PHD BY PUBLICATION

Development of methods to infer structural design properties from non-destructive testing, as a basis for bamboo grading

Trujillo, David

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Development of methods to infer structural design properties from non-destructive testing, as a basis for bamboo grading

Coventry University

By:

David J A Trujillo

PhD

January 2020

Development of methods to infer structural design properties for bamboo from non-destructive testing, as a basis for bamboo grading

Figure 1: sorted bamboo culms in a warehouse

By: David Trujillo

Critical Overview Document: a Portfolio of Published Articles submitted to the Faculty of Engineering, Environment and Computing, Coventry University, in partial fulfilment of the requirements for the degree of Doctor of Philosophy (PhD).

January 2020

Certificate of Ethical Approval

Applicant:

David Trujillo

Project Title:

Development of methods to infer structural design properties from nondestructive testing, as a basis for bamboo grading

This is to certify that the above named applicant has completed the Coventry University Ethical Approval process and their project has been confirmed and approved as Low Risk

Date of approval:

20 January 2020

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Synopsis

The six publications contained within this critical overview were developed in the period between 2012 and 2018. The first two publications in the portfolio start by assessing the state-of-the-art of structural design with bamboo in general (**Trujillo**, Ramage et al. 2013), and the process of grading of bamboo, in particular (**Trujillo** 2013). They conclude that some progress has been made in the development of structural design standards for bamboo, though there are evident gaps in terms of fire-resistance, connection design and grading. In terms of grading, little useful guidance existed at the time, and there was little consensus of how it should be done. Methods to infer strength of bamboo non-destructively had not been rigorously researched and were not adequately incorporated into any methodology; without these, machine grading is unviable.

The third publication (**Trujillo** and Lopez 2016) examines and critiques current experimental procedures to determine the physical and mechanical properties of bamboo necessary to characterise a species. It identifies properties that should be considered in the process of characterisation, including geometrical properties (diameter and thickness). The fourth publication (**Trujillo** et al. 2017) investigates the possibility of inferring non-destructively the flexural properties of *Guadua angustifolia* Kunt, a widely researched bamboo species. The fifth publication (**Trujillo** and Malkowska 2018) investigates three properties relevant to connection design: withdrawal, embedment and joint slip. It proposes ways by which these properties could be inferred from other properties such as density and wall thickness that can be measured non-destructively.

The sixth and final publication is an international standard: ISO 19624:2018 (ISO 2018). The project leader for this standard is the author of this portfolio. The standard creates a formal framework for the development of grading procedures, and as is to be expected in the current state-of-the-art, it requires producers at the national level to set-out appropriate grading parameters and limits thereof. It does however, provide relevant examples based on the work of **Trujillo** and Jangra (2016; not included in this portfolio).

This critical overview links the six publications and also set-outs the role played by the author in their development set in the context of his development as a researcher.

Abstract

This critical overview contains six publications. The first two publications (**Trujillo**, Ramage et al. 2013; **Trujillo**, 2013) identify that at their time of publication, grading of bamboo culms (or stems) was a poorly researched and understood topic. Extant guidance was cursory and rarely underpinned by research. Machine grading was non-existent. By identifying which properties and characteristics of bamboo culms affect their structural performance, the third publication (**Trujillo** and López, 2016) creates the basis for a grading methodology. This third publication also critiques some of the experimental procedures used to determine these properties and stresses the need to consider geometric characteristics of a species, as well as its physical and mechanical properties.

The fourth publication within the portfolio (**Trujillo** *et al.* 2017) presents the findings following the extensive flexural testing of *Guadua angustifolia* Kunth culms. Numerous non-destructively measured characteristics and properties were measured including linear mass (q_{test}) and flexural stiffness ($EI_{m,s}$). External diameter (D) and wall-thickness (t) were also recorded for each specimen. Moment at failure (or flexural capacity - M_{ult}) was also recorded. Correlations between the non-destructively measured properties and destructively-determined properties were undertaken. The publication identifies that correlations between extensive properties ($EI_{m,s}$ versus M_{ult} and q_{test} versus M_{ult}) are very strong ($R^2 > 0.86$), thus rendering them potentially very good predictors for bamboo machine grading.

The fifth publication, ISO 19624:2018, is an international standard that presents the framework to develop a visual or machine grading methodology by specifying the considerations or requirements in terms of sampling, testing and frequency of testing to develop a grading methodology. An example of a hybrid 'capacity grading' procedure is presented in Annex A.

Trujillo, Ramage *et al.* (2013) also identifies that bamboo connection design is an inadequately researched field. The sixth publication (**Trujillo** and Malkowska, 2018) addresses this inadequacy by experimentally determining three 'connection design properties' (dowel embedment strength, slip modulus and screw withdrawal capacity) for *Guadua angustifolia* Kunth.

Keywords:

Bamboo, standards, grading, connection design, non-destructive testing

Dedication

To my children: Sofia and Antonio, who deserve a ‘greener’ future.

Acknowledgements

I would like to thank the following people for their support and guidance:

- To all my students, but especially to Agu Kirss, Joel Gibson, Suneina Jangra and Dominika Malkowska.
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- To my funders. I am particularly grateful to Prof Pete Walker for inviting me to participate in LimesNET, and to Oliver Frith (formerly at INBAR) for having faith in me and my proposal to develop what became ISO 19624:2018.
- To my many mentors. I owe much of my understanding about grading to Dr Daniel Ridley-Ellis. I am truly grateful for his generosity, patience and insight. Similarly I have a debt of gratitude to the members of ISO Technical Committee 165 for the many hours of incisive questioning. To the many anonymous peer-reviewers. To Dr John Karadelis, my Director of Studies. And especially to Prof Kent Harries who has been my greatest mentor, sponsor and 'sparring partner'.

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Note to the reader

Dear reader, it is customary that academic publications, including PhD theses, are written in third person with the intent of providing a sense of objectivity to the endeavour by distancing the author from the text. However, this document is a Critical Overview of *my* work and progression as a researcher. I believe that a critique and appraisal of my own work seems more sincere if expressed in first person, hence this will be the voice adopted.

This Critical Overview discusses six publications; it is recommended that these are read before their respective portfolio chapter.

1 Introduction

1.1 About bamboo

Bamboo is a subfamily of the *Poaceae* (or *Gramineae*) family (i.e. it is a giant grass), with over 1640 species worldwide (Vorontsova et al. 2016). Bamboos are characterised as being fast-growing perennials. They produce an underground stem known as a rhizome and an aerial stem known as **culm**. Bamboo generally undergoes vegetative reproduction through its network of rhizomes, though some species are amenable to planting from seed. The culm is typically segmented, tapered and hollow. Bands are visible in mature culms, these are known as nodes. Externally nodes produce branches and internally they manifest themselves as a diaphragm (Figure 2). Some species produce very tall culms, reaching heights in excess of 25 metres. Growth for these species tends to be very fast, achieving full-height in less than six months, though it is customary to harvest culms that are between 3 to 5 years of age, as they are deemed to have optimal maturity. Figure 3 shows that some properties do indeed vary with maturity, albeit only slightly.

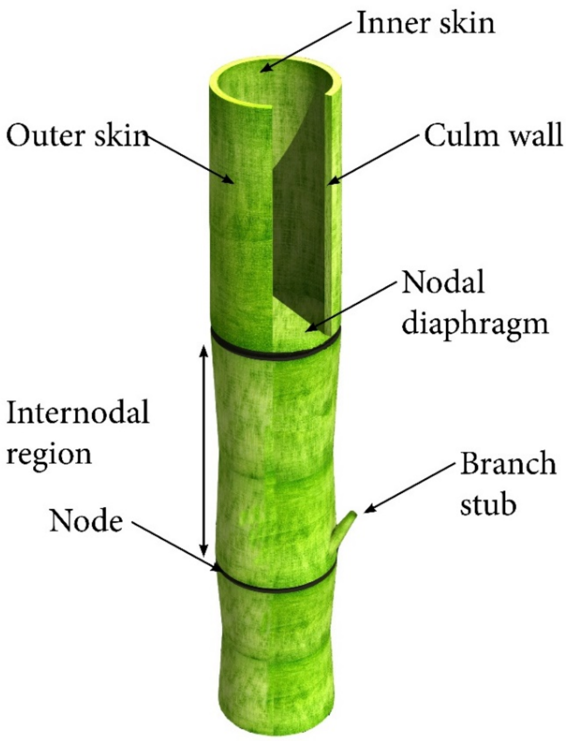


Figure 2: Schematic view of a culm segment, © Sebastian Kaminski, David Trujillo and Andrew Lawrence.

As could be expected from a giant grass with a complex root network, the felling of a single culm does not result in the death of the network. Extraction of a reasonable number of mature culms from a plantation does not affect its long term survival, though it can be detrimental to the network's health to extract too many mature stems in one harvest. Harvesting can be undertaken with tools as simple as a machete and transportation of the de-branched culm can be undertaken by one or two persons. As no heavy machinery is required, the exploitation of bamboo is non-capital-intensive and, if only the optimal amount of mature culms is harvested, disruption to the habitat of associated species of flora and fauna living within the plantation will be minimised (Figure 4).

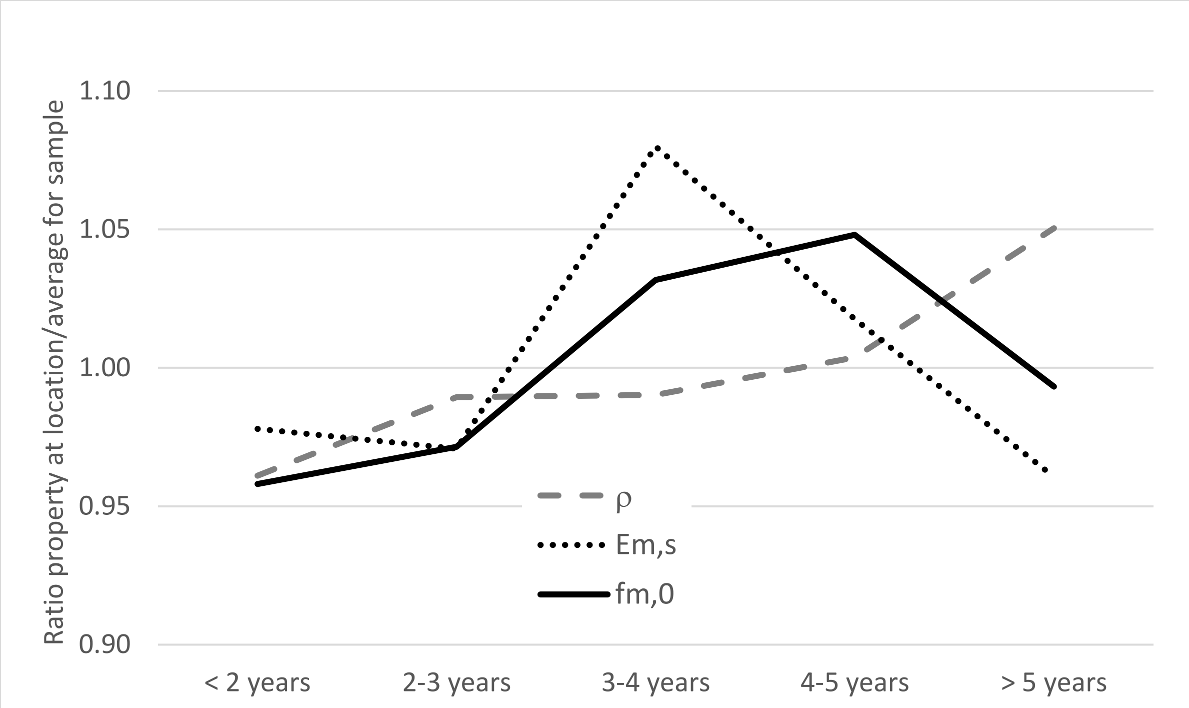


Figure 3: changes to density (ρ), modulus of elasticity in bending ($E_{m,s}$) and bending strength ($f_{m,0}$) – adapted from Trujillo et al. (2016)

Some materials have been removed from this thesis due to Third Party Copyright. Pages where material has been removed are clearly marked in the electronic version. The unabridged version of the thesis can be viewed at the Lanchester Library, Coventry University.

Figure 4: Howler monkey in Colombian bamboo forest – Courtesy of Natalia Mejía.

Bamboo plantations offer a range of other environmental services. The aforementioned root network can play an important role in controlling erosion and regulation of the water-cycle. Due to its fast growth and extensive root-network, bamboo may act as an important carbon sink. It is estimated that for some species of bamboo one hectare of forest can accumulate 300 tonnes of carbon over 60 years (Kuehl and Yiping 2012). If the culms are used within permanent products – such as buildings – much of this carbon is fixed. Bamboo culms require minimal transformation in order to be used in structural applications: they are cut to length, cleaned, preserved and dried. Therefore, when used within approximately 500 km of its source, the resulting embodied carbon is minimal: 0.20 kg CO_{2e}/kg (Vogtlander and Van der Lugt 2014) ignoring any potential carbon storage. Kuehl and Yiping (2012) list other benefits in terms of climate change adaptation: as a wind-break and a shelterbelt, as a form to rehabilitate degraded soils, reduce deforestation (by reducing pressure on other forest products), and as a source of biomass and bio-energy. For the above reasons, bamboo as a plant, and bamboo culms as a structural product, hold a great deal of promise as a means to minimise humanity's impact on the environment.

Not all species of bamboo are of structural interest; in fact, some grow no larger than shrubs. Indeed, there may be as few as one or two dozen species of structural interest across the world considering their availability, size, strength, durability and susceptibility to splitting. Jayanetti and Follett (1998) list fewer than ten species useful to construction. Arguably, *Guadua angustifolia* Kunth (or *Guadua* as it is commonly known) is one such species. *Guadua* is a species native to Colombia, Venezuela and Ecuador, though it has been introduced to numerous Central and South American countries and several Caribbean islands. Table 1, summarises the physical, mechanical and elastic properties for the sample of Colombian *Guadua* held at Coventry University's labs. The characteristic values have been determined in accordance to ISO 12122-1:2014 (ISO 2014), Figure 5 provides a representative frequency histogram for bending strength. For reference, the strength properties of *Guadua* are compared with the strength classes for timber contained in EN 338:2016 (BSI 2016). It can be noted that for most properties, albeit not all, this species of bamboo is stronger than softwood and as strong as the strongest hardwoods, which take much longer to grow and hence are frequently exploited from primary forests. In common with timber, bamboo has high strength-to-weight and stiffness-to-weight ratios, which makes it an appropriate material for roof structures or structures in seismically active locations. The very low tensile strength perpendicular to fibres ($f_{t,90,k}$) however should be noted.

Table 1: Mean and characteristic properties for Guadua angustifolia Kunth sample held at Coventry University.

Property	Symbol	Value	EN 338 strength class
Mean bending strength	$f_{m,mean}$	82.6 N/mm^2	-
Characteristic bending strength	$f_{m,k}$	52.0 N/mm^2	≈ C50 / D50
Mean compressive strength	$f_{c,0,mean}$	78.3 N/mm^2	-
Characteristic compressive strength	$f_{c,0,k}$	56.0 N/mm^2	>> D70
Mean shear strength	$f_{v,mean}$	10.2 N/mm^2	-
Characteristic shear strength	$f_{v,k}$	3.87 N/mm^2	≈ C40 / D40
Mean tension strength perpendicular	$f_{t,90,mean}$	1.25 N/mm^2	-
Characteristic tension strength perpendicular	$f_{t,90,k}$	0.40 N/mm^2	C14
Mean modulus of elasticity - bending	$E_{0,mean}$	17.4 kN/mm^2	> D60
5th percentile modulus of elasticity - bending	$E_{0,05}$	13.5 kN/mm^2	-
Mean density	ρ_{mean}	670-755 kg/m^3	D35 - D50
Characteristic embedment strength (with *d*=5mm)	$f_{h,k}$	40.3 N/mm^2	≈ D30

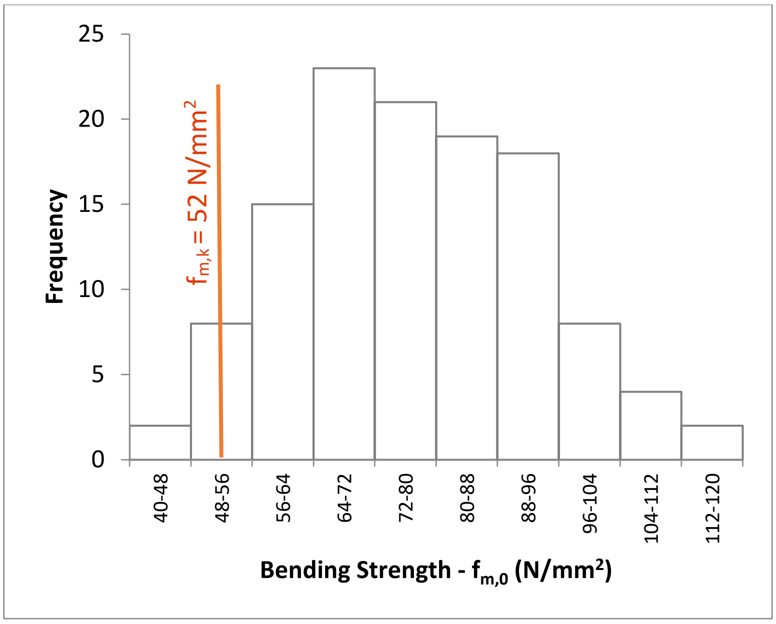


Figure 5: Frequency histogram for bending strength of the Guadua angustifolia Kunth sample held at Coventry University, showing characteristic value

Table 2 provides a comparison between a cold-rolled steel section and a bamboo culm of identical flexural stiffness (i.e. they have the same $E \times I$), hence similar performance as a beam. Evidently, steel is a much stronger material. Nevertheless, the bamboo culm, as a structural *product*, has a similar performance as a functional unit of similar depth, yet would have nearly a seventh of the carbon emissions (before making any considerations for potential carbon storage). This validates exploring ways to enable bamboo to be used as a structural material, and bamboo culms as a structural product.

Table 2: Comparison of steel and bamboo beams with identical flexural stiffness

Section	**Cold-rolled light gauge steel purlin (METSEC® 142 Z 13)**	***Guadua angustifolia* Kunth**	**Steel-to-bamboo ratio**
form	142 mm deep Z-section	150 mm diameter hollow round section	
Modulus (GPa)	E = 213	$E_{0,mean}$ = 17.4	11.49
Moment of inertia (cm^4)	117.4	1435	0.08
Flexural stiffness – EI (GNmm^2)	249.9	249.7	1.00
Density (kg/m^3)	7800	710	10.99
Depth (mm)	142	150	0.95
Thickness (mm)	1.3	14.3	0.09
Linear mass (kg/m)	2.85	4.33	0.66
Design strength (N/mm^2)	f_y = 450	$f_{m,k}$ = 52	8.65
Design moment – $M_{y,Rd}$ (kNm)	6.01 controlled by plate slenderness effects	5.04 controlled by modulus of rupture	1.19
Embodied Carbon of material (kg CO_2/kg)	2.03*	0.20	10.15
Embodied Carbon of beam (kg CO_2/m)	5.79	0.87	6.66

Notes: *Galvanised steel World average from University of Bath Inventory for Carbon and Energy.

As for all materials, bamboo has both advantages and limitations. Some of its numerous advantages, which include its fast growth, favourable mechanical properties, light-weight and minimal environmental impact, have been discussed. However, its limitations are arguably far more important to consider, as they will govern its applicability and design. Firstly it is important to distinguish bamboo as a *material* from bamboo culms as a structural *product*. Bamboo culms can be transformed into numerous structural products which include glue-laminated bamboo, parallel strand bamboo (i.e. scrimber), and cross-laminated bamboo, just to mention a few. Collectively these are referred to as *Engineered Bamboo Products* (EBPs). EBPs overcome many of the limitations of bamboo culms, in a similar way that engineered timber overcomes the limitations of timber logs. EBPs are sold as rectangular cross-section beams or board products. When sourced locally, bamboo culms are an inexpensive resource, which is not the case for EBPs. This critical overview focusses on the properties and applications of bamboo culms, therefore the advantages and limitations of EBPs are not discussed any further. However, the applicability of this work to EBP technology remains since the bamboo culms are the feedstock or constituent materials of the EBPs.

