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Prospects for a method to infer non-destructively the strength of bamboo: a research proposal

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ABSTRACT

This paper commends the merit of the standards that have been published over the last decade (e.g. ISO 22156 and NSR-10), but observes that these standards provide limited guidance on ways to ensure building material will have adequate strength and stiffness. It is recommended that a procedure similar to that used for timber – strength grading – is researched, particularly the more efficient 'machine strength grading', though visual grading for bamboo is discussed too. Evidence is presented that correlations between physical properties – that are readily measured through non-destructive tests – and strength properties can be inferred for bamboo; hence, in principle machine strength grading could be possible. The limitations of the current data are stressed and a research proposal is presented.

Keywords. bamboo, guadua, machine strength grading, non-destructive tests

List of abbreviations: ISO – International Standards Organisation, NTC – Norma Técnica Colombiana (Colombian Technical Standard), NSR – Norma Sismo-resistente (Seismic Design and Construction Code), MOE – Modulus of Elasticity, MOR – Modulus of rupture

INTRODUCTION

Despite the fact that it is estimated that over one billion people worldwide live in traditional bamboo houses (FAO, 2007), it is fair to say that most structural design with bamboo, if any, is currently achieved with little or no regard to design codes. Procurement of bamboo for structural use is precarious too, as it relies on an element of familiarity and skill to ensure the sourced material is of adequate quality. Structures are designed and built with a limited understanding of structural design, based occasionally on precedent and tradition. If experience from previous generations is used to design and procure bamboo, arguably it is only possible to interpolate from this experience, not extrapolate, i.e. traditional practices are generally limited to low-scale residential constructions, but are inadequate for the larger, more ambitious building types that are being designed and constructed of late.

During the first decade of the 21st century very important progress has been made in the drafting and publication of design codes of practical use to structural engineers. Undoubtedly the most important of these are the ISO standards: ISO 22156:2004 Bamboo – Structural design (ISO, 2004a), ISO 22157-1:2004 Bamboo – Determination of physical and mechanical properties – Part 1: Requirements (ISO, 2004b) and ISO 22157-2:2004 Bamboo – Determination of physical and mechanical properties – Part 2: Laboratory manual. These have influenced the development of Colombian bamboo codes such as the Bahareque Housing Code (*Capítulo E.7 – Casas de uno y dos pisos en bahareque encementado*) of the NSR-98 Seismic Design and Construction Code (*Reglamento colombiano de construcción sismo resistente*) and the newer Guadua-bamboo Structures Code (*Capítulo G.12 – Estructuras de Guadua*) of the NSR-10 Seismic Design and Construction Code (*Reglamento colombiano de construcción sismo resistente*) (AIS, 2010), and the Colombian Technical Standard for the determination of physical and mechanical properties of *Guadua angustifolia Kunth* (Norma Técnica Colombiana - NTC 5525, Métodos de ensayo para determinar las propiedades físicas y mecánicas de la guadua angustifolia Kunth).

DETERMINATION OF STRENGTH IN NATURAL MATERIALS

A fundamental aspect of any design code is the determination of strength of the structural materials. Natural materials, such as timber and bamboo, have a great deal of variability when compared to industrially man-made materials such as steel or aluminium. The current way to infer the strength of timber for structural use is by means of a process called strength grading. Strength grading is a process of sorting timber on the basis of its strength (Benham *et al,* 2003). Strength grading can be of two types: visual or machine grading. Visual grading for timber consists of observing and measuring physical characteristics such as those listed in table 1. The personnel implementing the process of visual grading must be trained and experienced in the task; it is a relatively slow process and is limited by those properties that are visually accessible (Johansson, 2003).

Machine strength grading uses mechanical means to infer the strength and stiffness of a sample of wood through non-destructive tests. The most common method is to subject a plank to a specific force or deflection, and measure hence its individual stiffness. The machine is calibrated to infer from the stiffness (Modulus of Elasticity or MOE), the strength in bending (Modulus of Rupture or MOR). The strength in bending is then used to classify the timber piece into a “strength class”. Each strength class has an associated list of physical and mechanical properties (Benham *et a,l* 2003). Other mechanical processes have been used and are being developed, sometimes in combination (table 2).

