

Flexural properties as a basis for bamboo strength grading

Trujillo, D. , Jangra, S. and Gibson, J. M.

Author post-print (accepted) deposited by Coventry University's Repository

Original citation & hyperlink:

Trujillo, D. , Jangra, S. and Gibson, J. M. (2016) Flexural properties as a basis for bamboo strength grading. Proceedings of the Institution of Civil Engineers - Structures and Buildings, volume (in press)

<http://dx.doi.org/10.1680/jstbu.16.00084>

DOI 10.1680/jstbu.16.00084

ISSN 0965-0911

ESSN 1751-7702

Publisher: ICE Virtual Library

This paper is published in Proceedings of the Institution of Civil Engineers - Structures and Buildings which can be found:

<http://www.icevirtuallibrary.com/toc/jstbu/current>

Copyright © and Moral Rights are retained by the author(s) and/ or other copyright owners. A copy can be downloaded for personal non-commercial research or study, without prior permission or charge. This item cannot be reproduced or quoted extensively from without first obtaining permission in writing from the copyright holder(s). The content must not be changed in any way or sold commercially in any format or medium without the formal permission of the copyright holders.

This document is the author's post-print version, incorporating any revisions agreed during the peer-review process. Some differences between the published version and this version may remain and you are advised to consult the published version if you wish to cite from it.

Date: 31/10/16

Title: Flexural properties as a basis for bamboo strength grading

Authors: David Trujillo MSc DIC CEng MIStructE
Senior Lecturer
Coventry University, UK

Suneina Jangra MEng
MRes/PhD student
University College London, UK

Joel Matthew Gibson MEng
Graduate Civil Engineer
Atkins, Bristol, UK

Contact details submitting author:

School of Energy, Construction and Environment
Faculty of Engineering, Energy and Computing
Sir John Laing Building
Coventry University
Priory Street, Coventry, CV1 5FB
david.trujillo@coventry.ac.uk

Number of words in text and tables: 4910

Number of figures: 15

Abstract:

Current design and construction codes and standards for bamboo do not contain strength grading procedures beyond cursory visual inspections. This deficiency arguably limits the safe and economic use of the material.

This paper presents findings from an international research project which seeks to develop a strength grading system for bamboo culms. Over 200 four-point bending tests were carried out on *Guadua angustifolia* Kunth (*Guadua* a.k.) culms for which numerous mechanical and physical properties were measured.

Correlations between flexural strength ($f_{m,0}$), static modulus of elasticity ($E_{m,s}$), dynamic modulus of elasticity from stress-waves (E_d) and density (ρ), provided mediocre results with R^2 ranging from 0.27 to 0.47. However, properties such as flexural stiffness ($El_{m,s}$), flexural capacity (M_{max}) and mass per unit length (q), which are less dependent on geometric properties, provided much stronger correlations with R^2 ranging from 0.86 to 0.92.

The quality of these correlations indicates that these could be used as Indicating Properties for flexural capacity in a simple yet reliable strength grading procedure for bamboo. The findings of this paper invite to reconsider the extant stress-based approach for bamboo design, and instead move to a capacity-based approach as is often used with engineered timber products.

Notation:

$f_{m,0}$ flexural or bending strength, in this paper taken to mean the same as modulus of rupture (MOR),

$E_{m,s}$ apparent static modulus of elasticity, established from static bending tests, in this paper taken to mean the same as modulus of elasticity,

E_d dynamic modulus of elasticity, established from a dynamic stress wave technique,

ρ density calculated as mass per volume,

El_d flexural stiffness, established from dynamic stress wave technique

$El_{m,s}$ flexural stiffness, established from static bending tests

q_{test} mass per unit length

M_{max} Maximum bending moment, moment at failure or flexural capacity, established from static bending tests

D_{mean} average external diameter of the culm

t_{mean} average wall thickness of the culm

List of three keywords:

Strength & testing of materials

Developing countries

Timber structures

INTRODUCTION

The reliable knowledge of the mechanical properties of any structural material forms the basis of any design code or standard. For natural materials, such as timber or bamboo, which are inherently variable, the process of determining mechanical properties differs significantly from factory made materials such as precast concrete, steel or aluminium, for which variations in quality can be controlled at source. The current practice in advanced economies, is to subject every single piece of timber that is supplied to market to a non-destructive process called *strength grading*. Current bamboo standards and codes contain very limited guidance for strength grading (Trujillo, 2013), which potentially hinders the establishment of a modern bamboo supply chain and henceforth the wider adoption of bamboo as a structural material.

Though research into bamboo dates back to the early 20th century (Janssen, 1981), the development of standards has taken longer. It was only in the early 21st century that bamboo design codes and standards emerged from India (BIS, 2004), Colombia (AIS, 2010), Peru (MinViv, 2012) and internationally, through the International Standards Organisation (ISO, 2004a). These codes and standards do contain some guidance about selection of material, but do not contain a formal grading procedure.

STRENGTH GRADING IN TIMBER

Strength grading is a process of sorting timber on the basis of its strength (Benham et al. 2003). Strength grading can be of two types: *visual* or *machine grading*. Visual grading for timber consists of observing and measuring physical characteristics that are visually accessible (e.g. size, position and number of knots). It is a manual process, though it can be machine assisted. Visual grading is the oldest form of grading and is the least capital intensive, however, it requires trained, experienced personnel to undertake the task. It is therefore a slow, labour intensive process and results in a more conservative use of the material (Johansson, 2003). However, visual grading has the benefit that it can be verified after it has taken place.

Machine strength grading relies on mechanical methods to infer the stiffness and strength of a sample of wood through non-destructive tests. Machine grading relates an indicating property (IP), measured non-destructively, to one or several grade determining properties, such as bending strength ($f_{m,0}$). Machine grading is faster than visual grading and less prone to human error; however, the method still requires visual inspection of defects (Ridley-Ellis et al. 2016). One of the most common machine grading methods is to use the modulus of elasticity in bending ($E_{m,s}$) of a plank of wood as the IP. The machine is calibrated to infer $f_{m,0}$ for the plank from $E_{m,s}$. $f_{m,0}$ is the grade determining property, and is then used to classify the timber piece into a "strength class". Each strength class has an associated list of physical and mechanical properties (Benham et al. 2003). Other mechanical processes have been used while more are continuously being developed, these include X-rays, ultrasonic waves, density, hardness or a combination.

