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Grading of Bamboo

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About the Author – Shortly after graduating from Civil Engineering at Universidad Nacional de Colombia in 2000, David Trujillo worked in the reconstruction of the Coffee-growing region following the 1999 earthquake. Here he became motivated to learn about bamboo structures, but felt he lacked the skills and experience to lead in this field. In 2003, he moved to the UK to study an MSc in Earthquake Engineering at Imperial College London, obtaining a distinction. In 2004, he started working for Chiltern Clarkebond (later CCB Evolution) a consultancy that specialised in the design of multi-storey timber-frame structures. In 2007 he moved to Buro Happold, a structural engineering consultancy. Here he contributed to the design of numerous landmark steel & concrete structures such as the Library of Birmingham. In 2010, he became chartered with the Institution of Structural Engineers, and was awarded the Bob Fischer memorial prize for his performance in the chartership exam. In 2009, determined to further his work with bamboo, David moved out of industry and into academia, joining Coventry University as a Senior Lecturer. He currently chairs the INBAR (International Network for Bamboo and Rattan) Task Force for Structural Uses of Bamboo and is the UK-nominated expert to ISO Technical Committee 165 Timber Structures Working Group 12 on bamboo structures.

Contributory Author – Suneina Jangra is a Civil Engineer (MEng) from the University of Bristol. For three years after graduating in 2012 she worked in the consulting and risk-assessment industry. Deciding to further pursue academia, in 2015 she joined David Trujillo's team at Coventry University to undertake an MSc by Research. Her thesis, "Flexural properties as a basis for strength grading of dry round bamboo", underpins the experimental work contained in this Working Paper. Currently, Suneina is pursuing her PhD in energy demand in the built environment at The Bartlett School of Environment, Energy and Resources at University College London (UCL).

About INBAR Working Papers

INBAR Working Papers detail and provide analysis of on-going research on bamboo and rattan. These are living documents that may be updated in the future based on further research and developments.

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Executive Summary

Structural designs codes and standards are based on a reliable knowledge of the mechanical properties of materials. Alongside seasoning and preservation, grading plays a fundamental role in the production of reliable, natural structural products such as timber. Unfortunately, grading of bamboo is not implemented in a standardised or systematic manner, if at all. This may partly explain why bamboo, despite its many sustainable attributes, remains a marginal material in engineered structures. Currently, in partnership with the International Standards Organisation (ISO) Coventry University and the International Network for Bamboo and Rattan (INBAR) *are* drafting a grading standard.

This INBAR Working Paper presents research into potential grading methodologies for one species of bamboo – *Guadua angustifolia* Kunth – and recommends criteria for both visual grading and machine grading. For visual grading, the diameter of bamboo culms is deemed to be an important consideration when grading for flexural capacity – a 10 percent increase in external diameter results in a 24 percent increase in flexural capacity. Wall thickness is considered to be critical to shear and tension perpendicular capacities.

For machine grading, three main properties were found to be significant: flexural stiffness – important for the design of beams, slender struts and portal frames; linear mass – to help infer density, which is closely correlated to strength properties; and external diameter – which correlated well with flexural capacity and stiffness. It is important to note, that measuring any of these properties can be undertaken in a quick, simple, cost-effective and non-destructive manner.

The paper suggests that additional properties that may be critical to design or other applications should be further researched – sheer strength or tensile strength perpendicular to fibres, for instance, which are important to the process of connection design.

Implemented effectively, the grading methodologies presented have the potential to enhance the supply of bamboo and deliver positive benefits to producers, contractors, engineers, and consumers.

Key messages:

- Grading methodologies currently used for bamboo culms are limited – potentially affecting the demand of bamboo for engineered structures, despite its sustainability and huge potential.
- Bamboo grading methodologies could be informed by those currently being used for timber and become incorporated into a new international standard for the grading of bamboo, currently being drafted by Coventry University and the International Network for Bamboo and Rattan (INBAR), in partnership with the International Standards Organisation (ISO).
- The diameter of bamboo culms is an important criteria to consider during visual grading if flexural properties are deemed important to the grading procedure, whereas wall thickness is critical for shear and tension perpendicular capacities.
- For machine grading, three main properties were found to be significant: flexural stiffness – important for the design of beams, slender struts and portal frames; linear mass – to help infer density, which is closely correlated to strength properties; and external diameter – which correlates well to flexural capacity and stiffness. These properties can be measured in a quick, simple, cost-effective and non-destructive manner.
- The recommended grading methodologies have the potential to enhance the supply of bamboo and deliver positive benefits to producers, contractors, engineers, and consumers.

Introduction and Glossary

This Working Paper is an output from INBAR's Technical Advisory Committee on Bamboo and Rattan Standardisation Task Force on Bamboo Construction. It presents primary findings on developing grading methodologies for one species of bamboo (*Guadua angustifolia* Kunth) akin to extant methods used for timber. Based on these findings, the working paper proposes and gives guidance to building professionals on how grading methodologies for bamboo could potentially be developed.

In parallel to this Working Paper, Coventry University and INBAR, in partnership with the International Standards Organisation (ISO), have also been developing an international standard for the grading of round culm bamboo.

The current draft version of *ISO CD 19624 - Bamboo structures — grading of bamboo culms — Basic principles and procedures* (ISO, 2016) states:

> *Grading is the process of sorting every piece of bamboo in a sample into grades according to a defined selection criteria. The criteria identify dimensional, visual, geometric, mechanical and/or physical properties that reflect bamboo's structural strength or structural capacity and may affect the utility of the product.*
>
> *Each grade will be associated to a range of structural properties derived from testing. The selection criteria are based on non-destructive measurements that have been established to be useful to the grading process.*
>
> *Grading provides a statistically significant prediction of the properties of the population within a grade, but cannot predict with absolute certainty the properties of each individual specimen.*
>
> *Grading is not proof testing, even though proof testing can be adopted to increase confidence in selected material, if desired. Proof testing is beyond the scope of this standard.*

Definitions and nomenclature

In the interest of consistency, clarity and avoidance of ambiguity some terms will be defined from the outset of this Working Paper. These are:

Strength: the stress at failure. Strength is a property that is dependent on the material and is independent of the geometrical shape of the element constituted from the material. It will be represented by f.

Bending strength: the maximum stress that an element subjected to bending moment can resist. In this Working Paper it will be interpreted to mean the same as Modulus of Rupture, and will be represented by $f_{m,0}$.

Capacity: the maximum force or bending moment an element can resist. It is dependent on both the material's properties and the geometry of the element. It will be represented as F for force and M, for bending moment.

Flexural capacity: the maximum bending moment an element can resist, and will be represented by M_0.

Static modulus of elasticity: the modulus of elasticity determined from a bending test such as that contained in *ISO 22157-1 Bamboo – Determination of physical and mechanical properties – Part 1: Requirements* (ISO, 2004a). Modulus of elasticity is material dependent, and assumed to be independent of element geometry. In the context of this Working Paper it will be interpreted to mean the same as apparent modulus of elasticity, or MOE. It will be represented by $E_{m,s}$.

Dynamic modulus of elasticity: the modulus of elasticity inferred from the velocity of propagation of stress waves along a bamboo culm. It will be represented by E_d. The technique utilised will be explained in greater detail in the body of this paper.

Flexural stiffness: the product of modulus of elasticity and the moment of inertia (or second moment of area) for an element. Also known as bending stiffness. It will be represented as EI, $EI_{m,s}$ when derived from bending tests, and EI_d when calculated using E_d.

Characteristic property: as defined in *ISO 22156 Bamboo – Structural Design* (ISO, 2004b). It is a material property estimated from test results, and represents the 5th percentile value with 75% confidence.

Chapter 1: What is grading?

Structural design codes or standards are based on a reliable knowledge of the mechanical properties of the material under consideration. All materials have intrinsic variability. However, the amount by which their mechanical properties vary differs substantially. Control over factory made products, such as steel, precast concrete and aluminium, is very high, whereas control over natural products, such as timber, or labour intensive products, such as masonry, is low. Wherever control is low, variability is high, and conversely where control is high, variability is low.

In the case of timber, one way to reduce variability is to subject every single piece of timber that is to be supplied to the market to a non-destructive process called *strength grading* (Trujillo *et al* 2016). Strength grading is a process of sorting timber on the basis of its strength (Benham *et al*, 2003). Other forms of grading, for example by aesthetic appearance, are also possible.

Strength grading in timber can be of two types: *visual* or *machine* grading. Visual grading relies on observing and measuring physical characteristics that are accessible on the surface of the piece of timber and detectable to the plain eye; for example the size, position and number of knots. It requires a trained operator to carry out the process, though it can also be machine assisted. Figure 1 briefly explains the process for timber and Table 1 lists such properties. Visual grading is the oldest form of grading and is not very capital intensive. It is slow and can be labour intensive, requiring specially trained, experienced personnel to undertake the task. It also results in a more conservative use of the material. It has the benefit that it can be checked after the grading operation has taken place. The sorting criteria used for visual grading are known as 'grading rules'. Traditionally, these grading rules have been set nationally and are influenced by the history and resource of a country. Grading rules can be adapted to suit the needs of a producer (Ridley-Ellis *et al*. 2016). The grading rules are then used to sort the material into grades. Each grade will have a list of properties associated with it.

In the case of bamboo, Janssen (1981) suggests that "compared with wood, bamboo seems to be more regular: problems as to knots or slope of grain do not occur." This implies that there are fewer visual characteristics to control for. This could be both beneficial and problematic if visual grading were to be adopted for bamboo. Table 2 from Trujillo (2013) lists some factors known to affect the strength of bamboo that could be controlled visually.

Table 1. Aspects to be considered in visual grading of timber and bamboo – adapted from Trujillo (2013)

Material	Timber (rectangular cross section)	Bamboo (round)
Example of code	e.g. EN 14081-1 or BS 4978	e.g. Chapter G.12 from 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 is also controlled.
Warp or distortion	Rectangular cross-section timber presents several forms of warp: bow, spring, twist and cup. All restricted, except cup.	Out-of-straightness 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.

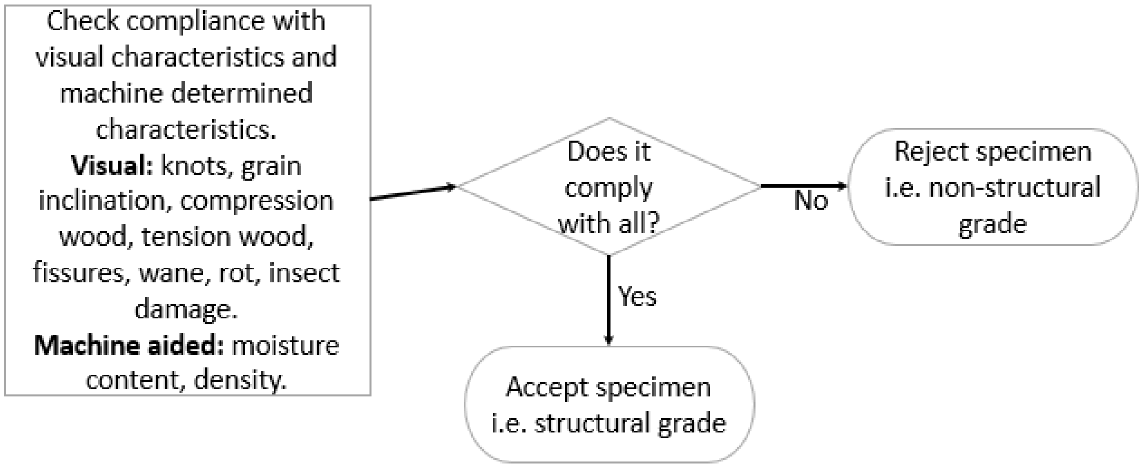

Figure 1. Summary of visual grading process for timber

Table 2: Known factors that affect the strength of bamboo – adapted from Trujillo (2013)

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.Not all mechanical properties are affected by age to the same extent.
Position along the culm	Strength (i.e. ultimate stress) increases with height. So 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.
Load duration	Similarly to timber, under the presence of a long lasting load, bamboo seems weaker than when subjected to a short-term load.
Geometric characteristics	Taper and warp (bow) reduce the load-bearing capacity of a member in compression.
Splitting	Splitting can seriously reduce the load-bearing capacity of a member in bending, shear and compression

Machine strength grading uses a machine to sense timber properties, predicting or inferring properties that are to be used as sorting criteria. The properties that are sensed non-destructively by machine are known as *indicating parameters or properties (IP)*. IPs are better predictors of quality than those that can be measured by visual grading, and the grading can be done faster and with less risk of human error (Ridley-Ellis et al. 2016). The most common IP is the modulus of elasticity of a plank of wood. The properties that are used for sorting are known as *grade determining parameters or properties (GDP).* In Europe, timber grading is based on three key GDPs: strength, stiffness and density. Typically, the modulus of elasticity is measured non-destructively and then used to infer the bending strength. Both properties act as GDPs.

Though machine grading is more accurate, faster and less conservative than visual grading, it still requires the visual inspection of defects. Figure 2 shows a strength grading machine capable of grading timber boards, by measuring their modulus of elasticity.

Prior to undertaking the grading operation, a machine must be calibrated. Calibration requires undertaking hundreds of destructive tests in order to find a reliable correlation between the IP (or IPs) and the GDP (or GDPs) for a given species originating from a specific plantation or region. Machine grading is capital intensive, because it has the upfront cost of purchasing the grading machine and undertaking the testing. Not all mechanical properties need to be tested to calibrate a machine, only those required for the IPs and GDPs.

Once the grading process has taken place, it is then possible to assign a piece of timber to a 'strength class'. Strength classes are not necessarily species specific. Each class has an associated list of physical and mechanical properties (Benham *et al*., 2003) that have been established to be adequate for the class. These properties are known as 'secondary properties' and can be inferred from the GDPs. Equations that relate one or more of the GDPs to these secondary properties deliberately provide conservative results, and are based on a great deal of past testing i.e. it does not need to be done in order to calibrate a grading machine. Secondary properties are typically properties that are not critical to design. Using secondary properties reduces the cost of preliminary testing.

Mechanical processes, other than bending, have been used for grading (and more are continuously being developed), including X-rays, ultrasonic waves, density, hardness, or a combination of these processes.