The calibration process of the machine requires hundreds of tests for a specific species and plantation; in EN 14081-2 (BSI, 2010) this can range from 100 to 900. Once calibrated the process of machine strength grading is applied to every single piece of timber in a batch. The statistical nature of the process implies that some pieces will be marked as rejects. The remaining pieces will be marked with a specific strength property (Behnam *et al,* 2003).

This means that every piece of timber used in a project has been subjected to a non-destructive test and due to the probabilistic methods used, there is a very high probability that it is stronger than the declared strength values. This results in an efficient yet safe use of the resource. Johansson (2003) points out that machine grading improves also the accuracy with which stiffness and density are known, which is desirable in design.

Table 1. Aspects to be considered in visual grading of timber and bamboo

Material	Timber (rectangular cross section)	Bamboo (round)
Example of code	e.g. EN 14081-1 (BSI, 2011b) or BS 4978 (BSI, 2011a)	e.g. NSR-10 (AIS, 2010)
Fissures	The effect of fissures is considered. The seriousness depends on length and thickness.	Fissures are controlled, and should not be placed in the neutral axis of member. Length of cracks controlled too.
Warp or distortion	Rectangular cross-section timber presents several forms of warp: bow, spring, twist and cup. All restricted, except cup.	Warp (bow) should not exceed 0.33%.
Wane	Rectangular cross-section timber can present wane, which needs to be limited.	Not mentioned, not applicable to round bamboo.
Rot	Generally not allowed.	Not allowed.
Insect damage	No active infestation allowed.	Not allowed.
Knots	Sizes, grouping and types are considered and controlled.	Not mentioned, not applicable to bamboo.
Slope of grain	Controlled.	Not mentioned, not applicable to round bamboo.
Taper	Not applicable to rectangular cross-sections.	Taper should not exceed 1% (ISO 22156 limits taper to 1 in 170).
Density and/or rate of growth	Density at 20% Moisture Content, or rate of growth to be considered.	No current consideration. Maturity is controlled.
Maturity	No direct consideration.	Culms must be 4 to 6 years of age.
Reaction wood (comp. & tension wood)	Compression wood is controlled in softwoods, and tension wood is controlled in hardwoods.	No current consideration. These phenomena have not been reported for bamboo.
Other	Mechanical damage, bark or resin pockets etc. are to be considered and limited.	Not mentioned. Bark and resin pockets not present in bamboo.

Table 2. Examples of timber grading methods and properties

Property	Examples
Modulus of Elasticity (static in bending)	Johansson (2003)
Modulus of elasticity (dynamic)	Johansson (2003); Olsson *et al* (2010)
Hardness (Janka)	Ballarin *et al* (2010)
Density	Johansson (2003)

Determination of strength properties in bamboo

The current processes available to determine the strength of bamboo using the ISO standards, or the Colombian codes, are discussed henceforth.

- Ways to infer strength: Clause 7.2.2 in ISO 22156 identifies three possible ways by which the strength and stiffness properties can be determined: testing, "*comparison with* *similar bamboo species*" and "*well-established relations between the different properties*".

- Destructive testing: ISO 22157 (ISO, 2004b) provides a standardised test procedure for some of the physical and mechanical properties of bamboo. It thus has created an international basis for the determination of some of the fundamental mechanical properties of bamboo, and as such is invaluable to researchers worldwide, as they can confidently compare results regardless of where they are testing.
- Determination of strength values from destructive testing: Clauses 7.2 and 7.4 in ISO 22156 provide guidance on ways by which characteristic and permissible strength values can be derived from test results using two simple equations. The characteristic value is the 5th percentile property with a 75% confidence (ISO, 2004a). The permissible strength or allowable stress is the characteristic strength divided by a series of factors of safety. Clause G.12.7.3 in the Colombian NSR-10 has adopted and adapted these equations. NSR-10 limits its scope to one species: *Guadua Angustifolia* Kunth. It provides for this bamboo species its permissible strength values for bending, tension, shear and compression parallel and perpendicular-to-grain. It also allows the structural designer to assess the mechanical properties through testing and then establish the permissible strength values of a specific sample. Clause 7.2.2 in ISO 22156 also notes "*special attention shall be given to differences between material originating from different localities*". No such mention is made in NSR-10.
- Grading: Section 17 in ISO 22156 requires the implementation of grading procedures for bamboo, which it suggests can be through visual assessment and/or non-destructive testing, but does not provide specifics. Section G.12.3 of NSR-10 provides visual grading parameters (refer to Table 1), but does not provide guidance on non-destructive tests that can be used for machine strength grading.
- Quality Control: Section 18 in ISO 22156 refers to the requirement to practice quality control throughout the supply chain including construction and workmanship. It is important to note that it requires that a quality assurance program is implemented for the handling of material. Grading is one aspect that should be controlled and verified. Clause G.12.6.2 in NSR-10 requires that structures are designed and built by competent personnel; however, there is no requirement for quality control of the grading process or specific clarification of competence of the personnel tasked with grading.

