Green	Green	Green	Green
Sample size (*n*)	86	136	211	142	34	N/A
Mean (N/mm^2)	13,904[a]	9082[a]	6542	564	634	0.35
Coefficient of variation	36.06	63.68	43.70	77	32.45%	19.97%
Moisture content	71%	87%	93%	81%	68%	N/A

[a]Correal and Arbeláez (2010) also use *Guadua angustifolia* in green condition, yet obtain a modulus of elasticity in bending of approximately 17,200 N/mm^2 and in compression of 16,900 N/mm^2.

for their characterisation work to control for effects in variation of strength/stiffness arising with working with bamboo with a moisture content below the FSP.

13.5 Derivation of design values

As mentioned earlier, ISO 22156 (ISO, 2004c) provides a means to derive characteristic values and allowable stresses. Although derivation of design values is arguably beyond the scope of the process of characterisation of a material, this procedure is presented here due to its practical benefit to engineers intending to use bamboo. Clause 7.2.1 of ISO 22156 (ISO, 2004c) proposes the following equation (Eq. [13.1]) corresponding to the fifth percentile value defined with 75% confidence:

$$R_k = R_{0,05}\left(1 - \frac{2,7\frac{s}{m}}{\sqrt{n}}\right) \tag{13.1}$$

where R_k is the characteristic value; $R_{0,05}$ is the fifth percentile from the test data; m is the mean value from the test data; s is the standard deviation of the test data; n is the number of tests (at least 10) (ISO, 2004c)

Clause 7.4 complements it with equation (Eq. [13.2]):

$$\sigma_{\text{all}} = R_k \times G \times \frac{D}{S} \tag{13.2}$$

where σ_{all} is the allowable stress, in N/mm^2; R_k is the characteristic value; G is the modification for the difference between laboratory quality and practice, default value 0.5; D is the modification value for duration of load: 1.0 for permanent load, 1.25 for permanent plus temporary load, 1.5 for the above plus wind-load; S is the factor of safety, default value 2.25 (ISO, 2004c)

This procedure has been adopted and adapted in the Colombian Legislation for Earthquake Resistant Construction − NSR-10 (*Reglamento Colombiano de Construcción Sismo Resistente*), in chapter G.12 − Guadua (bamboo) structures. As the name suggests, this procedure is only appropriate for one species of bamboo: *G. angustifolia* Kunth. Equation (G.12.7-2) of NSR-10 (AIS, 2010) states:

$$F_i = \frac{\text{FC}}{F_s \times \text{FDC}} f_{ki} \tag{13.3}$$

where F_i is the allowable stress; f_{ki} is the characteristic value (derived exactly as R_k in Eq. (13.1)); FC is the modification for the difference between laboratory quality and practice, taken as 0.5 in tension, 0.6 in shear and 1.0 for compression and bending; F_s is the factor of safety, taken as 2.0 for bending and tension, 1.8 for shear and compression perpendicular to the axis and 1.5 for compression parallel to the fibres; and FDC is the modification value for load duration in accordance to the load type: taken as 1.5 for bending and tension, 1.2 for compression and 1.1 for shear. This

Table 13.5 Allowable stress for *Guadua angustifolia* at a moisture content = 12% (AIS, 2010)

Type of stress	Allowable stress value
Bending	15
Tension	18
Compression parallel to fibres	14
Compression perpendicular to axis (assumes internode has been filled with cement mortar)	1.4
Shear	1.2
Moduli of elasticity	
Mean modulus of elasticity, $E_{0.5}$	9500
Modulus of elasticity at 5th percentile, $E_{0.05}$	7500
Minimum modulus of elasticity, E_{min}	4000

differentiation based on load type is a legacy from the timber code, as explained in López and Trujillo (2002). Allowable stresses are modified further to account for load duration (to reduce the overall factor of safety when load duration is short), moisture content, operational temperature, buckling of beams, presence of shear and buckling of columns.

The allowable stress values and moduli of elasticity for *G. angustifolia*, as stated in NSR-10, are presented in tables G.12.7-1 and G.12.7-2 of the standard and are summarised in Table 13.5 (AIS, 2010). The stated modulus of elasticity is surprisingly low, when compared to the results of aforementioned authors with green bamboo. The reason for this low value is that the code writers adopted an 'apparent modulus of elasticity' as observed in whole frames and not individual elements. Their concern was that the state of the art in connection design did not allow for reliable predictions of slippage, so a low modulus of elasticity (about 50% of experimentally observed values in dry conditions) would result in satisfactory designs for frames and trusses. As this point is not caveated in the code, designers will tend to overdesign simply supported members such as beams. According to the code, three values of modulus of elasticity are provided $E_{0.5}$, to be used for general structural analysis of elements, $E_{0.05}$, for stability calculations (ie, buckling) and E_{min}, for safety critical elements. Examples of safety critical members are not provided.

13.6 Further work and future developments

As argued earlier, if the characterisation of bamboo is carried out with the aim of adopting it for structural purposes in its pole, or round form, direct adoption of timber tests is not possible. Similarly, characterisation of bamboo species should not be

limited to the determination of physical and mechanical properties. Since bamboo in pole form has not undergone any transformation other than cutting to length, it will not have a standard diameter, wall thickness, internode length, cross-sectional shape or taper. It is equally important to characterise these geometric properties for a given species, as to characterise the mechanical properties, since they will also affect the resulting strength characteristics of pole bamboo. Future characterisation work should try to arrive at generalisations about these characteristics in a similar manner as was done by Shigematsu (1958) for 15 species of Japanese bamboo.

