Structural use of bamboo. Part 3: Design values

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Technical Note Series: Structural Use of Bamboo

Technical Note 3: Design Values

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Synopsis

Bamboo is a strong, fast growing and 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 third Technical Note proposes: strengths and other properties for the scheme design of any bamboo species, a method of calculating characteristic strength values from test data, and a method for calculating design values of strengths for limit state design. It is believed to be the most up-to-date guide for determining design values for bamboo elements.

Introduction

Bamboo typically has a strength similar to high grade (e.g. D40) hardwood. Testing for strength will in most cases be required before detailed design as little reliable published data is available. Some tests are more important than others, for example flexure, shear and tension perpendicular are more important than compression and tension parallel since in most structures it is rare for bamboo elements to be loaded close to their failure in the latter two modes. For very simple structures it may be possible to use conservative design values without any testing.

The methods proposed in this Note have been developed based on ISO 22156: Bamboo – Structural Design (ISO, 2004a), ISO 22157: Bamboo – Determination of Physical and Mechanical Properties (ISO, 2004b & ISO, 2004c), NSR-10 G.12: Colombian Code for Seismically-Resistant Construction: Structures of Timber and Guadua Angustifolia Kunth Bamboo (AIS, 2010), EN 384:1995 Structural timber – Determination of characteristic values of mechanical properties and density (CEN, 1995) and EN 1995-1-1: Eurocode 5: Design of Timber Structures (CEN, 2014). The methods should be used in conjunction with the Eurocode suite of codes. Where there is any ambiguity, refer to EN 1995-1-1: Eurocode 5 (CEN, 2014), and use good practice timber design theory.

The values proposed assume rigour is applied to the process of testing the bamboo to obtain the test data, and selecting bamboo that is of appropriate condition and quality for construction, as outlined in Technical Note 1 (Kaminski et al. 2016a).

This note is divided into four sections:

Section 1: Calculation of characteristic strength values from test data
Section 2: Suggested characteristic strengths for any bamboo at scheme design stage
Section 3: Calculation of design values
Section 4: Other values for design

Nomenclature

Nomenclature used throughout this Note:

$f_{c,0,i}$ = characteristic compressive strength parallel to fibre (N/mm^2)
$f_{i,0.05}$ = 5th percentile value of strength results from test data (N/mm^2)
$f_{i,k}$ = characteristic value of population (N/mm^2)
$f_{m,i}$ = characteristic flexural strength about any axis (N/mm^2)
$f_{t,0,i}$ = characteristic tensile strength parallel to fibre (N/mm^2)
$f_{v,i}$ = characteristic shear strength about any axis (N/mm^2)
k_{len} = laboratory test conditions correction factor
k_{mod} = laboratory test conditions correction factor
k_{sys} = laboratory test conditions correction factor
$X_{i,d}$ = design strength (N/mm^2)

m = mean value of test data
n_c = number of culms connected together to form one element
n_t = number of tests (minimum 12, recommended at least 20)
s = standard deviation of test data
γ_M = material factor of safety

C_{mois} = moisture content correction factor
C_{lab} = laboratory test condition factor

1.0 Calculation of characteristic strength values from test data

1.1 Introduction

The following method can be used to calculate characteristic strength values for design from test data derived in accordance with ISO 22157 (ISO 2004b & ISO 2004c). This standard includes tests to determine strengths in compression parallel to the fibres, flexure, shear and tension parallel to the fibres. The sample used for testing must be fully representative of the variability of the material that is proposed to be used for the actual structure. This variability should include origin, age, position along the culm, etc. The minimum sample size stated in the standard is 12, however in the authors' opinion a larger sample size is probably required considering the many sources of variability. In addition, if budgets are limited it is generally better to focus resources on conducting more bending and shear tests than tension and compression tests, since buildings constructed from bamboo are more likely to be highly stressed in the former modes compared with the latter. The number should also take into consideration how well understood and studied a given species is and the available budget. Additionally, it should be noted that the larger the sample size the less 'punished' the design values will be (see Equations 1 and 2).