It is evident from the above that the referenced bamboo design codes do not provide guidance for mechanical strength grading, and that though some principles for visual strength grading have been presented, it is unclear as to how rigorous and effective this process will be. Under the current state-of-the-art for bamboo engineering, it would seem random destructive testing of a small sample within a batch is the most reliable process to determine strength. To ensure safe structural design the test results need to be coupled with two concepts outlined in ISO 22156: the statistical tool provided by characteristic strength, and factors of safety. The combination of these two concepts can imply that a permissible strength value can be one-seventh of the average ultimate strength obtained through testing (Janssen, 2000). This is a quite punitive, though necessary, limitation to the strength of the material. This paper argues that a safer and more efficient procedure is desirable and possible if strength grading, particularly machine strength grading is implemented within the supply chain.

FACTORS KNOWN TO INFLUENCE THE STRENGTH OF BAMBOO

Janssen (1981) identifies that "*compared with wood, bamboo seems to be more regular: problems as to knots or slope of grain do not occur*", hence it is possible that the derivation of procedures to infer the strength of bamboo through non-destructive testing might be simpler, yet that is still to be established. Some factors that are known to affect the strength of bamboo are listed in Table 3.

Table 3: Known factors that affect the strength of bamboo

Factor	Effect
Species	Different species have different strength properties.
Maturity	The optimum maturity for strength varies from species to species, but typically is around 3 to 6 years (Janssen, 1981; Liese, 1998; Correal and Arbelaez, 2010). It is thought that this increase in strength results from the continuous thickening of the walls of both the fibre and parenchyma cells (Liese 1998; Murphy and Alvin, 1997) during the life of the culm. Correal and Arbelaez (2010), identify also that not all mechanical properties are affected by age to the same extent.
Position along the culm	Strength (in N/mm^2) increases with height (Correal and Arbeláez, 2010) as does density.
Node or internode	Mechanical properties vary from node to internode, this is a consequence of the change in the direction of the fibres at the node.
Position within the wall	There is a greater density of fibres towards the outer part of a bamboo wall, than to the inner.
Density	There seems to be a correlation between density of a culm or a species and its strength (refer to table 4).
Load duration	Similarly to timber, under the presence of a long lasting load, bamboo seems weaker than when subjected to a short term load (Janssen 1981)
Geometric deviations	Taper and warp (bow) reduce the resistance (in kN) of a member in compression
Splitting	Splitting can seriously reduce the resistance (in kN) of a member in bending, shear and compression

INFERRING STRENGTH OF BAMBOO

Observations made by Janssen (1981)

The basis for machine strength grading is to establish strong correlations between readily measureable properties (through non-destructive tests) with strength (or stiffness) properties. Some correlations have been observed in bamboo for quite some time, examples of these were compiled by Janssen (1981) (refer to table 4), which form the basis for the equations postulated later in Janssen (1995).