Figure 2: A Metriguard stress testing machine used for grading of timber planks

There are two types of machine grading: *output control* and *machine control*. In machine control calibration of a machine is done through carrying out thousands of destructive tests and correlating the GDPs to the IP (or IPs) – as depicted in figure 3. Machine control is costly to develop, but since it does not require regular destructive testing, it is fairly simple to run. However, it does require strict assessment and control of the machines used. Output control requires a smaller initial set of tests, but requires the organisation using the grading machine to regularly undertake destructive testing, or proof loading. This increases the operational costs. The settings of the machine are regularly adapted to optimise yield (Ridley-Ellis et al, 2016).

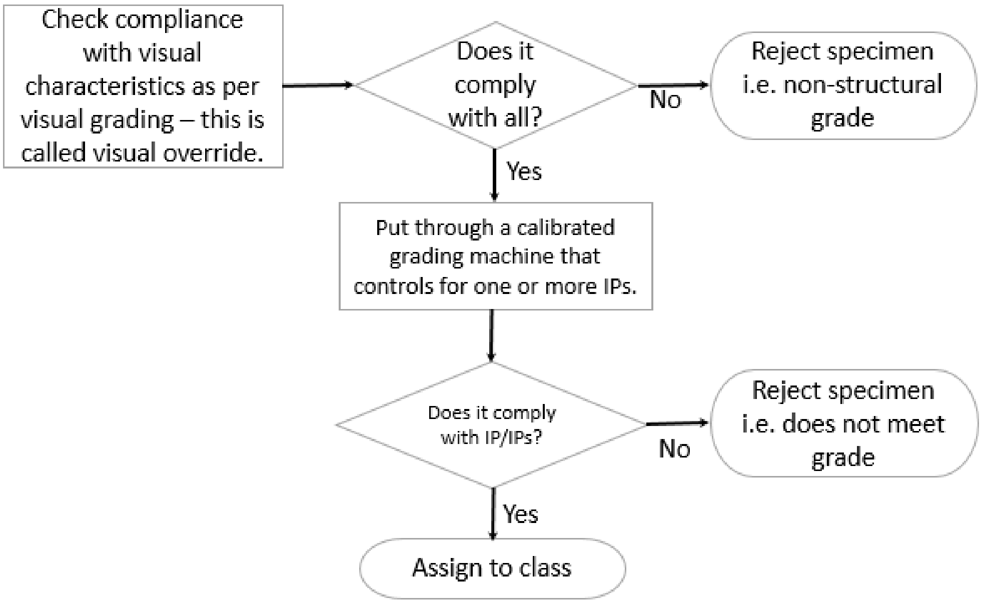

Figure 3. Summary of Machine Grading process

The statistical methods used for calibration and grading imply that some pieces will be marked as rejects. The pieces that are not rejected will be marked with a specific strength property (Behnam *et al*, 2003). It is important to note that the strength of every single piece in a batch is not known; all that is known is that there is a high probability that the strength of a graded piece will have the specified strength (Ridley-Ellis*et al* 2016). It is therefore meaningless to regrade pieces of timber that were rejected. If regrading is to take place, the whole batch needs to be regraded. This is a disadvantage of machine grading.

Grading instils confidence into the supply-chain. It is beneficial to the process of designing and building with timber, as it reduces the variability of the material and minimises the risk that very weak pieces are used within a structure. It allows suppliers of higher strength material to commercialise it as such, and therefore receive a better price for their product. It allows engineers to reduce factors of safety associated with material properties in the process of design, as they will have greater confidence in the strength and stiffness properties of the material. The outcome is safer yet more economical structures, alongside a more formal supply-chain. The downside to grading, particularly machine grading, is that the large capital costs associated with developing and operating it may marginalise smaller producers or dissuade larger producers from making an initial investment.

Status quo of bamboo grading

Although visual grading of timber is a very old practice, it only became standardised in the early twentieth century. Machine strength grading emerged in the second half of the twentieth century. Wherever a tradition of building with bamboo exists, bamboo builders use some form of visual grading. A formalisation of these visual grading practices has been incorporated into the few existing codes and standards for bamboo throughout the world. Table 1 contains some examples of these grading rules contained in Colombia's NSR-10 (AIS, 2010). The National Building Code of India (NBC,2004) contains similar grading rules. It also contains a grading system for bamboo, based on external diameters and material properties (Tables 3 and 4). At an international level, ISO 22156 Bamboo – Structural Design, suggests in clause 17 that grading needs to take place, but provides very few specifics.

Table 3 – Grading by mean outer diameter to NBC of India (Clause 4.4.2.1)

Group(s)	Grade	Diameter
A & B	Special	$> 70, \leq 100$
	I	$> 50, \leq 70$
	II	$> 30, \leq 50$
	III	≤ 30
C	I	$> 80, \leq 100$
	II	$> 60, \leq 80$
	III	≤ 60

Table 4 Species grouping to NBC of India (Clause 4.1.1.)

Group	MOR (N/mm2)	MOE (kN/mm2)
A	> 70	> 9
B	$> 50, \leq 70$	$> 6, \leq 9$
C	$> 30, \leq 50$	$> 3, \leq 6$

No national or international building code (or standard) contains any guidance on machine strength grading for bamboo. However, there is some experimental evidence that non-destructive testing can be used to infer strength properties of bamboo, which could form the basis of a machine grading process. Janssen (1995) identified that density could be correlated to several mechanical properties, including compression, bending and shear strengths. These proposals have been written into India's NBC, but are only suggested as an alternative to testing, not as part of a grading procedure. Gnanaharan *et al* (1994) identified the potential to infer $f_{m,0}$ and $E_{m,s}$ from data that had been measured non-destructively, such as diameter and density. Lin *et al.* (2006) demonstrated that readings of dynamic modulus of elasticity (E_d) by means of an ultrasonic wave test instrument, combined with drilling resistance techniques, could be used to establish relationships between E_d against density (ρ), $E_{m,s}$ and $f_{m,0}$. Trujillo (2013) identified that $E_{m,s}$ could act as predictor of $f_{m,0}$, and density (ρ) as a predictor of compression strength parallel to fibres $f_{C,0}$, based on experimental data obtained by others. However, none of these publications could be used as a basis for a machine grading procedure for bamboo.

Currently, as discussed, only national building codes (e.g. NSR-10 and NBC 2004) provide mechanical property values for use in design, which have been determined from experimental data. NSR-10 provides the design values, as *permissible stresses*, for only one species, *Guadua angustifolia Kunth*, whereas NBC provides *safe working stresses* for 16 species. NBC declares a different safe working stress for each species, and therefore does not seem to make use of the groupings or grades contained in tables 3 and 4.

NSR-10 explains how the permissible stress values were derived, which could also be used to derive design values from destructive tests. However, this is not a requirement or allowance of the code. NBC provides a method to determine permissible stress values from density values for species of unknown properties if there is no access to testing facilities. This procedure is presumably based on that presented by Janssen (1995). However, NBC does not require that the density of culms is controlled for during the grading process.

In summary, there is no international standard for grading bamboo. National codes contain some visual grading rules, but these are limited to a 'binary' form of grading: accepted or rejected. The possibility of using the visual grading process to sort bamboo into a range of grades has not been developed. Machine grading procedures do not exist despite some evidence that it may be possible. It is likely that the status quo of bamboo grading results in either unsafe or uneconomical structures, and hinders its perception. This Working Paper will demonstrate that grading (visual or machine) is possible for bamboo. It will also outline some potential methodologies to be considered, with the hope that they result in a more formal supply chain and promotion of bamboo to the mainstream.

Chapter 2: Visual grading of bamboo

Some form of visual grading of bamboo already is taking place around the world, albeit to different standards and compliance levels. Since October 2013 INBAR's Bamboo Construction Task Force has been working towards an international bamboo grading standard through ISO Technical Committee 165. It is expected that this process will be completed in 2018. This section discusses the current thinking behind the development of the standard with regards to visual grading.

The process of arriving at a visual grading procedure is fairly straightforward. Firstly, the organisation developing the procedure will need to propose grading rules that can be assessed visually, though it may be possible to combine these with readings from instruments for better results. The grading rules should be based on characteristics known to affect the strength or load-bearing capacity of bamboo elements. The aforementioned draft ISO standard (CD 19624) proposes that these characteristics are divided into: conditional, geometric and dimensional properties. It defines them as follows: *"conditional properties refer to the state of the material in terms of moisture content, age at time of harvesting, insect and/or fungal damage, and defects such as fissures and longitudinal indentation. Dimensional properties refer to diameter, wall thickness, internodal length and culm length. Geometrical properties refer to bow, taper and ovality."* The specifics of each of these will be discussed later.

Once the grading rules have been set, the material will be graded accordingly. One possible outcome of the grading process for any given piece is that it is rejected. It is important to note that, unless a piece complies with all of the grading rules for the given grade, it will be rejected.

Conditional requirements

It is not the intention of this Working Paper to set out the exact requirements that are to be adopted during grading, but it will layout some recommendations and suggestions. It is recommended that grading rules state that pieces with some indication of insect or fungal damage are rejected, though grading rules could adopt a more nuanced view accepting some exceptions. In terms of age at the time of harvesting, although there is evidence for optimal ages at which to harvest in terms of strength properties, this is a requirement that is very difficult to enforce at the point of grading. This is more readily controlled at the plantation, if at all. Therefore, it is not recommended to include age at harvesting as a grading rule unless it can be controlled for elsewhere in the supply chain. Nevertheless, there is a real risk that age is only controlled for during Initial Evaluation (i.e. the stage when strength characteristics are being determined), but becomes untenable during the day-to-day operation of the grading process. In this case an unsafe bias will have been introduced, which could result in an over-estimation of the strength of the species. For more on this refer to the section titled 'Initial Evaluation'.

Finally, there is the matter of cracks or splits. Bamboo tends to split longitudinally. The width, depth, length and position of these cracks or splits will affect the load-bearing capacity of an element, though the extent of this effect has yet to be established. Fissures are cracks that are clearly visible on the surface of the culm, originating on the surface of the culm and developing towards the interior (figure 4). Interior cracks are harder to identify visually, they originate in the interior face of the culm wall and may only manifest themselves as a depression or indentation on the surface of the culm (figure 5). The Indian NBC refers to this phenomenon as ‘collapse’.

Splitting tends to take place during the drying process and can be minimised if the drying is undertaken in a controlled manner. Therefore, it is recommended that only dry[1] (or seasoned) pieces of bamboo are graded, as green (unseasoned) bamboo could develop this defect after the grading process has taken place. However, a two stage grading process is possible, where material is graded for other criteria that can be measured in green (or unseasoned) condition, in order to avoid the expense of drying a piece that will not pass other criteria. As rejecting all manifestations of cracks is likely to be too onerous, acceptance of limits needs to be proposed within the grading rules. These should be based on experimental evidence of their effect. The Colombian NSR-10 limits cracks to 20% of the length of the culm, but the basis for this criteria is unknown to the authors.

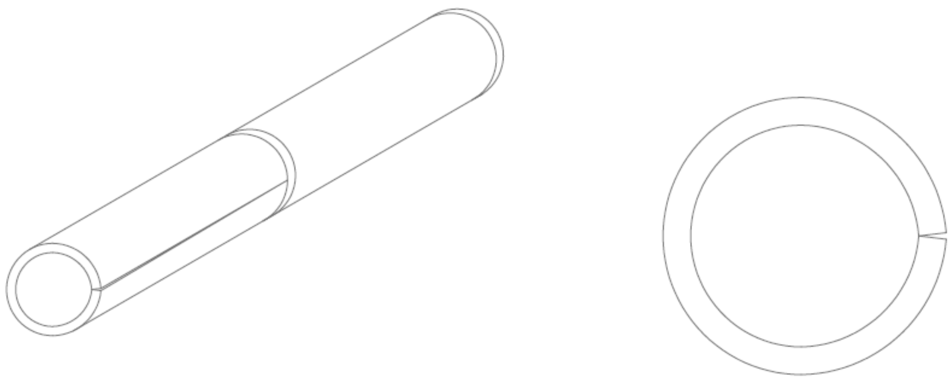

Figure 4: manifestation of fissure on surface of culm and cross -section through fissure.

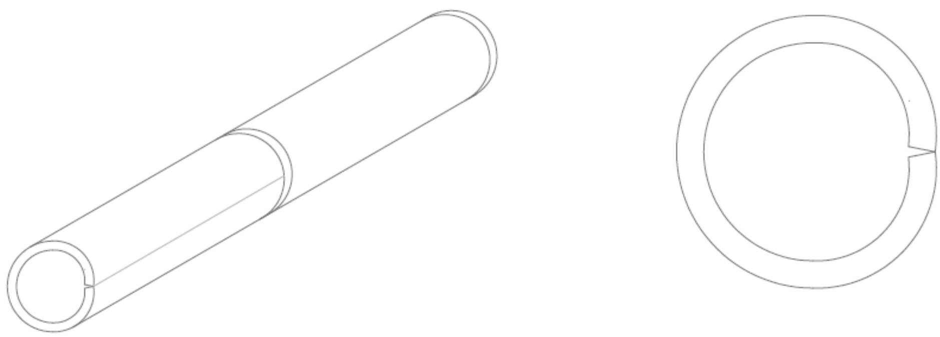

Figure 5: manifestation of longitudinal indentation (very faint) and cross -section through internal fissure and associated indentation.

[1] Dry bamboo may be defined as bamboo with a moisture content very close to the Equilibrium Moisture Content i.e. the moisture content of a piece of bamboo that has been in a given environment for a very long period of time. This will typically be between 10% and 18%.

Dimensional requirements

External diameter

Arguably the most important dimensional property of a bamboo culm is its external diameter. This is demonstrated in figures 6 and 7, which show the effect of changing a single parameter to a benchmark for a hypothetical section with a wall thickness of 10 mm and external diameter of 100 mm. From figure 6 it may be observed that a 10% increase in bending strength ($f_{m,0}$) of a section results in a 10% increase of its flexural capacity (M_0). A 10% increase in wall thickness, without increasing the external diameter, increases the flexural capacity by less than 7%. Whereas, a 10% increase to the external diameter will result in more than a 24% increase in the flexural capacity. The argument is even more compelling for flexural stiffness (EI), where a 10% increase to diameter will result in a 37% increase (figure 7). Therefore, it is recommended that any grading process beyond a binary 'accept-reject' system should use diameter as a grading criteria if flexural capacity (M_0) is a GDP.