Strength grading of timber imbues confidence, reliability and traceability to the supply chain, allowing a natural and highly variable material to be specified with similar confidence to its man-made counterparts. Johansson (2003) points out that machine grading improves also the accuracy with

which stiffness and density are known, which is desirable in design. The supply chain of bamboo culms for construction remains a far more ad hoc process, based more on trust and experience than certification and validation. The bamboo supply chain requires more formal operations if it is to become a mainstream product.

EXPERIMENTAL PROGRAMME

In October 2013 the International Network for Bamboo and Rattan (INBAR) appointed Coventry University to develop grading methodologies and standards for bamboo, akin to extant ones for timber. This paper sets out the primary findings for bending properties for one species of bamboo, *Guadua angustifolia* Kunth (*Guadua* a.k.), and based on these, identifies a possible grading methodology for bamboo.

100 *Guadua* a.k. culms were harvested, cut to length and dried in the municipality of Caicedonia in Colombia and shipped to the UK. Only the first 12m of each culm was utilised, and cut to approximately 4m lengths. The age at harvesting and position along the culm of each specimen was recorded on the specimen using the system described in Table 1. A range of ages and positions along the culm were included as these factors have been observed to affect the behaviour of bamboo (Trujillo and López, 2016). To avoid confusion between languages, the identifiers for position I, M and S (Inferior, Middle and Superior respectively) were used. Age at harvesting was identified by a number inscribed on each specimen.

The specimens were stored in the structures laboratory of the Sir John Laing Building of Coventry University, at a fairly stable temperature and relative humidity. Due to technical and logistical difficulties, it was not possible to store them in a conditioning room at a constant temperature and relative humidity. Table 2 summarises the moisture content readings taken over one year throughout testing. The small spread of values evidenced by the box-plot and standard deviation demonstrates that the laboratory offered a relatively stable environment.

With the aim of deriving correlations between destructively and non-destructively measured properties, 199 specimens from the sample were subjected to a four-point bending test using a modified procedure to that outlined in clause 10 of ISO 22157-1 (ISO, 2004b), refer to Figure 1. Modifications to the procedure include the following: loads were not placed at thirds, but instead a constant shear span (a) of 1150mm was observed; instead of solid timber saddles, fabric saddles were used to minimise risk of local crushing; and linear variable differential transducers (LVDTs) were placed over the supports to subtract any local deformation from the total deflection of the specimen. For each specimen the load vs. displacement at mid-span was recorded, in addition to the observed failure mode.

Prior to the bending test, the data listed in Table 3 was recorded for each specimen, including the recording of the natural frequency of the specimen by means of stress-waves. This data was used for the determination of the geometrical, physical and mechanical properties of interest for each specimen – refer to Table 3. Similarly, the condition of each specimen was observed and recorded. Relatively short, shallow splits were tolerated and seemingly had little effect on capacity. Specimens showing severe splitting were excluded from the sample.

Measurement of Density

ISO 22157-1 contains a procedure to determine density at discrete locations, however as density varies along the culm (Trujillo and López, 2016) this procedure was deemed of limited value. It was opted for a density estimation based on 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.

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

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 3 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 3 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).

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

Where

ρ is the density in g/mm^3 ,

m is the mass in g.

To corroborate whether this cylindrical approximation is accurate, the volume of 15 culms was measured using both the cylindrical approximation method and by immersion in water (volume displacement). Table 4 summarises the findings. It was found that the cylindrical method consistently underestimates the volume of the culm, which results in overestimating the density. As on average this inaccuracy is relatively small, for the purposes of this paper, it has been deemed acceptable.

Measurement of Moisture Content:

ISO 22157-1 states that moisture content should be determined by calculating the loss in mass resulting from oven-drying. In the interest of expediency, the validity of using a moisture meter instead was investigated. Table 5 summarises the findings for both Guadua a.k. and *Phyllostachys pubescens* (Moso). The chosen instrument was a Brookhuis FMC microprocessor controlled moisture meter to determine the most accurate setting (setting 1), whilst Table 6 summarises the validation for setting 1. It was found that placing the electrode pins perpendicular to the fibres provided the most accurate results, but due to the curved surface of bamboo the pins could bend, therefore it was opted to place probes at 45° to the fibre.

Dynamic modulus of elasticity:

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 was sufficient and positive linear relationships were established between E_d against ρ , $E_{m,s}$ and $f_{m,0}$. Therefore it was felt necessary to investigate the potential use of a similar handheld non-destructive grading instrument. The chosen instrument is a Brookhuis Timber Grader MTG; a hand held device developed by Brookhuis Micro-Electronics and TNO and approved for use in Europe. The test equipment is typically used in timber strength grading to give the user a value for E_d of a specimen based on a number of parameters. 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).

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

Where

ρ is the density calculated as in (2),

v is the speed of sound in the specimen calculated thus

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

Where

l_{sp} is the total length of the specimen

f_1 is the fundamental frequency of the specimen, determined using the Brookhuis MTG.

The fundamental frequency, f_1 , was not validated independently, however, for consistency readings were routinely repeated.

Static bending properties:

As discussed, bending tests are ubiquitous in grading of timber, and this is due to the importance of both $f_{m,0}$ and $E_{m,s}$ in the design of timber elements and frames, though connection design is arguably more influenced by density and shear strength, than by these two properties. The same is true for bamboo, therefore bending tests were deemed the centrepiece of this project. Though bending tests to bamboo date back to the 1920s (Janssen, 1991), it was Gnanaharan et al (1994) who first 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. The correlations obtained were reportedly very strong, though the sample was quite small (n=12).

For the analysis of results, the second moment of area, or moment of inertia, I_B for each specimen was calculated using equation (5) from ISO 22157-1.

$$I_B = \frac{\pi}{64} [D_{mean}^4 - (D_{mean} - 2t_{mean})^4] \quad (5)$$

Where

D_{mean} is the average external diameter of the culm,

t_{mean} is the average wall thickness of the culm.

The location and form of failure was observed and recorded. Failures that occurred within the constant moment region were treated as failures in bending (Figure 1). Failures that occurred in either shear

span were excluded from bending moment and $f_{m,0}$ analyses, but were included in stiffness and $E_{m,s}$ calculations. For specimens that were deemed to have failed in bending, as detailed in Table 8, $f_{m,0}$ was calculated as follows. The applied bending moment onto the specimen was calculated:

$$M_{max} = \frac{F_{ult} \times a}{2} \quad (6)$$

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 as shown in Figure 1. For the first 13 tests this would be 1/3 of the free span, but due to the span to diameter ratios of the specimens, this was altered for the remaining tests to 1150mm.