Observations based on more recent tests

Sánchez and Prieto (2001) carried out 117 bending tests to *Guadua Angustifolia* Kunth elements using samples that were sourced from two different regions in Colombia. Samples were 1.5m, 2m, 2.5m and 3m in length. The shorter samples failed in crushing or shear. To prevent crushing failures, eventually the authors opted to fill the internodes at the supports with mortar grouting. Source, position along the culm, deflections, ultimate strength, dimensions and moisture content were recorded; though unfortunately density was not. The data was reanalysed by the author of this paper to establish whether there is a discernible correlation between MOR and MOE. Only the data for the 2.5m and 3m span tests using mortar filling have been used, to ensure failure modes were due to bending and not crushing or shear. Only the 19 test results complying with these requirements were analysed, a significant impoverishment of the sample. Moisture content readings were initially considered in the regression analysis, these were later removed because most samples had moisture contents above 18% (the assumed Fibre Saturation Point) therefore this factor made little difference. In the analysis the position along the culm was also considered. When MOE and position along the culm where correlated to MOR, a strong correlation was observed (Table 5).

Table 4: equations to infer strength in N/mm^2 (=MPa) from density

	Test observations (Janssen 1981)		Permissible stress (Janssen 1995)		Modulus of Elasticity (Janssen 2000)
	Dry (MC=12%)	Green	Dry (MC=12%)	Green	
Compression	0.094G	0.075G	0.013G	0.011G	24G
Bending	0.14G	0.11G	0.020G	0.015G	
Shear		0.021G	0.003G		

Where G is mass by volume (density) in kg/m^3

From table 5 it is possible to observe that as an initial indication for the existence of a correlation this is seemingly quite promising, a coefficient of determination R^2 of 0.642 would be deemed good for timber strength grading (Johansson, 2003). However, the validity of this linear regression is hampered by the size of the sample (Figure 1).

Table 5: Linear regression results for MOR and MOE based on Sánchez and Prieto (2001)

Variables	Equation	Coefficient of determination (R^2)
MOE	$MOR = 10.03 + 0.00283 \times MOE$	0.375
MOE & location	$MOR = -39.39 + 0.00515 \times MOE + 25.53 \times P$	0.642
Where: MOR is the modulus of rupture, MOE is the modulus of elasticity and P is the position along the culm. P = 1 for *cepa*, or the bottom part of the culm, and P = 0 for *basa*, or the middle part of the culm.		

Uribe and Duran (2002) carried out 45 compression tests to *Guadua Angustifolia* Kunth elements using samples that ranged in length from 90mm to 3000mm. Deformation, failure loads, failure modes, dimensions, moisture content and density were recorded for all samples in accordance to the then draft version of ISO 22157. The data was reanalysed by the author of this paper to establish whether there is any discernible correlation between Compressive strength (σ_C), Modulus of Elasticity in compression (E_C), density (or mass by volume - ρ) and moisture content (MC). Only stocky samples that failed in crushing were considered for the linear regression analysis, which meant that the sample consisted of only 30 test results. The moisture content was taken as 18%, if greater than 18%, or the actual moisture content reading if less, as 18% being the assumed Fibre Saturation Point (Table 6).

From table 6 it is possible to observe that the correlation between the modulus of elasticity and compressive strength was surprisingly weak (R^2 = 0.063), but a strong correlation was established between density and compressive strength (R^2 = 0.45), which improved significantly if moisture content was also considered ($R^2 = 0.55$), which would be considered good for timber grading (Johansson 2003), but as previously mentioned, the sample considered here is inadequately small to be considered conclusive (Figure 2).