A point to consider is the definition of external diameter, which could be any of the following:

a) The average of the two orthogonal readings taken at the top and the two orthogonal readings taken at the bottom of a piece. For sections with a large taper, it has the disadvantage that the flexural capacity or the buckling load of a piece may be overestimated, which is undesirable. This can be resolved by controlling for taper (see geometrical requirements).
b) The average of two orthogonal readings made at the thinnest end of a piece. This would ensure that everywhere along the culm the required diameter is met. It will also be faster than method a). However, if a specimen has a very ovalled cross-section, this can lead to overestimating or underestimating the piece's flexural capacity, which is also undesirable. This can be resolved by controlling for ovality (see geometrical requirements).
c) The smallest reading for diameter at the thinnest end of the piece. This approach avoids any concern about ovality or taper, and should be very quick to record. However, there may be applications were it may be desirable to ensure pieces have a diameter within a certain range, in which case method a) may be the most appropriate.

Measurements of diameter can be done by means of a ruler, tape or, preferably, a Vernier calliper. Alternatively, diameter could be measured with a 'diameter tape', which is a tape that reads diameter from the circumference, and therefore provides an immediate average for the section.

During Initial Evaluation, only method a) should be used, as any correlation derived using methods b) or c) could lead to an unsafe bias, if the test pieces were more tapered than normal. This does not preclude the use of other methods to measure a diameter that may be required in ISO 22157-1.

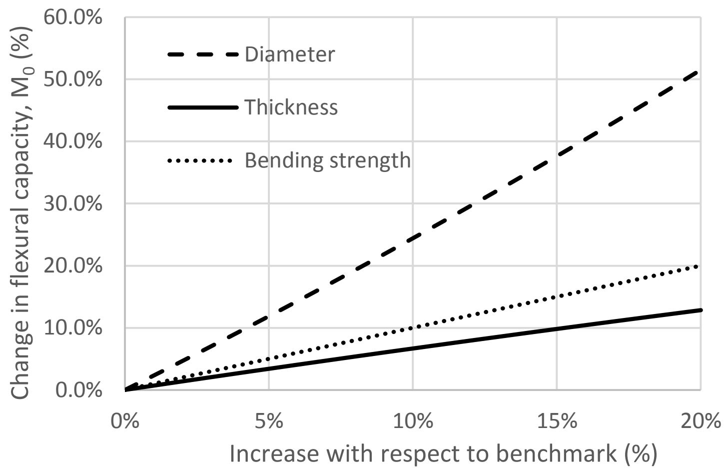

Figure 6 – Sensitivity of flexural capacity (M_0) to changes to other properties of a hypothetical bamboo culm

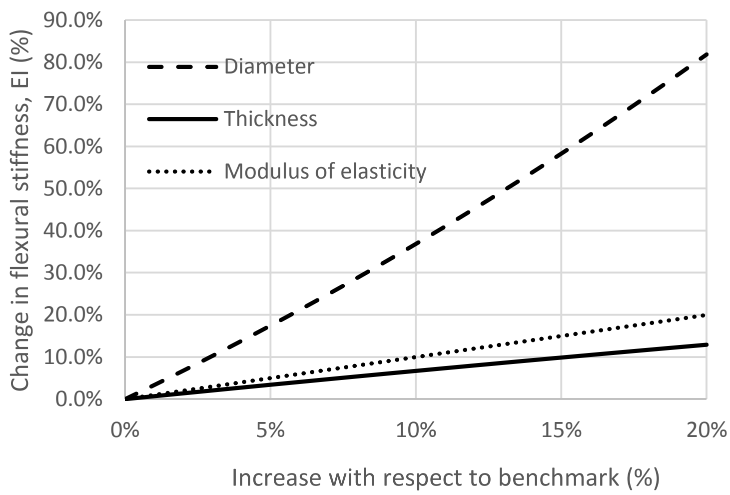

Figure 7 – Sensitivity of flexural stiffness (EI) to changes to other properties of a hypothetical bamboo culm

Wall thickness

Wall thickness may have a relatively small effect on flexural capacity and stiffness as evidenced in figures 6 and 7, but it is arguably critical to shear and tension perpendicular capacities. As these failure modes can also be critical in design, it is recommended that some consideration should be given to wall thickness during grading.

Wall thickness can be either directly measured during the grading process, inferred from species specific diameter-to-thickness relationships, if known, or calculated from the measured mass and diameter of the specimen and an assumed density for the material.

When directly measured, wall thickness is typically measured at the middle of the internode region, and away from a node, and can be controlled during grading by any of the following methods:

a) The average of four measurements taken around the circumference of the culm at angular spacing of 90° at both ends of the piece,
b) The average of four measurements taken around the circumference of the culm at angular spacing of 90° at the narrowest end of the piece,
c) The smallest measurement taken at the narrowest end of the piece.

Measuring wall thickness can be difficult if the piece of bamboo was cut in the proximity of a node, and for this reason using methods to infer thickness can be beneficial. It may be possible to use species' specific equations that permit inference of a wall thickness. Shigematsu (1958) and Harries *et al* (2016) provide examples of such equations. Tables 13 and 15 of this Working Paper provide an example of characteristic wall-thicknesses derived from the tests.

As was noted for external diameter, during Initial Evaluation only method a) should be used to determine wall thicknesses during the Initial Evaluation phase, to avoid unsafe biases. This does not preclude any other requirement contained in ISO 22157-1.

Other dimensional properties
Although less critical to structural design, it may be deemed necessary as part of a grading process to control for internode length. Nodes play a role in the prevention of propagation of splits and buckling, and therefore specimens with very long internode lengths maybe considered undesirable for certain species and/or applications.

When directly measured, internode length can be controlled during grading by either of the following methods:

a) The average of all internode lengths along piece,
b) The average of internode lengths readings measured at the top and bottom of the piece.

The mechanical properties and dimensions of bamboo vary along the culm. Typically diameter and wall thickness decrease, but density and strength increase along the culm, therefore the length of pieces during grading should be fairly consistent with the lengths studied during Initial Evaluation. Failure to do so could result in introducing a bias into the grading procedure.

Geometrical requirements
Dimensional properties are typically directly measured from the specimen. Geometrical properties are obtained from making measurements to the specimen *and* making calculations. The geometrical properties listed require consideration as they may be strength reducing.

External taper
External taper, or simply taper, is the variation in diameter along the length of a piece. Nugroho and Bahtiar (2013) define external taper as

$$t_e = \frac{D_{e,b} - D_{e,t}}{L}$$

Where

$D_{e,b}$ is the external diameter at the base of the piece

$D_{e,t}$ is the external diameter at the top of the piece

L is the length of the piece.

ISO 22156 and India's NBC limit external taper to 1:170 (0.58%), whereas Colombia's NSR-10 limits external taper to 1%. ISO 22156 points out that external taper has the effect of reducing the load bearing capacity of columns, and recommends using 90% of the moment of inertia for this reason. It also recommends that the moment of inertia used for calculations in design is calculated from the average of wall-thicknesses and external diameters, and not from an average of the moments of inertia from the top and bottom of a piece. This results in a lower (i.e. safer) moment of inertia for calculations.

Figure 8. Side elevation of a bamboo culm showing external taper.

Internal taper

Internal taper is the variation to the internal diameter along the length. Nugroho and Bahtiar (2013) define it as:

$$t_i = \frac{D_{i,b} - D_{i,t}}{L}$$

Where

$D_{i,b}$ is the internal diameter at the base of the piece, i.e., $D_{e,b} - 2t_b$, where t_b is the wall thickness at the base of the piece

$D_{i,t}$ is the internal diameter at the top of the piece, i.e., $D_{e,t} - 2t_t$, where t_t is the wall thickness at the base of the piece

L is the length of the piece.

According to Nugroho and Bahtiar (2013), if stress at failure in a four-point bending test, such as used in ISO 22157-1, is calculated at mid-span, this results in an underestimation of the real stresses. For example, for a 0.5% taper ($t_e = t_i$) the real stress will be underestimated by 8.5%. During Initial Evaluation, this is no serious grounds for concern, as this results in conservative bending strength, $f_{m,0}$, values. However, the opposite is true also during design. In the presence of taper, the flexural capacity, M_0, of a member may be overestimated if taper is not taken into account. This could result in an unsafe design. Analysis produced by Nugroho and Bahtiar (2013) indicates that internal taper can also lead to significant under/over estimation of strength in four-point bending, particularly if the internal taper is negative. Negative internal taper occurs when the internal diameter is larger at the top than at the bottom, which is common for pieces originating from the lower part of the culm. Therefore it is recommended that special consideration is given to the effect of internal taper, particularly negative internal taper, at both grading and Initial Evaluation. No current standard recommends controlling for internal taper.

The level of taper varies from species to species. If limits are to be adopted, it is recommended that these are consistent with the characteristics of the species in order to avoid using a limit that results in excluding too many pieces in the grading process. As mentioned earlier, if diameter and wall-thickness are assessed using methods b) and c), consideration for taper can be omitted during grading. However, the effect of taper (both internal and external) should still be considered during initial evaluation.

Figure 9. Longitudinal section through a bamboo culm showing the taper in the culm walls, which is measured by the internal taper.

Out of straightness

Out-of-straightness may be defined as a measure of variation of the culm from a straight condition; reported as the ratio of transverse variation to culm length. Other names are given, such as curvature and bow. The specifics of these differences are rarely discussed. Standards and authors have a wide range of limiting values. Table 5 lists some of these.

Table 5 – Examples of out-of-straightness limits in standards and publications

Source	Limit
NSR-10	L/300
NBC 2004	L/80
Yu *et al*(2003)	For Kao Jue (*Bambusa pervariabilis*) L/100 or $0.15D_e$, whichever is smaller Mao Jue (*Phyllostachys pubescens*) L/200 or $0.15D_e$, whichever is smaller
Moreira and Ghavami (2001)	L/150 (species studied: *Dendrocalamus giganteus*)

Though these limits may be species specific, it appears that the limits for bamboo potentially need not be as onerous as those for timber. The important consideration is that the limits set in a grading standard are consistent with the limits assumed during calculation of elements subject to compression. ISO 22156 states in the design of members subject to compression "*the bending stresses due to initial curvature, eccentricities and induced deflection shall be taken into account*".

Ovality or eccentricity
Ovality, defined as the ratio between the smallest external diameter and largest external diameter reading measured at one end of a specimen, should also be considered during grading. Bahtiar *et al* (2013) considered the effect of ovality in flexural members, though the authors characterised it as eccentricity in the geometric definition of an ellipse. Their finding is that ovalities can result in an overestimation or underestimation of the moment of inertia (or second moment of area), if the section is assumed to be round. They found for a range of species that on average specimens are more elliptical shaped than round. However, on average the level of ovality was around 0.98 (eccentricity = 0.20), resulting only in a 1% over or underestimation of strength. The highest level of ovality they observed was 0.86 (eccentricity = 0.51), resulting in an over or underestimation of strength of up to 8.7%, which indicates that ovality may be meaningful and important to consider during grading, and particularly during Initial Evaluation. As mentioned, consideration for ovality may be omitted during grading if method c) for measurement of external diameter is used.

Initial Evaluation
Prior to the implementation of a visual grading procedure it is necessary to obtain evidence of what the structural properties of the given grade(s) will be. This evidence will typically be obtained experimentally following the test procedures contained in ISO 22157-1. *Initial Evaluation* is the process of relating grading rules to experimentally derived structural properties.

The sample used during Initial Evaluation requires careful consideration, as it may lead to a bias in the data. When determining a sample for initial evaluation the main requirement is that the sample is representative of the material that is to be graded during production.

When selecting the sample the ISO CD 19624 states:

1. *The sample must originate from the same source region (i.e. geographical region)* [and same species]*that is to be used during production. Grading cannot be applied to material originating from outside the source region used in the initial evaluation.*

2. *The sample must be similar to the production material in terms of variability of material originating from the source region. If within the source region particularly large or small specimens are known to occur, these are to be included in the sample. If zones within the region are known to produce material of lower quality, and are to be exploited during production, these must be included.*

3. *If the source region covers more than one country, material originating from each country should be included.*

4. *If control for age at plantation is not possible or practical to implement, the sample must contain specimens of a range of ages.*

5. *Samples that fail any of the grading rules should not be included in the sample.*

On this last point, it is worth noting that the value of a grading procedure depends upon the selection of appropriate grading rules.

Care should be given to introducing a bias through level of maturity, taper or ovality. A conservative approach for taper and ovality is to determine wall thickness and external diameter during initial evaluation using the respective methods a), but then using methods b) or c) during the grading operation. However, care should be given to ensure that the sample contains few pieces with negative taper, or no more than would be expected to normally occur in the day-to-day grading process.

The size of the sample also presents a challenge. Larger samples will result in less conservative design values increasing the commercial advantage of grading, but as tests can be costly, this will increase the initial investment. Harries and Glucksman (2016) have proposed economical test methods, which should lower testing costs, and thus encourage larger samples. ISO 22156 suggests that a minimum of 12 specimens should be used. However, it is statistically advantageous to use a sample size of at least 20 specimens, the larger the sample the greater the confidence in the results. Therefore at least 20 tests per grade should be considered, though 40 would be preferable. This might seem costly, but when all the possible sources of variation are considered e.g. position along the culm, diameters, and variations in quality and maturity, it is by no means excessive.