Bamboo is an orthotropic material which is relatively strong in the longitudinal (axial) direction, but weak in the transverse directions. Timber is also an orthotropic material, however, the difference between axial and transverse properties is larger for bamboo than timber as is evidenced in Table 1. The hollow, cylindrical shape of bamboo enhances its axial properties, since it maximises the second moment of area for a given area. The hollow round shape, however, limits transverse properties, as it reduces the area that resists shear and transverse stresses, and is readily crushed when subject to compression forces perpendicular to the longitudinal axis. The nodes and diaphragms contribute to mitigating these effects, but their distribution corresponds to the needs of the plant whilst alive and is a factor that cannot be readily controlled during design.

These characteristics have resulted in designs that use bamboo culms mostly as columns and props, and limited its use as beams – due to the relatively poor resistance to the shear and bearing stresses that are induced. Connection design is similarly limited by bamboo's thin walls, as shear failure or splitting is easily induced by mechanical fasteners (bolts, screws and nails). Physically constructing joints is similarly complex, as culms are not perfectly circular and of variable diameters. Numerous methods of constructing connections exist in the vernacular and more have been developed by researchers and practitioners alike (e.g., Hong et al. 2019, Widyowijatnoko and Harries, 2020), yet most have limited efficiency, performance and practicality.

In common with other bio-based materials, bamboo is combustible and is destined to biodegrade. This can be seen as a hindrance to the safety and durability of a structure, though of course is advantageous when considering end-of-life disposal. The fire resistance of bamboo is not dissimilar to that of timber (Mena et al. 2012), but hollow culms lose cross-sectional area rapidly in a fire and therefore have negligible fire-performance (Webb 2015). This implies that adoption in multi-storey structures requires additional fire protection, typically in the form of cement-mortar render encapsulation (Salzer et al. 2016). Bamboo has poor natural durability; unlike timber, it does not accumulate specific naturally occurring chemicals during its life, which impart resistance to pests and rot (Janssen 2000). Bamboo culms must be chemically treated and protected from wetting throughout its life. This means that outdoor applications, such as footbridges, require careful detailing and constant inspection. Many such structures are designed to be continually maintained, such as the traditional footbridges built by Colombian natives (Azuola-Guerra 1887).

There is evidence that humans have been building with bamboo for millennia (Salgado et al. 1993). The practice remains so widespread that in 2007 the United Nations Food and Agriculture Organisation (FAO 2007) estimated that 1 billion people across the world live in bamboo housing.

Despite this, the reality is that an engineered approach to structural design with bamboo is in its infancy. Most structural designs with bamboo are based on traditional practices, trial-and-error, crude numerical approximations or a mixture of these. For most of the 20th century, research into the structural use of bamboo was marginal. In the context of the 21st century, however, rapid urbanization in the developing world and the urgency to decarbonise the economy has led to increased relevance of bamboo research. Bamboo shares with timber many of its environmental qualities: renewable production, low-carbon transformation, potential carbon sequestration, environmental services, etc. However, due to its rapid growth and low-cost harvesting, bamboo offers the possibility of rapidly replacing other carbon-intensive materials in countries where there is no sustainable forestry sector. Figure 6 provides an indication of the difference in terms of carbon emissions (including potential carbon storage), between conventional concrete and/or brick construction and bamboo technologies in the Colombian context (Zea et al. 2018).

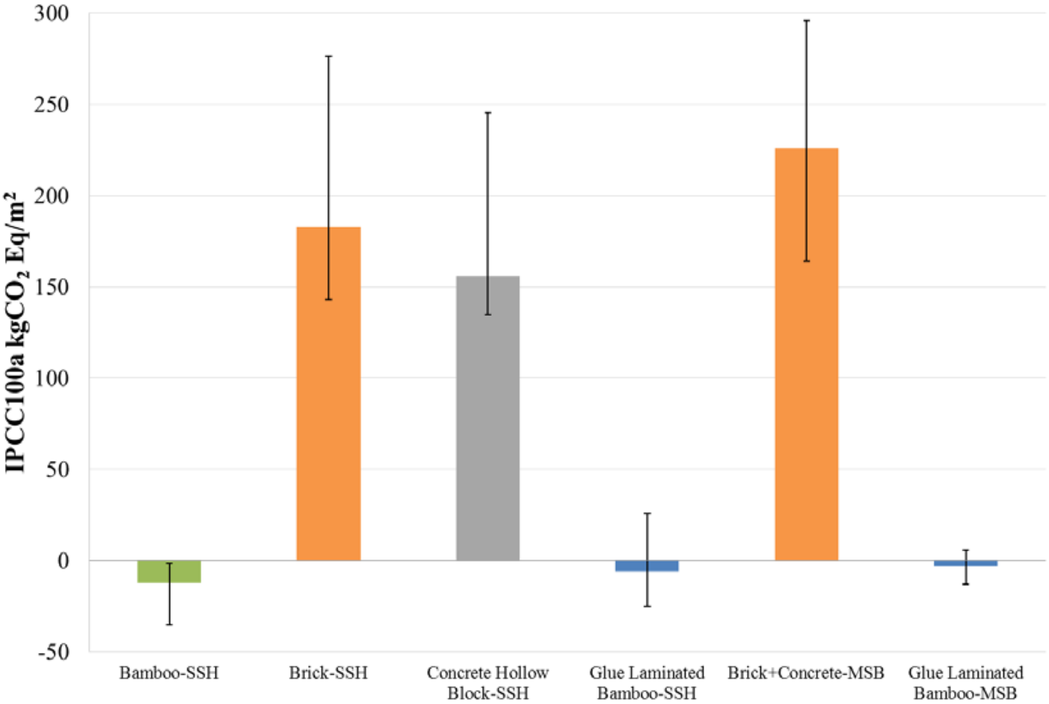


Figure 6: CO_2 balance per m^2 of floor area for Single Storey Houses (SSH) or Multi Storey Buildings (MSB) located in Colombia – Zea et al. (2018)

The advantages of bamboo are not only environmental. In common with timber-based frames, certain types of bamboo frames have exhibited good seismic performance (Janssen 1995, MacDonald 1999, Sharma 2010), though this can be hampered if damaged by rot or termites (Franco et al. 2017).

In conclusion, bamboo culms can be used as structural components in applications that overcome its limitations and exploit its strengths. One such application is one- and two- storey housing in tropical and sub-tropical developing countries where appropriate bamboo is native, especially if these locations are seismically active. In 2004, the first international building standard for bamboo was published: ISO 22156:2004. This early document provides a roadmap to design with bamboo, but its application was limited by a lack of data on bamboo materials and performance. This situation is evolving and a significantly updated version of ISO 22156 with much-improved utility is anticipated in 2021. A cornerstone of the revisions to this standard is the development of grading approaches for bamboo as described in the portfolio and culminating in ISO 19624:2018. Without such approaches, structural design with bamboo will remain severely limited and would remain a largely *ad hoc* endeavour.

1.2 About the Portfolio

In countries where larger species of bamboo are native, it is common to find vernacular structural applications, especially in rural housing and amongst the urban poor. However, despite all its qualities and potential, engineer-designed applications of full-culm bamboo remain a rarity around the world. The scarcity is a consequence of a self-reinforcing cycle I proposed in 2016 (Figure 7) (TEDx: Trujillo, 2016). It has been my career ambition to disrupt this cycle by addressing the lack of research, standardisation and education, leading eventually to the adoption of bamboo as a 'mainstream' structural commodity.

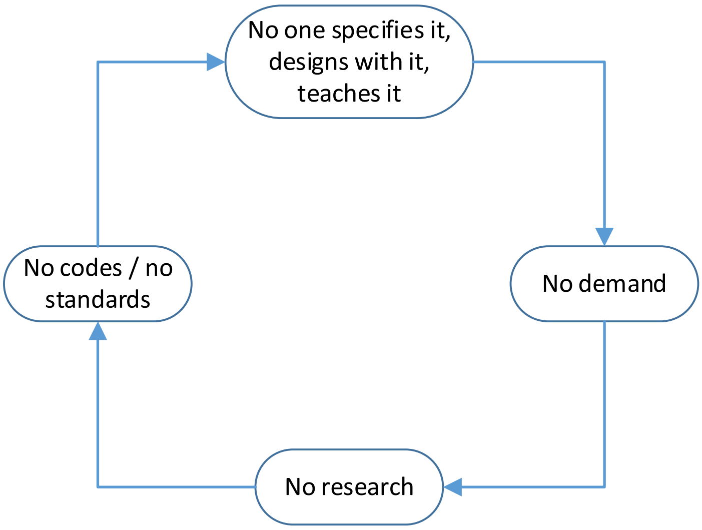


Figure 7: the self-reinforcing cycle that prevents bamboo from becoming mainstream (TEDx, 2016).

This portfolio contains a selection of my publications with the common theme of addressing this ambition; specifically, the development of methods of grading bamboo – providing the link between the physical, material and geometric properties of bamboo and structural design with the material. It spans a period of my research framed between 2012 and 2018. The portfolio is composed of the following six publications:

Publication 1: Trujillo, D., Ramage, M. and Chang, W.S. (2013) 'Lightly modified bamboo for structural applications'. *Construction Materials – Proceedings of the Institution of Civil Engineers* 166(4), pp.238-24

Publication 2: Trujillo, D. (2013) 'Prospects for a method to infer non-destructively the strength of bamboo: a research proposal' in *Proceedings of Sustainable Construction Materials and Technologies (SCTM3 conference)*. held 19 – 21 August at Kyoto, Japan. Paper E74.

Publication 3: Trujillo, D. and López, L.F. (2016) 'Chapter 13: Bamboo material characterisation' in *Nonconventional and Vernacular Construction Materials: Characterisation, Properties and Applications.* ed. by Harries, K.A. and Sharma, B. London: Woodhead (Elsevier) Publishing, pp. 365 – 392. ISBN-13: 978-0-08-100038-0

A second edition to **Publication 3** was published in 2019:

Trujillo, D. and López, L.F. (2019) 'Chapter 18: Bamboo material characterisation' in *Nonconventional and Vernacular Construction Materials: Characterisation, Properties and Applications.* 2nd edition. ed.

by Harries, K.A. and Sharma, B. London: Woodhead (Elsevier) Publishing, pp. 491-520. ISBN: 978-0-08-102704-2

For chronological coherence, the latter version is not included in the portfolio.

Publication 4: Trujillo, D., Jangra, S. and Gibson, J. (2017) 'Flexural properties as a basis for bamboo strength grading'. *Structures and Building - Proceedings of the Institution of Civil Engineers*, Vol. 170, No. 4. pp 284-294

Publication 5: Trujillo D and Malkowska D (2018) 'Empirically derived fastener properties for Guadua bamboo'. *Construction and Building Materials* – 163 pp. 9-20.

Publication 6: International Organization for Standardization (2018) *Bamboo structures – Grading of bamboo culms – Basic principles and procedures*. ISO 19624:2018. Geneva, International Organization for Standardization.

Figure 8 provides a visual guide as to how I believe the publications are linked, to which field they align and what phase in research they can be attributed to. One publication that has been included in the figure is not part of the portfolio, this is Trujillo and Jangra (2016) which contains supplementary and fundamental links to the rest.

Other than the obvious common thread of promoting structural applications of bamboo culms, it is argued that this portfolio constitutes a single and coherent narrative about the potential for non-destructive testing, particularly with the aim of *grading* bamboo. An important hypothesis of this portfolio is that the concept of grading *is* applicable to bamboo. Section 1.3 clarifies what is meant by 'grading'.

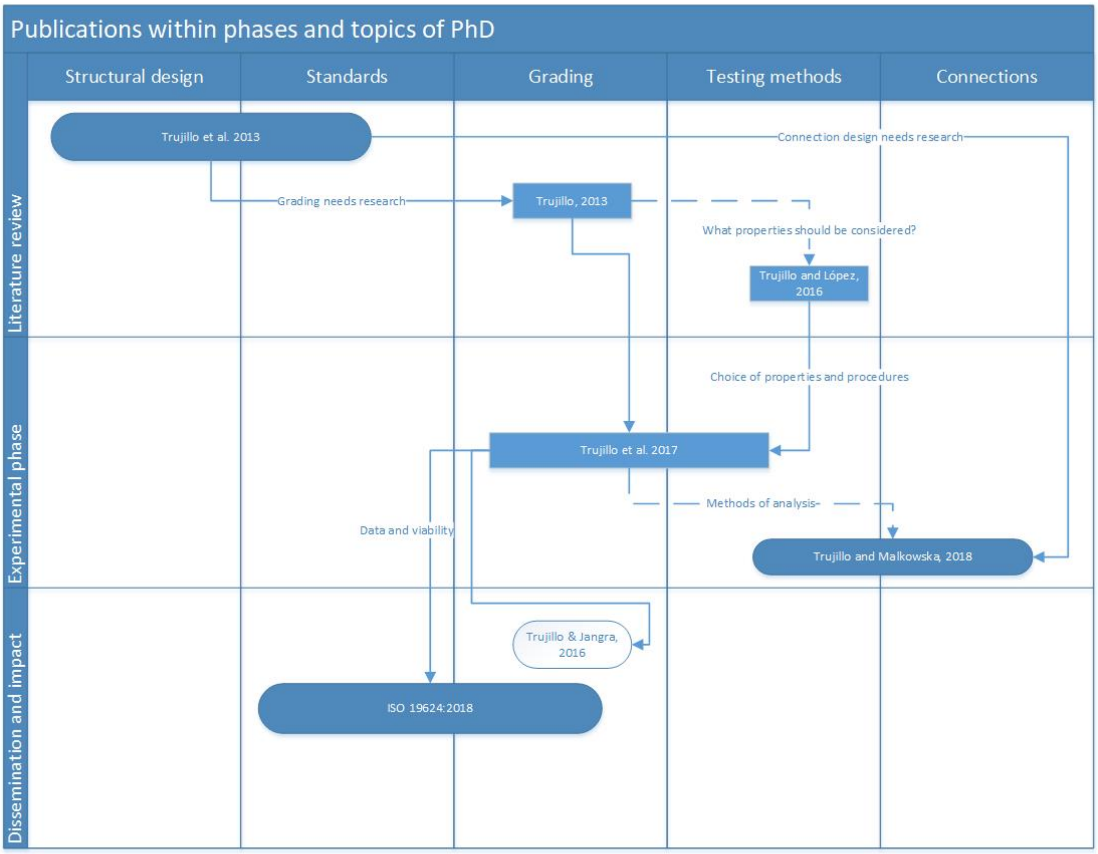


Figure 8: the six publications within the parts and topics of the PhD

1.3 Grading of sawn timber

In order to produce safe and economical design, structural engineering demands that the physical, mechanical and geometric properties of structural materials are known with confidence. In the case of sawn-timber, some relevant properties can be measured non-destructively, such as density and modulus of elasticity. Other properties of interest to structural engineers can only be measured through destructive tests (say bending strength), which precludes knowing with certainty the strength of a piece of sawn timber without destroying it. Wood, being a natural, rather than engineered material, these properties exhibit significant variability due to a range of factors that include: the genetics of the tree, the environment in which it grew and how the forest was managed. Even sawing and drying can affect these properties (Ridley-Ellis et al. 2016).

The timber industry has overcome the challenge presented by the *unknowability* and *variability* of the strength properties through a process called 'grading'. Grading requires the assessment of one or more characteristics which are used to sort a sample of material. Grading should not be confused with 'proof-loading', as the pieces are not subject to working stresses. Grading requires that the whole batch is subject to the process, it is *not* based on the assessment of a representative sample.

The most common form of grading of structural timber is 'strength grading' (also known as 'stress grading'). Despite the name, the process sorts sawn timber not only on the basis of strength, but also considers stiffness and density. The selected criteria that define a grade are known as 'grade-determining properties' (GDPs) (Ridley-Ellis et al. 2016).

Each 'strength grade' is associated to a 'strength class'. A 'strength class' is similar to a strength grade, but also has some additional mechanical and physical properties assigned to it. These additional properties, which are not GDPs, have not been assessed through the grading process, but are conservatively estimated for a grade from extensive previous study. These additional properties are known as 'secondary properties' and are typically estimated from the GDPs (Ridley-Ellis et al. 2016). For example, in Annex A of EN 338:2003 *Structural timber – Strength classes* (BSI 2003) contains equations that allow for the inference of characteristic tensile strength parallel to grain, $f_{t,0,k}$ (a secondary property) on the basis of characteristic bending strength, $f_{m,k}$ (a GDP) – refer to Equation 1.

$$f_{t,0,k} = 0{,}6 f_{m,k} \qquad \text{Equation 1}$$

There are two fundamental types of grading: visual grading and machine (or mechanical) grading. Table 3 explains the differences between the methods. Before either type of grading is undertaken, due to the great variability of timber, extensive experimental testing needs to take place. In the case of machine grading experimental testing needs to be very extensive in order to correlate 'indicating properties' (IPs) (properties that can be detected by the machine) to GDPs.

Table 3: Some differences between visual and mechanical grading

	Visual Grading	**Machine Grading**
Basis of process	Identifies visual characteristics known to affect strength. For example, size, location and number of knots. The criteria used for sorting are known as **grading rules**.	The machine senses one or more properties known to reliably predict **grade-determining Properties (GDPs)**. The properties detected by the machine are known as **indicating properties (IPs)**.
Advantages and disadvantages	Easy to adopt. Visual characteristics are not powerful predictors, and depend on human factors. Generally developed with smaller sample sizes. Lower upfront costs, but results in less optimal use of resource and larger factors of safety.	Produces better predictions, but requires extensive preliminary testing, resulting in smaller factors of safety and hence better utilisation of the resource. A much faster process, but requires a larger initial investment. Some form of visual grading may still be needed.
Process of development	1. Propose grading rules. 2. Grade material according to rules. 3. Test specimens in each grade (typically, at least 40 tests per property being assessed). 4. Determine characteristic values.	1. Exclude specimens which contain visual defects that the machine cannot detect. 2. Undertake extensive tests (typically hundreds per property being examined) to determine **GDPs** and potential **IPs**. 3. Correlate **GDPs** to **IPs**. 4. Develop machine grade settings based on the relationship between **IPs** and **GDPs**.

1.4 Aims and objectives

The aim of the body of work contained within this portfolio is to develop approaches to bamboo grading and specific methods to non-destructively infer properties useful to the structural design process for bamboo.

The objectives are:

1. To assess the state-of-the-art of characterisation and grading of bamboo,
2. To develop methods to non-destructively infer the flexural stiffness (EI) and bending moment at failure (M_{ult}); demonstrating this approach for one species of bamboo,
3. To develop a model by which connection properties, including embedment strength (f_h), screw withdrawal strength (F_{ax}) and slippage (K_{ser}), can be inferred non-destructively and demonstrate this for one species of bamboo,
4. To propose methods for grading bamboo based on non-destructive measurements.

This portfolio of publications constitutes a coherent body of work that is equivalent to a PhD.

2 Context of Portfolio

2.1 The *status quo* of bamboo grading

Since the early 21st century there has been a steady emergence of structural standards and codes for bamboo across the world (Gatóo et al. 2014). However, in Trujillo (2018) I argued that the majority of these codes and standards are of limited use to a structural engineer, with the notable exception of Colombia's NSR-10, which is the only standard that contains connection capacities, and one of the few to contain shear wall capacities (refer to Table 4). I have added the proposed revisions to ISO 22156, anticipated in 2021, to this listing of standards – it illustrates its completeness and degree of harmonisation with other standard.