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

$$f_{m,0} = \frac{M_{max} \times D_{mean}}{2 \times I_B} \quad (7)$$

Where

M_{max} as calculated in (6),

D_{mean} is the average external diameter of the culm,

I_B is the second moment of area, as defined in (5).

The flexural stiffness from of the section, $EI_{m,s}$, was determined from equation (8).

$$EI_{m,s} = \frac{(F_{60} - F_{20}) \cdot a(3L^2 - 4a^2)}{48(\delta_{60} - \delta_{20})} \quad (8)$$

Where

F_{20}, F_{60} is the applied load at 20% and 60% of F_{ult} respectively,

δ_{20}, δ_{60} is the deflection at mid-span at F_{20} and F_{60} respectively,

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.

$E_{m,s}$ was calculated by dividing equation (8) by (5).

RESULTS

Table 7 summarises all experimental results. Strength and stiffness values for the sample are similar to previously published results for Guadua a.k. For example, Trujillo and López (2016) cite $f_{m,0}$ 68N/mm² and $E_{m,s}$ ranging from 13,900N/mm² to 17,200N/mm² for bamboo in green condition. The observed increases to ρ , $f_{m,0}$ and $E_{m,s}$ along the culm and with age – Figures 2 and 3 – are similar to published observations for other species (Trujillo and López, 2016).

Table 8 and Figures 4 to 8 show the observed failure modes and rates of occurrence. A quarter of the specimens failed in shear. . The five failure modes that occurred within the constant moment zone were interpreted as bending failures, though some are representative of more complex phenomena. 40% of specimens failed under a support. The mean $f_{m,0}$ for this failure mode was only 12% higher than for the remaining bending failure modes, therefore deemed accepted for analysis.

Seeking strong correlations

The prospects of developing a grading methodology for bamboo will largely depend upon the reliability of correlations between destructively and non-destructively measured properties. Correlations were sought between $f_{m,0}$ results and some non-destructively measured properties, as shown in Figures 9 and 10. The obtained correlations between $f_{m,0}$ and $E_{m,s}$, and between $f_{m,0}$ and ρ , which are traditionally used for grading timber, were not particularly strong. This can be partly explained by the inadequacy of adopting a prismatic model in analysis. In an analogous manner to the discussed variability for volume, the second moment of area, I_B , varies along the culm, and equation (5), is inherently an approximation only. Similarly, comparing $E_{m,s}$ and E_d , (Figure 11) shows a relatively weak correlation. Arguably better correlations may be obtained by adopting more rigorous models for the culm that account for the effects of taper, as proposed by Nugroho and Bahtiar (2013).

However, an alternative approach to the analysis was adopted, by which the concepts of stress and modulus of elasticity, which are arrived at by using I_B , are replaced with concepts that can be determined without geometric approximations. These concepts are: maximum bending moment (M_{max}) and flexural stiffness (EI). Both are fundamental to the design of any element subject to flexure. This approach provides much stronger correlations (Figures 12 and 13), which evidences the appropriateness for bamboo of such analysis, as it overcomes the limitations placed by adopting a prismatic model. The approach is further validated when static flexural stiffness (EI_s) is compared to dynamic flexural stiffness (EI_d) (Figure 14). The strength of this apparently whimsical correlation is explained hereafter.

Calculation of $EI_{m,s}$ relies on equation (8). Calculation of EI_d comes from the product of (5) and (3), both values for flexural stiffness have inherent geometric approximations, but when combined their effect is reduced.

By substituting (2) in (3) and multiplying by (5), EI_d is calculated thus

$$EI_d = v^2 \times \rho \times I = \frac{v^2 \times m \times \frac{\pi}{64} [D_{mean}^4 - (D_{mean} - 2t_{mean})^4]}{l \times \frac{\pi}{4} [D_{mean}^2 - (D_{mean} - 2t_{mean})^2]} \quad (9)$$

Which can be simplified to

$$EI_d = \frac{v^2 \times m \times [D_{mean}^2 + (D_{mean} - 2t_{mean})^2]}{16 \times l} \quad (10)$$

Therefore, by comparing $EI_{m,s}$ with EI_d , instead of $E_{m,s}$ with E_d , the geometric uncertainty has been reduced overall, as D and t are calculated only to the power of two.

It was also found that average external diameter, D_{mean} , fits a cubic regression when correlated to M_{max} , see Figure 15. A summary of the tested linear correlations between two variables is contained in Table 9.

Multiple regressions

On the basis of the strong correlations observed between q_{test} , EI and D_{mean} , and M_{max} , multiple regressions were undertaken to try to identify whether these correlations could be improved on. Table 10 summarises the findings. Reported R^2 values were determined using multiple regressions with a 95% confidence level. Where the P-value for one of the variables was greater than 0.05, it was deemed as not significant and that particular combination of variables was not explored further. Table 11 summarises the equations derived from the simple and multiple regressions. Only equations from multiple regressions with R^2 values exceeding the R^2 values found for simple regressions were included in Table 11.

POTENTIAL GRADING METHODOLOGIES:

Tables 9 and 10, validate that linear mass, q_{test} , can potentially be a good indicator for both M_{max} and $EI_{m,s}$. EI_d and $EI_{m,s}$ could potentially be good indicators for $EI_{m,s}$ and M_{max} respectively. D_{mean} can also act as a good indicator for $EI_{m,s}$, though it correlates less well to M_{max} than the other non-destructively measured properties. Combinations of two variables offer some improvement, though only slight. Combinations of three variables offer very slender improvements and frequently contain variables that are not significant. On this basis, three potential indicating properties (IPs) are presented hereafter.

Linear mass as IP:

Using q_{test} as an IP for M_{max} (or $E_{m,s}$) in a grading system would seem promising, given the strong correlations, the simplicity of the process and low cost of required instruments (scales and moisture meter), but is likely to be limited to dry specimens. The suitability of moisture meters to green bamboo was not investigated.