An important question is whether all mechanical properties listed in ISO 22157-1 would need to be included during Initial Evaluation (four mechanical tests in current version – compression, bending, shear and tension – and this is likely to increase to six in the new version expected in 2017). Some testing can be avoided, depending on how well a species, source region and grading procedure is understood. If some tests can be avoided, resources can be focused on the grade determining properties (GDPs), ensuring that the sample for these was as large as possible. Here are some possible scenarios:

1) The grading procedure that is proposed has been successfully used by other producers for the same species and source region. In which case, new testing can be avoided entirely and the properties per grade used by other producers may be linked to this new grading operation. If a new procedure is being proposed, e.g. different set of grading rules, it is not appropriate to link the new grades to any extant grade properties.
2) If a species has been studied across several regions, it may be possible to set **secondary properties** using these properties. A conservative approach would be to use the lowest result from all of the regions for each of the properties. The tests during Initial Evaluation would be limited to those required for determining the GDPs. For example, if shear and bending are selected to be the GDPs, compression and tension tests could be avoided.
3) Alternatively, **secondary properties** could be linked to experimentally derived GDPs using conservative links across properties that have been postulated and demonstrated. Examples could be:
    a. Determining compression strength from density as proposed by Janssen (1995), and suggested in NBC 2004.
    b. Assuming that the tension strength parallel to the fibres, $f_{t,0}$, equals the bending strength, $f_{m,0}$. This is possible because bamboo specimens tested for bending rarely, if ever, fail in tension.

c. Assuming that the compression strength parallel to fibres, $f_{c,0}$, equals half of the bending strength, $f_{m,0}$. Observation of the declared strength values across the 16 species contained in Table 1 from NBC 2004, demonstrates that this is a conservative assumption (the average ratio is 1.23).

It is worth noting that some GDPs can be measured without undertaking destructive testing. For example, density, linear mass, external diameter and wall thickness can be measured for tens, if not hundreds of specimens without incurring major costs. Therefore, an effort should be made during Initial Evaluation to make the sample for *these* properties as large as possible, increasing the reliability of this data, even if the sample for the mechanical (i.e. destructive) testing is smaller.

Finally, it is important to reiterate that the value of a grading procedure will depend upon the selection of appropriate grading rules. This means, grading rules should include criteria that are known to affect strength or capacity, and that can be readily measured during grading.

Periodic evaluation

The structural properties derived from the Initial Evaluation should be routinely evaluated to ensure they remain consistent. The frequency at which periodic evaluations should take place depends on the levels of production. A suggested interval between periodic evaluations for visual grading could be two years or 60,000 m of graded culms, depending on whichever comes first.

Summary

Some form of visual grading of bamboo already exists within codes and standards across the world. Most grading consists of an exclusion of material of inadequate properties, but does not serve to link the grading process to a list of properties unique to the grade. Properties stated in codes are universal across the species, without due regard to the origin of the material. These values are either excessively conservative, punishing producers of better quality material, or unsafe, taking no account of material of lower quality. The next section of this working paper focuses on experimental data obtained with the aim of piloting a grading methodology for a species of bamboo.

Chapter 3: Experimental basis

Research for this Working Paper collated over 1000 experimental results for two bamboo species (*Guadua angustifolia* Kunth and *Dendrocalamus asper*) of commercial interest in South America. The paper provides a summary of the findings for *Guadua angustifolia*. A fuller explanation for the work with *Guadua angustifolia* is contained in Trujillo *et al* (2016). The findings for *Dendrocalamus asper* will be presented in a subsequent publication(s).

Findings for *Guadua angustifolia* Kunth

Three hundred specimens of dry Guadua angustifolia culms were harvested in the municipality of Caicedonia in Colombia and shipped to the UK. Each specimen was 4 metres long, and its age at harvesting and position along the culm was recorded on the specimen using a system as described in Table 6. A range of ages and positions along the culm were included,since it has been observed by numerous authors to affect the behaviour of bamboo (e.g. Correal and Arbeláez, 2010; Trujillo and López, 2016). Age at harvesting was identified by the number shown in italics in Table 6. Therefore a specimen with reference 'M27' was taken from culm 27, which was 2 – 3 years old at the time of harvesting and was the second 4m long piece from the culm from bottom to top.

Table 6: composition of sample identifying range of positions along the culm and age at harvesting.

	Age at harvesting Number of specimens shipped				
Position along the culm	**< 2 yrs** *1-20*	**2 - 3 yrs** *21-40*	**3 - 4 yrs** *41-60*	**4 - 5 yrs** *61-80*	**> 5 yrs** *81-100*
Inferior - I	20	20	20	20	20
Middle - M	20	20	20	20	20
Superior - S	20	20	20	20	20

Specimens were subjected to a range of tests to determine their mechanical and physical properties. Some properties were measured using non-destructive methods, such as mass, moisture content, hardness, modulus of elasticity (determined through bending and/or stress waves). Other properties could only be measured destructively, such as bending strength (MOR). As some of the proposed tests were not contained in ISO 22157-1 Bamboo – Determination of physical and mechanical properties – part 1: requirements (ISO, 2004b), new test procedures were trialled and developed as part of the project. Similarly, adaptations were made to ISO 22157-1 tests to make the testing process either faster or more accurate. The new test procedures and adaptations are discussed hereafter.

Density

While the method contained in ISO 22175-1 for determining density, referred to as 'mass by volume', is an accurate procedure, it is also laborious, requiring the cutting of smaller pieces of bamboo that can be readily measured. The method implies that density can only be recorded at discrete locations, not throughout the whole length of a culm. As density varies along the culm (Trujillo and López, 2016), this procedure was deemed of limited value, particularly for the determination of dynamic modulus of elasticity, E_d. For this reason, density was estimated using a representation of culm as a hollow cylinder, as per equation (1). This approximation to a cylinder allows for linear taper of both wall thickness (t) and external diameter (D), but ignores the slight bulging that occurs at the nodes, the presence of the diaphragms to the interior of the node, and the fact that taper can be non-linear (Trujillo et al, 2016).

$$V = l_{sp} \times \frac{\pi}{4}\left[D_{mean}{}^2 - (D_{mean} - 2t_{mean})^2\right] \qquad (1)$$

Where

V is the volume in mm^3

l_{sp} is the length of the specimen in mm

D_{mean} is the average diameter as explained in Table 2 and calculated thus: $\left[\frac{\sum_{i=1}^{4} D_i}{4}\right]$, in mm

t_{mean} is the average wall thickness as explained in Table 2 and calculated thus: $\left[\frac{\sum_{i=1}^{8} t_i}{8}\right]$, in mm.

Based on this equation, density could alternatively be estimated for the culm as shown in equation (2).

$$\rho = \frac{m}{l_{sp} \times \frac{\pi}{4}\left[D_{mean}{}^2 - (D_{mean} - 2t_{mean})^2\right]} \qquad (2)$$

Where

ρ is the density in g/mm^3

m is the mass in g.

The accuracy of this method was tested by Walker (2015) by measuring the volume of 15 pieces of 4m length by immersion in water (volume displacement). It was found that the cylindrical model in equation (1) tends to underestimate the volume, yet the correlation is very good ($R^2 = 0.99$) – as shown in Figure 10. Therefore, it was deemed acceptable to estimate the volume, and hence the density, using the cylindrical model. The validity of this approach is also discussed in Trujillo *et al* (2016).

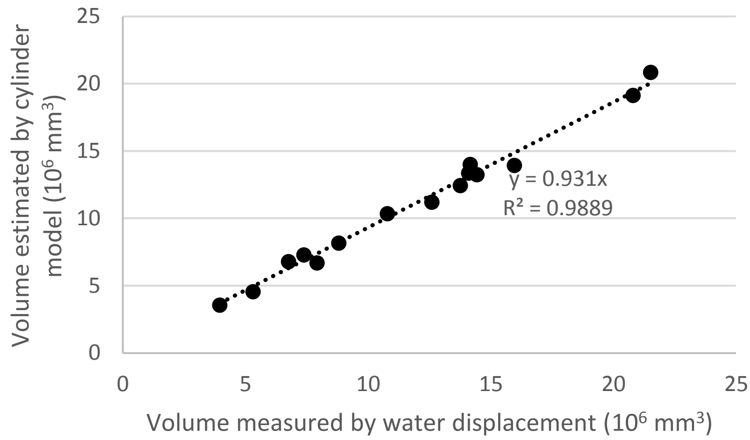

Figure 10 – correlation of volume of bamboo measured by two different methods

Hardness

As discussed, measuring density in accordance to ISO 22157-1 can be a slow, laborious process, which would not be practical to adopt as part of a grading process. Hardness was explored as a proxy for density. Hardness has been correlated successfully to density in timber, and it was felt this could work well for bamboo. The methodology proposed is an adaptation of the Janka hardness test as presented in ASTM D 143, albeit with a smaller size sphere (6 mm diameter – figure 11), as the standard sphere was found to cause splitting of the specimen. Hardness was defined as the average of the forces required to cause a 3 mm indentation to the interior and exterior wall of the culm.

Single correlations between hardness and density were not strong, and multiple regressions that included hardness, wall thickness and position along the culm offered only slight improvements. The strongest multiple regression obtained had an adjusted R^2 of 0.43. This weak correlation, compared to the accuracy found for the cylindrical model discussed above, showed that hardness as a proxy for density did not warrant further research.

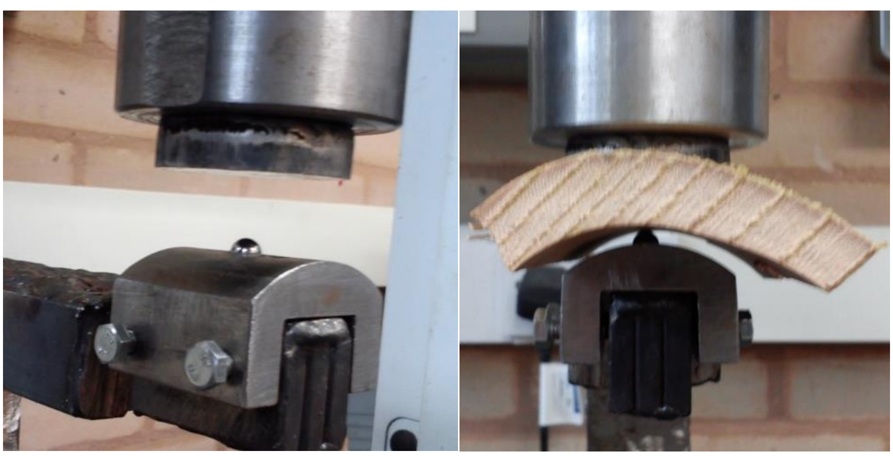

Figure 11 – Device used for measuring hardness to the interior (concave) face of the bamboo wall specimen.

Moisture content

ISO 22157-1 contains a procedure for the determination of moisture through loss of mass by oven-drying. This procedure is accurate, but impractical for a grading process, as specimens are required to remain in an oven for over 24 hours. The use of a moisture meter was investigated. The selected instrument was a Brookhuis FMC microprocessor controlled moisture meter. The process of calibration is discussed in Trujillo *et al* (2016). The accuracy of the moisture meter was found to be acceptable and therefore adopted for the rest of the project.

Static Bending

Flexural tests are ubiquitous to grading in timber. Determination of flexural strength and stiffness properties in timber are pivotal to structural design. The same is arguably true for bamboo, at least when the design of elements and frames is being considered, though connections and splitting also play an important role. ISO 22157-1 provides a procedure for testing bamboo culms in bending, which was adopted for this project with some adaptations.

The first adaptation was to use fabric straps in lieu of the rigid wooden supports and loading blocks as suggested in the standard (Figure 12). Rigid blocks lead to stress concentrations, which could result in lower stresses at failure.

**Figure 12: straps attached to a spreader beam,
which are attached through a hinge to the main loading beam**

The second adaptation was that displacement was not only measured at mid-span to measure deflection, but also over the supports to subtract any deformation caused at the supports. This would result in a more accurate calculation of deflection. Figure 13 shows an LVDT placed over one of the supports.

Figure 13: Displacement was also measured at the supports, to ensure any local deformation could be subtracted from the overall deflection.

The third adaptation was that the loading did not take place at thirds of the span, but instead, the separation between the loading points, shown in figure 12, which was less than a third. The loading arrangement is shown in figure 14.

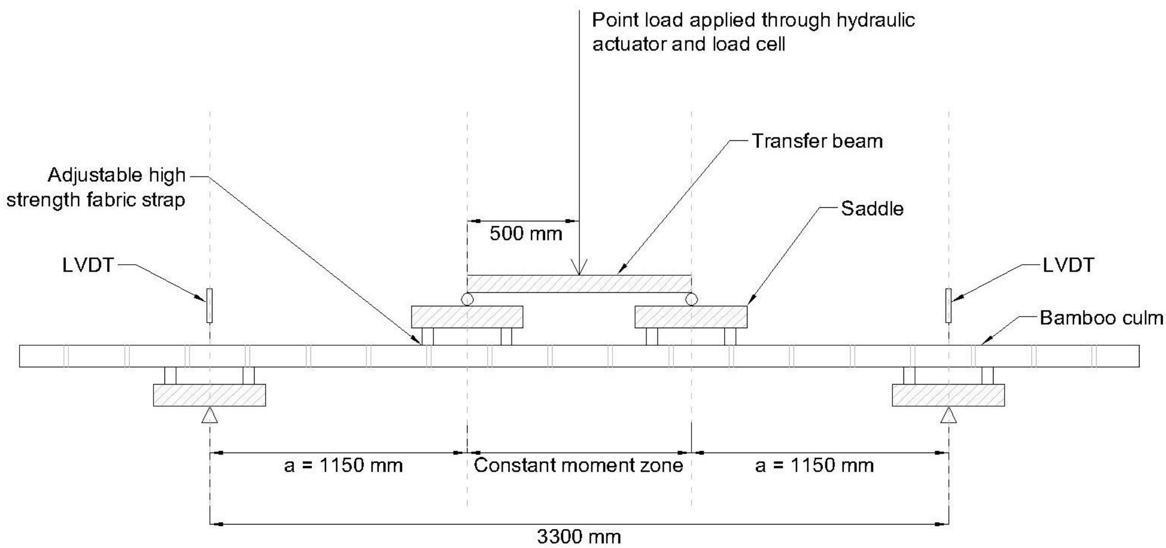

Figure 14: Set-up of static bending test (source: Trujillo *et al*, 2016)

Dynamic modulus of elasticity

Since it had been shown that dynamic modulus of elasticity (E_d) can be reliably measured with equipment developed for timber, it was decided to explore this route for bamboo. Measurement of the dynamic modulus of elasticity (E_d), is a simple process requiring handheld non-destructive instruments, that although quite costly, are not as expensive as the equipment shown in figure 2. If it could be shown E_d correlates to other properties of interest, it would indicate that this approach towards grading could be further explored and developed.