The process of characterisation of a bamboo species should also take into account the phenomenon of splitting. Do all species exhibit the same sort of behaviour? It is important to note that if a single split occurs in a member subject to bending, and it were in the proximity of the neutral axis of the member, it is bound to reduce the shear strength of the member by half. If the split were to occur in a slender member subject to compression, the effect on the resistance to hoop stresses is likely to compromise the resistance to buckling of the member. The severity and gravity of this phenomenon has not been adequately studied to the authors' knowledge. The mechanics of splitting in bamboo needs to be better understood, including the factors that induce it, the frequency of the phenomenon, the consequences in terms of strength reduction and means to control or prevent it. The recent growth in interest in characterising the tensile strength perpendicular to the fibres will make a significant contribution to this process.

The destructive testing procedures contained in ISO 22157-1 (ISO, 2004a) have proven useful to the process of characterisation of bamboo species; however, more guidance is needed with regard to sampling within a batch. For example, with what frequency should sampling be done? Should a sample be subjected to all the tests contained in the standard, or can a single test be used as a reference or perhaps stand surrogate for the others, in a similar manner as to concrete's compression strength is used for the determination of its shear and tensile strengths and modulus of elasticity? Which test would be the best such reference? Alongside this guidance, more economical and field-ready means to infer strength of bamboo need to be considered, as access to the specialist laboratories required to carry out all ISO 22157-1 (ISO, 2004a) tests is impractical or prohibitively expensive in many parts of the world where bamboo is being used structurally. Simple field tests that correlate well to all other mechanical properties should be developed, as proposed by Sharma et al. (2013). More importantly, can nondestructive tests be used to develop a grading system, such as that used for timber? Lin et al. (2006) demonstrated that nondestructive tests could be used to correlate density and modulus of elasticity. It should be possible to develop visual or mechanical grading (through nondestructive means) for bamboo, as proposed by Trujillo (2013). These different initiatives are clearly complementary.

ISO 22156 states "strength and stiffness parameters shall be determined on the basis of tests for the type of action effects to which the material will be subjected (…), or on the basis of comparisons with similar bamboo species (…) or on well-established relations between the properties" (ISO, 2004c). It might be possible to combine or select procedures according to the context of application. As well as the preceding,

if the current freedom of methods as outlined in ISO 22156 is to be maintained, to avoid burdening users of bamboo species that do not have access to the costly process of characterisation of a species or a species within a region, a range of factors of safety could be adopted. Species that are poorly understood and not subject to any grading methods, having higher factors of safety than those that are subjected to a rigorous mechanical strength grading regime, reflecting the confidence level generated by the process.

Factors of safety and serviceability limits need to be subjected to greater scrutiny and discussion. Not all failure modes in bamboo are as potentially catastrophic as the others. Compression strength parallel to the fibres exhibits a relatively ductile failure mode, while tension perpendicular to the fibres is brittle. Situations where shear failure could occur, for example members subject to bending or connections, need to account for the risk of splitting, which could reduce the resistance by half if it coincided with a dowel or with the neutral axis of the flexural member. The effect of splitting on long members subject to compression should be considered too, as it is likely to affect the member's resistance to both local and global (Euler) buckling.

It might be of value to separate tests that have more academic value to the process of characterisation from tests that can be readily used in the field and are more useful from the structural point of view. This approach is analogous to the separation of clear specimen tests from structural-size tests in timber (Dinwoodie, 2000). An example is the tension parallel to fibres test, which is of little value for most structural applications, as it is a failure mode that is extremely uncommon in large-scale bamboo structures. Introducing tests aimed at characterising the behaviour of connections might be more beneficial, for example, an adaptation of EN 383 (BSI, 2007) or ASTM D 5764 − 97a(2013) (ASTM, 2013) to bamboo.

13.7 Concluding remarks

Although our understanding of bamboo has progressed immensely over the last 90 years, a great deal still needs to be done to place it on par with timber. Like timber, bamboo is a renewable natural resource that has many associated environmental services during its period of growth, including carbon sequestration, erosion control, water cycle regulation, etc. Additionally, it is a more rapidly renewable resource − reaching full height in less than 6 months and maturity in 3−5 years. This is an important quality, as there is a smaller period of return on investment compared to timber. Bearing in mind that bamboo grows primarily in developing economies, where long-term capital investments are riskier and less common, its adoption as a mainstream structural material would seem more appealing as a business model to a small-scale farmer.

Pole-form bamboo is generally an inexpensive commodity when purchased close to its source; presumably this is due to its rapid growth, although it is also possibly due to the low regard in which bamboo is often held (poor man's timber). Although low-cost is an appealing quality, it is bamboo's remarkable strength and good environmental

credentials which should serve to change perceptions. In many parts of the world where bamboo grows, sustainably grown timber of structural quality is simply not available. Therefore, bamboo's real competitors are reinforced concrete, masonry and steel: artificial materials that are perceived to be of superior quality. Bearing in mind that the many regions of the world where most urbanisation is going to take place in the 21st century are precisely those where bamboo grows, changing perceptions and enabling its use could make a significant difference to the carbon emissions, safety in the built environment and the overall quality of life these countries will have in the future. Using bamboo in place of its artificial competitors could potentially improve environmental conditions, reduce exploitation of nonrenewable resources, generate employment among rural workers, reduce dependence on imported materials and exposure to commodity price fluctuations, just to mention a few. Hopefully, this chapter makes a small contribution to that change.

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