Table 4: contents of structural design codes and standards from across the world (adapted from Trujillo, 2018)

Design code/standard	Year	Country	Species specific? (species included)	Mechanical properties	Derivation of design values	Beams	Columns	Connections / joints	Shear walls	Grading
AC 162	2000	Calif., USA	N	✗	✓	✗	✗	✗	✗	✗
NSR-98	2002	Colombia	Y (*Guadua*)	✗	✗	✗	✓ (simple)	✗ (Details)	✓	Some
ISO 22156:2004	2004	International	N	✗[1]	✓	✗	✗	✗ (Test)	✗	✗
NBC	2004	India	Y (20 & 16 species)	✓ (few)	✗	✗	✗	✗ (Details)	✗	Some
NSR-10	2010	Colombia	Y (*Guadua*)	✓	✓	✓	✓	✓	✓	Some
E.100	2012	Peru	Y (*Guadua*)	✓	✗	✓	✓	✗ (Details)	✗ (Details)	Some
Andean Standard	2015	International	Y (*Guadua*)	✗	✗	✓ (simple)	✓ (simple)	✗ (Details)	✓	Some
NEC – SE – GUADÚA	2016	Ecuador	Y (*Guadua*)	✓	✗	✓	✓	✗ (Details)	✗ (Details)	Some
Reglamento de construcciones del DF	2017	México	Y (3 species)	✓	✗	✓	✓	✗ (Details)	✗	Some
ISO 22156 revision	expected 2021	International	N	✗[2]	✓	✓	✓	✓	✓	✗[3]

Notes: [1] by reference to ISO 22157:2004; [2] by reference to ISO 22157:2019; [3] by reference to ISO 19624:2018

Most of these structural design codes contain some visual grading requirements, which are discussed in further detail in chapters 3.2 and 5.1 herein**.** Though not explicitly stated, the grading procedure in these cases can be represented by Figure 9. This results in a 'binary' grading output: structural or non-structural. In terms of mechanical properties, it is customary to assume that the mechanical properties of the graded sample are similar to those that have been previously determined experimentally for the same species, without *any* regard for the *representativeness* of the original experimental sample. The values are often assumed valid even if the graded material originates from a different plantation or indeed an entirely different region! In some instances, the original experimental sample could have been as small as 12 specimens, as this was the minimum set-out in ISO 22156:2004. Therefore, the data used to 'characterise' the species is unlikely to capture any intra-species variability. Furthermore, designers need to make assumptions about diameters and wall-thicknesses of the graded material, and specify these. These dimensional assumptions are typically based on each designer's experience, and not necessarily representative of the material that *can* be sourced.

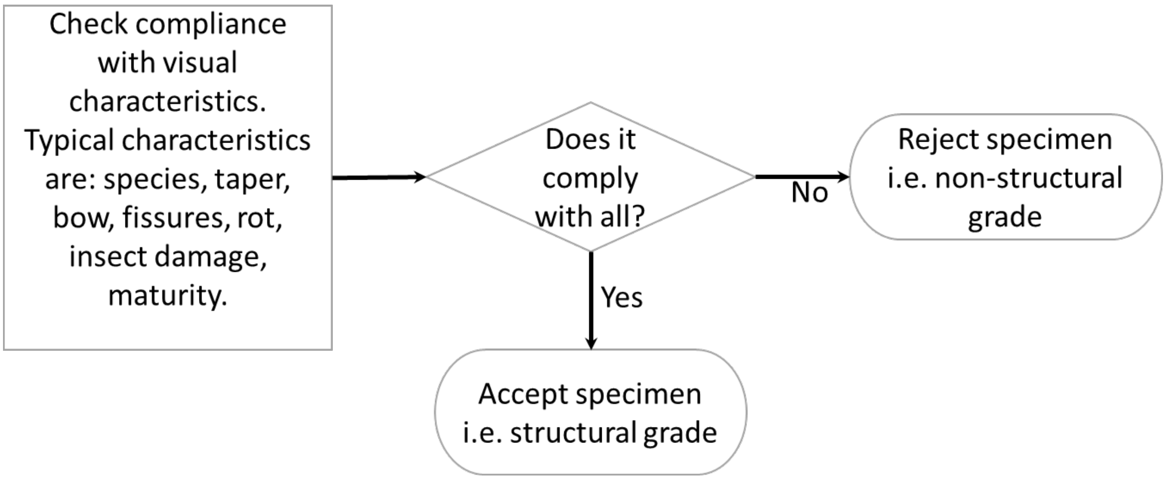


Figure 9: Flow-diagram of current visual grading practice

In summary, the current approach compounds two levels of uncertainty. The first is uncertainty about mechanical properties; the second is uncertainty about geometric properties. These uncertainties have rarely been critical because design tends to be governed by either stiffness or connection resistance, and not element strength. Yet, structural failure is not unknown to bamboo structures – see for instance Figure 8 in Publication 1, which provides an example of a buckled strut.

Arguably, designers could address the aforementioned uncertainties by requiring that no dimension be less than that which was specified, and commissioning 'characterisation' tests to a sample of the culms originating from the bamboo forest to be exploited. The former is subject to the contractor's disposition and skill. The latter is unlikely to be funded by a client. These uncertainties are likely to generate further distrust and trepidation towards the material.

In order to disrupt the self-reinforcing cycle presented in Figure 7 and achieve acceptance of bamboo as a 'mainstream' structural material, the following changes need to take place:

a) the existence of a supply chain that provides to market a relatively standardised and reliable quality product,
b) the training of a workforce that knows how to design and build quality buildings and structures with bamboo,
c) the development of standards and codes that determine best practice for the two previously mentioned points,
d) the adoption of the aforementioned standards and codes within national building regulations.

This portfolio contains some of the work I have produced to address points a) and c).

2.2 Autobiographical context and chronological development of portfolio

My interest in bamboo as a structural material started during the final years of my undergraduate in Civil Engineering at *Universidad Nacional de Colombia*. I struggled to reconcile the curriculum's strong emphasis on reinforced concrete design with the needs and realities of the poorest people. On 25th January 1999 an earthquake struck the Coffee-growing region of Colombia, numerous masonry and reinforced concrete structures collapsed killing over 1200 and leaving as many as 200,000 without adequate shelter (Cardona 2000). Bamboo structures in the region were mostly unaffected

(MacDonald 1999). Here was an overlooked abundant, low-cost and renewable material that also had good seismic performance.

This disaster sealed my determination to research bamboo for my undergraduate dissertation, particularly bamboo connection design – as I identified this to be a key issue needing investigation. During my last term at university, I moved to the Coffee-growing region to observe first-hand the reconstruction efforts, I was particularly interested in the housing projects that used bamboo as the primary structural material. After graduation, I returned to the region to design, build, research and teach bamboo. During this period, I met numerous foresters, botanists, architects, engineers and builders working with bamboo, and I learnt a great deal about the material and its limitations. I also became uncomfortable with the bravado displayed by some designers in light of the lack of experimentally validated knowledge. In 2003, I decided to undertake an MSc in *Earthquake Engineering* at Imperial College London to address my own limitations.

After finalising my MSc in 2004 and up to 2009, I worked in structural engineering consultancy in the UK. During this period in industry I shared, when I could, my bamboo experience by running workshops or delivering evening talks at regional branches of the *Institution of Structural Engineers*. However, I was very keen to continue my work with bamboo, and in May 2009 I joined *Coventry University* with the strong determination to undertake meaningful research in bamboo.

In September 2009, I published my first conference paper based on the experimental findings from my undergraduate dissertation (Trujillo 2009). Soon after, I looked into undertaking a PhD on a part-time basis, the topic would be grading of bamboo, as I had arrived at the conclusion that without addressing this issue, it would not be possible to develop a modern structural design standard.

This would require securing sufficient funding to import a large sample of bamboo. Therefore, I embarked on preparing a proposal to the *Engineering and Physical Sciences Research Council's* (EPSRC) *First Grant*, which was unsuccessful. The proposed project was to develop a strength grading system for bamboo. **Publication 2** reflects the academic work that went into the preparation of the proposal.

My first successful grant proposal was framed within the *Low Impact Materials and Innovative Engineering Solutions Network* (LimesNet) led by Professor Pete Walker from the University of Bath. The grant funded a fact-finding trip to Colombia by a group of UK academics and consultants to assess the state-of-the-art of Colombia's research and practice. The trip took place in April 2012, and the findings of this mission are described in **Publication 1**.

Whilst preparing the *EPSRC First Grant* proposal, I established a link with the *International Network for Bamboo and Rattan*, INBAR, an intergovernmental organisation dedicated to the promotion of bamboo and rattan. Oliver Frith at INBAR felt that the project had genuine merit and decided to support it, and appointed Coventry University to undertake a project to develop a strength grading method for bamboo. Two research students, Mr Agu Kirss and Ms Suneina Jangra, supported the INBAR-funded research project (referred to as INBAR Grading Project hereafter) at different times. The most significant outputs from this project are reported in **Publication 4**, Trujillo and Jangra (2016) (a working paper published by INBAR not included in this portfolio) and **Publication 6** (an international standard); other publications are being prepared. This project is undoubtedly the most important in my career so far.

The **INBAR Grading Project** included within its dissemination activities the drafting and development of an international standard for grading of bamboo. This standard would be led by me and developed within Technical Committee 165 – Timber Structures (TC165), of the International Organization for Standardization (ISO). It soon became apparent that this would be one of several international standards for bamboo, and that INBAR should pool expertise from across the world. With this goal in mind the 'Task Force for Bamboo Construction' was created which I was invited to chair.

In 2014, I joined forces with Professor Kent Harries from the University of Pittsburgh to submit a proposal to the *Global Innovation Initiative*. The bid was unfortunately unsuccessful; undeterred, in 2015 we resubmitted an improved proposal, 'Bamboo in the Urban Environment', which was successful. The 'Bamboo in the Urban Environment' project funded three international gatherings for members of the INBAR Task Force, and funded student and staff exchanges between the three participating countries: UK, USA and Indonesia. One such exchange allowed Mr Effendi Tri Bahtiar from Bogor Agricultural University in Indonesia to undertake a two and a half month fellowship at Coventry University (resulting in an article presently in review for *Construction and Building Materials* and not included in this portfolio: Bahtiar et al. (2020)).

My role within the INBAR Task Force and ISO TC165 have resulted in the creation of a large network of collaborators. I have collaborated with researchers from the UK, USA, Switzerland, Mexico, Colombia, Ecuador, Indonesia, India and China (refer to Figure 10). Undoubtedly, my strongest collaboration has been with Professor Harries. Professor Harries and I have worked together in the redrafting of ISO 22157 (ISO 2019b) and ISO 22156 (due in 2021) (ISO 2019a), and co-authored three publications to date: (Harries et al. 2017), (Archila et al. 2018) and (Harries et al. 2019). **Publication 3** is a book chapter written in 2016 following an invitation from Professor Harries to contribute to *Nonconventional and Vernacular Construction Materials: Characterisation, Properties and Applications,* a book that he co-edited with Dr Bhavna Sharma. This book chapter reflects much of my input to ISO 22157:2019. The book was published in a second edition in November 2019 in which my chapter was revised and updated. The first edition version of **Publication 3** is provided in this portfolio.

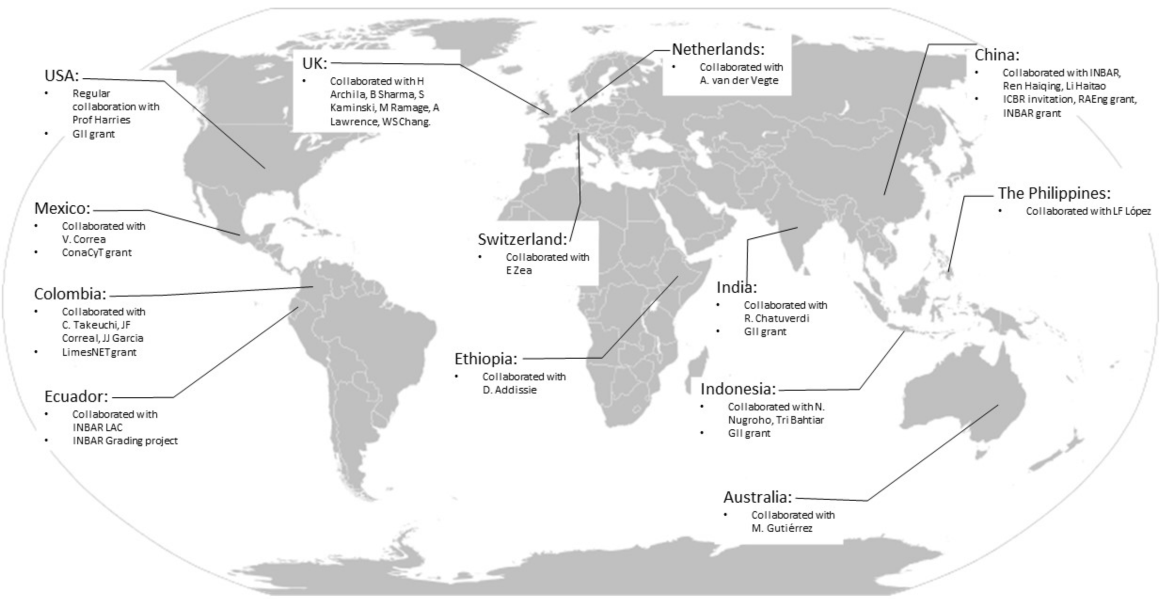


Figure 10: My network of collaborators and research projects

Enabling safe structural design with bamboo has been my career ambition, and connection design is determinant to its viability as a structural material. **Publication 5** reflects what I expect to be a major component of the proposed direction of my future research.

In the interest of brevity, I have not mentioned other significant collaborators, projects and publications. It was not for lack of merit that these were not discussed, but simply because the outputs have not been included in this portfolio. Figure 11 is a non-exhaustive list of my main publications in the field of bamboo structures set into themes and organised chronologically from top (oldest) to bottom (newest).

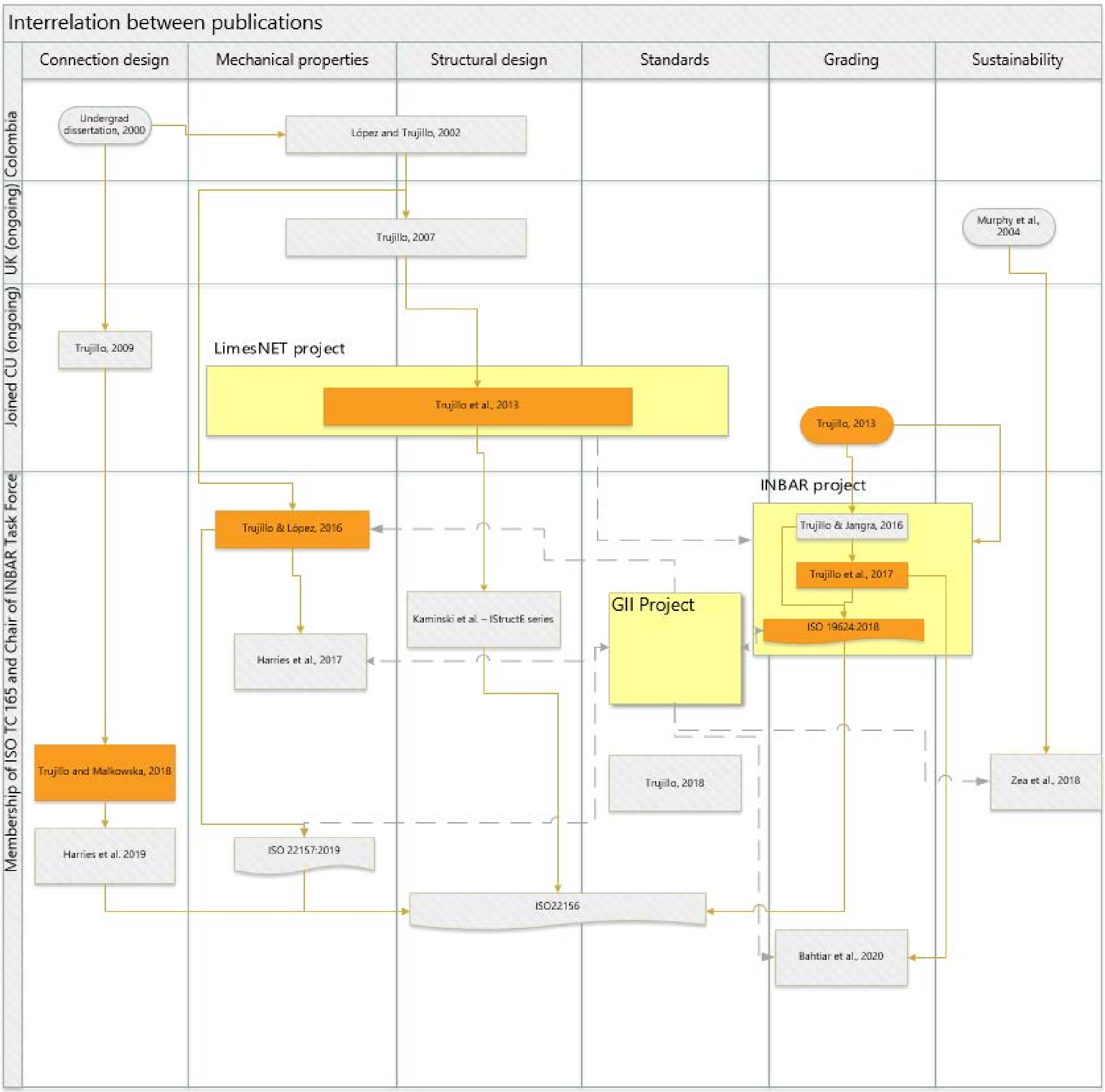


Figure 11: Interrelation between my main research activities and publications

2.3 Summary of contributions

The publications contained within this portfolio make the following independent and original contributions to the field of bamboo structures. Firstly, in combination, the publications provide a comprehensive literature review into bamboo grading and testing for characterisation.

Publications 1 and **2** identify two extant-at-the-time gaps in the state-of-the-art of bamboo engineering; these are grading and connection design. In terms of the former, **Publication 2** hypothesises and proves that mechanical grading is possible, because mechanical properties *can* be inferred non-destructively. **Publications 3** lists properties of bamboo culms that need to be considered in a visual grading process as well as identifying that during the early stages of characterising a species, its geometric properties should be recorded as well as its physical and mechanical properties. This will aid the development of grading procedures.

Publications 4 and **5** contain numerous methodological innovations, these include: demonstrating that some specialist equipment developed for timber can be used for bamboo (e.g. moisture meter and hand-held timber grader), the use of non-destructively measured properties (e.g. density) as a means to predict destructively-measured properties for bamboo, and the use of regression analysis techniques in order to identify potential indicating properties. The tested sample sizes and sample design (i.e. including a range of ages and locations along the culm), are uncommonly rigorous for the field, as is the systematic reporting of the observed failure modes. Observations surrounding the effects of culm age on properties, demonstrate that though age does in effect affect these, the observations provide a nuance that had not been previously discussed: the mechanical properties of young culms (< 2 years of age) is not significantly different to that of mature culms (3-5 years). Another methodological innovation contained in **Publication 4** that is validated, is the measurement for density of whole culms, as extant methods only allowed for the measurement of density at discrete locations.

The whole body of work validates the concept that grading through non-destructive testing is possible; hence, machine grading of bamboo culms is possible. It demonstrates that destructively-determined properties can be reliably inferred, especially if extensive properties (e.g. maximum bending moment, mass per unit length) are considered instead of intensive properties (e.g. bending strength, density). This finding leads to the conclusion that capacity-grading maybe more appropriate for bamboo than strength-grading. This leads to the revaluation of what should be the grade-determining properties (GDPs) for bamboo culms. The work postulates that flexural capacity (i.e. maximum bending moment) and flexural stiffness (EI) may be more suitable GDPs than bending strength and modulus of elasticity, as commonly used in timber. Three possible indicating properties are identified within **Publication 4** and put forward for further consideration: flexural stiffness (EI), external diameter (D) and linear mass (or mass per unit length – q). The concept of using linear mass as an indicating property is entirely novel. It has been demonstrated (in publications beyond this portfolio) that q is a powerful predictor for other properties (e.g. flexural stiffness and compressive capacity) and across several bamboo species, further validating the notion that machine grading with bamboo is viable.