Flexural stiffness as IP:

Flexural stiffness, either $EI_{m,s}$ or EI_d , as an IP for M_{max} offers promise too, and is potentially less affected by moisture content, though green bamboo was not tested. Measurement of EI_d can be done using a handheld device similar to the MTG Timber Grader, which can also be used to infer $EI_{m,s}$. However, this type of device is relatively costly and the process is slower, as it requires measuring geometrical properties as well as mass. An alternative is discussed by Trujillo and Jangra (2016) who successfully trialled a low-tech measurement of $EI_{m,s}$ using a lump-mass placed on a simply-supported specimen.

External diameter as IP:

Despite not offering the strongest correlations to M_{max} and $EI_{m,s}$, D_{mean} is promising as an IP, as its measurement is relatively simple and can be undertaken on green specimens. From the builders' point of view, controlling for diameter is of greater practical use than controlling for mass or stiffness, and is likely to take place regardless. Therefore, a grading system would very likely combine measurement of diameter, with either or both of the aforementioned IPs to provide a more complete picture.

CONCLUSIONS AND FURTHER WORK:

This paper presents the results from over 200 bending test results to Guadua a.k. with the aim to determine whether properties that can be measured non-destructively. It was found that if the analysis is not undertaken in terms of units of cross-sectional area (i.e. stress and density), but in terms of overall section properties such as flexural stiffness (EI) and linear mass (q_{test}), the maximum moment (M_{max}) correlates well to q_{test} , EI and average diameter (D_{mean}) ($R^2 > 0.74$). It is argued that each of these three non-destructively measured properties could act as IPs. Though low-cost means of determining

EI may be available, the simplicity of measuring D_{mean} or q_{test} , implies that are likely IPs for a grading system in which M_{max} is the grade determining parameter.

Alternatively, D_{mean} and q_{test} could form the basis for a classification system for bamboo. This system could use a given diameter and linear mass values as a class, and associate to it a series of characteristic capacities (moment, shear, compression, etc.), in a manner not unlike the properties for steel sections. It is recommended that this process be coupled with a visual grading process to control for factors known to affect the strength of bamboo, as listed in Trujillo (2013).

However, the conclusiveness of this paper is limited, as only one species of bamboo, in dry condition, from one plantation was studied. The universality of these observations needs to be corroborated for other species, at other levels of moisture content, as well as determining whether its usefulness extends to prediction of a specimen's other destructively measured properties e.g. shear and compressive capacity. The practicalities of implementing a grading procedure for bamboo, regardless whether it is visual or machine grading, would also need to be assessed.

ACKNOWLEDGEMENTS

This project was funded by the International Network for Bamboo and Rattan (INBAR), under contract 13-1258C. The authors would like to thank Agu Kirss and David Walker from Coventry University for their contributions.

REFERENCES

Asociación Colombiana de Ingeniería Sísmica – AIS (2010) Reglamento colombiano de construcción sismoresistente – capítulo G.12, Bogotá (in Spanish).

Benham, C., Holland, C. and Enjily, V. (2003). Guide to machine strength grading of timber. BRE digest 476, Building Research Establishment, Watford, UK. 12pp.

Bureau of Indian Standards - BIS (2004) National Building Code of India – Section 3B, New Delhi.

Gnanaharan, R, Janssen, J and Arce, O (1994) Bending strength of bamboo: Comparison of different testing procedures with a view to standardization. INBAR Working Paper No. 3, Kerala Forest Research Institute and International Development Research Centre, Peechi, India.

International Standards Organization (ISO) (2004a) "ISO 22156 Bamboo – Structural design." ISO, Geneva, Switzerland

International Standards Organization (ISO) (2004b) "22157-1 Bamboo – Determination of physical and mechanical properties – Part 1: Requirements" 17 pp. ISO, Geneva Switzerland

Janssen, J.A. (1981). Bamboo in Building Structures. Doctoral Thesis. Eindhoven University of Technology, Netherlands. 253pp.

Janssen, J.A. (1991) Mechanical Properties of Bamboo. Kluwer Academic Publishers, Dordrecht, the Netherlands

Johansson, C.J. (2003). Grading of Timber with Respect to Mechanical Properties. In Thelandersson, S. and Larsen H. J. editors, Timber Eng., pp23-43. Wiley, NJ, USA

Lin, C., Tsai, M. and Wang, S. (2006). Nondestructive evaluation techniques for assessing dynamic modulus of elasticity of moso bamboo (*Phyllosachys edulis*) lamina. *Journal of Wood Science*, 52(4), pp342-347.

Ministerio de Vivienda, Construcción y Saneamiento – MinViv (2012) Reglamento Nacional de Edificaciones (RNE) Norma E.100 Bambú, Lima (in Spanish).

Nugroho, N. and Bahtiar, E.T. (2013). Bamboo taper effect on third point loading bending test. *International Journal of Engineering and Technology*, 5(3), pp.2379-2384.

Ridley-Ellis, D., Stapel, P. and Baño, V. (2016). Strength grading of sawn timber in Europe: and explanation for engineers and researchers. *European journal of wood and wood products*. Pp291-306.

Trujillo, D. (2013). Prospects for a method to infer non-destructively the strength of bamboo: a research proposal, *Proceedings of the Third International Conference on Sustainable Construction Materials and Technologies*. 18-21 Aug 2013, Kyoto, Japan, paper e74.

Trujillo, D and Jangra, S (2016) Grading of Bamboo – INBAR Working Paper 79. International Network for Bamboo and Rattan, Beijing.

Trujillo, D. and Lopez, L.F. (2016). Bamboo material characterisation. In Kent Harries and Bhavna Sharma (Ed). *Nonconventional and Vernacular Construction Materials: Characterisation, Properties and Applications*. Woodhead Publishing, pp365-392.