During a first phase a *SylvaTest Duo* was trialled with *Phyllostachys pubescens*, and fairly consistent results were found. Subsequently,*a Brookhuis Timber Grader MTG* (or MTG for short) was utilised. The MTG works by propagating sound waves through the specimen and calculating the wave velocity based on an input of length. As the MTG was not designed for use with bamboo, only readings for fundamental frequency, f_1, were recorded, as it was observed to depend only on the measurement of length. The E_d was calculated as set out in equation (3).

$$E_d = v^2\rho \qquad (3)$$

Where

ρ is the density calculated as in (2),
v is the speed of sound in the specimen calculated thus

$$v = 2l_{sp}f_1 \qquad (4)$$

Where

l_{sp} is the total length of the specimen
f_1 is the fundamental frequency of the specimen, determined using the Brookhuis MTG.

Results

Interpretation of results

Failure modes from the bending test were interpreted as follows:

- Any of the five failure modes observed occurring in the middle third, i.e. the zone of constant moment, were interpreted as being bending failure. Trujillo *et al* (2016) presents a further discussion about the observed failure modes.
- Failure modes occurring in the outer thirds, i.e. the zone of constant shear, were interpreted as being shear failures.

Failure modes occurring directly underneath points of load application were generally interpreted as bending failure modes, unless there was evidence of a shear failure mode. If aspecimen was deemed to have failed in bending, the bending strength, $f_{m,0}$, was calculated as described hereafter. Firstly, the applied bending moment onto the specimen was calculated:

$$M_{ult} = \frac{F_{ult} \times a}{2} \qquad (5)$$

Where

F_{ult} is the maximum applied load (the total load applied onto the two points of load),

a is the shear span, i.e. the distance from one support to the nearest point of load application (this assumes that **a** is the same for both ends of the pole tested). For some of the tests this would be one-third of the free span, but for larger diameter specimens, a shear span equal to 10D (ten times the diameter) was observed.

The bending strength parallel to the fibres, $f_{m,0}$, was calculated from

$$f_{m,0} = \frac{M_{ult} \times D}{2 \times I_B} \qquad (6)$$

Where

M_{ult} as calculated in (5),

D is the average external diameter of the culm,

I_B is the moment of inertia (or second moment of area), calculated thus:

$$I_B = \frac{\pi}{64}\left[D^4 - (D - 2t)^4\right] \qquad (7)$$

Where

t is the average wall thickness of the culm.

When sections were interpreted to fail in shear, the shear strength was calculated as follows:

$$f_v = \frac{2F_{ult}}{3\pi t(d-t)} \frac{(3D^2-4Dt+4t^2)}{(D^2-2Dt+2t^2)} \qquad (8)$$

With all terms previously explained.

The apparent modulus of elasticity from static bending tests, $E_{m,s}$, was calculated as described hereafter. Firstly the flexural stiffness of the section, $E_m I_B$, was determined from the equation

$$E_m \cdot I_B = \frac{(F_{60}-F_{20}) \cdot a(3L^2-4a^2)}{48(\delta_{60}-\delta_{20})} \qquad (9)$$

Where

F_{20}, F_{60} is the applied load at 20% and 60% of F_{ult} respectively, though in some instances different values were used to ensure that only linear behaviour of the specimen was included

δ_{20}, δ_{60} is the deflection at mid-span at 20% and 60% of the deflection attained at F_{ult} respectively, though if the values for F were changed, these would be changed correspondingly.

L is the full clear span (note that it is not the same as l_{sp}),

F_{ult} as previously defined,

a as previously defined.

The value of the modulus of elasticity in bending, $E_{m,s}$ was determined simply by dividing equation (9) by (7).

Summary of Experimental Data

Table 7 summarises the findings for the *Guadua angustifolia* Kunth tests carried out in the UK. It is worth making the following observations from this table:

- Strength values obtained for the sample are not unlike those published by other authors for Guadua (e.g. Correal and Arbeláez, 2010; Lozano, 2010), albeit they are slightly higher, which is attributable to the lower moisture contents used in these tests.
- Despite observing the shear span shown in figure 14, 25% of specimens failed in shear.
- The large coefficient of variation for wall thicknesses reflects the range of positions along the culm that were included in the sample.
- The small variation in moisture content reflects the stable environment offered by the labs.
- The average dynamic modulus of elasticity, E_d ,is fairly similar to the static modulus of elasticity, $E_{m,s}$.

Table 7. Summary of experimental results (Adapted from Trujillo *et al*. 2016)

Property	D_{mean} (mm)	t_{mean} (mm)	ρ (kg/m^3)	E_d (N/mm^2)	$E_{m,s}$ (N/mm^2)	f_m (N/mm^2)	f_v (N/mm^2)	Moisture Content (%)
Sample size	207	207	207	199	168	121	47	207
Mean	103.0	12.9	669	18132	17204	77.9	5.45	11.20%
CoV	13.30%	31.79%	14.63%	15.25%	17.47%	21.52%	23.18%	10.68%

If the results are analysed in terms of age (table 8) and position along the culm (table 9), the data reflects similar trends to those observed by other authors for *Guadua angustifolia Kunth*, and across bamboo species. These trends are:

- Density seems to increase with age.
- The modulus of elasticity and bending strength peak at around 3 to 4 years and then start dropping.
- Density, modulus of elasticity and bending strength increase along the culm.

Table 8. Variation of density, stiffness and strength with age.

	Row Labels	< 2 years	2-3 years	3-4 years	4-5 years	> 5 years	Sample Total
	Sample size	42	41	40	38	46	207
ρ (kg/m^3)	Mean	643	662	663	672	703	669
	CoV	14.9%	15.5%	15.4%	14.1%	12.6%	14.6%
$E_{m,s}$(N/mm^2)	Mean	16825	16701	18579	17508	16526	17204
	CoV	19.4%	13.9%	18.0%	17.1%	16.7%	17.5%
$f_{m,0}$ (N/mm^2)	Mean	74.65	75.70	80.39	81.66	77.39	77.92
	CoV	18.7%	25.3%	23.8%	17.0%	22.5%	21.5%

Table 9. Variation of density, stiffness and strength with position along the culm.

		Bottom	Middle	Top	Total sample
	Sample size	78	73	56	207
ρ (kg/m³)	Mean	602.5	707.5	712.9	669.4
	CoV	11.8%	12.5%	12.9%	14.6%
$E_{m,s}$ (N/mm^2)	Mean	15715	18363	18491	17204
	CoV	14.5%	16.2%	16.6%	17.5%
$f_{m,0}$ (N/mm^2)	Mean	73.87	80.54	84.57	77.92
	CoV	18.3%	17.7%	31.1%	21.5%

Correlations between properties

The prospect of developing a grading methodology will depend to some extent upon identifying correlations that permit reliable properties that can only be measured destructively, to properties that can be readily measured non-destructively. For the subsequent analysis, bending characteristics have been used as the target properties to be inferred, i.e. the grade determining properties (GDPs).

Initial analysis

Timber strength grading is often based on the ubiquitous $f_{m,0}$(MOR) versus $E_{m,s}$ (MOE) correlation. For the tested sample of *Guadua angustifolia*, a fairly strong relationship was obtained for $f_{m,0}$(MOR) versus $E_{m,s}$ ($R^2 = 0.41$), which is not unlike values obtained by some authors for timber, albeit not as strong as expected (Figure 15).

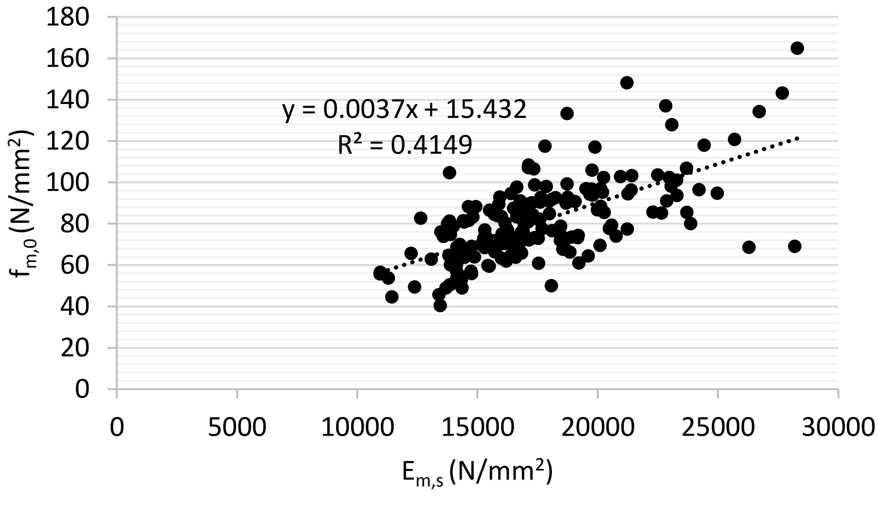

Figure 15: Correlation between $f_{m,0}$, and $E_{m,s}$ (Jangra, 2016)

This would seem to indicate that $E_{m,s}$ could act as a potential Indicating Property (IP) for $f_{m,0}$ in a machine grading process. However, it is worth noting that calculating accurately the effective moment of inertia (or second moment of area) of a given specimen is complex and the procedure used here (and contained in ISO22157-1) is only an approximation. As discussed, taper may have an effect on the correct calculation of $f_{m,0}$. The same would be true for $E_{m,s}$.

Density has also been used in grading of timber as a non-destructive test that can aid the process of both machine and visual grading, though correlations tend to be weaker than for $E_{m,s}$. As discussed in chapter 1, Janssen (1981) found that correlations between strength and density can be found for bamboo. The correlations found for density (ρ) versus$f_{m,0}$ were not very strong either, but not unlike those found for timber (figure 16).

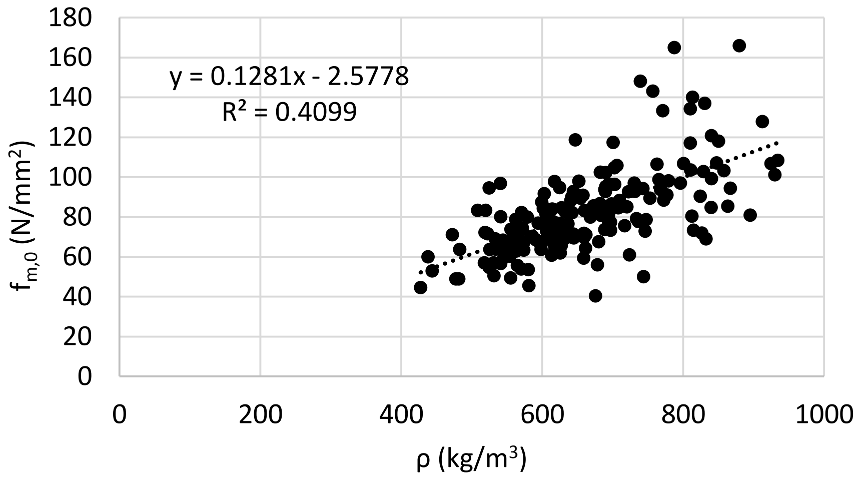

Figure 16: Correlation between ρ and $f_{m,0}$ (Jangra, 2016)

The equation derived from this regression is compared to those derived by other authors in figure 17.

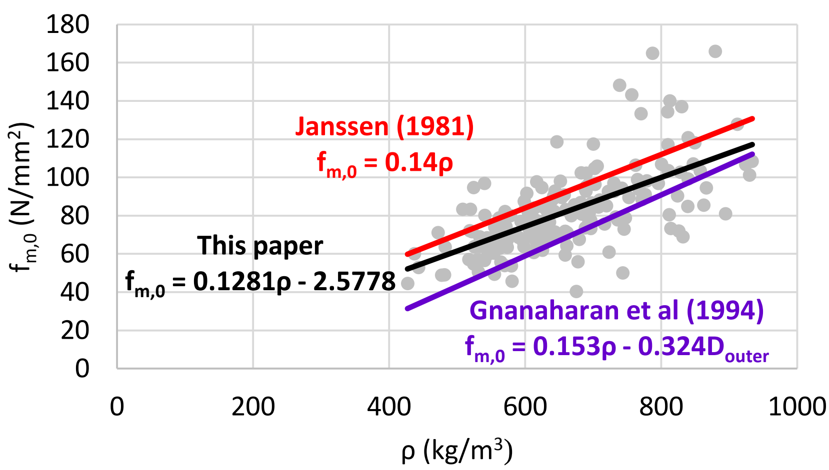

Figure 17. Comparison on density versus bending strength equations (Jangra, 2016)

At the outset it was uncertain whether hand-held devices such as the MTG would be a reliable means to infer modulus of elasticity. Though ultrasonic instruments that measured time of flight, such as the Sylva test, were shown to be reliable, there was some concern with the MTG, and similar handheld devices, in so much that the emitter of the longitudinal vibrations is located at the same point as the receptor, and could prove to be useless if some waves bounced back from the nodes and not the end of the culm. It was therefore fundamental that the value for dynamic modulus of elasticity, E_d, derived from the MTG, was corroborated by modulus of elasticity derived from bending, $E_{m,s}$. The correlation between E_d and $E_{m,s}$ corroborated this to some extent, though it was not as strong as expected with $R^2 = 0.47$ (see figure 18).