Publication 6 is the world's first international bamboo grading standard, as well as (possibly) the world' first stand-alone grading standard – all other standardised grading procedures are nested within design codes. **Publication 6** propels the field of bamboo grading in numerous ways. It firstly provides a *lingua franca* for the field. The section called 'initial evaluation' is entirely novel for bamboo and explains how to develop grading rules for visual grading, and calibrate machines for machine grading, ensuring correct sampling, testing and statistical analysis is observed in the process. Finally, it provides examples of what a grading standard could contain.

Publication 5 is one of the first papers to investigate embedment strength (f_h) in bamboo and potentially the first to report screw withdrawal capacity (F_{ax}) and joint slippage (K_{ser}) properties for bamboo. In timber engineering, these three properties (f_h, K_{ser} and F_{ax}) form the basis for the reliable prediction of capacity and behaviour of complex connections reliant on dowel-type mechanical fasteners. By investigating these properties for bamboo and presenting an experimental and analytical methodology, this paper opens a new field of research with significant transformative potential.

3 Part 1: Literature Review

Three publications exemplify the earlier part of my research career at Coventry University, which was characterised by network building and documentation of the state-of-the-art. These three publications contain what can be described as the 'literature review' of the Portfolio.

3.1 Publication 1: Trujillo *et al*. (2013)

3.1.1 Summary, context and justification

This journal paper was published in a *LimesNET* special issue within *Construction Materials – Proceedings of the Institution of Civil Engineers*. It is an appraisal of the state-of-the-art of bamboo research in Colombia that resulted from an EPSRC-funded fact-finding mission in April 2012 by a team of UK academics and consultants. Colombia was identified as a worthwhile destination due to their advances in bamboo construction, in particular their structural design code, NSR-10.

The paper provides a summary of the locations visited in Colombia and the experts met during the fact-finding mission, as well as a literature review based on the work of these experts, and an analysis of best detailing practices for durability based on observations of a range of structures including housing and footbridges. Significantly, the paper identifies numerous gaps in knowledge that should be addressed including: determination of compressive and tensile strength perpendicular to fibres, strength grading, fire resistance, connection design (including slippage and ductility of joints), consequences of splitting and effects of environmental degradation (durability).

3.1.2 Collaboration

The paper was authored by three academics who attended the fact-finding mission: Dr Michael Ramage from the University of Cambridge, Dr Wen-Shao Chang formerly from the University of Bath and myself. Following the trip to Colombia, the same team agreed to publish a paper on our findings. It was agreed that I – having led the mission – would lead on the writing of the paper. I wrote the first draft of the paper, and produced all the illustrations. Dr Ramage provided editorial support and most of the photographs. Dr Chang acted as a second reviewer.

3.1.3 Contribution to the subject

Publication statistics	*Google Scholar*	*ResearchGate*
Citations:	14	11
Reads:		1883
Checked: December 2019		

The paper makes four significant contributions to the subject of bamboo structures. Firstly, it is the most consistently cited and widely read publication contained in this portfolio. Secondly, it helps disseminate the work of Colombian researchers beyond Latin America. In fact, many of the citations for this paper originate from China. Thirdly, it provides a convenient list of topics that had not at the time of publication, been investigated with enough rigour. Finally, it produces evidence-based guidance for best practice in detailing for durability.

As discussed in 1.1, bamboo has limited natural durability. Newcomers to bamboo, either poor urban dwellers or naïve professionals, tend to make all-too-common detailing mistakes that lead to the rapid deterioration of bamboo *in situ*. In this paper, we sought to address the problem by providing the evidence of what constitutes good and bad detailing, and summarise the discussion through Figure 12. Best practice in detailing is common knowledge for experienced bamboo designers; however, this paper was the first to provide empirical, albeit non-experimental, evidence of best practice in an international journal. The observations made about durability are a novel and necessary contribution to bamboo research and design. Kaminski et al. (2016) followed up and expanded upon these points.

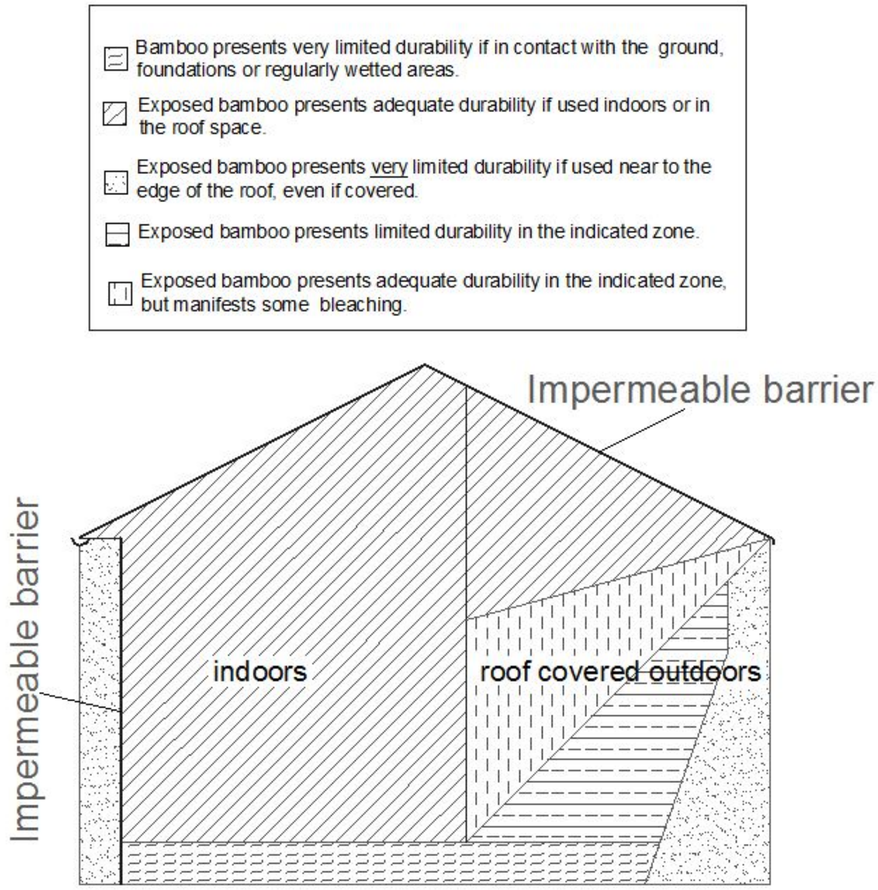


Figure 12: Observations on detailing bamboo for durability (Figure 10 in Publication 1)

3.1.4 Critique

This was my first publication in an academic journal Trujillo (2007) was published in *The Structural Engineer*, a journal with a more professional than academic outlook. I believe the paper to be well written, engaging, and makes a genuine contribution to an otherwise relatively unknown material for structural applications. The literature review is sufficiently rigorous, but centred only on the experts visited. As mentioned, the paper contains little in terms of experimental or methodological discussion, however, this was not one of the objectives of the *LimesNET* mission. Admittedly, I tackled the mission as a logistical task, and did not pursue opportunities to systematically collect observational or empirical data.

3.2 Publication 2: Trujillo (2013)

3.2.1 Summary, context and justification

This conference paper was presented at the third *Sustainable Construction Materials and Technologies (SCMT3)* conference in Kyoto in August 2013. It defines what strength grading is and outlines the principle of strength grading for timber, reports on extant grading requirements for bamboo contained in Colombian Design Code (NSR-10) (AIS 2010), and ISO 22156:2004 (ISO 2004b). It also identifies trends contained in published research that could serve as a basis for bamboo strength grading. Significantly, it reports on correlations between non-destructively-measured properties (such as modulus of elasticity and density) and destructively-measured mechanical properties (compressive and bending strengths). The paper concludes by suggesting that these correlations provide evidence that machine grading for bamboo *may* be viable.

Publication 1 demonstrates that Colombian researchers working with bamboo were not researching bamboo 'grading', and were unlikely to. In Colombia, in common with most of the developing world, forestry has not developed in a manner commensurate with its potential, and consequently grading of timber is poorly understood and implemented. Consequently, researchers had focussed their attention on species 'characterisation', and not on the processes that would ensure product performance.

The paper was written with the aim of informing fellow bamboo researchers of the identified 'need', outline initial findings and signal my intended field of research, should someone want to collaborate with me. Indeed, it closes with an invitation to collaborate.

3.2.2 Collaboration

This is the only publication contained in the portfolio for which I am the sole author. As at the time I had no experimental results of my own, in order to test the hypothesis that mechanical properties of bamboo could be inferred non-destructively, I relied on others' experimental findings, which were kindly provided by Dr Caori Takeuchi, from *Universidad Nacional de Colombia*. Professor Claisse reviewed and critiqued the first draft of the paper.

3.2.3 Contribution to the subject

Publication statistics	*Google Scholar*	*ResearchGate*
Citations:	6	4
Reads:		187
Checked: December 2019		

This paper makes four contributions to the subject. Firstly, it assesses and identifies the state-of-the-art for bamboo (strength) grading. Secondly, it postulates the need to develop (strength) grading methodologies for bamboo. Trivial as this point may seem, many bamboo researchers were unaware of this knowledge gap. Thirdly, it postulates the hypothesis that mechanical properties can be inferred non-destructively, and therefore machine grading for bamboo is viable. A common theme for the subsequent publications contained in the portfolio is non-destructive inference of mechanical properties. Fourthly, it postulates a list of factors known to affect the strength of bamboo.

The conference paper has attracted proportionately less attention than other publications in the portfolio, with only six citations according to *Google Scholar*. This is not surprising, as the paper does not contain novel methodologies or extensive, original research. Trujillo and Jangra (2016) and **Publications 4** and **6** supersede it. Conference proceedings are not readily available to many – especially practitioners – affecting dissemination of this paper.

3.2.4 Critique

This paper provides an introduction to the topic of (strength) grading for timber and bamboo, however, as my understanding of grading improved, so did my command of the topic. This is evident within the literature review contained in **Publication 4** and Trujillo and Jangra (2016), which is far more comprehensive and accurate. The paper also identifies factors known to affect the strength of bamboo. **Publication 3** is far more rigorous in identifying what they are and how they relate.

The paper does not include in its discussion anything about India's NBC-2004 (BIS 2004). In hindsight, this was an important omission, which is addressed hereafter. India's NBC-2004 provides a list of criteria that should be considered during grading of bamboo. These are: a) diameter and length of culm, b) taper of culm, c) straightness of culm, d) inter nodal length, e) wall thickness, f) density and strength, and g) durability and seasoning. It then sets out a list of criteria for exclusion for some of these criteria, which are mostly similar to those contained in Table 1 of **Publication 2**. However, the inclusion of diameter and wall thickness as grading criteria is an important consideration that I did not consider in **Publication 2**. NBC-2004 proposes three species groupings: A, B and C. The groupings are based on strength and stiffness properties (refer to Table 5). It then creates four grades to which the groups can be assigned. The grades are based on external diameter. The concept of grading bamboo on the basis of external diameter is one I would eventually arrive at in **Publications 4** and **6**, and in Trujillo and Jangra (2016).

Table 5: Characteristics and species of groupings – adapted from NBC-2004

Group	Limiting Strength Values (in Green Condition)		Grades by diameter of bamboo (mm)				Species within group
	Modulus of Rupture (R') (N/mm^2)	Modulus of Elasticity (E) in Bending (10^3 N/mm^2)	Special	I	II	III	
A	R' > 70	E > 9	70-100	50-70	30-50	< 30	*Bambusa glancenscens, Dendrocalaumus strictus, Oxytenanthera abyssincia.*
B	50 < R' ≤ 70	6 < E ≤ 9	70-100	50-70	30-50	< 30	*Bambusa balcooa, B. pallida, B. nutans, B. tulda, B. auriculata, B. burmanica, Cephalostachyum pergracile, Melocanna baccifera, Thyrostachys oliveri*
C	30 < R' ≤ 50	3 < E ≤ 6	n.a.	80-100	60-80	< 60	*Bambusa arundinacea, B. ventricasa, B. vulgaris, Dendrocalamus longispathus*

India's NBC-2004 postulates an alternative manner to determine mechanical properties of bamboo (other than testing) for a species that is not contained in the groupings (Table 6). This procedure was postulated by Janssen (1995), based on his own findings contained in Janssen (1981), and are mentioned in **Publication 2**. This approach, though of questionable validity, is an example of inference of mechanical properties from non-destructive tests.

Table 6: Allowable Long-Term Stress (N/mm^2) per Unit Density (kg/m^3) – from NBC-2004

Condition	Axial Compression (no buckling)	Bending	Shear
Green	0.011	0.015	-
Air dry (12%)	0.013	0.020	0.003

Publication 2 contains one inaccuracy, as it suggests that the Fibre Saturation Point for *Guadua angustifolia* Kunth bamboo is 18%. Gutiérrez et al. (2012) identified that this value is closer to 35%. This inaccuracy is unlikely to have significantly skewed the findings, after all the paper only sought to outline the hypothesis that non-destructive inference of mechanical properties was possible, to do so it relied on a very small sample of secondary data. The regression analysis undertaken is rather crude and focussed only on obtaining the highest possible coefficient of determination (R^2). Yet small sample sizes are quite common in bamboo research, for example, Gnanaharan et al. (1994) reported a sample size of 14 specimens. My future work would seek to ensure that statistical analysis was more robust.

3.3 Publication 3: Trujillo and López (2016)

3.3.1 Summary, Context and Justification

This book chapter was included in both 2016 and 2019 editions of *Nonconventional and Vernacular Construction Materials: Characterisation, Properties and Applications,* a book edited by Professor Kent Harries and Dr Bhavna Sharma. The chapter was written with the intention of aiding the process of 'characterising' a bamboo species. It is strongly reliant on experimental observations made by others, though it is also informed by our own experimental experience. On this basis, it identifies two physical properties and three factors that need to be considered when 'characterising' a species of bamboo, these are: density, moisture content, origin and age at harvest of the culm, and position along the culm from where a specimen was extracted. **Publication 3** discusses how density, or moisture content, have been observed to vary along the culm or with age. Similarly, it discusses how these physical properties and factors may affect the mechanical and elastic properties of bamboo, which serves to explain the importance of measuring and controlling them during testing. The chapter suggests that geometrical characteristics of a given bamboo species need to be considered, namely external diameter and wall thickness, and how these vary along the culm. The chapter then proceeds to provide practical guidance on the testing of bamboo in bending, compression parallel to fibres, shear, tension (both parallel and perpendicular to the fibres) and edge bearing (also referred to as bending perpendicular to fibres), as well as providing a commentary to extant test standards, namely ISO 22157-1:2004 (ISO 2004a). The chapter complements this section with numerical values obtained for *Guadua*, which serve as a reference. Though arguably it is not relevant to characterisation, the process of derivation of design values from experimental values was included for completeness.

One goal for **Publication 3** was to make it a reference document for bamboo researchers, especially those embarking on species 'characterisation' for the first time. As characterisation should be inherent to the process of grading, this chapter informed much of the **INBAR Grading Project**.

3.3.2 Collaboration

The title and scope of the chapter was decided by the editors, which required me to think in detail about what was meant by 'characterisation', a challenge that I accepted with gusto. I extended the co-authorship invitation to Luis Felipe López due to his extensive experience with testing bamboo and his role in co-authoring the Colombian NSR-10 design code. Nevertheless, I took upon myself to author the majority of this book chapter (including most illustrations) simply because gaining a deeper understanding about the process of characterising bamboo was aligned to the aims of the **INBAR Grading Project**. Luis López reviewed the chapter and authored Section 13.5 (1st edition; 18.1.4 in 2nd) based on his own first-hand experience. Mr Agu Kirss, a former research student, manufactured some of the apparatus included in the photographs. The chapter is strongly dependent on secondary data, because at the time we did not have access to disclosable primary data. The chapter also incorporates conclusions about best practice derived from discussions with INBAR Task Force peers.

When we presented the first draft, Figure 13.13 intrigued the editors; therefore, they procured the original 1958 paper in Japanese and arranged for an English translation. After this, Professor Harries and I collaborated in the development of Figure 13.13.

3.3.3 Contribution to subject

Publication statistics	*Google Scholar*	*ResearchGate*
Citations:	14	9
Reads:		1910
Checked: December 2019		

This book chapter is fundamentally a critical literature review, and offers readers a valuable list of publications, many of them seminal, to which to refer back when undertaking a characterisation or starting a project. By identifying what factors are known to influence the physical, mechanical and elastic properties of bamboo, it seeks to help researchers design better projects. The critical appraisal of test methodologies should aid the design of more reliable tests and avoid common pitfalls. Though the chapter is based primarily on secondary data, the analysis, graphs and discussion contained in the chapter is novel and would significantly influence my subsequent work. Overall, the work towards this chapter deepened my understanding of bamboo and helped frame the objectives and methodologies of **Publications 4, 5** and **6**.

The graphs contained within **Publication 3** merge different sources from different periods and countries. One particularly persuasive publication reviewed was Shigematsu (1958). The patterns identified by the author suggest that the geometric properties of the culm *can* be characterised for a species. The notion that the characterisation of bamboo culms should not be limited to understanding its intensive properties (i.e. physical, mechanical and elastic properties), but should also extend to its geometric properties is one of the key contributions this chapter makes to the subject, and greatly influenced the analysis contained in **Publication 4**. This concept would also inform the methodologies for testing (contained in ISO 22157:2019), grading (contained in ISO 19624:2018 - **Publication 6**), and for design (contained in DIS 22156). Ultimately this results in treating bamboo culms not so much as a material, but as a structural product as first postulated by (Chaturvedi 2015).

3.3.4 Critique

At the time of writing this chapter I was aware that much of my knowledge about bamboo was biased towards the work Colombian researchers had done with *Guadua* in the 21st century. I also was unsure whether characteristics observed for *Guadua*, were universal for 'all' bamboo species. This chapter furthers the literature review contained in **Publications 1** and **2**, and includes much more literature from Asia and from the 20th century, this has resulted in what I believe to a be more systematic and wide-reaching publication. By drawing information from a wide-range of sources and by attempting to provide an organised analysis and contrasting it with our experience, I believe this chapter reflects a step-change in my approach towards research. It also allowed me to adopt best practice in my subsequent research, which *would* include primary data.

4 Part 2: experimental work

The publications contained in this section report on the experimental and analytical work aimed at developing non-destructive tests and procedures that could be used to reliably infer properties used in structural design.

4.1 Publication 4: Trujillo et al. (2017)

Errata: Figure 13 *within* the paper contains an error. The values for q_{test} and M_{max} were inadvertently swapped. Figure 13, below, shows the corrected scatterplot.