TABLES

Table 1: composition of sample identifying range of positions along the culm and age at harvesting.

| Position along the culm | Age at harvesting | | | | |
|-------------------------|--|--------------------|--------------------|--------------------|-------------------|
| | Number of specimens shipped (number of specimens tested) | | | | |
| | < 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 (19) | 20 (15) | 20 (14) | 20 (15) | 20 (15) |
| Middle - M | 20 (12) | 20 (15) | 20 (15) | 20 (14) | 20 (17) |
| Superior - S | 20 (11) | 20 (11) | 20 (11) | 20 (9) | 20 (14) |

Table 2: Range of moisture content results in sample at time of testing

| Sample size | 207 | Box plot for moisture content data | |
|--------------------|-------|------------------------------------|--|
| Mean | 11.2% | | |
| Standard deviation | 1.2% | | |

Table 3: Data recorded per specimen

| Property recorded | | Units | Precision |
|----------------------------------|--|-------|-----------|
| Prior to four-point bending test | | | |
| External diameter | Orthogonal readings at both ends (i.e. four readings) using digital callipers | mm | 0.01 mm |
| Wall thickness | Recorded at both ends at each quadrant (i.e. eight values) using digital callipers | mm | 0.01 mm |
| Length | Recorded using a standard tape measure | mm | 1 mm |
| Mass of whole specimen | Recorded using digital scales | Kg | 0.01 kg |
| Moisture content | Recorded using Brookhuis FMC microprocessor controlled moisture meter on setting 1 | % | 0.1 % |
| Natural frequency | Recorded using Brookhuis MTG Timber Grader | Hz | 1 Hz |
| From the four-point bending test | | | |

| | | | |
|-----------------------|--|----------|-----------------------------------|
| Load-deflection graph | Load at midspan v deflection at midspan. Midspan deflection reduced by average of deflection at left and right supports. All readings recorded and hydraulic actuator operated using a Si-Plan 32 bit Servo controller. Loading rate: 0.5mm/s. | kN mm | 0.000001 kN / 0.00001 mm |
| Failure mode | Photographic evidence of each failure was recorded, alongside the location. Interpretation of failure modes discussed in Table 8. | - | - |

Table 4 – Error in estimation of volume

| | | |
|---|--------|-----------------|
| Sample size | 15 | <p>Box plot</p> |
| Mean | -7.39% | |
| Standard deviation | 4.77% | |
| <p>Calculation of error:</p> $\text{Volume error} = \frac{\text{Volume as cylinder} - \text{Volume from immersion}}{\text{Volume from immersion}} \times 100$ | | |

Table 5 – Summary of preliminary exercise to select correct setting on FMC moisture meter

| | Average ratio between moisture meter readings and moisture content from oven-drying. | |
|--|--|--|
| FMC microprocessor controlled moisture meter Setting | Probes inserted <u>parallel</u> to fibres | Probes inserted <u>perpendicular</u> to fibres |
| 1 | 0.94 | 0.99 |
| 2 | 0.79 | 0.80 |
| 3 | 0.67 | 0.67 |
| 4 | 0.58 | 0.57 |

Table 6 – Summary of exercise to corroborate validity of moisture meter readings

| | | |
|--|---|------|
| Species tested | <i>Guadua a.k</i> and <i>Phyllostachys pubescens</i> (Moso) | |
| Sample size | 16 (10 Moso, 6 <i>Guadua a.k.</i>) | |
| Mean moisture content | 11.5% | |
| Moisture content range | 9.8% - 15% | |
| Average ratio between moisture meter readings and moisture content from oven-drying. | Probes inserted <u>perpendicular</u> to fibres | 0.99 |
| | Probes inserted <u>parallel</u> to fibres | 0.95 |

Table 7. Summary of experimental results

| 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% |
| SD | 13.7 | 4.1 | 98 | 2765 | 3005 | 16.8 | 1.26 | 1.20% |
| CoV | 13.30% | 31.79% | 14.63% | 15.25% | 17.47% | 21.52% | 23.18% | 10.68% |

Table 8. Observed failure modes.

| Type | Failure mode | Description | Figure | Frequency (%) |
|---------|-----------------------|--|--------|---------------|
| Shear | - | Shear plane between fibres. Always present in shear span. | 4 | 25% |
| Bending | Compression | Culm kinks, with crushing of fibres to topside, splitting may be present. | 5 | 12% |
| | Collapse of culm | Integrity of culm is lost through tension perpendicular to fibres failure. | 6 | 12% |
| | Failure under support | Crushing of culm under load application straps. | 7 | 40% |
| | Combined | Combination of any two bending mechanisms | - | 9% |
| | Tension failure | Failure of fibres to underside of specimen. | 8 | 1% |
| TOTAL | | | | 100% |

Table 9. Summary of simple linear regressions

| Variables tested | R ² values | |
|---------------------|-----------------------|--------------------|
| | $f_{m,0}$ | $E_{m,s}$ |
| ρ | 0.31 | 0.401 |
| $E_{m,s}$ | 0.342 | - |
| E_d | 0.268 | 0.474 |
| | M_{max} | $EI_{m,s}$ |
| q_{test} | 0.863 | 0.897 |
| EI_d | 0.823 | 0.919 |
| $EI_{m,s}$ | 0.87 | - |
| D_{mean} | 0.751 ⁺ | 0.884 ⁺ |
| D_{mean}^3 | 0.745 | 0.879 |
| D_{mean}^4 | 0.748 | 0.884 |

⁺quadratic regression

Table 10: summary multiple regressions explored

| Variables tested | Adjusted R ² | |
|------------------------------------|-------------------------|------------|
| | $f_{m,0}$ | $E_{m,s}$ |
| $\rho + E_d$ | 0.299* | 0.923 |
| $\rho + E_{m,s}$ | 0.379 | - |
| | $M_{ult,0}$ | $EI_{m,s}$ |
| $q_{test} + D_{mean}$ | 0.861* | 0.911 |
| $q_{test} + D_{mean}^3$ | 0.863 | - |
| $q_{test} + D_{mean}^4$ | - | 0.922 |
| $q_{test} + D_{mean} + EI_d$ | 0.870* | 0.927* |
| $q_{test} + D_{mean} + EI_{m,s}$ | 0.889 | - |
| $q_{test} + D_{mean}^3 + EI_d$ | 0.871* | 0.948* |
| $q_{test} + D_{mean}^3 + EI_{m,s}$ | 0.889 | - |
| $q_{test} + D_{mean}^4 + EI_d$ | - | 0.927* |
| $D_{mean} + EI_d$ | 0.822 | 0.916* |
| $D_{mean} + EI_{m,s}$ | 0.869 | - |
| $q_{test} + EI_d$ | 0.868 | 0.926 |
| $q_{test} + EI_{m,s}$ | 0.886 | - |