The method described here adjusts the test data to Service Class 1 and 2 conditions, and also includes adjustment factors for laboratory test conditions. Service Class 1 and 2 correspond to a moisture content in the material corresponding to a temperature of 20°C and the relative humidity of the surrounding air only exceeding 85% for a few weeks per year. This is applicable to all air-conditioned spaces and most indoor/outdoor covered areas with normal humidity (CEN, 2014). Service Class 3 corresponds to climatic conditions exceeding 1 and 2. As outlined in Technical Note 2 (Kaminski et al., 2016b), bamboo should not be used outside exposed to water or rain, therefore this Service Class 3 assumes that the bamboo is under cover and protected from direct rain/water however in a very humid environment with a relative humidity >85% – this scenario only exists in tropical countries. Bamboo must be treated if in this environment as otherwise it is liable to rot in the high humidity.

To use the strengths for design, the characteristic values must then be factored by the modification factors in Section 3. These may be conservative, but test data is limited.

1.2 Determining the characteristic strength

The characteristic value of strength for a whole population, $f_{i,k}$, can be determined from the following equation (based on ISO 22156 (ISO, 2004a) and NSR G-12 (AIS, 2010)):

$$f_{i,k} = C_{mois} C_{lab} f_{i,0.05} \left[1 - \frac{2.7s}{m\sqrt{n_t}}\right] \qquad \text{Eq 1}$$

where $f_{i,0.05}$ can be calculated as follows:

$$f_{i,0.05} = m - 1.645s \qquad \text{Eq 2}$$

Alternatively, for samples of 20 or more specimens, the data can be ranked and the value corresponding to the n^{th} term in the rank may be used as the 5^{th} percentile. The n^{th} term would be determined as: total sample/20.

For elements in axial compression only, where an element is formed from four or more culms connected together such that they equally share the load (for example a column), the characteristic value of strength for a whole population, $f_{i,k}$, can be determined from the following equation:

$$f_{i,k} = C_{mois} C_{lab} \left[m - \frac{1.645s}{\sqrt{n_c}}\right]\left[1 - \frac{2.7s}{m\sqrt{n_t}\sqrt{n_c}}\right] \qquad \text{Eq 3}$$

This modification takes Equations 1 and 2 and divides *s* by $\sqrt{n_c}$, which is essentially using standard statistical theory to say that the characteristic value of a number of samples selected from a population is likely to be greater than the characteristic value of a single sample.

Alternatively, EN 1990:2002 Annex D can be used, adjusting for C_{mois} and C_{lab} as above.

1.2.1 Moisture content correction C_{mois}

Like timber, bamboo exhibits an increase in strength as it dries below the fibre saturation point. Therefore, it is important to consider the moisture content (MC) of both test specimens and members that will constitute permanent parts of a structure. Ideally, tests would be carried out at a MC similar to that which the bamboo will experience in service, which in most cases will be “dry”. However, if this is not the case, the test data should be normalised to Service Class 1 or 2 (a MC ~12%) by applying a correction factor C_{mois}, dependent on the MC of the bamboo at the time of the test. Suggested values are shown in Table 1 – these values are based on NSR G-12 (AIS, 2010) and EN 384 (CEN, 1995).

Table 1: Moisture content correction factor C_{mois}, as a function of the moisture content at time of testing

Moisture content (MC) (%)	Flexure	Shear	Tension parallel to fibre	Compression parallel to fibre
MC ≤ 12	1.0	1.0	1.0	1.0
12 < MC ≤ 18	Interpolate between above and below			
MC > 18	1.2	1.2	1.2	1.2

Using “green” (unseasoned) bamboo for construction should be avoided at all cost. “Green” bamboo is cheaper and carpenters will tend to push for it, because it is much easier to work than dry bamboo, however as the bamboo dries and shrinks it is likely to split, weakening it and failing the connections.