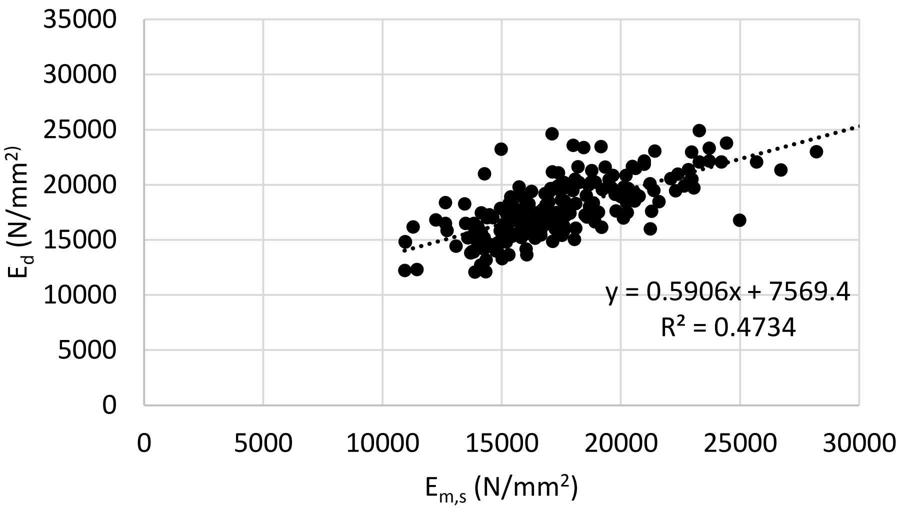

Figure 18: Correlation between $E_{m,s}$ and E_d (Jangra, 2016)

However, as discussed previously, determination of $E_{m,s}$ relies on an inaccurate model for the moment of inertia of the section. Similarly, the calculation of E_d relies on calculation of density, which, as also discussed, has also some inaccuracies too.

Capacity v stress

Chaturvedi (2011) proposed that round bamboo should be treated as a structural product and not a material, therefore grading should be done on the basis of EI (bending stiffness) and bending moment at failure, and not stress and modulus of elasticity, as geometric properties for bamboo vary substantially between bamboo pieces.

This approach was trialled in analysis to see whether better correlations could be obtained. When flexural stiffness (EI) as calculated in equation (9) (which is directly calculated from the experimental data without incurring in the use of an inaccurate model for the moment of inertia) was compared with bending moment at failure, or *flexural capacity, M_0*,(obtained also directly from experimental data and as calculated in (5)), great improvements were found to the correlations ($R^2 = 0.87$ – see figure 19). This would indicate that flexural stiffness from bending tests, $EI_{m,s}$, is a very good Indicating Property for flexural capacity, M_0. It also suggests that a grading system based on section capacities, and not on strength, would be a more reliable system.

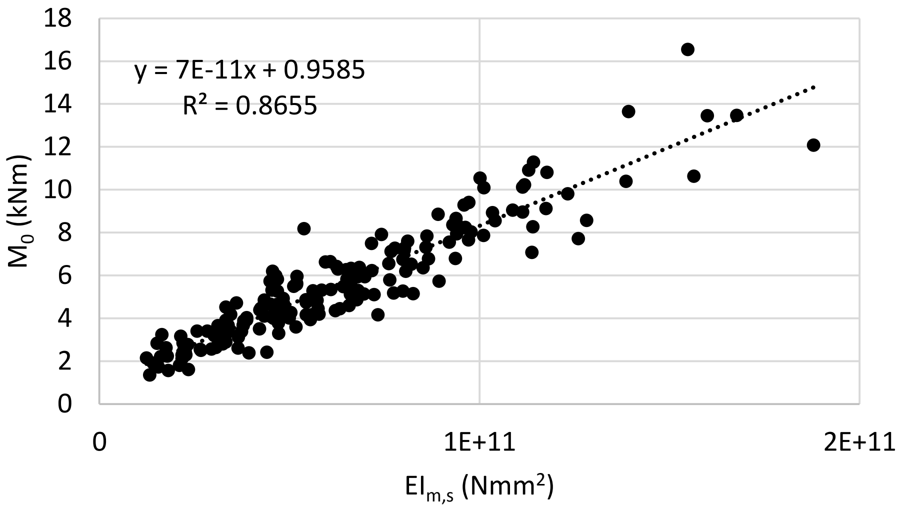

Figure 19: Correlation between M_0, and $EI_{m,s}$ (Jangra, 2016)

Similar success was obtained when flexural capacity was compared to linear mass, q (i.e. the mass of the culm divided by its length), where the correlation also had an impressive R^2 = 0.87(see figure 20).

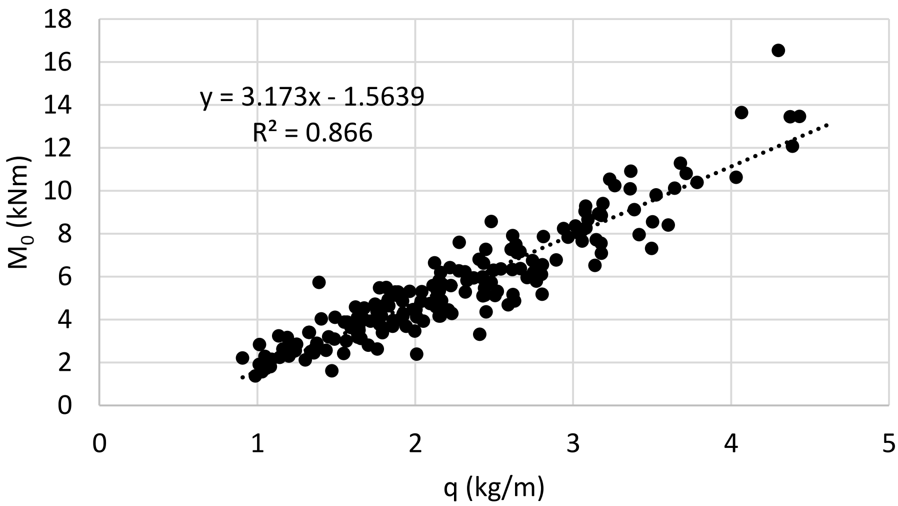

Figure 20: Correlation between M_0, and linear mass, q (Jangra, 2016)

When flexural stiffness from bending, $EI_{m,s}$, was compared to dynamic flexural stiffness EI_d (i.e. the product of the dynamic modulus of elasticity and calculated moment of inertia) a very strong correlation was obtained (R^2 = 0.93) – see figure 21. The reason for the improvement of figure 21with respect to figure 18 is not discussed within this Working Paper. However, it would seem to indicate that hand-held dynamic instruments such as the Brookhuis MTG could also be deployed as a means to reliably infer $EI_{m,s}$.

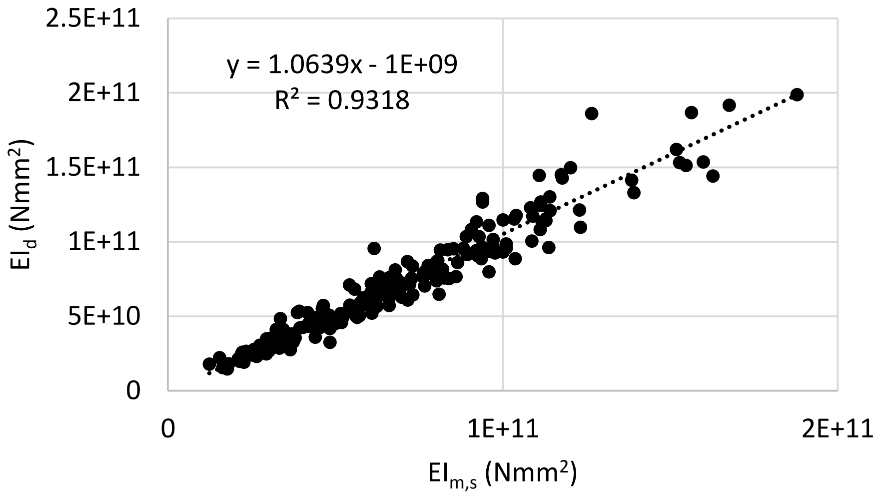

Figure 21: Correlation between $EI_{m,s}$ and EI_d (Jangra, 2016)

Other properties that can be readily measured non-destructively in bamboo are its wall thickness and external diameter. Geometric properties are not normally used for grading sawn timber, as each specimen within a sample would typically be of the same nominal size. However, consideration for defects such as knots is arguably a way to consider geometric properties of timber, as a knot effectively reduces the cross-sectional area.

It is the opinion of the authors of this Working Paper that due to constructional requirements, external diameter will nearly always be part of a grading system for round bamboo. Therefore, a grading system will need to combine control for diameter with the process, even if linear mass or flexural stiffness are used as the Indicating Parameter. Therefore, the correlation between average external diameter, D_{mean}, and flexural capacity, M_0, was considered too, and was found to be strong ($R^2 = 0.75$). As could be expected, a cubic equation fits the correlation very well (see figure 22).

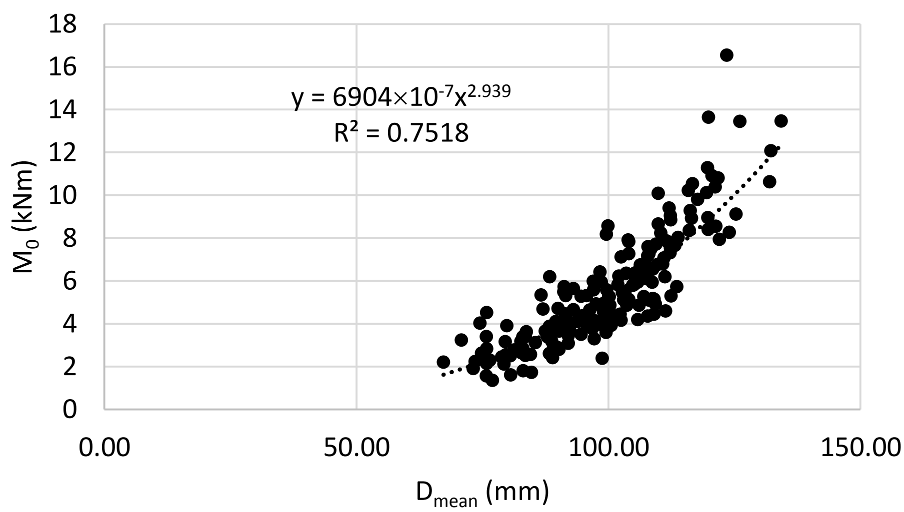

Figure 22: Correlation between M_0, and D_{mean} (Jangra, 2016)

Multiple regressions

The simple regressions contained in figures 15 to 22 provide strong evidence that reliable correlations can be found if round bamboo is treated as a product instead of being considered as a material. A summary of all the simple regressions considered is presented in table 10. Note that these regressions consider predicting flexural capacity, M_0, and flexural stiffness, EI, as both Grade Determining Properties. If multiple regressions are considered (refer to Table 11), correlations are improved upon, but not to a large extent. Moreover, many of the multiple regressions contain terms that are not significant to the regression, i.e. there is no need to use the term in the regression as it contributes very little to its improvement.

The most notable improvement was found for the following two multiple regressions:

- $q + D_{mean}^4$ as a predictor of $EI_{m,s}$ with an adjusted $R^2 = 0.903$
- $q + EI_d$ as a predictor of both M_{ult} and EI_{ms} with an adjusted $R^2 = 0.890$ and 0.944 respectively.

Table 12 presents the equations obtained from the regressions.

Table 10: Summary of simple linear regressions (Jangra, 2016)

Variables tested	**R^2 values**	
	$f_{m,0}$	**$E_{m,s}$**
ρ	0.410	0.306
$E_{m,s}$	0.483	-
E_d	0.303	0.473
	M_{max}	**$EI_{m,s}$**
q	0.866	0.890
EI_d	0.851	0.932
$EI_{m,s}$	0.866	-
D_{mean}	0.773^+	0.869^+
D_{mean}^3	0.766	0.865
D_{mean}^4	0.771	0.869

$^+$polynomial regression

Table 11: Summary of multiple regressions

Variables tested	Adjusted R^2	
	$f_{m,0}$	$E_{m,s}$
$\rho + E_d$	0.342*	0.469*
$\rho + E_{m,s}$	0.557	-
	$M_{ult,0}$	$EI_{m,s}$
$q_{test} + D_{mean}$	0.865*	0.887
$q_{test} + D_{mean}^3$	0.867	-
$q_{test} + D_{mean}^4$	-	0.903
$q_{test} + D_{mean} + EI_d$	0.892*	0.944*
$q_{test} + D_{mean} + EI_{m,s}$	0.893	-
$q_{test} + D_{mean}^3 + EI_d$	0.893*	0.944*
$q_{test} + D_{mean}^3 + EI_{m,s}$	0.892*	-
$q_{test} + D_{mean}^4 + EI_d$	-	0.944*
$D_{mean} + EI_d$	0.850*	0.932*
$D_{mean} + EI_{m,s}$	0.864*	-
$q_{test} + EI_d$	0.890	0.944
$q_{test} + EI_{m,s}$	0.865*	-

*The P-value for one of the variables in the combination is not significant.

Table 12: Equations for strong correlations

<table>
<tr><th></th><th></th><th>M_{max} (kNm)</th><th>$EI_{m,s}$ (Nmm^2)</th></tr>
<tr><td rowspan="5">Single regressions</td><td>q_{test} (kg/m)</td><td>$= (3.17 \times q_{test}) - 1.56$</td><td>$= 1.78 \times 10^{10} \times q_{test}{}^{1.46}$</td></tr>
<tr><td>EI_d (Nmm^2)</td><td>$= \left(7.00 \times 10^{-11} \times EI_{m,s}\right) + 1.08$</td><td>$= (1.06 \times EI_d) + 1 \times 10^9$</td></tr>
<tr><td>$EI_{m,s}$ (Nmm^2)</td><td>$= \left(7.00 \times 10^{-11} \times EI_{m,s}\right) + 0.959$</td><td></td></tr>
<tr><td>D_{mean} (mm)</td><td>$= (0.00256 \times D^2) - (0.343 \times D) + 13.9$</td><td>$= (3.15 \times 10^7 \times D^2) - (4.09 \times 10^9 \times D) + 1.51 \times 10^{11}$</td></tr>
<tr><td>$D_{mean}{}^4$ (mm^4)</td><td>$= (4.01 \times 10^{-8} \times D^4) + 1.19$</td><td>$= (526 \times D^4) + 5.00 \times 10^9$</td></tr>
<tr><td rowspan="2">Multiple regressions</td><td>q_{test} (kg/m) + $D_{mean}{}^4$ (mm^4)</td><td></td><td>$= (1.95 \times 10^{10} \times q_{test}) + (281 \times D^4) - 1.28 \times 10^{10}$</td></tr>
<tr><td>q_{test}(kg/m) + EI_d (Nmm^2)</td><td>$= (2.38 \times q_{test}) + (2.04 \times 10^{-11} \times EI_d) - 1.14$</td><td>$= (1.60 \times 10^{10} \times q_{test}) + (0.545 \times EI_d) - 8.74 \times 10^9$</td></tr>
</table>

The equations in Table 12 could be used to predict a property, such as flexural capacity, from a non-destructively measured property, such as linear mass. However, it should be noted that these equations predict the mean property, which means that on average 50% of the real results would be less than the predicted value, which would be unsafe in the case of flexural capacity (Figure 23). However, these equations could be adjusted to provide a statistically safe result. Typically, this prediction would be the characteristic value, which could be derived using equation (10). Figure 23 shows how the mean and characteristic predictions compare to the experimental data. Note that for the characteristic line, most, but not all, experimental results are above. This is to be expected. Similarly, flexural stiffness can be predicted from a non-destructive measurement, such as linear mass. For some applications, such as deflections, determining the mean flexural stiffness should be adequate. However, for safety critical applications such as buckling, a reduced flexural stiffness, for example the 5th percentile, would be more appropriate (see Figure 24).