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

Table 11. Equations for strong correlations

| | M_{max} (kNm) | $EI_{m,s}$ (Nmm ²) |
|---|---|---|
| q_{test} (kg/m) | $= (3.39 \times q_{test}) - 2.15$ | $= (4.00 \times 10^{10} \times q_{test}) - 2.69 \times 10^{10}$ |
| EI_d (Nmm ²) | $= (6.83 \times 10^{-11} \times EI_{m,s}) + 1.11$ | $= (0.863 \times EI_d) + 7 \times 10^9$ |
| $EI_{m,s}$ (Nmm ²) | $= (7.75 \times 10^{-11} \times EI_{m,s}) + 0.626$ | - |
| D_{mean} (mm) | $= (0.00276 \times D^2) - (0.383 \times D) + 15.7$ | $= (3.43 \times 10^7 \times D^2) - (4.66 \times 10^9 \times D) + 1.81 \times 10^{11}$ |
| D_{mean}^4 (mm ⁴) | $= (4.09 \times 10^{-8} \times D^4) + 1.02$ | $= (525 \times D^4) + 5.01 \times 10^9$ |
| q_{test} (kg/m) + D_{mean}^4 (mm ⁴) | - | $= (2.17 \times 10^{10} \times q_{test}) + (268 \times D^4) - 1.60 \times 10^{10}$ |
| q_{test} (kg/m) + EI_d (Nmm ²) | $= (2.47 \times q_{test}) + (2.01 \times 10^{-11} \times EI_d) - 1.38$ | $= (1.47 \times 10^{10} \times q_{test}) + (0.574 \times EI_d) - 7.60 \times 10^9$ |
| q_{test} (kg/m) + $EI_{m,s}$ (Nmm ²) | $= (1.61 \times q_{test}) + (4.26 \times 10^{-11} \times EI_{m,s}) - 0.835$ | - |

FIGURES

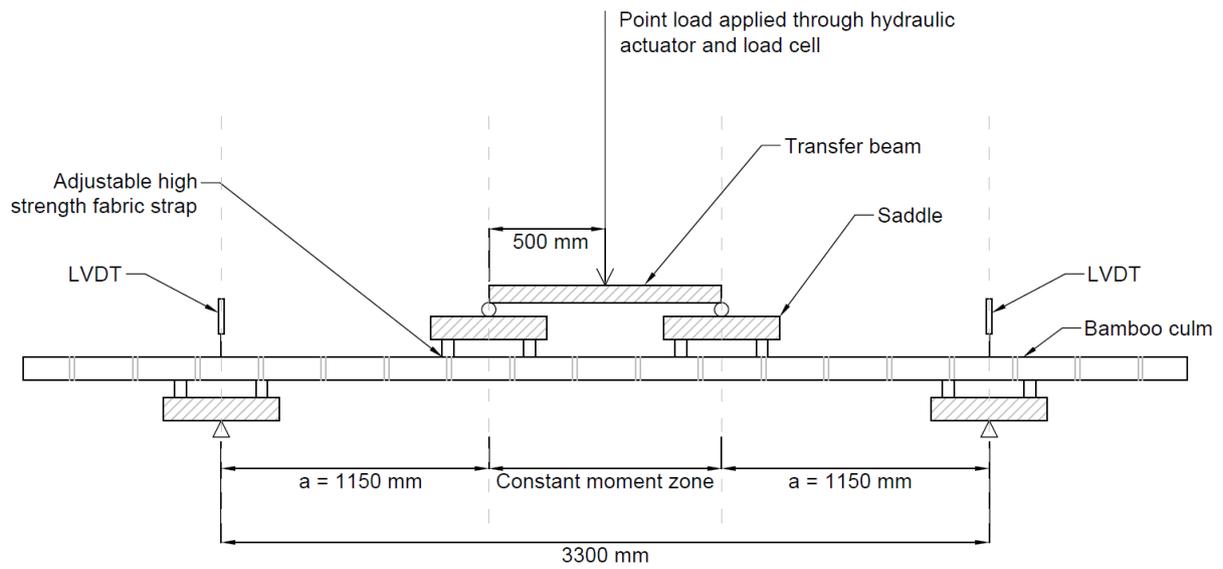


Figure 1: Schematic representation of test rig

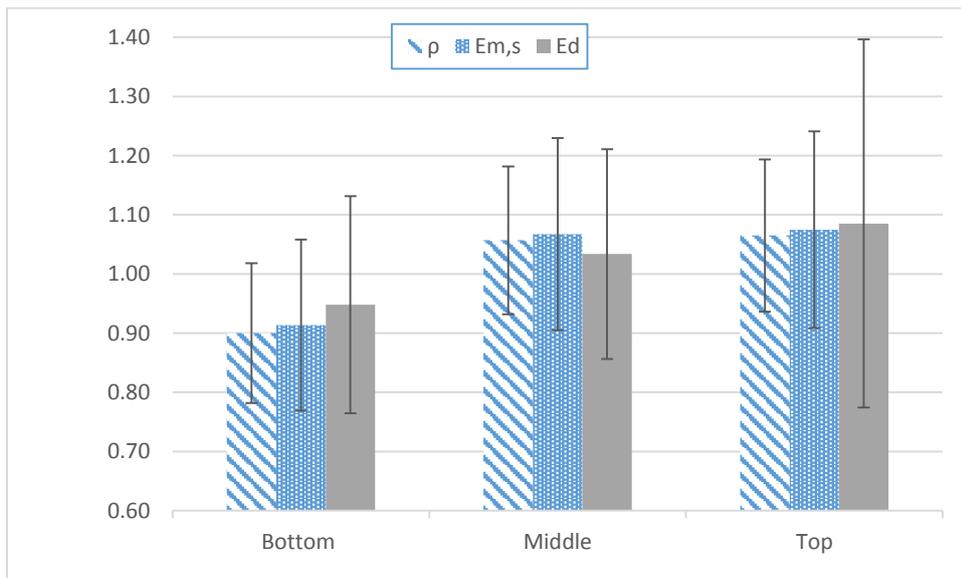


Figure 2: Ratio of properties at a given location to average of sample (1.0 is the average value from table 7)