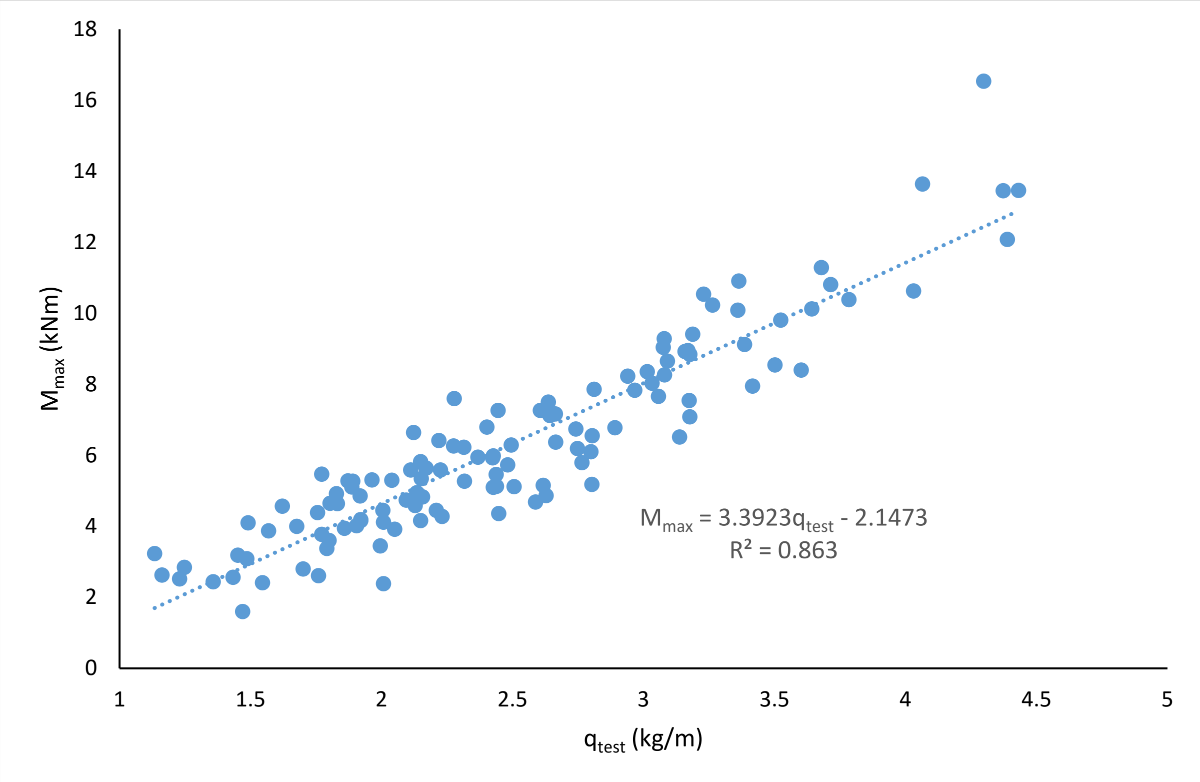


Figure 13: corrected Figure 13 - Correlation between M_{max} and q_{test} – note change to inset equation and ranges in axes.

4.1.1 Summary, context and justification

This paper was published in a bamboo-themed special issue of *Structures and Building - Proceedings of the Institution of Civil Engineers*. This paper is central to the portfolio. The paper is the first within the portfolio to contain original experimental output. It explains the care given to procuring the sample and ensuring it contained a range of ages and positions along culm. It also describes how density and moisture content (two physical properties known to affect mechanical properties) were recorded. It proposes and validates ways to quicken their measurement. Around 200 culms were subjected to four-point bending tests in order to measure load versus deflection and thus calculate their flexural properties (i.e. bending strength and apparent static modulus of elasticity). The dynamic modulus of elasticity of the culms was measured as well. The failure modes observed during the bending tests are reported.

The paper is also the first in the portfolio to include significant data analysis. Regression analysis was undertaken to correlate non-destructively-measured properties (such as density) to potential 'grade-determining properties' (GDPs - such as bending strength). It was found that correlations used in timber grading, which are based on *intensive* properties such as stress, provided lower coefficients of determination (R^2) than those based on *extensive* properties such as member capacities (e.g. bending moment at failure or ‘flexural capacity’). On this basis, the paper proposes three ‘indicating properties’ (IPs) that could form the basis of a grading methodology.

4.1.2 Collaboration

I authored most of the paper and also planned, designed and developed the experimental procedures reported. Ms Suneina Jangra undertook the regression analysis contained, under my direction. Ms Jangra and I jointly produced the illustrations. A former research student (Mr Agu Kirss) built the bending rig, whilst Ms Jangra, Mr Joel Gibson and I, undertook the data acquisition. Both Mr. Gibson and Ms. Jangra used the collected data for their dissertations (undergraduate and MSc by Research, respectively), which I supervised. Other important contributors were: Mr David Walker, who undertook the volume tests and Mr Mingjie Tang, who undertook some additional bending tests.

4.1.3 Contribution to the subject

Publication statistics	*Google Scholar*	*ResearchGate*
Citations:	9	9
Reads:		381
Checked: December 2019		

This paper contains a range of methodological innovations for bamboo; however, the level of innovation needs to be qualified. Some innovations are ‘new-to-bamboo’, these include: a) the use *and* calibration of a moisture meter; b) the use of a *Brookhuis MTG timber grader*, a device that measures the speed of sound waves travelling through a specimen that was developed for timber; c) the systematic recording of moisture content *and* density with the aim of including them in regression analysis; and, d) the use of regression analysis techniques to find correlations between non-destructively measured properties (potential IPs) and properties of importance to a grading methodology (potential GDPs).

Other innovations are improvements or refinements to current practice. These draw from other researchers and are included in the methodology to ensure that best practice is adopted, these include: a) the design and size of the sample; b) the use of straps in the bending rig to avoid stress concentrations; c) the reporting, description and interpretation of all the observed failure modes in bending; and, d) the reporting of the variability within findings aimed at conveying levels of uncertainty, including use of Coefficients of Variation in tables, box-plots and ‘whiskers’ in bar charts.

In terms of the sample size and design, authors such as Correal and Arbeláez (2010) had tested up to 100 culms, but our sample was twice as large and used kiln-dried bamboo. Vaessen and Janssen (1997) had reported observed failure modes, but had not attempted to classify these, as the sample size was only nine specimens. Many of the authors listed in **Publication 3** that ascribe behavioural trends to bamboo (e.g. increase of strength with age), fail to present the range of their data. We felt it was important to convey to the readership the level of uncertainty surrounding the findings. For example, Figures 2 and 3 (of **Publication 4**) present how density, bending strength and apparent static modulus of elasticity vary along the culm and with age. **Publication 3** cites several sources that have made similar observations. However, by presenting the range, the reader can appreciate that a very young culm (<2 years) can still be stronger than a culm of optimal maturity (3-5 years). This provides a nuance to the prescribed levels of maturity contained in building codes and standards, which would inform the drafting of **Publication 6**.

In terms of original contributions, to my knowledge it is the first publication that explores and discusses ways to measure density of whole culms, instead of relying on measurement of the density of discrete pieces cut from culm ends as presented in ISO 22157-1:2004 (ISO, 2004a). The validation of this method of measuring density allowed us to speed-up the process of data collection significantly. This was important because of the size of the sample. Of note, the approach presented in **Publication 4** was adopted into the revised ISO 22157:2019 (ISO 2019b).

The paper also experimentally validates the hypothesis postulated in **Publication 2,** that grading of bamboo culms through non-destructive testing is possible. However, the paper's most important conceptual breakthrough is that grading of bamboo culms is more effective if treated as a structural product (i.e. considering its extensive properties) and not as a material (considering its intensive properties). Admittedly, Chaturvedi (2015) had already postulated this idea, but this paper provides the numerical evidence that this is a preferable approach.

As discussed in 2.1, current 'grading' and specification practices leads to a great deal of uncertainty. Part of this uncertainty is due to an excessive emphasis on intensive properties (e.g. strength). Figure 14 demonstrates that flexural capacity, M_0 or M_{Max}, (i.e. ultimate bending moment) and flexural stiffness, EI_m or $EI_{m,s}$, (i.e. the product of apparent modulus of elasticity and the second moment of area) are far more sensitive to variations in diameter than to variations to mechanical properties. This is simply because flexural capacity and flexural stiffness are modified by the square and the cube of the diameter respectively, whereas the mechanical properties vary linearly. Therefore, a seemingly small reduction to the assumed diameter, say by 5%, would result in a 12% reduction to the flexural capacity and an 18% reduction to the flexural stiffness. Thus, it is self-evident that diameter should be central to a grading process.

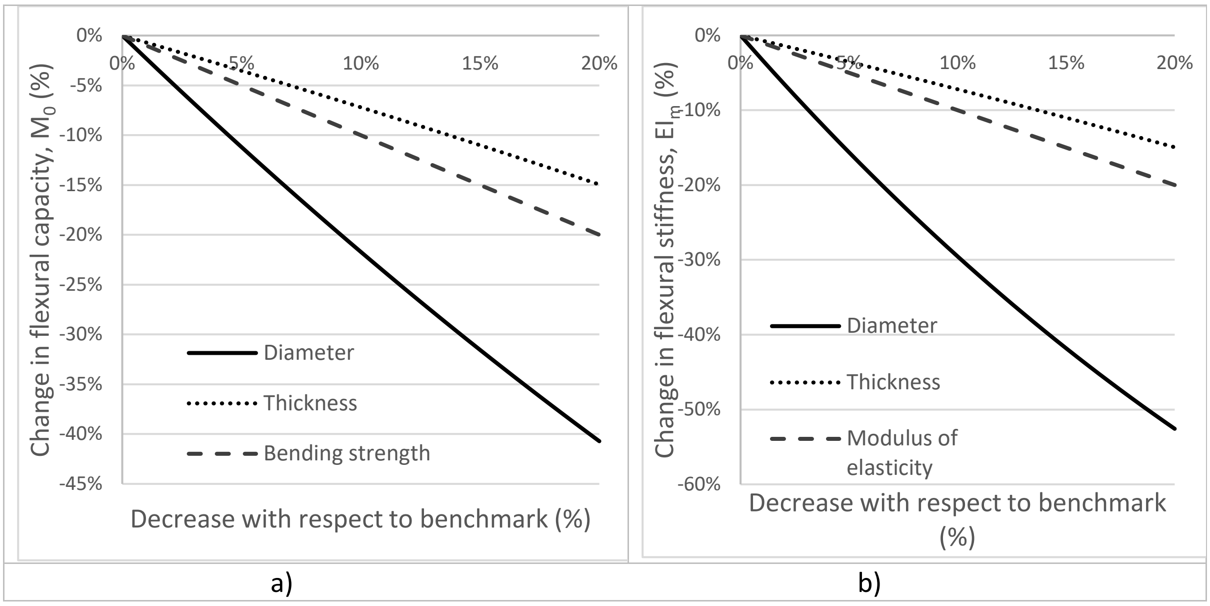


Figure 14: The theoretical effect of change to external diameter (D) to the a) Flexural Capacity (M_0) and b) Flexural Stiffness (EI_m) of a bamboo culms

The change in approach presented in **Publication 4**, whereby bamboo is treated as a product and hence capacity-graded, and not a material, which would be strength-graded, will ultimately result in a better grading process with increased levels of safety and efficiency in structural design. This new capacity-based approach has informed the drafting of **Publication 6**, ISO 22157:2019 (ISO 2019) and the new version of ISO 22156 (ISO 2019a).

Publication 4 presents three potential Indicating Properties (IPs) that could be used to infer flexural properties, particularly flexural capacity (M_0): flexural stiffness (EI), linear mass (q) and external diameter (D). Chaturvedi (2015) had already postulated EI as being a good basis for grading bamboo culms. It should not be entirely unexpected that *EI* correlates well to flexural capacity, M_0. From beam theory we know that *EI* relates to *M* as shown in Equation 2.

$$M = -EI\frac{d^2v}{dx^2} \qquad \text{(Equation 2)}$$

Where $\frac{d^2v}{dx^2}$ is the curvature of the beam.

This is analogous to the relationship between stress (σ) and modulus of elasticity (*E*), that are linked by strain (ε), as shown in Equation 3.

$$\sigma = E\varepsilon \qquad \text{(Equation 3)}$$

For a beam, Equation 3 can be rewritten in terms of curvature thus:

$$\sigma = -yE\frac{d^2v}{dx^2} \qquad \text{(Equation 4)}$$

Where *y* is the distance from the neutral axis to the fibre being analysed.

By inspecting Equation 2, it seems trivial that M_0 can be predicted from *EI*, as they are linked to the curvature $\left(\frac{d^2v}{dx^2}\right)$ in a linear manner. This would only be true if the material in question did not exhibit any non-linearity. But this is not true for timber which, for example, exhibits a non-linear behaviour in bending (Dinwoodie 2000). Similarly, the experimental data for **Publication 4** mostly exhibited a non-linear behaviour. Figure 15 contains a sample of load-versus-deflection graphs for six bending tests. The graphs have been presented as normalised loads and displacements for comparability. Most curves have been plotted above the thick black line, which represents a linear behaviour. This was characteristic for the majority of tests. The dotted line below the thick black line represents an anomaly in which the stiffness of the culm appears to *increase* under load. This phenomenon was associated with large deflections, and was interpreted to be an interaction between specimen and test supports. The few specimens that exhibited this behaviour were excluded from the sample.

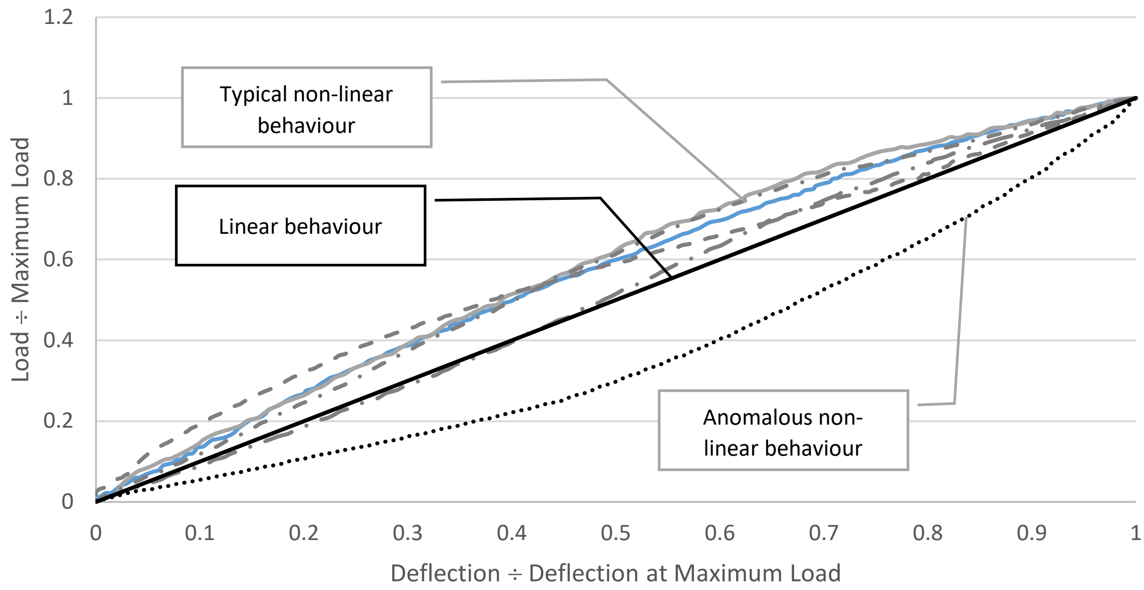


Figure 15: normalised load versus deflection graphs for six culms

The typical non-linear stiffness softening behaviour is the reason why in ISO 22157:2019 apparent modulus of elasticity is determined experimentally for bamboo at the range between 20% and 60% of the maximum capacity. A similar approach is used in BS EN 408:2010 for timber in the range between 10% and 40% of the maximum load. This non-linearity means that ultimate stress (or strength) cannot be calculated by determining all the terms in Equation 4, even if the critical curvature or strain were known. Hence the need for grading.

Publication 4 identifies that the link between stress and modulus of elasticity is weak for *Guadua* bamboo, but proposes that this is due to the geometric variability of the section, as the second moment of area needs to be calculated. Lorenzo et al. (2019) established that prismatic models for determining the second moment of area for bamboo, as contained in ISO 22157-1:2004, are inadequate and can lead to incorrect interpretation of results. The authors propose that individual bamboo culms undergo a 3D scanning and are then digitised for analysis. One solution postulated by Chatuverdi (2015) and validated by **Publication 4** is that the inadequacy of the prismatic models can be avoided simply by treating bamboo culms as a product and not a material.

One way to de-couple *EI* from *M*, is to determine the *EI* in an independent test from that used to determine *M*. Trujillo and Jangra (2016) reports that the *EI* obtained from a non-destructive three-point bending test correlated well to both the *EI* and *M* obtained from the primary four-point bending test (R^2 = 0.878 and 0.819, respectively). However, (Nurmandina et al. 2017) did not report a similarly strong correlation for Indonesian *Gigantochloa apus* (R^2 = 0.243 for *M,* R^2 = 0.290 for *EI*) when undertaking a similar test.

The second proposed Indicating Property in **Publication 4** is external diameter, *D*. Gnanaharan et al. (1994) found a linear expression for both density and external diameter that correlated very well to apparent modulus of elasticity and bending strength (R^2 = 0.99). This finding has not been validated by our research. However, it is unsurprising that *D* does have a strong correlation to flexural capacity, *M*. From rearranging Equations 2 and 4, we can obtain:

$$M = \sigma \frac{I}{y} \qquad \text{(Equation 5)}$$

Which can be written for bamboo thus:

$$M = \sigma \frac{\pi D^3}{32}\left(1 - \left(1 - \frac{2t}{D}\right)^4\right) \qquad \text{(Equation 6)}$$

Where *D* is the external diameter and *t* the wall-thickness.

Therefore, it is evident that *M* is proportional to D^3. Trujillo and Jangra (2016) argue that using diameter as the basis for grading offers many benefits: it is of practical use, it is inexpensive to obtain for both green and dry bamboo, and it is easily verifiable. For these reasons I believe it will be inherent to any grading procedure.

The final Indicating Property (IP) proposed in **Publication 4** is linear mass, *q*, which is the total mass divided by the length of the specimen. As any other hygroscopic material, a percentage of the mass of a bamboo culm is water. Therefore, the validity of the method requires that the moisture content is known. In my experience, the moisture content of bamboo can only be readily assessed with hand-held instruments if the moisture content is below the Fibre Saturation Point ($\approx$ 30%). Moisture Content can still be determined through conventional oven-drying methods, but this is impractical for a grading operation, therefore linear mass can *only* be used as an IP for dry bamboo.

Janssen (1981) had established links between density and compressive and flexural strengths. However, to my knowledge no one had explored using *linear mass* as an IP. This is an original idea that has demonstrated to be very promising. It is necessary to explore the reasons for its effectiveness. Linear mass is proportional to D^2, t^2 and density, ρ, as seen in Equation 7.

$$q = A\rho = \frac{\pi}{4}\left(D^2 - (D-2t)^2\right) \times \rho = \frac{\pi\rho D^2}{4}\left(1 - \left(1 - \frac{2t}{D}\right)^2\right) \qquad \text{(Equation 7)}$$

As discussed previously, D is a strong predictor of capacity, and linear mass increases with the square of the diameter. Additionally, linear mass is sensitive to variations in density, which is also known to correlate with strength (refer to **Publication 3**). These two characteristics seem to make D a particularly effective IP. The universality of this finding was first validated by Víctor Ordóñez Candelaria from INECOL in México (at my request) for Mexican grown *Guadua angustifolia* and *Bambusa olhamii*. Nurmandina *et al.* (2017) obtained a similar result for Indonesian *Gigantochloa apus* (R^2 = 0.940 for EI and R^2 = 0.951 for M). Figure 16 and Figure 17 have been plotted using the linear regression equations arrived at by these researchers, combined with data from **Publication 4**.