The equations used in figure 23 and 24 could be used as the basis for a machine grading or machine–assisted visual grading of bamboo.

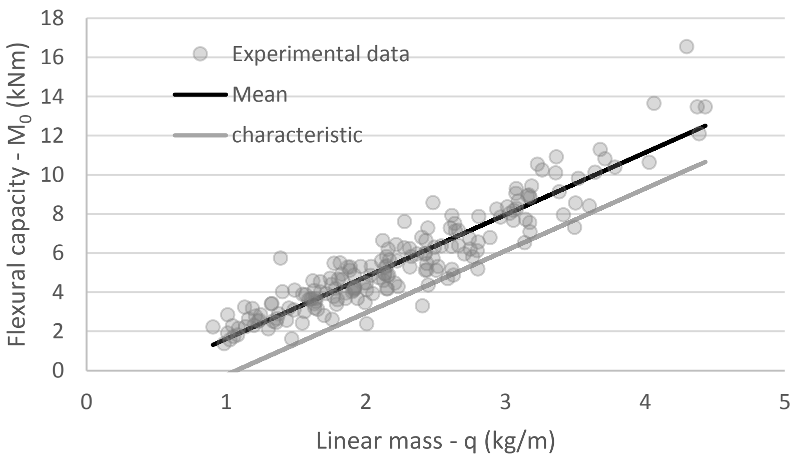

Figure 23: Prediction of flexural capacity from linear mass

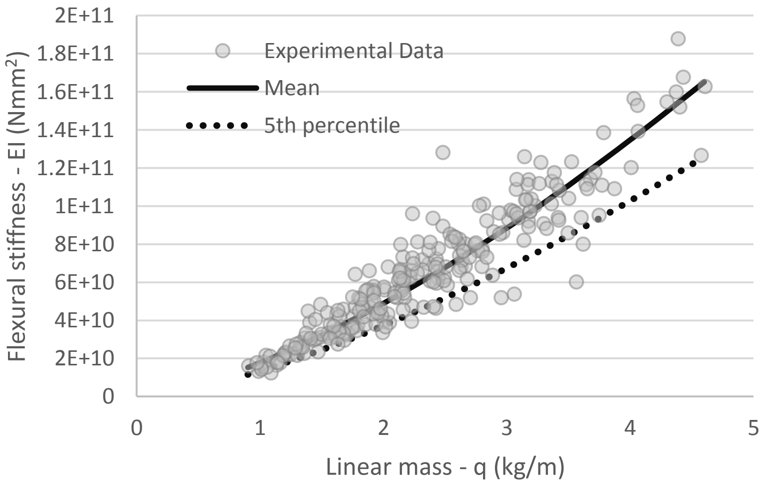

Figure 24: Prediction of flexural stiffness from linear mass

Chapter 4: Potential grading methodologies

As observed very strong correlations were obtained for *Guadua angustifolia Kunth* when flexural capacity, M_0,(i.e. maximum bending moment) was compared individually against flexural stiffness, EI, linear mass, q,or average external diameter, D_{mean}. A similar trend was observed for predicting flexural stiffness, EI. It was also observed that combining these non-destructively measured properties offered limited improvement. Therefore, it is possible to hypothesise that a grading methodology could be done on the basis of any of these three properties (flexural stiffness, external diameter or linear mass), or a combination of them. In this case M_0 and EI_{ms} could be treated as two of the Grade Determining Properties, and flexural stiffness (dynamic or static), linear mass or external diameter could be the indicating properties (IPs). The implications and potential procedures for each are discussed hereafter.

Flexural stiffness as an IP

Flexural stiffness can be measured non-destructively by means of a bending test or an ultrasonic instrument similar to the MTG. Flexural stiffness, EI, is likely to be selected as a Grade Determining Property because stiffness generally governs the design of beams, slender struts and portal frames when flexible materials, such as bamboo, are being used. Therefore measuring it during the grading process would have the advantage of directly measuring a GDP, which also happens to be a good IP for flexural capacity. The processes described so far for measuring EI, are either cumbersome or expensive, particularly when using an ultrasonic instrument, as the instrument is relatively costly and requires measuring the geometry and mass of the specimen, which may slow down a grading process. Furthermore, the validity of using this type of instrument has only been demonstrated for Guadua in dry condition, hence more work would be needed with other bamboo species with a range of moisture contents.

Flexural stiffness can also be measured from simple bending tests, e.g. placing a lump mass at mid-span on a simply-supported culm and measuring its deflection on a dial gauge (refer to figure 25). Figures 26 and 27 show that this approach was investigated with some success, as flexural stiffness measured by the use of a lump mass, EI_p, correlated very well to flexural stiffness from the four-point bending test, $EI_{m,s}$ and flexural capacity, M_0. This approach could be adopted with minimal capital investment, and could eventually be mechanised once the supply and demand warranted such an investment.

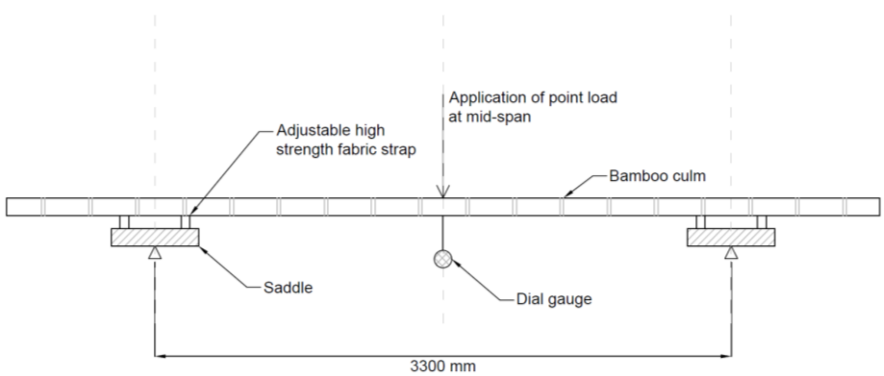

Figure 25: lump mass setup (Jangra, 2016)

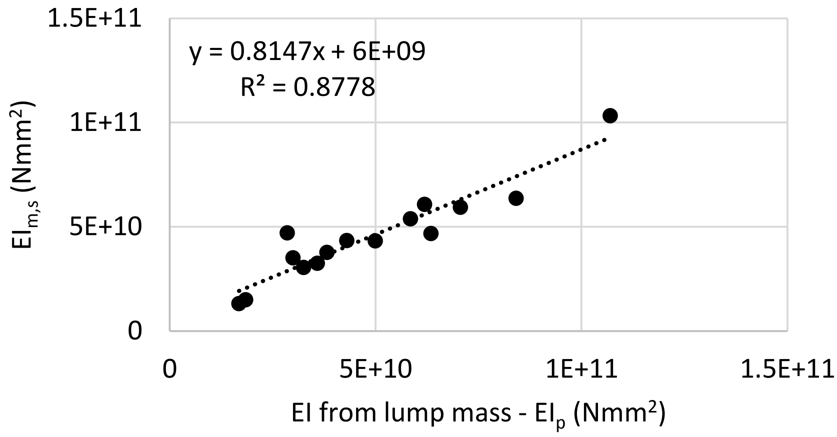

Figure 26: Comparison of flexural stiffness derived from four-point bending and from the application of a lump mass (Jangra, 2016)

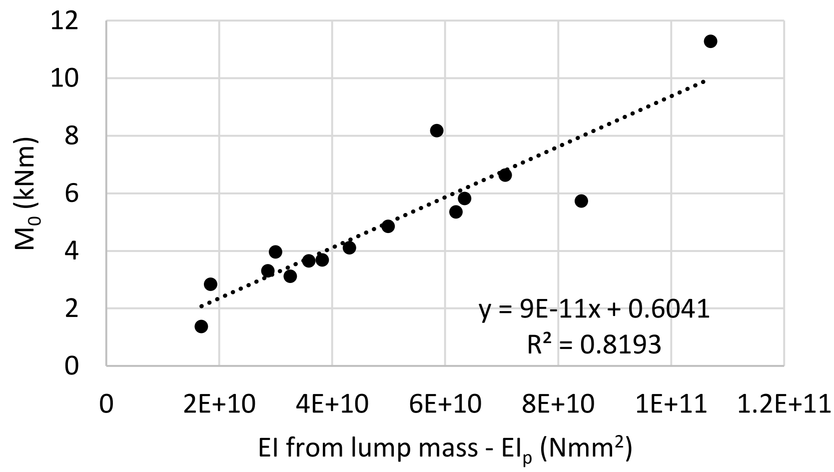

Figure 27: Comparison of flexural capacity, M_0, and flexural stiffness from the application of a lump mass (Jangra, 2016)

Two further methodologies will be discussed hereafter.

Linear mass as the IP

Measuring linear mass is a very fast process, requiring very simple and inexpensive instruments: a tape measure, a set of scales, and a moisture meter. The latter is required to determine how much of the mass is water. The downside to this method is that it would be limited to dry specimens i.e. with moisture contents below 18%, as moisture meters are unlikely to give sufficiently accurate values at higher moisture contents, and without knowing the moisture content, it is not possible to distinguish between water and bamboo in a culm. Determination of moisture content by oven-drying would not be an option for a fast process such as grading.

The reason for the strong correlation between linear mass, as an IP, and flexural stiffness and flexural capacity, as GDPs, is that mass is sensitive to external diameter, wall-thickness and density. Figure 28 shows how linear mass is affected by external diameter, wall-thickness and density, and that it is more sensitive to changes in diameter than the other properties, which, as shown in figures 6 and 7, is the property that will most affect stiffness and strength of a given piece of bamboo. Initial investigations into other species of bamboo show that this method is promising. Figure 29 shows how the findings from this work compare to similar comparisons undertaken with Mexican grown *Guadua angustifolia* and *Bambusa olhamii* (Data kindly provided by Víctor Rubén Ordóñez Candelaria from INECOL in México).

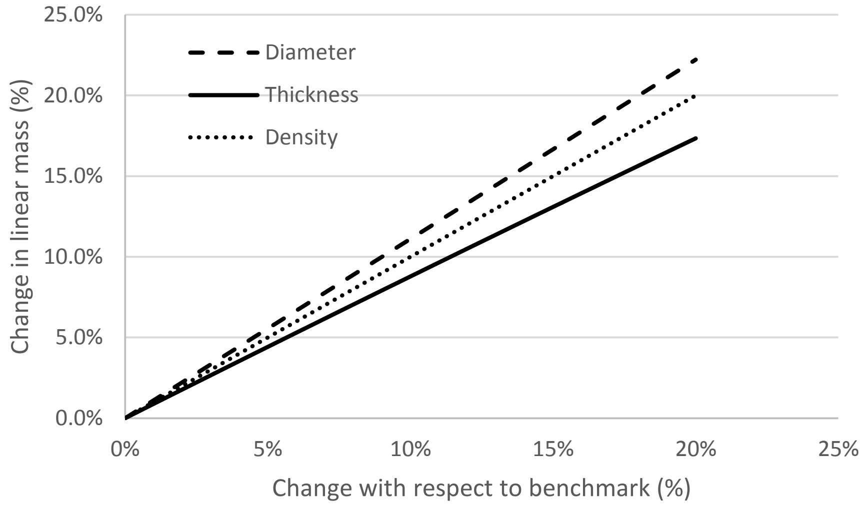

Figure 28: Sensitivity of linear mass (q) to changes to other properties of a hypothetical bamboo culm

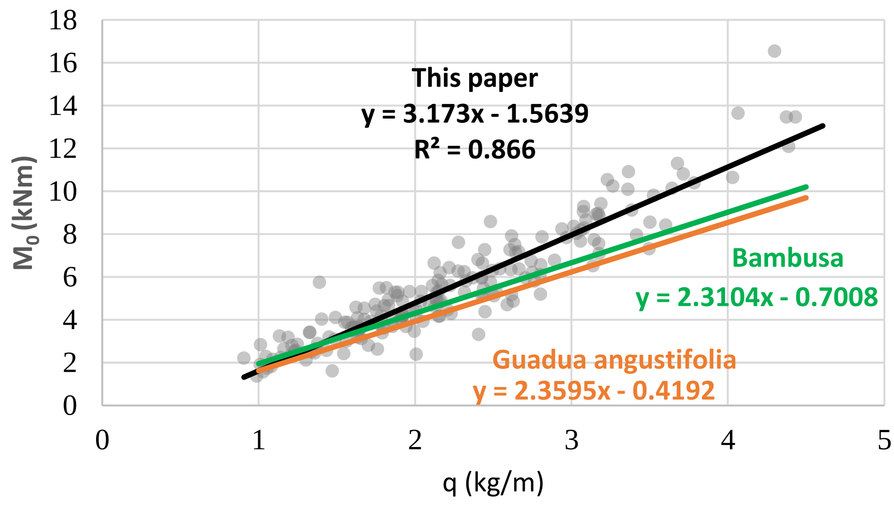

Figure 29: Flexural capacity (M_0) versus linear mass for *Guadua angustifolia* (Colombian and Mexican) and *Bambusa oldhami*

Measurement of mass is simple and could readily be mechanised, and though linear mass is not a GDP, it could be used to infer density, which, as is the case for timber, could in turn potentially be correlated with connection strength properties.