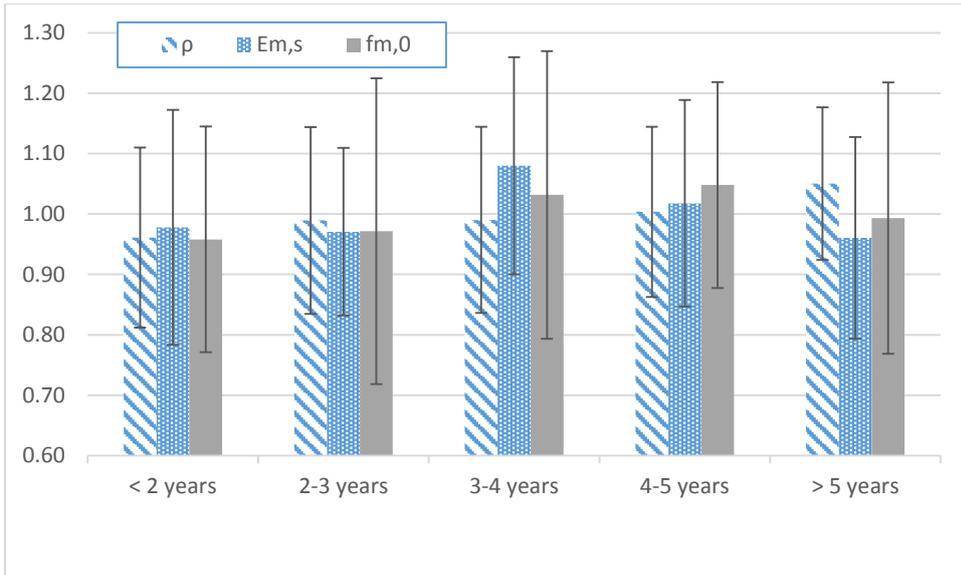


Figure 3: Ratio of properties at a given age to average of sample (1.0 is the average value from table 7)