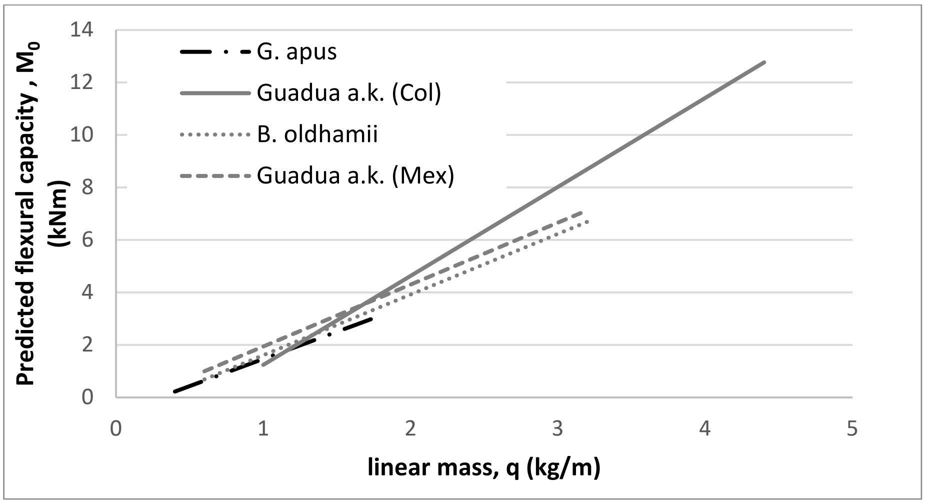


Figure 16: predicted flexural capacity (M_0) versus linear mass (q)

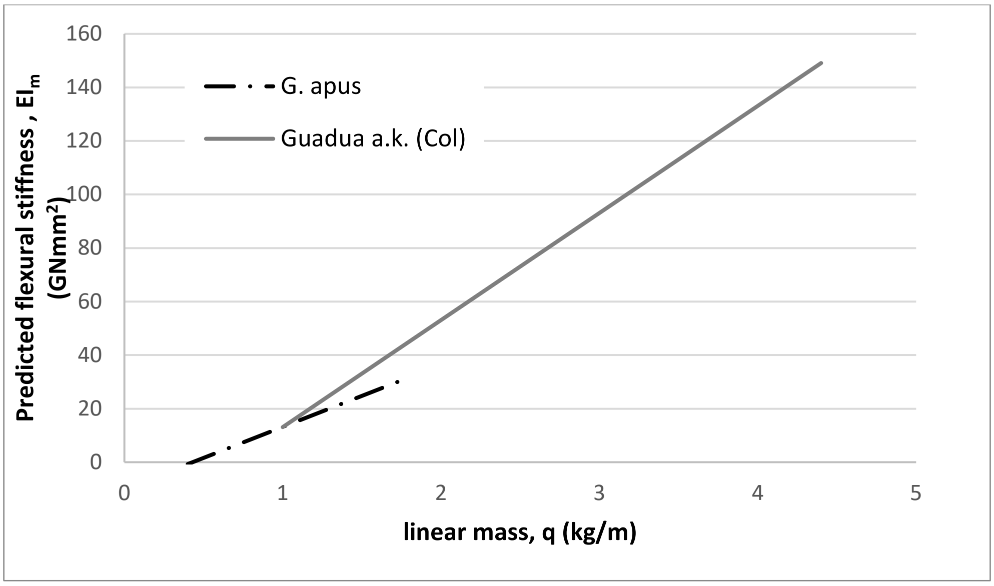


Figure 17: predicted flexural stiffness (EI_m) versus linear mass (q)

Both Figures 16 and 17 suggest that Colombian *Guadua* has a better performance at higher linear mass values, yet this needs further analysis. Linear mass has also demonstrated to be a reliable predictor of compressive capacity (F_u), (Bahtiar et al. 2019) for *Gigantochloa atroviolacea*, *Gigantochloa apus* and *Gigantochloa pseudoarundinacea* – three species of Indonesian bamboo, with values of R^2 ranging from 0.89 to 0.98. A similar finding was reported for Colombian *Guadua angustifolia* Kunth with R^2 = 0.94 (Bahtiar et al. 2020). Figure 18 combines the findings from both publications.

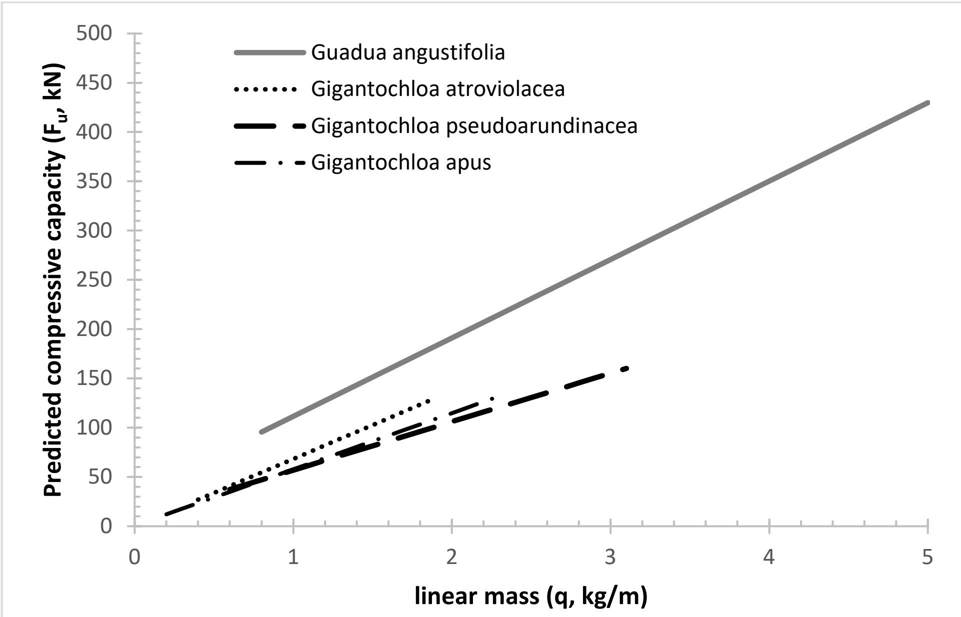


Figure 18: predicted compressive capacity (Fc) versus linear mass (q)

Once again, it appears that *Guadua* has a better performance, but it should be noted that the Indonesian bamboos were tested with a moisture content of around 16%, whilst the moisture content of the *Guadua* held at Coventry University, was closer to 8.6%. Therefore, the apparently superior performance of *Guadua* may simply be attributable to its lower moisture content. This requires further analysis beyond the scope of this Portfolio.

Publication 4 explores the use of combining IPs by means of multiple linear regressions of the type $y = ax_1 + bx_2 + c$, where x_1 and x_2 are two distinct potential IPs, for example *D* and *q*. This approach provided some improvement to the R^2 values. Nurmandina *et al.* (2017) postulate using the *product* of two IPs. As may be expected, they find that the product $q \times D$ is a very strong predictor of M_0 (R^2 = 0.972) since this value is proportional to D^3. Similarly, $q \times D^2$ is a very strong predictor of *EI* (R^2 = 0.989), as both are proportional to D^4. By revisiting the data used for **Publication 4** and undertaking a simple regression analysis using *qD* as a predictor for *M* an R^2 = 0.874 is obtained, which is nearly as high as the highest adjusted R^2 obtained from the multiple regression analyses. Similarly, a simple regression analysis using qD^2 as a predictor of *EI* results in an R^2 = 0.913, which is strong, although not as strong as that obtained by the multiple regression analyses. Figure 19 and Figure 20 show the linear regression equations obtained for this analysis compared to the equations obtained by Nurmandina *et al.* (2017). The figures offer a valuable insight: that the gradient of the line for two significantly different species of bamboo is remarkably similar, unlike the gradients of the lines in Figure 17 and Figure 18. This finding presents the intriguing possibility that *qD* and qD^2 are not only excellent predictors of flexural performance, but that a suitably calibrated equation could be used to predict the flexural capacity and stiffness for a range of bamboo species. This, of course, needs to be demonstrated experimentally.

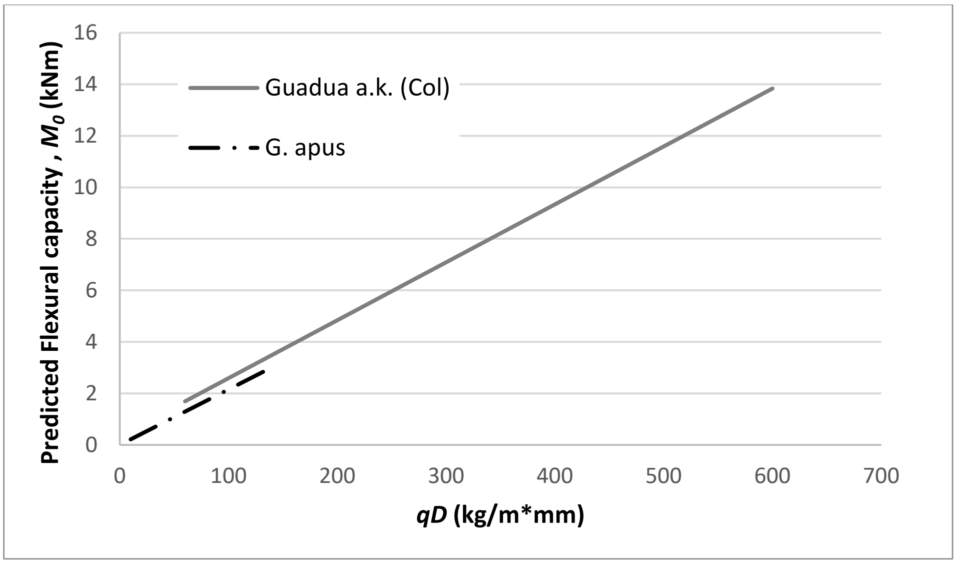


Figure 19: Predicted flexural capacity (M_0) v. the product of linear mass by external diameter (qD).

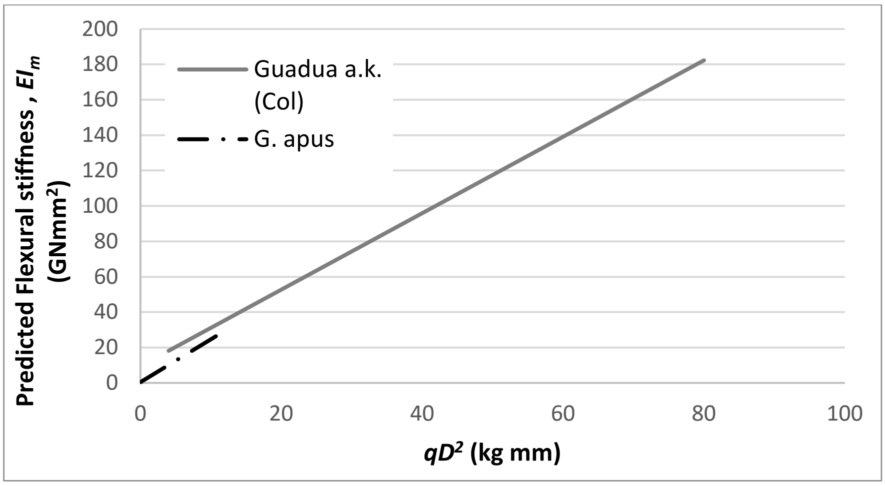


Figure 20: Predicted flexural stiffness (EI_m) versus the product of linear mass by the square of the external diameter (qD^2).

4.1.4 Critique

Following the observations and literature review contained in **Publications 1** to **3**, the research design reflected in **Publication 4** attempted to be as methodologically rigorous as possible. The sample was carefully designed and judiciously sourced. All factors believed to affect flexural properties were recorded. The experimental set-up was carefully designed, though there were some pitfalls to the latter. ISO 22157-1:2004 requires that a bamboo culm is subject to four-point bending with loads applied at third points. The overall simple span should be 30*D* (i.e. 30 times the diameter). The culms that were shipped were cut to lengths of 4 and 5 metres. The support conditions developed to avoid crushing, limited our simple span to 3300 mm (as illustrated in Figure 1 in **Publication 4**), which meant that any specimen with a diameter larger than 110 mm would not meet the 30*D* simple span requirement. Based on discussions and proposals for modifying ISO 22157-1, it was determined that what truly mattered was not the simple span, but the shear span: providing a shear span of 10*D* was observed to generally mitigate an undesirable shear mode of failure. The loading arrangement was therefore revised as shown in Figure 1 of **Publication 4**.

However, this arrangement was still inadequate, as 15% of the specimens in the sample had a diameter greater to 115mm, yet we did not realise at the time that we were not meeting our own requirements. The incidence of shear failures for these specimens was 36%, whereas the incidence of shear failures for specimens with D <115mm was 23%. Therefore, had the 10D shear span requirement always been enforced, the incidence of shear failures *may* have been reduced, thus increasing the sample of bending failures on which our subsequent analysis of flexural capacity was based.

Though the literature review of **Publication 4** is adequate in terms of explaining what grading is for the newcomer, it does not attempt to investigate the history or the state-of-the-art of timber grading. I believe this may have limited the analytical and statistical methods adopted.

4.2 Publication 5: Trujillo and Malkowska (2017)

4.2.1 Summary, context and justification

This journal paper was published in *Construction and Building Materials* in February 2018. The paper seeks to outline, and contribute to, the process of creating a theoretical basis for bamboo connection design using dowel-type fasteners. The paper starts by providing a short, yet comprehensive account of the development of dowel-type, metal-fastener connection design equations for timber contained within EN 1995-1-1 *Eurocode 5 Design of timber structures* (BSi 2014). It then proposes a goal: to develop similar equations for bamboo for three connection design properties – dowel embedment strength (f_h), slip modulus (K_{ser}) and screw withdrawal capacity (F_{ax}). The paper explains the experimental methods that were developed for bamboo to determine dowel embedment and screw withdrawal. The methods were adapted from timber research and are novel to bamboo.

The experimental data is summarised and presented by means of tables, graphs and box-plots. Trends, such as reduction in embedment strength with an increase in dowel diameter are identified. By undertaking numerous multiple linear and non-linear regressions using Analysis of Variance (ANOVA), predictive equations for the three properties are derived. These are then adapted so that their output predicts *characteristic* (5th percentile with 75% confidence) values.

Janssen (2000) correctly identified that connection design is an important 'sticking point' for bamboo engineering. The fact that bamboo culms are (generally) hollow and thin-walled, tapered, not perfectly round, with nodes at variable spacing, and highly susceptible to splitting, has made joint design very challenging.

It may be argued that the sheer ubiquity of dowel-type fasteners (nails, screws, dowels and bolts) in timber engineering demonstrates its effectiveness as a connection method for sawn timber. There is no similarly ubiquitous connection method for bamboo. Nails trigger splitting, and are only used structurally to fix secondary elements. Dowel-type fasteners, such as bolts with diameters, *d*, greater than 10 mm can trigger splitting *and* shear failures. They are also significantly weakened if they coincide with a fissure. In fact, some practitioners advocate the avoidance of holes in bamboo entirely, as they argue that they will lead to splitting (Moran and García, 2019).

Possibly the most successful approach – first published by Morisco (1995) though Colombian architect Simón Vélez had been using the method from at least the early 1990s (Hidalgo López, 2003) – is to infill the internode with mortar in combination with large dowel sizes (d > 12mm) which are placed transversely or coaxially (Figure 21). This approach enabled Vélez to build the world's largest bamboo structures, albeit relying on infilling many internodes with mortar whenever large tensile forces occur. The Colombian bamboo design code, NSR-10 (AIS 2010), contains allowable capacities for the connection types presented in Figure 21, which makes them the *only* published connection capacities in the world. The mortar infilled connection is a pragmatic approach that has not been universally accepted by researchers, designers and builders.

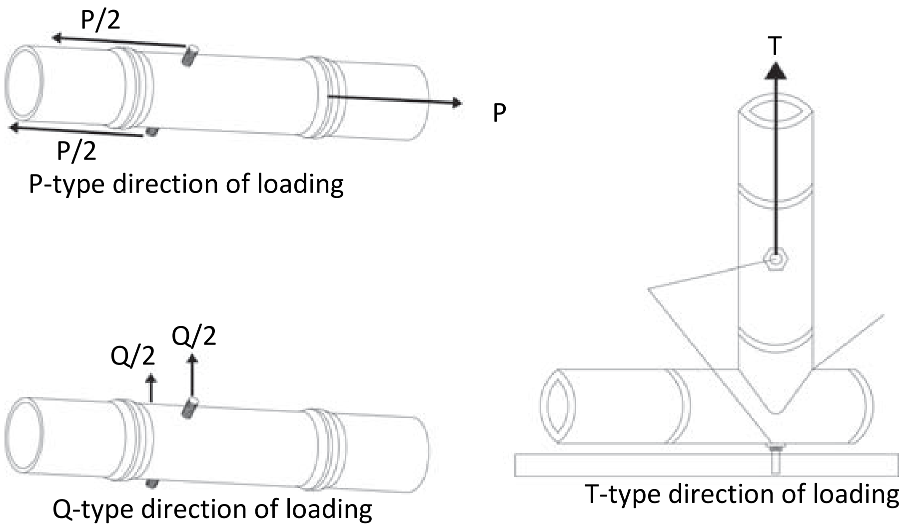


Figure 21: P, Q and T type mortar infilled joints – adapted from NSR-10 (AIS 2010) and Correal (2016)

This absence of consensus has resulted into a continuous and broad investigation into alternative ways to connect bamboo. Over time several authors have tried to capture the multitude of approaches available and trialled (e.g., Jayanetti and Follett (1998), Janssen (2000), Widyowijatnoko and Harries (2020)). Presently, ISO 22156:2004 offers two ways in which connection design can be proposed and validated experimentally. The first is the 'complete-joint alternative', described as:

> *"(…) the complete joint for a given load and geometry is fully specified for members of a particular size. This includes the description of all fastening-element sizes and locations. Data for this alternative shall be based on full-scale tests."*

The second is the 'component-capacities alternative'.

> *"This allows a joint to be designed for a given load using the capacity of each of the components of the joint. The capacity of each component shall relate to a specific geometry and load direction. Data about this capacity shall be based on full-scale tests."*

Researchers, such as (Widyowijatnoko 2012), have (perhaps unwittingly) tended tend to adopt the 'complete-joint alternative'. Their adopted approach has typically consisted of the following steps: 1) identify and critique extant joint-types for bamboo, 2) propose an entirely novel joint that exploits or addresses a characteristic of bamboo and that overcomes identified deficiencies, 3) experimentally determine the resistance (capacity) of the joint for a given species of bamboo, and 4) report the mean capacity of the joint. This approach does not allow extrapolation of results if parameters are changed. What if a different species is considered? What if the bamboo culms are slightly larger or smaller? What if the composition or arrangement of the parts changes slightly? All too frequently ductility, stiffness and characteristic capacity of the tested joints are not reported, which further obscures a comprehensive understanding of the joint's performance. Some researchers partially address these points by validating their findings by means of Finite Element Analysis models.

The 'component-capacities alternative' describes a design process that is more closely aligned to the steel and timber connection design process. For example clause 2.4(1) of EN 1993-1-8:2005 *Eurocode 3: Design of steel structures - Part 1-8: Design of joints states*: "*the resistance of a joint should be determined on the basis of the resistances of its basic components" (BSi 2005).* This means that if all the possible failure modes of all the components (i.e. bolts, welds and plates) have been checked, the connection's capacity has been verified.

In the case of bamboo, once the *connection design properties* can be reliably determined or inferred for a range of species, the 'component-capacities alternative' would no longer require experimental validation, and the design process would become similar to that for steel or timber connection design. Additionally, once reliable determination or inference of connection design properties is achieved, innovative joint designs may be initially developed as a desk-based exercise prior to experimental validation, conferring dynamism and economy to the process.

The current draft of the revised ISO 22156 (2019a) requires that *"Joints shall be designed to have appropriate capacity, stiffness, ductility and robustness against bamboo culm splitting."* It has been a longstanding belief of mine, that a joint that relies on numerous, yet small, metal fasteners transferring load onto the culm wall, will meet these requirements. This approach would work on the principle of transferring force from one culm to another by first transferring force through numerous small fasteners into a metal transition piece such as a clamp, sleeve or washer, and then from there to a bolt. Figure 22 shows two possible ways by which loads can be transferred using steel plates and screws. Therefore, it was deemed that the best starting point would be to determine the *connection design properties* most relevant to smaller fasteners, particularly self-drilling/self-tapping screws, as these could mitigate the splitting phenomena associated with nails.