1.2.2 Laboratory test conditions C_{lab}

The relationship between experimental procedures and the strength exhibited by full-scale specimens is poorly understood for bamboo. It is likely that test pieces contain fewer defects than full-scale specimens, and therefore ISO and NSR recommend the use of factors to reduce experimental results. A laboratory test condition factor C_{lab} should therefore be applied to the characteristic values to represent the variability of the actual culm. Suggested values are provided in Table 2 – these values are adapted from NSR G-12 (AIS, 2010) and ISO 22156 (ISO, 2004a). This correction follows similar theory to timber, as laid out in EN 384 (CEN, 1995).

Table 2: Laboratory test condition factor C_{lab}

Flexure	Shear	Tension parallel to fibre	Compression parallel to fibre
0.7	0.5	0.5	0.7

2.0 Suggested characteristic strengths for any bamboo at scheme design stage

Table 3 proposes characteristic strengths for any bamboo species normalised to Service Class 1 or 2. Only detailed published test data is available for Colombian grown Guadua angustifolia Kunth – this is based on NSR G-12 (AIS, 2010) and Lozano (2010). For detailed design, testing would normally need to be undertaken to validate the values below. However, they are intended to be conservative and so for simple structures (low rise, low occupancy and low stresses) it may be possible to use these design values without any testing, depending on local regulations. Where bamboo is sourced from a single consistent source, a large amount of testing is undertaken, and testing and selection are rigorous, it is possible that better characteristic strengths can be achieved.

Table 3: Characteristic strengths, $f_{i,k}$, for design of dry*, mature bamboo, free of visual defects (splits, decay etc.) and assuming a 10min test load (N/mm^2)**

	Flexure ($f_{m,k}$) (N/mm^2)	**Shear ($f_{v,k}$) (N/mm^2)**	**Tension parallel to fibre ($f_{t,0,k}$) (N/mm^2)**	**Compression parallel to fibre ($f_{c,0,k}$) (N/mm^2)**
Colombian grown *Guadua angustifolia Kunth*	35-50	3-5	40	20
For scheme design, all species	30	2	40	20
C24 softwood	24	2.5	14	22

* at 12% moisture content.
** within 'mature' age range for that particular species – normally 3-5 years.

Note that some widely available published data on bamboo strengths is misleading, as the form of the strength is not immediately obvious (e.g. characteristic, ultimate, average, design, allowable etc.). Testing methodologies affect the interpretation of results too, hence the recommendation to adhere to ISO standards. Strengths do vary between bamboo species, however it is unlikely that they would be significantly different from the above. If published strengths are found to be widely different from these then care should be taken to ensure that the strengths are in the correct form. For example, it is commonly quoted that "bamboo is stronger than steel", which is misleading and can lead to bamboo being used in a structure when it is in fact inappropriate.

3.0 Calculation of design values

3.1 Design Strengths

The design value $X_{i,d}$ of a strength property shall be calculated as follows:

$$X_{i,d} = k_{mod} k_{sys} k_{len} \frac{X_k}{\gamma_M} \quad \text{Eq 4}$$

3.2 Modification Factors

3.2.1 Service class and load-duration factor k_{mod}

The stresses in Table 3 are normalised to Service Classes 1 and 2 and 5-15 minute loading conditions, as is typical for most laboratory tests, and hence must be corrected for both Service Class and duration of load – suggested values are given in Table 4 based on EN 1995-1-1 (CEN, 2014), and are in broad agreement with NSR G-12 (AIS, 2010) and ISO

22156 (ISO, 2004a). As with timber design, the duration of load for a particular load combination depends on the lowest duration load in that combination.

Table 4: Service class and load duration factor k_{mod}

Service Class	Permanent (self-weight)	Long-term (storage, imposed)	Medium-term (imposed)	Short-term (construction)	Instantaneous (wind, seismic)
1	0.6	0.65	0.75	0.8	1.05
2	0.6	0.65	0.75	0.8	1.05
3*	0.4	0.45	0.55	0.6	0.75

* As outlined in Technical Note 2 (Kaminski et al., 2016b), bamboo should not be used outside exposed to water or rain, therefore this Service Class 3 assumes that the bamboo is under cover and protected from direct rain/water however in a very humid environment with a relative humidity >85% – this scenario only exists in tropical countries. Bamboo must be treated if in this environment as otherwise it is liable to rot in the high humidity.