Figure 4 – Typical shear failure



Figure 5 – Typical compression failure



Figure 6 – Typical culm collapse



Figure 7 – Typical failure under loading straps



Figure 8 – Typical tension failure

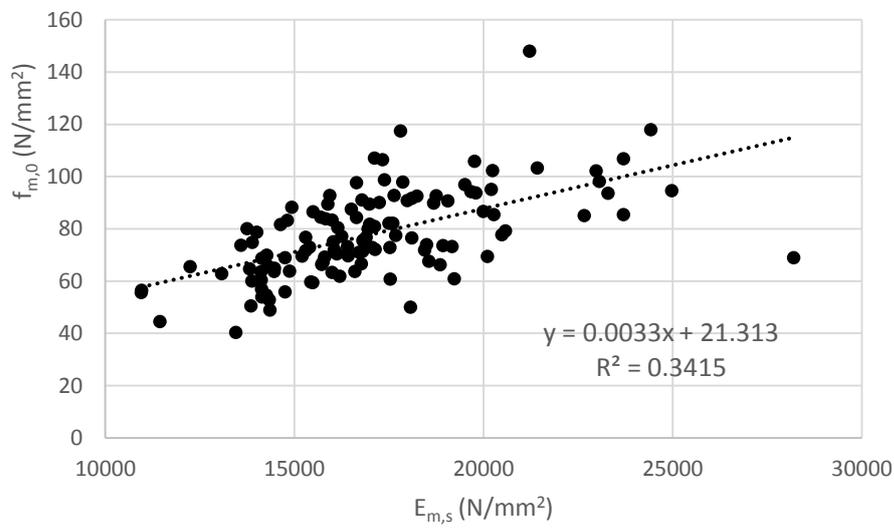


Figure 9. Correlation between $f_{m,0}$, and $E_{m,s}$

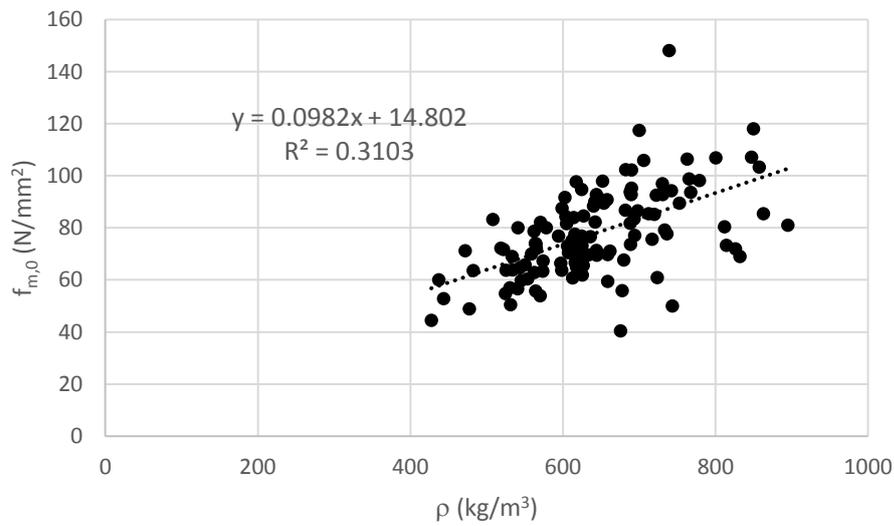


Figure 10. Correlation between ρ and $f_{m,0}$

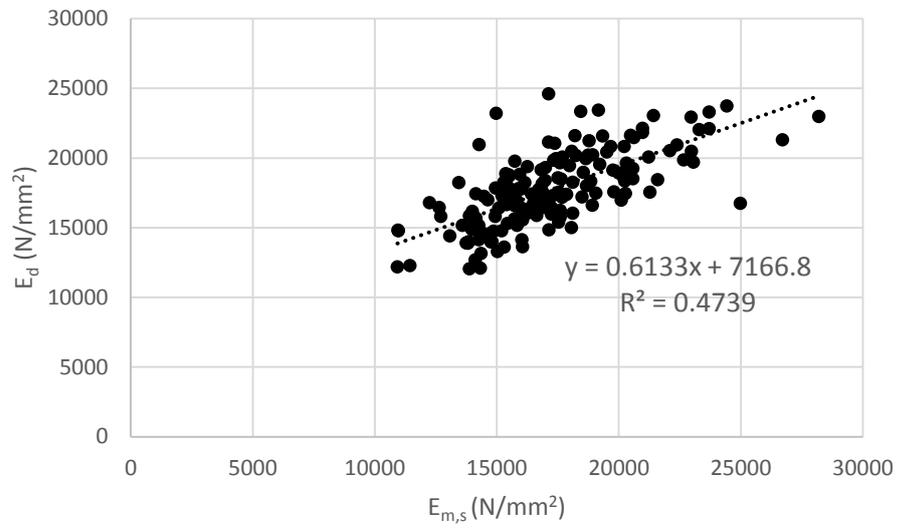


Figure 11. Correlation between $E_{m,s}$ and E_d

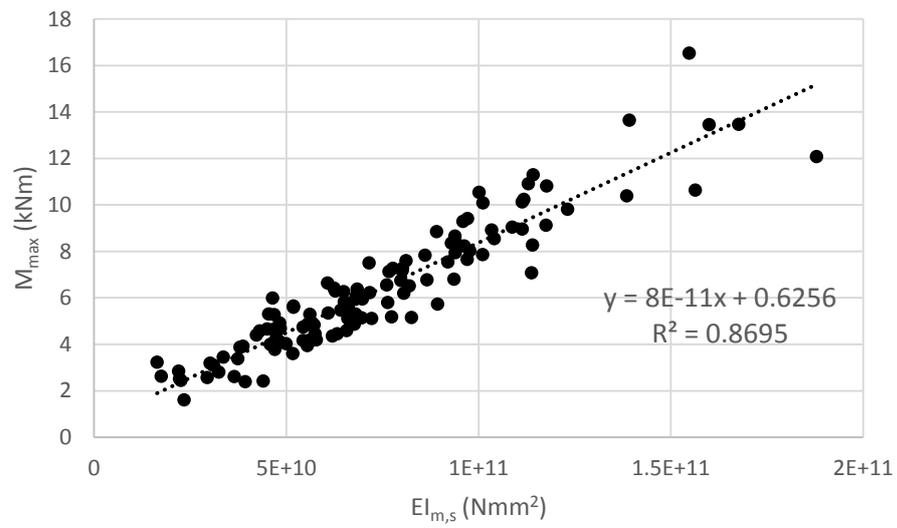


Figure 12. Correlation between M_{max} and $EI_{m,s}$

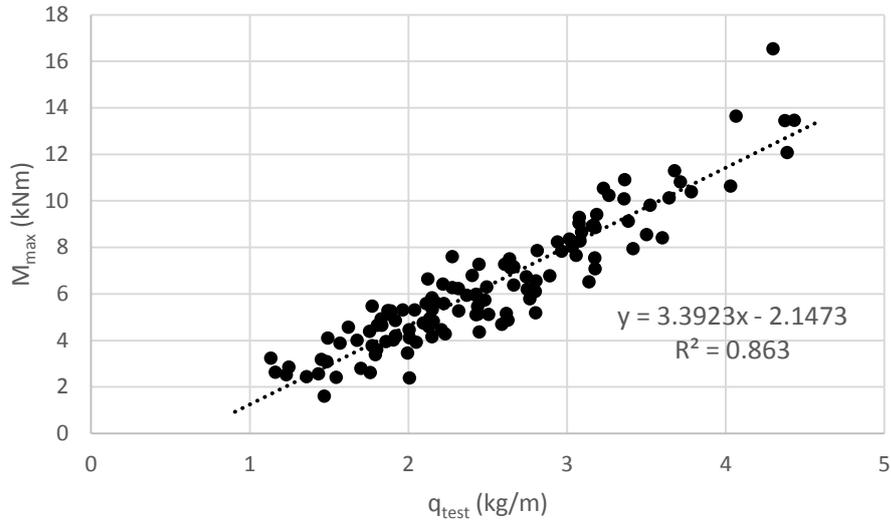


Figure 13. Correlation between M_{max} , and q_{test}

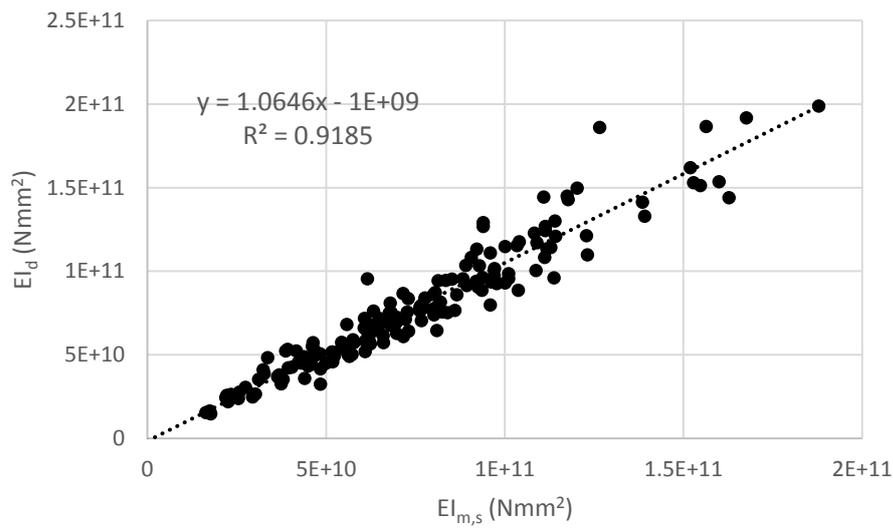


Figure 14. Correlation between $EI_{m,s}$ and EI_d

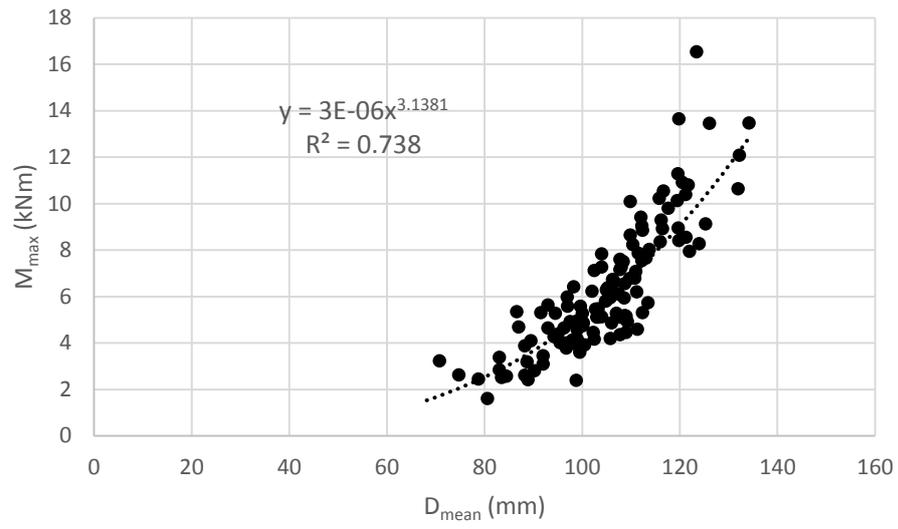


Figure 15. Correlation between M_{max} , and D_{mean}