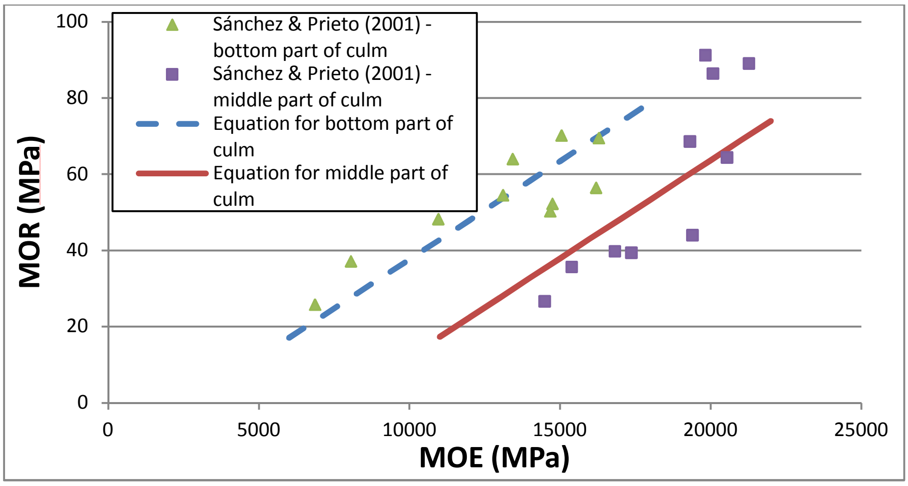

Figure 1: Results from Sánchez and Prieto (2001) and from linear regression analysis

Table 6: Linear regression results for $\sigma_{C,ult}$ based on Uribe and Durán (2002)

Variables	Equation	Coefficient of determination (R^2)
E_C	-	0.063
ρ	$\sigma_{C,ult} = 13.38 + 0.0499 \times \rho$	0.45
ρ & MC	$\sigma_{C,ult} = 46.72 + 0.0439 \times \rho - 1.699 \times MC$	0.55
Where: $\sigma_{C,ult}$ is the ultimate compressive strength parallel to the grain, E_C is the modulus of elasticity in compression, ρ is the density (Mass by volume) and MC is the moisture content if less than 18%.		

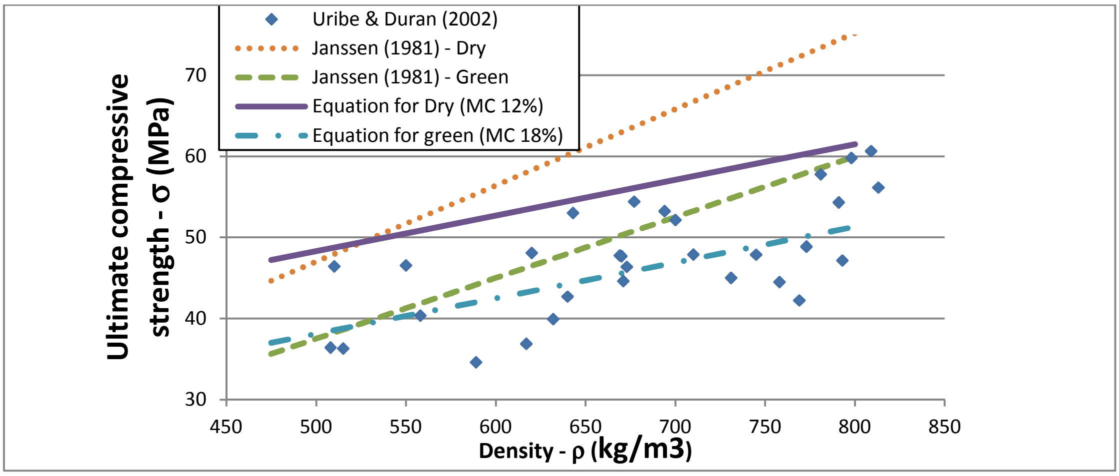

Figure 2: Results from Uribe and Durán (2002) and from linear regression analysis.

DISCUSSION AND PROPOSAL

From the correlations presented in tables 5 and 6, and figures 1 and 2, it is possible to observe that in principle the strength of an individual element of bamboo can be inferred from non-destructive tests, which forms the basis of machine strength grading such as that used in timber engineering. To give the process any true validity very many destructive tests (hundreds instead of tens) need to be undertaken, as well as investigation into the tests themselves, i.e. which test(s) have the best cost/benefit ratio, and whether all the mechanical properties (including shear and tension perpendicular-to-the-grain) can be inferred from theses non-destructive tests, in order to enable a strength classification system analogous to that used in EN 338. In summary, though machine strength grading might be possible, it needs to be adapted to bamboo. If such a procedure where established for bamboo, this would be a step in the direction towards making this resource part of the mainstream of tightly controlled construction materials with reliable strength and a dependable supply chain.

The described work is currently underway at Coventry University, but this is admittedly a huge international effort, requiring hundreds of tests into several species. Therefore this is a call to an international concerted effort into this task.

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