External diameter as the IP

Measuring external diameter is even simpler than measuring mass and the equipment required is very inexpensive. It has the added benefit that it can be undertaken on both green (i.e. unseasoned) and dry (i.e. seasoned) pieces, though it might be necessary to consider the effect of shrinkage in green bamboo pieces. A further advantage of this method is that it can be checked even in a finished structure– provided the bamboo is accessible. From the constructional point of view, controlling for external diameters is of great practical use, as builders would want to use matching size pieces. While external diameter does not correlate as well to flexural capacity or flexural stiffness as linear mass and flexural stiffness do, it still correlates very well. Grading for external diameter is arguably a form of visual grading, though there is also potential to mechanise the process, and it could be used in combination with either or both of the aforementioned methods (linear mass or flexural stiffness) to obtain a more accurate grading methodology.

Combining IPs

In timber grading, more than one property may be used as an IP. This is likely to be based on multiple regressions that offer good results. In chapter 3 only two multiple regressions were found that provided significant improvements to the simple regressions:

- Linear mass, q, plus dynamic flexural stiffness, EI_d, as IPs for flexural stiffness, $EI_{m,s}$ and flexural capacity, M_0.
- Linear mass, q, plus average external diameter, D_{mean}, as IP_S for flexural stiffness, $EI_{m,s}$.

The first of these multiple regressions requires the use of an expensive instrument, and therefore is unlikely to be adopted for bamboo grading in the near future. The second uses external diameter, which as argued, is likely to be selected as a GDP for ease and practical use, but only predicts flexural stiffness. Predictions for flexural capacity showed little improvement to predictions based on linear mass alone.

Therefore, based on the sample of *Guadua angustifolia Kunth* studied, it would seem the use of several IPs may be of limited value for bamboo, as using any of the proposed IPs ($EI_{m,s}$, q or D_{mean}) provided sufficiently strong correlations to the flexural properties (i.e. flexural stiffness and capacity) of the culms.

Prediction of properties other than flexural properties

So far it has been demonstrated that flexural capacity and flexural stiffness can be inferred non-destructively quite reliably for one species of bamboo. It is likely that the same would be true for other species, but this needs to be demonstrated experimentally. It is important to note that in the process of grading, a grade can be set to correspond to a particular bamboo resource in order to make optimum use of the resource. A grade can also be set to meet the requirements of a particular end useFor many applications flexural properties are likely to be selected as Grade Determining Properties, because flexural properties are very important to the design of frames and beams, but this need not be the case. In some circumstances other properties may be deemed to be more critical to design or a specific application. For example, it may be felt shear strength, f_v, and tensile strength perpendicular to fibres, $f_{t,90}$, are so important to the process of connection design, that these are set to be the GDPs.

Regardless of the grading criteria adopted, some properties will not or cannot be measured or inferred directly during the grading process. In timber grading, some propertiesare conservatively estimated from the Grade Determining Properties (Ridley-Ellis *et al*., 2016), and are called 'secondary properties'. ISO CD 19624 states "[secondary]*properties are typically estimated from the grade determining properties on the basis of previously derived correlations that are valid for the species. [...] Secondary properties should be inherently conservative, and therefore not critical to the end application of the culms.*" Chapters 2 and 5 of this Working Paper provide suggestions of secondary properties that could be used when grading bamboo.

Chapter 5: Example of a Diameter based grading procedure

This chapter sets out a visual grading procedure based on average external diameter, D_{mean} as the grading criteria. The data obtained from the experimental work outlined in chapter 3 will be treated as the ‘Initial Evaluation’ for this procedure.

The data across all tests was separated into bins according to their average external diameter, D_{mean}. The data directly measured during the tests for each bin, or grade, is presented in table 13. Bins that contained fewer than 20 specimens were excluded from the analysis. Characteristic values were obtained on the basis of the equation contained in clause 7.2.1 from ISO22156, shown here as equation (10). 5th percentile values were determined using the MSExcel function: ‘PERCENTILE’, though alternatively, they could have been obtained by ranking. For characteristic wall thickness, 25th percentile was used instead of 5th percentile, as it was deemed that combining a characteristic wall thickness based on 5th percentile with a characteristic strength also based on the 5th percentile would be excessively conservative. For design purposes, table 13 would contain information of limited use. Therefore, a more appropriate format may look like table 14. Figure 30 visually represents how grading works for one property.

$$R_k = R_{0,05}\left(1 - \frac{2.7\frac{s}{m}}{\sqrt{n}}\right) \qquad (10)$$

Where

R_k is the characteristic value,

$R_{0,05}$ is the 5 percentile from the test data,

m is the mean value from the test data,

s is the standard deviation from the test data,

n is the number of tests.

Table 13: Properties for each Diameter based Grade

	Grade	70-80mm	80-90mm	90-100mm	100-110mm	110-120mm
$EI_{m,s}$	N	20	39	49	68	44
($GNmm^2$)	Mean	22.5	32.9	49.8	69.6	96.0
	SD	8.2	8.7	15.1	14.9	15.5
	5th percentile	13.1	21.9	32.7	46.8	68.7
	Char. Value	10.2	19.4	28.9	43.5	64.2
M_0	n	18	28	44	52	26
(kNm)	Mean	*	3.27	4.62	5.98	8.43
	SD	*	1.05	1.23	1.27	1.95
	5th percentile	*	**1.76**	**3.12**	**4.23**	**5.41**
	Char. Value	*****	**1.47**	**2.79**	**3.90**	**4.75**
q	n	26	51	63	72	52
(kg/m)	Mean	1.22	1.56	1.97	2.46	3.07
	SD	0.22	0.31	0.32	0.38	0.47
	5th percentile	**0.98**	**1.18**	**1.57**	**1.92**	**2.33**
	Char. Value	**0.88**	**1.09**	**1.48**	**1.83**	**2.19**
t	n	26	51	63	72	52
(mm)	Mean	9.0	9.3	11.1	13.3	15.4
	SD	2.8	1.7	3.9	3.3	3.5
	25th percentile	**7.5**	**8.5**	**9.0**	**10.7**	**13.0**
	Char. Value	**6.2**	**7.9**	**7.9**	**9.8**	**11.9**

Table 14: Design values for Diameter based grades

	Grade	70-80mm	80-90mm	90-100mm	100-110mm	110-120mm
$EI_{m,mean}$	($GNmm^2$)	22.5	32.9	49.8	69.6	96.0
$EI_{m,0,05}$		13.1	21.9	32.7	46.8	68.7
M_k	(kNm)	*	1.47	2.79	3.90	4.75
q_{mean}	(kg/m)	1.22	1.56	1.97	2.46	3.07
q_k		0.88	1.09	1.48	1.83	2.19
t_{mean}	(mm)	9.0	9.3	11.1	13.3	15.4
t_k		6.2	7.9	7.9	9.8	11.9

Where:

$EI_{m,mean}$ is the Mean flexural stiffness
$EI_{m,0,05}$ is the Minimum flexural stiffness
M_k is the Characteristic flexural capacity
q_{mean} is the Mean linear mass
q_k is the Characteristic linear mass
t_{mean} is the Mean wall thickness
t_k is the Characteristic wall thickness.

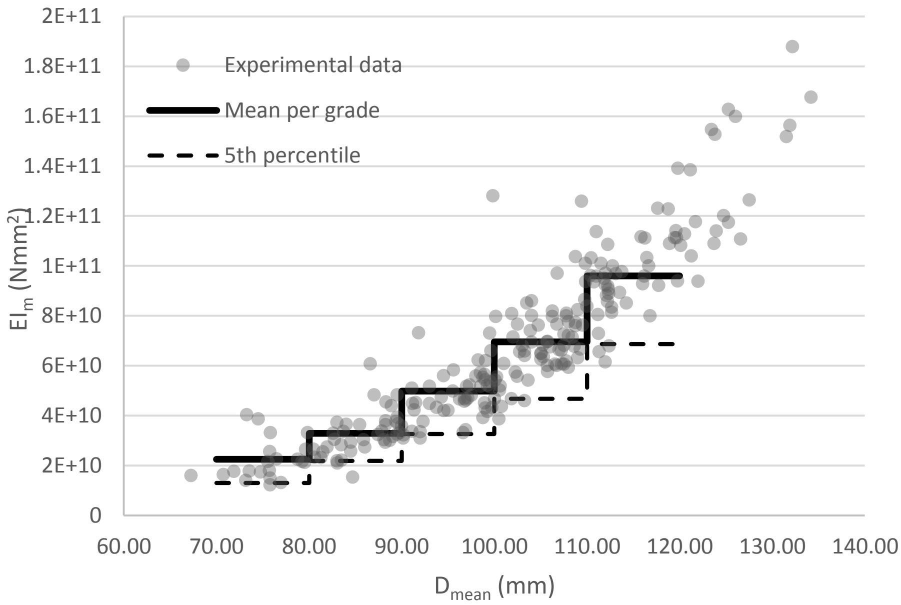

Figure 30: Experimental results of flexural stiffness versus average external diameter, with the lines representing the values from tables 14 and 15

Tables 13 and 14 do not include secondary properties that could be used in design. Summarising the discussion from Chapter 2, secondary properties could be based, but not limited to, any of the following:

1) The lowest set of results for a species that has been studied across several regions.
2) Derived from density, as proposed by Janssen (1995) and NBC 2004.
3) By relating some secondary properties to Grade Determining Properties, for example:
    a. $f_{t,0} = f_{m,0}$ where $f_{t,0}$ is the assumed tensile strength, and $f_{m,0}$ is the experimentally derived bending strength.
    b. Assume that: $f_{c,0} = {}^{f_{m,0}}/_{2}$ where $f_{c,0}$ is the assumed compressive strength, and $f_{m,0}$ is the experimentally derived bending strength.

Machine-assisted visual grading

An alternative approach to the one used for populating tables 13 and 14 would be to use linear mass to support the grading process, in a machine-assisted or hybrid grading method. Grading would still be done by diameter, but properties per grade could be determined by means of equations, similar to those derived in chapter 3, and discussed for figures 23 and 24. Linear mass in this instance would act as the Indicative Property. Table 15 presents the design values per grade derived using this method. Table 16 presents the equations used for the derivation of these values.

In general it may be seen that the values determined from the equations are less conservative than those determined from treating each grade as an individual data set, because the number of samples used for the derivation of the characteristic equations is much larger than the sample used for the individual grade. Notice also that it is possible to provide a value for the 70-80mm class for flexural capacity, unlike for Tables 13 and 14.

Table 15: Design values for Diameter based grades using linear mass as an IP

Property	Grade	70-80mm	80-90mm	90-100mm	100-110mm	110-120mm
q_{mean}	(kg/m)	1.22	1.56	1.97	2.46	3.07
q_k		0.88	1.09	1.48	1.83	2.19
$EI_{m,mean}$	(GNmm^2)	23.9	35.6	51.9	71.7	96.1
$EI_{m,0,05}$		18.2	26.0	36.5	50.6	69.9
M_k	(kNm)	0.48	1.56	2.85	4.42	6.36
t_{kmean}	(mm)	8.1	9.5	11.1	13.0	15.4
t_k	(mm)	6.2	7.5	9.2	11.1	13.5

Table 16: Calculation of grade determining properties inferred from IPs (linear mass), based on observed correlations

Characteristic property	Symbol	Equation	
Mean flexural stiffness	$EI_{m,mean}$	$17.8 \times q_{mean}{}^{1.46}$	(11)
Minimum flexural stiffness	$EI_{m,0,05}$	$13.6 \times q_{mean}{}^{1.46}$	(12)
Characteristic bending capacity parallel to fibres	M_k	$3.17 \times q_{mean} - 3.4$	(13)
Mean wall thickness	t_{mean}	$3.93 \times q_{mean} + 3.32$	(14)
Characteristic wall thickness	$t_{0,25}$	$3.93 \times q_{mean} + 1.41$	

To ensure the values contained in Table 15 are valid, a quality control system would need to be in place. It could work as follows: during the grading operation, the linear mass for each piece would be recorded. Once a batch had been graded, or at the end of the day, the bamboo producer would check that the average mass for the material sorted into a given grade was at least as large as the average mass declared in a table similar to Table 15. A similar check could be run for the characteristic mass for the batch. If these checks failed, the batch would need to be regraded in its entirety and all specimens with a linear mass inferior to the one declared in the grade would be rejected. If this problem became recurrent, it would be recommended to revise down the linear mass for the grade and all associated properties that correlate to it.

Conclusions and Further Work

One of the possible explanations as to why bamboo culms remain in the fringes of engineered structures is that the supply chain is still strongly based on trust, experience and intuition. Mainstream products instead are standardised, certified and verifiable. Alongside seasoning and preservation, grading is a fundamental consideration to achieve a reliable structural product. It is hoped that this Working Paper demonstrates some ways by which the grading of bamboo culms could take place. It is by no means a conclusive document. Also, as a word of caution, it must be noted that the equations postulated in this Working Paper are valid only to the sample of *Guadua angustifolia* that was investigated.

This Working Paper has demonstrated the following:

- Visual grading of bamboo of some kind is already practiced, although it is generally limited to acceptance/rejection.
- Examples of criteria that may be used for visual grading were presented. Some of these limits need further research, for example the influence of splitting on the load-bearing capacity of members.
- Grading by external diameter is a logical progression from current practice.
- The grading process is made simpler if instead of trying to infer the strength properties of bamboo culms, the grading process seeks to infer the section capacities. Grading by external diameter is well suited to such an approach.
- External diameter can be used reliably to infer either flexural capacity or flexural stiffness of bamboo culms. In a similar manner linear mass can be sued to infer either flexural capacity or flexural stiffness. Also, flexural stiffness can be used to infer flexural capacity.
- An example of a method for grading using external diameter was presented.

These observations need to be corroborated for *Guadua angustifolia* originating from other plantations, other species of bamboo, and other properties, not just flexural properties.

It is hoped that this Working Paper helps promote new approach to the supply of bamboo, which should benefit producers, contractors, engineers and end users alike.

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