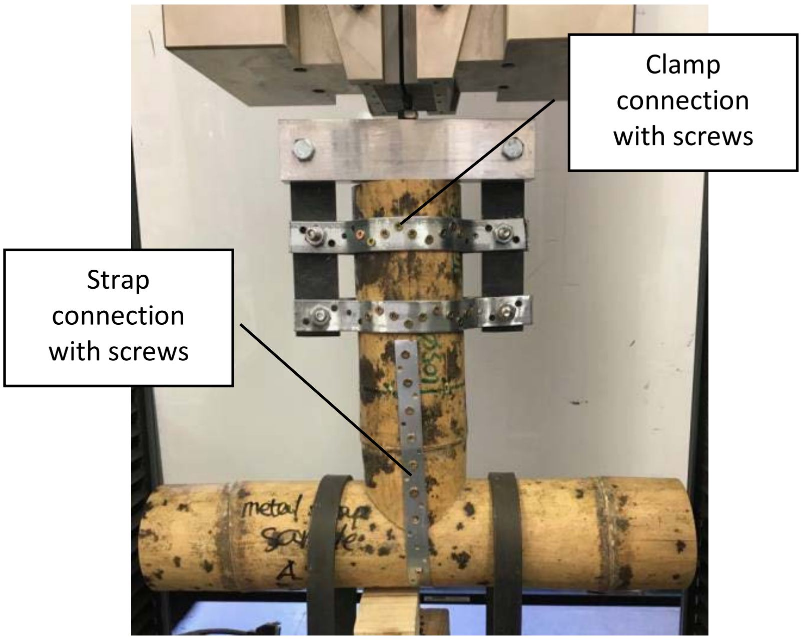


Figure 22: two types of joints using screws and steel plates (Chen, 2019)

4.2.2 Collaboration

Publication 5 is the product of a very close collaboration with Ms. Dominika Malkowska. From January 2016 until September 2016 Ms Malkowska worked at Coventry University under my supervision on her MSc dissertation in Structural Engineering and Building Technology at Chalmers University of Technology. The experimental data contained within **Publication 5** is based mostly on the data she collected for her MSc project, though some of the large diameter dowel (LDD) data was collected by Mr Aaron Stanway as part of his MSc dissertation, also under my supervision. In both instances, I supervised the experimental design, data collection, interpretation and analysis. I authored the paper whilst undertaking a fellowship in Cali, Colombia in the second quarter of 2017. During this period, I significantly expanded the literature review, curated and verified all of the experimental data, produced the illustrations and descriptive statistics. Ms. Malkowska ran the regression analyses, though I adjusted the resulting equations so that they would present characteristic values.

4.2.3 Contribution to subject

Publication statistics	*Google Scholar*	*ResearchGate*
Citations:	7	7
Reads:		131
Checked: December 2019		

At the time of publication much had been researched into bamboo connections, but, as argued previously this had followed a 'complete-joint' approach. Instead, very little had been attempted in terms of determining connection design properties that could be used in a 'component-capacity' approach. Fewer still, had researched methods that would enable inference of these connection design properties from non-destructively determined properties.

The literature review of the paper identifies how empirically-derived equations contained in Eurocode 5 were the outcome of hundreds, if not thousands of tests. These equations allow a timber designer to calculate safe design capacities from a simple physical property (density) and fastener dimensions (dowel diameter). Prior to the publication of this paper, only (Ramirez et al. 2012) had attempted to derive similar equations for bamboo. As discussed earlier, by focussing on a 'Complete-Joint' testing, previous publications had limited the applicability and comparability of their findings. Therefore, this paper makes the following contributions to the field: a) it makes fellow bamboo researchers aware of the historical process of determination of connection design properties for timber, b) it presents the need and possibility of working towards a component-capacity approach, c) it postulates experimental methods to determine these properties, d) and derives predictive equations that can be used to determine characteristic values for these from non-destructively determined properties. Admittedly, the experimental and analytical methods used are inspired by previous work in timber engineering, their use in bamboo, however, is novel.

The approach adopted should open a new field of experimental enquiry for bamboo. In fact, Harries *et al.* (2019) follows on from this paper and investigates screw withdrawal for *Phyllostachys edulis* using twenty combinations of screw types and installation methods (predrilled or not). The findings arrive at a simpler equation for (mean) screw withdrawal capacity (F_{ax}), that relies simply on the product $d×t$ (Equation 8). The authors also reanalysed the data from **Publication 5** and postulated an equation based on the product $d×t$ (Equation 9). Their findings are encouraging, as the experimental approach and concept within **Publication 5** were validated and improved upon.

$F_{ax} = 41.1dt$ Screw withdrawal capacity for *P. edulis* (Equation 8)

$F_{ax} = 0.041\rho dt$ Screw withdrawal capacity for *G. angustifolia* (Equation 9)

Harries *et al.* (2019) finds that there seems to be a small species specific discrepancy (15%) for F_{ax}, even controlling for screw type and density. It may well be that the species specific differences prove to be of little importance once F_{ax} is investigated for numerous species. If this is the case, it may be possible to derive a general F_{ax} equation that applies to all commonly used species of bamboo. The paper also vindicates a concept presented by **Publication 5**: that screws are viable fasteners for bamboo. Similarly, Moran and Garcia (2019) were influenced by **Publication 5** and, despite their misgivings to perforations in bamboo, explored the use of a small number of screws within their bamboo clamping system.

However, the potential of our findings has yet to be researched systematically. Preliminary experimental work undertaken by students at Coventry University exemplifies the potential of the equations contained within **Publication 5**. One example is the experimental work undertaken by Ms. Kaiyue Zhou as part of her MSc dissertation, who undertook nine tests of screwed clamped joints similar to those shown in Figure 23. Figure 24 identifies the force against crosshead displacement recorded for six of the tests.

Figure 23: screwed-clamp connector (Chen, 2019)

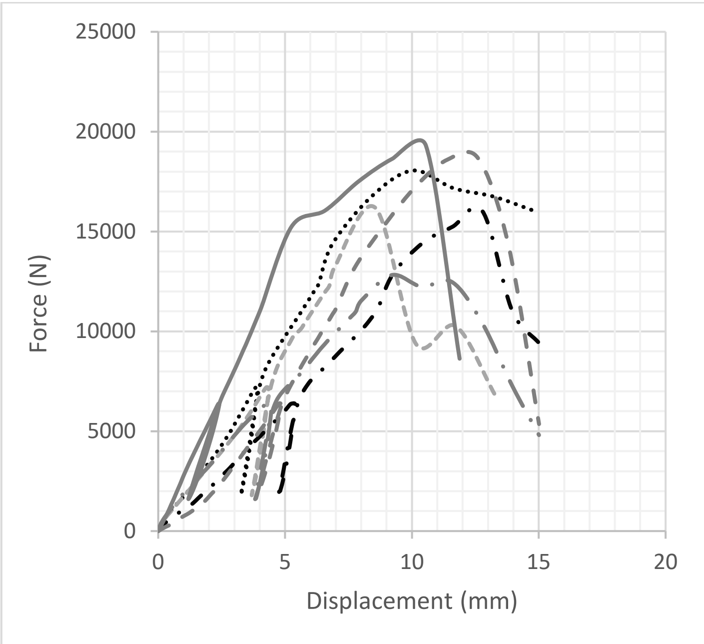


Figure 24: Force against crosshead displacement (adapted from Zhou, 2018)

Hereafter, I have furnished an example of how the equations contained in **Publication 5** could be used to predict the capacity of the tested joints. The calculations are based on Equations (8.9) and (8.10) from chapter 8 of Eurocode 5 – shown here as equations 10 and 11 respectively. These are based on the equations first proposed in Johansen (1949). According to clause 8.2.3 from Eurocode 5, Equation (8.9) is applicable to thin steel plates in single shear, defined as those with plate thickness (t_{steel}) less than or equal to 0.5d. Equation (8.10) is applicable to thick steel plates in single shear, defined as those with $t_{steel} \geq 1.0d$. In this instance the plate may be classed as "intermediate", since $t_{steel} = 0.75d$, in which case the result is interpolated. Unfortunately, Ms Zhou did not report all necessary parameters, and therefore calculations are based on some *assumptions*, this does not detract from the value of the example. Table 7 and Table 8 summarise the data from both the calculations and the experimental data. Figure 25 presents a scatter-plot for the predicted values versus the experimental values for both the mean and characteristic values.

$$F_{v,Rk} = min \begin{cases} 0.4 f_{h,k} t_1 d & \text{(a)} \\ 1.15 \sqrt{2 M_{y,Rk} f_{h,k} d} + \frac{F_{ax,Rk}}{4} & \text{(b)} \end{cases}$$ (Equation 10 or (8.9))

$$F_{v,Rk} = min \begin{cases} f_{h,k} t_1 d & \text{(c)} \\ f_{h,k} t_1 d \left[\sqrt{2 + \frac{4 M_{y,Rk}}{f_{h,k} t_1 d^2}} - 1 \right] + \frac{F_{ax,Rk}}{4} & \text{(d)} \\ 2.3 \sqrt{M_{y,Rk} f_{h,k} d} + \frac{F_{ax,Rk}}{4} & \text{(e)} \end{cases}$$ (Equation 11 or (8.10))

Where the definitions of terms provided in Table 7.

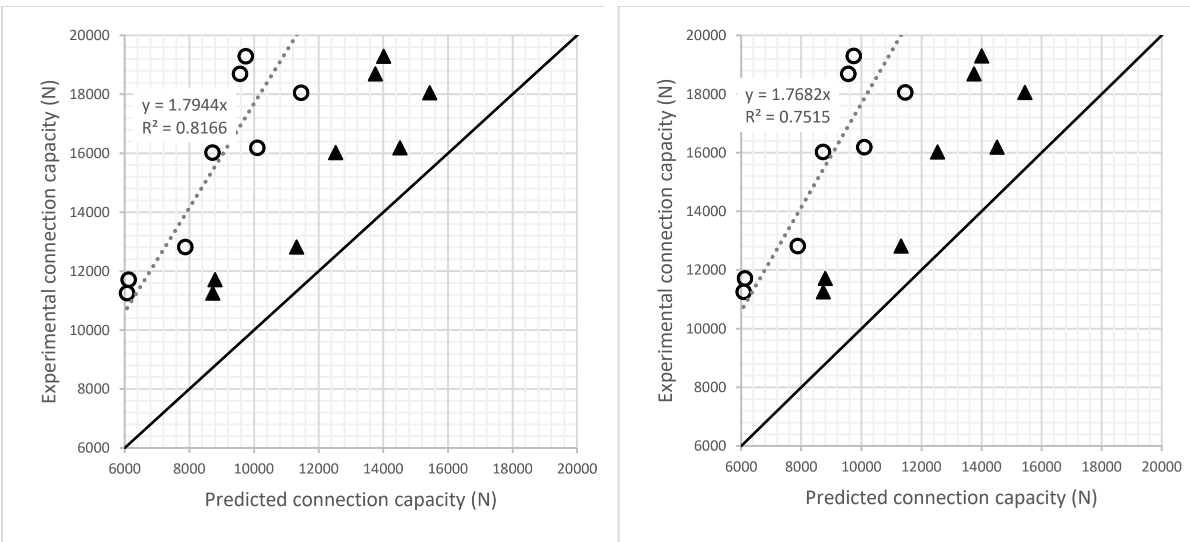
Table 7: Parameters used in example

Parameter	Symbol	Value	Source/comment
Mean density	ρ_{mean}	755 kg/m^3	Assumed, taken from **Publication 5**
Characteristic density	ρ_k	621kg/m^3	
Tensile strength of the wire	f_u	400 to 600 N/mm^2	Brand of screw not reported. Assumed
Characteristic value for the yield moment	$M_{y,Rk}$	4411 to 6617Nmm	Calculated using equation (8.14) from Eurocode 5
Thickness of steel plate	t_{steel}	3 mm	Measured
Diameter of screw	d	4 mm	Reported by student, shank diameter unknown.
Number of screws	N	8 - 10	Reported by student
Mean embedment strength	$f_{h,mean}$	60.7N/mm^2	Calculated from $f_{h,mean} = 0.058 d^{-0.21} \cdot \rho_{mean}^{1.09}$
Characteristic embedment strength	$f_{h,k}$	42.2N/mm^2	Calculated from $f_{h,k} = 0.051 d^{-0.21} \rho_k^{1.09}$
Mean withdrawal capacity (from **Publication 5**)	$F_{ax,mean}$	varies	Calculated from $F_{ax} = 0.09 d^{0.53} \rho_{mean}^{0.92} t^{1.19}$
Characteristic withdrawal capacity (from **Publication 5**)	$F_{ax,k}$	varies	Calculated from $F_{ax,k} = 0.083 d^{0.53} \rho_k^{0.92} t^{1.19}$
Ratio of t_{steel} to d		0.75	Interpolate between results for thin and thick plates

Table 8: Specimen specific parameters and connection capacities. Theoretical values calculated on the basis of $F_{ax,mean}$, $f_{h,mean}$ *and* f_u *= 600N/mm²*.

Wall-thickness	**Max load**	**Number of screws**	**Withdrawal capacity**	**Theoretical joint capacity (calculated)**				
t_1	F_{max}		F_{ax}	Eq. 10 Thin plate		Eq. 11 Thick plate		Interpolated
mm	N		N	N	Failure mode	N	Failure mode	N
7.25	Excluded	10	897	7043	(a)	17606	(c)	12324
8.54	16179	10	1090	8296	(a)	20739	(c)	14517
7.37	16021	10	915	7159	(a)	17898	(c)	12528
8.09	18686	10	1022	7858	(a)	19646	(c)	13752
6.66	12810	10	811	6469	(a)	16174	(c)	11321
6.47	11711	8	783	5028	(a)	12570	(c)	8799
6.42	11253	8	776	4989	(a)	12473	(c)	8731
8.24	19289	10	1044	8004	(a)	20010	(c)	14007
9.69	18053	10	1267	9413	(a)	21470	(d)	15441

Overall, the finding is that the predicted values tend to be *too* conservative. An accurate prediction would show the mean values clustering around the black line (i.e. mean experimental values similar to the mean predicted values), with roughly half of the data points above and below the black line. Similarly, an accurate prediction would show at least 95% of the characteristic values above the black line, but clustering in its close proximity. It is worth noting that the coefficient of determination (R^2) ranges from 0.75 to 0.81 which is reasonably high and hence indicates that the predictions are consistent. It should be noted that the number of assumptions made in this example compromises its the conclusiveness. Nevertheless, it illustrates the potential of the connection design properties determined in **Publication 5**.



(a) (b)

Figure 25: Predicted versus experimental connection capacities. Circles represent characteristic values, whilst triangles represent mean values. Values in (a) were derived with f_u *= 400N/mm², whilst in (b) they were derived with* f_u *= 600N/mm².*

4.2.4 Critique

Publication 5 illustrates the level of skill and understanding I had developed over the years. It combines a strong literature review identifying seminal publications as well as recent exemplary work; it includes rigorous analysis using advanced methods of statistical analysis; diversifies the use of software for analysis (both SPSS and Matlab), and proposes a process to derive characteristic values from a regression analysis. It is the product of intensive and committed work.

This publication is intended to illustrate an approach or methodology - it does not aim to, and cannot settle in a conclusive manner, what the embedment strength, slip modulus or withdrawal axial capacity for *Guadua* bamboo are. This is particularly true for the embedment strength equation, which had a low coefficient of determination (R^2 = 0.446). The applicability of K_{ser} also needs to be further researched, as the half-hole method adapted from ASTM D5764 - 97a (ASTM 1997) does not reflect deformation caused by bending of the dowel-type fastener. Based on this work, I anticipate further development of test methods appropriate for dowel connections in bamboo.

5 Part 3: synthesis and impact

This final part represents the crystallisation of the findings contained in Parts 1 and 2 into a single publication having impact on bamboo engineering practice.

5.1 Publication 6: ISO 19624:2018

5.1.1 Summary, context and justification:

ISO 19624:2018 Bamboo structures — grading of bamboo culms — Basic principles and procedures, is an international standard published in 2018. The standard defines what *grading* is, provides visual grading requirements and outlines how *machine grading* for bamboo could work. Significantly, it explains the process of creating visual grading rules and machine settings (for machine grading) through a process referred to as 'initial evaluation'. Annex A of ISO 19624 provides an example of how the standard could be adopted. The standard should be interpreted as a framework or 'recipe' for writing a national grading standard, and not an 'industry-ready' standard. The standard challenges researchers and producers across the world to work towards appropriate grading procedures.

One of the objectives of the INBAR Grading Project was to write an ISO standard on grading. INBAR shared my view that this was the starting point towards making bamboo a 'mainstream' product – ultimately empowering the ISO 22156 Structural Design Standard. When I set out to develop the grading standard I was not sure what the standard would eventually look like, beyond the content of **Publication 2**. However, due to the protracted nature of drafting ISO standards (60 months from proposal to publication), INBAR felt we could not wait for the experimental aspect to be resolved first.

5.1.2 Collaboration:

In September 2013 at the 27th annual meeting of ISO TC 165 in Stuttgart I assumed the role of project leader for the revision to ISO 22157-1 and the development of new grading standard ISO 19624. As project leader, I am the primary author and additionally responsible for establishing a consensus that would ultimately be accepted by the 31 voting member countries of ISO TC 165. The role of project leader for ISO 19624 required that firstly I deepened my understanding of timber grading and capture the state-of-the-art of bamboo grading; I also needed to canvas the opinion of bamboo experts around the world on the subject and engage their support. Simultaneously, I needed to undertake my own original experimental work in the UK and invite researchers elsewhere to replicate our work with their local species. Once this phase was finished, we needed to analyse our findings and see if we had identified trends that would underpin a grading standard. Subsequently, the evolving standard needed to be proposed and presented to the ISO TC 165 annual meetings and to the INBAR Task Force.

The process taught me that drafting standards requires collaboration with a team of peers, as well as much debate, persuasion and compromise. The writing style is different to that of a journal, and the level of scrutiny and peer review is much higher, as there are many more participants and many more opportunities for 'reviewers' to comment. The document is a technical and political achievement.

As project leader, I wrote most of the standard and designed the illustrations. The standard was structured around ISO 9709:2018 and ISO 13912:2017 and was harmonised with ISO 22156:2004, ISO 22157:2019 and ISO 12122-1:2014. As should be expected for a standard, many people influenced the document, namely my fellow members of ISO Technical Committee 165, in particular Working Group 12, especially those in attendance to the meetings at Stuttgart 2013, Tokyo 2014, Jogor Bahru 2015, Melbourne 2016 and Vienna 2017; as well as my fellow members of the INBAR Task Force, especially those in attendance at the meetings at Winnipeg 2015, Pittsburgh 2016 and Bogor 2017.

I must also acknowledge all the support I received in the development of this standard, as this cannot be captured in the text of the standard. I owe much of my understanding about timber grading to Dr Daniel Ridley-Ellis, especially everything concerning 'initial evaluation'. Professor Kent Harries made numerous conceptual and editing contributions to the final text. Yann Barnet from the INBAR Task Force improved the appearance of the illustrations. INBAR funded my attendance to all the annual ISO TC 165 meetings, and through the Working Group convenors (Oliver Frith and Liu Kewei), resolved many of the practicalities of developing a standard.

5.1.3 Contribution to subject

This publication is the world's first international bamboo grading standard, and to my knowledge there is no separate national grading standards. All grading criteria are embedded within national structural design codes. Hence, this may be the first stand-alone bamboo-grading standard. The broad level of contribution and scrutiny demonstrates that this work is novel, pertinent and internationally recognised. The standard does not respond to an explicit clamour to *harmonise* the market, it instead addresses a perceived need and seeks to *shape* the market in response. Therefore, its impact will not be evidenced immediately.

Nevertheless, it is already starting to have some impact. The standard has already been adopted in the UK as a British Standard (BS ISO 19624), in the Philippines as a Philippine National Standard (PNS ISO 19624), and it is in the process of being adopted in Colombia. According to *Google Scholar* it has already been cited seven times in academic publications.

The first contribution **Publication 6** makes is to introduce concepts to the bamboo industry, clarifying others and creating a *lingua franca*. Table 9 demonstrates the extent to which **Publication 6** expands and clarifies concepts – indeed, introducing new paradigms in some cases – by comparing concepts included in ISO 19624 to five other codes/standards that (partially) address issues of grading. The standard emphasises the importance of including bamboo external diameter and wall-thickness within the grading process, which is only considered in India's code. As discussed in subchapter 4.1 of this Critical Overview, external diameter has a strong correlation to flexural capacity, flexural stiffness and compressive capacity. In turn, wall-thickness significantly affects connection capacity, as discussed in subchapter 4.2. Excluding these from the grading process, implies reduced certainty about these properties during design.