3.2.3 System strength factor k_{sys}

Where four or more elements of the same stiffness are connected to a continuous load distribution system, such as is the case with floor joists, rafters, purlins and trusses, and in addition either:

1. The continuous load distribution system is capable of redistribution of loads, or;
2. The elements are no further than 0.6m apart, the load distribution members are continuous over at least two spans and any joints are staggered;

then it is suggested that the allowable stresses provided in Table 3 are modified by a system strength factor k_{sys} of 1.1.

This is based on NSR G-12 (AIS, 2010) and EN 1995-1-1 cl. 6.6 (CEN, 2014). $\boldsymbol{k_{sys}}$ should only be applied if the characteristic stress obtained is as per Equation 1 and not Equation 3.

3.2.3 Factor of safety γ_M

A factor of safety must be applied to the characteristic values to bring them to a standard probability of being exceeded of about 0.1% (1/1000) (EN 1995-1-1 (CEN, 2014)) by applying a material factor of safety for limit state design. Suggested factors of safety are provided in Table 5 – these values are based on NSR G-12 (AIS, 2010) and ISO 22156 (ISO, 2004a), and are more conservative than the values in EN 1995-1-1: (CEN, 2020149), however "grading" of bamboo, when undertaken, is not as rigorous as it is for timber in the European market (see Technical Note 1 (Kaminski et al., 2016a).

Table 5: Factor of safety γ_M

Flexure	Shear	Tension parallel to fibre	Compression parallel to fibre
1.5	1.5	1.5	1.5

4.0 Other values for design

4.1 Youngs Modulus and Deflection

Bamboo is not very stiff, and therefore deflection, especially flexural deflection, will often govern. Deflection checks should be conducted using standard elastic engineering formulae. Table 6 proposes a range of typical moduli of elasticity E at 12% and 19% moisture content. The lower values are based on NSR G-12 (AIS, 2010) while the upper values are based on other experimental data – the difference is believed to be a lack of test data coupled with slippage of bamboo connections which is poorly understood. The authors believe the higher values are more appropriate for deflection purposes, while the lower values of the 5th percentile should be used for Euler buckling checks (with a further appropriate safety factor required — to be described in detail in a subsequent technical note forming part of this series. Separate allowance should always be made for connection slip.

Some authors believe creep to be negligible (3-5% of the elastic deformation) (Janssen, 2000), however recent research suggests it could be as high as 50% of the initial deflection – limited research has been conducted on this topic. Note that the values below are typical values and like strength, there is likely to be a wide variation in stiffness depending on species, origin, distance from the ground, etc.

Table 6: Typical moduli of elasticity E for bamboo at 12% and 19% moisture content

Moisture content (%)	Average modulus $E_{0.5}$ (N/mm^2)	5th percentile modulus $E_{0.05}$ (N/mm^2)
12	10,000-17000	7500-13,000
19	8500-15,000	6700-8000

4.2 Ductility in earthquakes

As discussed in Technical Note 1 (Kaminski et al., 2016a), like timber, bamboo elements possess several brittle failure modes. As such, an appropriate behaviour factor for a bamboo structure should in most cases be q = 1.5 and Eurocode 8 should be followed as for timber structures (CEN, 2013). Where failure is confined to connections which use steel nails where the failure mode is a plastic hinge forming in the nail (i.e. modes b, d, e, g, h, k, m, Figure 8.3, steel-to-bamboo connections (CEN, 2014)) and rigorous capacity design/overstrength principles are applied, it is possible that more global ductility can be achieved, however little test data exists on this.

Summary

This Technical Note proposes strengths and other properties for the scheme design of any bamboo species, a method of determining characteristic strength values from test data, and a method for calculating design values of strengths for limit state design. Significantly more research is still required for all species of bamboo to provide more accurate design values and coefficients – current values are therefore likely to be conservative. Bamboo will be as well understood as timber is, but we have some way to go before that happens.

The next paper in this Technical Note series will cover element design equations.

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