Also shown in Table 9 is that ISO 19624 introduces numerous concepts known to affect load-bearing capacity such as 'internal taper', as demonstrated by Nugroho and Bahtiar (2013) and 'ovality' as demonstrated Bahtiar et al. (2013). In fact, the diversity of methods included in ISO 19624 for measuring external diameter and wall-thickness have been proposed to capture the effects that taper and ovality have on load-bearing capacity. The standard also leaves room to introduce other grading criteria that may prove to be useful, yet not demonstrated experimentally, for example length of specimen and internode length.

Controlling for 'age at harvesting' has been a long-standing tenet of bamboo grading. However, current technology does not allow for this control to take place *during* grading, only during harvesting. Moreover, some species of bamboo grow so tightly together (sympodial-tufting or clumping bamboos) that it is difficult to control for maturity during harvesting. For other species, such as *Guadua angustifolia* Kunth (a sympodial-scattered or open-clumping species) visual cues on the culm, rather than real metrics, are relied on to determine the *presumed* level of maturity. The primary and secondary evidence collated in **Publications 3, 4** and **5** for the effect of maturity, demonstrate that maturity does affect strength and stiffness, but it is not determinant. For all these reasons, a more nuanced requirement for 'age at harvesting' was introduced in **Publication 6**. The expectation is that this will result in a grading system that can be better implemented and complied.

From Table 9, it is also noticeable that two further concepts are introduced: machine grading and initial evaluation. The former introduces a range of concepts foreign to bamboo engineering, such as grade-determining properties, indicating properties and secondary properties. However, in my opinion, the concepts surrounding initial evaluation are the most important innovation of the standard. Trivial as they may seem, the sampling requirements (sample size, ascribing findings to a 'source region', inclusion of a range of ages and lower-quality specimens), constitute a large step-change from the *status quo*. Including these will ensure that the properties associated to a given grade are *reliable* and *representative*, and avoid unquantifiable and potentially unsafe biases. The standard also creates the basis for a quality assurance process including checks on the accuracy of visual grading, checks to ensure *repeatability* and *calibration* for machine grading, and requirements for *periodic evaluation* for both procedures. In combination, these innovations have the potential to bring bamboo closer to being a 'main-stream' product.

The final significant contribution is Annex A, which is furnished with a series of examples that aim to clarify to the industry how the standard could be implemented in a practical context. The discussions surrounding recent research contained in 4.1 demonstrate that these examples will require updating.

*Table 9: Scope of grading clauses within **Publication 6** and five bamboo codes*

Aspect of Grading	Publication 6 ISO 19624:2018	Existing Bamboo Standard		
		NBC (India - 2004)	NSR-10 (Colombia - 2010) E.100 (Peru – 2012) NEC–SE–GUADÚA (Ecuador – 2016)	Reglamento de construcciones del Distrito Federal (Mexico City – 2017)
Illustrations to explain phenomena	Descriptive figures and grading example provided in Annex A	None, but provides comprehensive descriptions.	None.	None.
Presence of insect damage and rot	Reject if present.	Reject if present.	Reject if present.	Reject if present.
Fissures	Illustrates phenomena. Both should be considered. Annex A provides examples.	Describes and tolerates fissures. Reject if depth greater than 3 mm.	Maximum fissure length no more than 20% of the length of the piece.	Only limits fissures that penetrate the full-depth of the culm wall. A single fissure should not be more than 30% of the length of the piece, and the sum of all fissures should be no more than 50% of length of the piece
Longitudinal indentation		Yes, but called 'collapse'.	Not mentioned or described.	Not mentioned or described.
Diameter	Should be considered. Provides several methods to control. Annex A uses diameter-based output grades.	Yes, proposes a diameter-based grading system	Not a grading criteria.	Not a grading criteria.
Thickness	Should be considered or inferred. Provides several methods to control. Annex A illustrates how it can be inferred.	8 mm minimum	Not a grading criteria.	Not a grading criteria.
Internode length	May be considered. Provides methods to control.	Not mentioned.	Not mentioned	Not mentioned
Length	May be considered.	6 m minimum	Not a grading criteria.	Not a grading criteria.
External taper	Illustrates phenomena. All should be considered. Explains how to calculate each. Annex A provides examples.	Limit to 5.8 mm/m (0.58%)	Limit to 1%. Ecuadorian standard provides variable tolerances according to position along the culm.	Limit to 1%.
Internal taper		Not mentioned.	Not mentioned.	Not mentioned.
Bow		Limit to 75 mm/6 m (1.25%)	Limit to 0.33%	Limit to 0.33%
Ovality		Not mentioned.	Not mentioned.	Not mentioned.
Moisture Content	Recommends grading with seasoned bamboo.	less than 20%	Target Equilibrium Moisture Content (EMC) for site	Target EMC for site
Age at harvesting	Provides guidance.	older than 4 years	4-6 years. Ecuadorian standard also includes observations required during harvesting.	4-6 years.

*Table 9: Scope of grading clauses within **Publication 6** and five bamboo codes (continued)*

Aspect of Grading	Publication 6 ISO 19624:2018	Existing Bamboo Standard		
		NBC (India - 2004)	NSR-10 (Colombia - 2010) E.100 (Peru – 2012) NEC–SE–GUADÚA (Ecuador – 2016)	Reglamento de construcciones del Distrito Federal (Mexico City – 2017)
Machine grading	Defines concept, terms and quality control. Annex A provides an example of a hybrid grading system.	Not mentioned.	Not mentioned except Colombian code, which mentions it, but defines it incorrectly.	Not mentioned.
Initial evaluation and mechanical properties	Provides in detail explanation for visual and mechanical grading.	Not mentioned or described, but allows properties to be inferred from density (see secondary properties). Provides *some* 'Safe Working Stresses' for 16 species.	Provide admissible mechanical properties for *Guadua* only. Colombian code explains how admissible stresses can be determined from experimental results, but it also stipulates that only the provided properties can be used for design.	Provides design mechanical properties for three species of bamboo (*Guadua angustifolia, Guadua aculeata* and *B ambusa oldhamii)*.
Secondary properties	Defines concept. Annex A provides examples.	Permits s*ome* mechanical properties to be determined from density-based equations proposed by Janssen (1995).	Not mentioned.	Not mentioned.

5.1.4 Critique

It may be argued that grading is not the only way by which reliable properties for bamboo can be determined or inferred. Chatuverdi (2015) proposes a form of 'grading' on the basis of applying compressive *and* bending loads to all specimens in a batch, in a process more akin to *proof-loading*. The concept is not incompatible with what is proposed in ISO 19624, but is cumbersome and likely to deter practitioners. Alternatively, it may be possible to infer the properties of every bamboo culm as a unique specimen (instead of a production batch), by comprehensive 3D-mapping, thereby capturing *all* its geometric characteristics in great detail, as proposed by Lorenzo et al. (2019). It may be possible to combine this technique with simple non-destructive tests known to work for bamboo (e.g. dynamic modulus of elasticity) to obtain a full picture of load-bearing capacity piece by piece. However, this option is computationally demanding and may be ill-suited to many regions where bamboo is used. Of course, another option is to maintain the *status quo* described in 2.1.

My view has been that the best route for bamboo to be accepted as a 'mainstream' product is, at first, to mirror as closely as possible the process used by the timber industry, adapting it to the unique characteristics of bamboo. This would allow bamboo to be regarded as a product at a similar level to timber in terms of credibility and acceptance. Therefore, a 'strength' grading standard is the benchmark. When I embarked on this process, I was not aware of other researchers working on grading of bamboo. Standards and codes around the world were inadequate, hence a new standard that set-out the process was needed. The preferred vehicle was an international (so-called) model standard that countries around the world could *adopt* and *adapt* to their needs and species.

The procedures presented in **Publication 6** are the output of an academic process, not an industrial process. In fact they are yet to be trialled in an industrial production plant within a producer nation. Ideally, this phase would have *preceded* the drafting of the standard. In fact, it is likely that the standard will need to be rewritten to align itself to an expanded body of evidence across numerous species. Despite this, **Publication 6** disrupts the cycle described in Figure 7 – an overarching objective this work.

One aspect not addressed within the standard is the distinction between 'grade' and 'class'. In fact, the examples contained within Annex A are more akin to structural classes than grades. The fusion of both concepts was the outcome of compromise made during the drafting of the standard. This standard was built on the experimental data for one (seemingly representative) species of bamboo. Further distinction may be possible once a better appreciation is achieved of inter-species variation. Though, it may be the case that for bamboo the distinction is not necessary.

6 Final Reflection

6.1 Links within Portfolio

The six publications within this Portfolio constitute a coherent body of work. **Publication 1** serves as an introduction to construction with bamboo culms. When it concludes *'Aspects that have been identified for further development include strength grading, (…) connection design, (…)'*, it identifies two fields of research addressed subsequently in the Portfolio.

Publication 2 makes the case for bamboo grading and identifies its viability, including a potential paradigm for grading. It also sets the aims, hypothesis and ambition of much of the subsequent portfolio. It concludes: '*To give the process any true validity very many destructive tests (hundreds instead of tens) need to be undertaken, as well as investigation into the tests themselves, (…) and whether all the mechanical properties (…) can be inferred from theses non-destructive tests, in order to enable a strength classification system analogous to that used in EN 338.'*

Publication 3 identifies which factors influence the mechanical properties of bamboo, and as such should be included in a grading process. Under 'Further work and future developments' it provides a route-map for the remainder of the Portfolio, including: a) the need to record a species' geometric characteristics; b) proposing the exploration of surrogate and non-destructive tests; c) stressing the need for frequent testing; while also d) suggesting that there may be ways to reduce sample sizes and need for testing.

Publication 4 is central to the Portfolio as it demonstrates experimentally that the flexural properties of a bamboo culm can be inferred non-destructively, thus corroborating the hypothesis that machine grading is possible. The research design is strongly informed by **Publication 3**; for example, the sample was designed to include a range of ages and culm positions.

Publication 5 furthers the experimental demonstration that design properties can be inferred non-destructively, and though it is only tangentially related to the common thread of bamboo grading, it addresses a research topic identified in **Publication 1.** The research design builds upon that of **Publication 4**, including recording age, position along the culm, physical properties; as well as pursuing a large sample size. The statistical analysis techniques used in **Publication 4** were replicated and improved using specialist software and non-linear regression.

Publication 6 is the outcome of five years' work. It is underpinned by and synthesises the whole of the Portfolio. Numerous concepts identified in **Publication 3** are translated into the process of Initial Evaluation (e.g. record geometric characteristics). Similarly, frequent testing is addressed in 'Periodic Evaluation', and reduced sample size is addressed in clause 8.4. Though no surrogate tests were specified, the concept of secondary properties is introduced. **Publication 4** provided the experimental evidence that machine grading was viable, and much of the example contained in Annex A is based on its data. The finding within **Publications 4** and **5**, that age and position along the culm were influential, yet not determinant, allowed me to take a more nuanced approach to these when drafting **Publication 6**.

6.2 Development as a researcher

The Portfolio of publications also evidences my learning and development as a researcher in the period April 2012 to August 2018. When I arrived at Coventry University from the consulting industry, I had a 'pragmatic' perspective towards research: the measure of its merit was its practical utility to structural engineering. Based on my experience, I thought I knew what the extant gaps in knowledge were and what needed to be researched to address them. In the context of Figure 26, I could be described as a 'pragmatist'. **Publications 1** and **2** reflect this stage of my career. The **INBAR Grading Project** enabled me to gain 'concrete experience' and thereby transition towards an 'activist'. **Publication 3** reflects this transition away from pragmatism. Its preparation required me to review my knowledge and reconsider my preconceptions. **Publications 4** and **6** outline a full learning cycle from planning to conceptualisation in the topic of 'grading'. **Publication 5** outlines a separate learning cycle in the topic of 'metal fasteners in bamboo'. These learning cycles have elevated my capacity as a researcher who can adopt *all* learning styles.

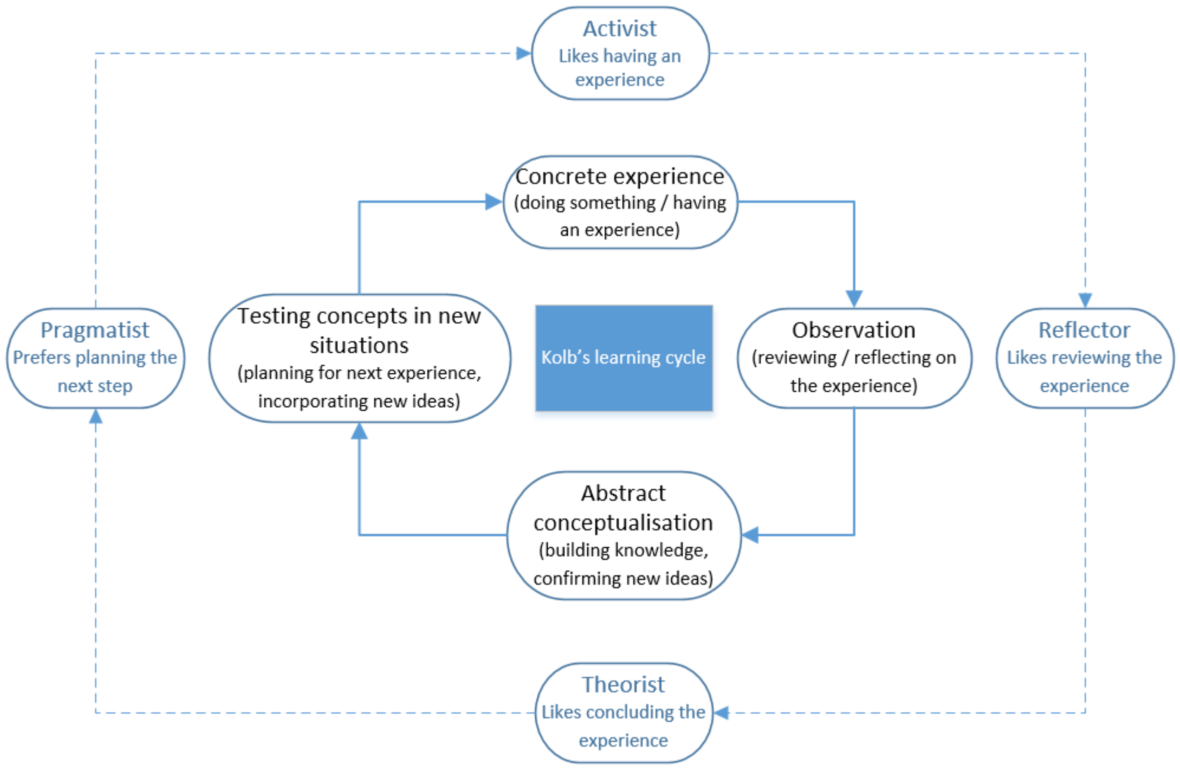


Figure 26: Kolb's learning cycle, adapted to include Honey and Mumford's learning styles - adapted from Dearden et al. (1999)

6.3 Conclusions

The Publications within this portfolio review and appraise the state-of-the-art of bamboo grading throughout the world. At the time **Publications 1** and **2** were published, bamboo grading was a poorly researched topic. The existing visual grading criteria omitted important considerations and could only provide 'binary grading'. Most codes/standards were not linked to the process of creating distinct grades (or classes). Machine grading was non-existent. **Publication 3** investigates the state-of-the-art of 'species characterisation', and identifies what factors are known to affect the structural properties of bamboo. The literature review identified that species characterisation was not linked whatsoever to grading protocols, hence there was no guarantee that what had been characterised was what was on the market.

The findings within **Publication 4** demonstrate that flexural stiffness (EI) and flexural capacity (or bending moment at failure - M_{ult}) can be reliably inferred non-destructively. M_{ult} can be inferred from external diameter, D, linear mass, q, and EI. Whereas EI can be inferred from D and q. These correlations demonstrate that it may be more effective to grade bamboo culms as a *product*, than as a *material*. Recent research has validated this approach for other species and for compressive capacity (F_c).

The findings within **Publication 5** demonstrate that three connection design properties – embedment strength (f_h), screw withdrawal strength (F_{ax}) and slippage (K_{ser}) – useful to design with metal fasteners can also be inferred non-destructively, though with variable levels of confidence. Nevertheless, these initial findings identify that further research into bamboo connections with small metal fasteners is warranted.

The Annex of **Publication 6** provides an example of 'capacity grading' based on diameter, D, and linear mass, q, as the non-destructively measured 'indicating properties'. The example classifies bamboo culms on the basis of their diameter and then allocates to each class a series of 'grade-determining properties' and 'secondary properties'.

The body of work contained within this portfolio demonstrates that numerous properties useful to structural design with bamboo can be inferred non-destructively. This knowledge can be used to create machine or hybrid grading procedures, as exemplified within **Publication 6**. Similarly, it could lead to reliable and predictable bamboo connection design.

6.4 Future work and development

The trends identified in Figures 18 to 20 present the possibility of developing a multi-species grading (or classification) system for bamboo based solely on external diameter and linear mass. The findings suggest that the system could work on the basis of two 'indicating properties' (external diameter, D, and linear mass, q) and one to three 'grade-determining properties' (compressive capacity, F_c, flexural capacity, M, and flexural stiffness, EI). EI can be inferred from $q \times D^2$, M from $q \times D$, and F_c from either q or D. These trends need to be validated and calibrated for more bamboo species. During this process due care should be given to recording and controlling moisture content, to ensure experimental values are truly comparable.

Publication 4 and the Annex of **Publication 6** suggests that linear mass is an appropriate means to grade bamboo. Experimental work demonstrates that this is the case, and that it is more reliable than density. However, density correlates well to connection properties as identified in **Publication 5**. This 'dissonance' will need to be considered when structural grades (or 'classes') are proposed. It may be possible to reliably infer density from D and q, though further experimental evidence is required to demonstrate this. Further experimental evidence, may preclude the need to measure density entirely, as suggested by Harries *et al.* (2019). **Publication 5** also identifies that connection design properties correlate to wall-thickness, which can be inferred from D or q, as suggested in **Publication 6**, this may help to resolve any remaining 'dissonance'.

Visual grading limits need to be based on evidence. Currently much of the criteria seems to be based on professional (or artisanal) judgement. Examples of limits requiring investigation are: what are the tolerable limits to fissures and longitudinal indentations? Are these tolerances affected by other characteristics, making them species specific? What are practical limits to bow and taper? Should these be set by structural criteria, or be species specific?

The proposed grading methodologies need to be piloted with producers, in order to establish their feasibility and practicability. Furthermore, grading outcomes need to applied in real design scenarios to assess ultimate utility.

Finally, the experimental work on metal fastener-based bamboo connections needs to be continued, including: expanding the database for embedment and joint slippage, and including more species, exploring a new criterion for yield, and testing the predictive equations against experimental findings for complete connection systems.

These directions (and more) will be pursued through the myriad of collaborations described in this portfolio and my continued leadership on ISO TC 165 and the INBAR Construction Task Force.

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Appendix 1: Letters from co-authors

Letters from co-authors have been omitted in this version for confidentiality purposes.

Appendix 2: Publications included in this portfolio

Publication 1: Trujillo, D., Ramage, M. and Chang, W.S. (2013) 'Lightly modified bamboo for structural applications'. *Construction Materials – Proceedings of the Institution of Civil Engineers* 166(4), pp.238-24

Available at: https://pureportal.coventry.ac.uk/en/publications/lightly-modified-bamboo-for-structural-applications OR https://doi.org/10.1680/coma.12.00038

Publication 2: Trujillo, D. (2013) 'Prospects for a method to infer non-destructively the strength of bamboo: a research proposal' in *Proceedings of Sustainable Construction Materials and Technologies (SCTM3 conference)*. held 19 – 21 August at Kyoto, Japan. Paper E74.

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Publication 4: Trujillo, D., Jangra, S. and Gibson, J. (2017) 'Flexural properties as a basis for bamboo strength grading'. *Structures and Building - Proceedings of the Institution of Civil Engineers*, Vol. 170, No. 4. pp 284-294

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Publication 5: Trujillo D and Malkowska D (2018) 'Empirically derived fastener properties for Guadua bamboo'. *Construction and Building Materials* – 163 pp. 9-20.

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