Bamboo as a Sustainable Engineering Material:

Mechanical Properties, Safety Factors, and Experimental Testing

by

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DEDICATION

Dedico este trabalho a Deus, sem o qual não sou nada e com o qual posso tudo

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ABSTRACT

With exponential global population growth occurring and associated environmentally destructive consumption of natural resources, alternative materials that are fast growing and sustainable are being sought out to satisfy human needs. One material that is fast growing and sustainable that can be used to meet most basic needs of humans (i.e. shelter, food, tools) is the plant bamboo, of the grass family *Poaceae*. Bamboo was used in the past by native peoples who lived in the environment where bamboo natively grows (all continents except Europe and Antarctica) with proven success for uses such as shelter, piping, tools, wells, food, fencing, baskets and much more. These practices were mostly abandoned and deemed obsolete due to the introduction of long lasting 'modern' building materials of steel and concrete which gained popularity in the 1800s. Now, in the current century with much advancement in science, technology, and education, humanity is reconsidering many practices and returning to more ancient practices and ways that are better for human health, the environment, and overall sustainability.

These environmental considerations are drivers of this research, which focuses on how to use bamboo for engineering applications. First, in order to use a material for engineering and design applications, a material must be destructively tested to attain material property values. Therefore, a critical examination of the bamboo mechanical property values published literature was performed. It was found that although many scientists all over the world have been working on mechanical property testing of bamboo, their results have been published in different journals,

in different languages, and had not yet been aggregated and compared. This led to the first study in this work that analyzed mechanical property data from 43 bamboo peer-reviewed publications written in English, Spanish, and Portuguese (the three main languages in which bamboo literature is published). This study focused on aggregating mechanical property values, establishing a range of values for each property as well as an average, and correlating the difference in property values to bamboo variables stated in bamboo literature (age, bamboo species, density, moisture content, post-harvest treatment, and testing standard employed). The five mechanical properties reviewed were: shear strength, compressive strength, tensile strength, bending strength / modulus of rupture (MOR), and modulus of elasticity (MOE) and their average values were 9 MPa, 52 MPa, 159 MPa, 120 MPa, and 16 GPa, respectively. Although a thorough graphical set of analyses were performed attempting to correlate the difference in mechanical property values to the previously listed variables, and only main variables found to influence strength values were moisture content and specific testing standard employed.

The results of the high range of mechanical property values with no variable with which to separate the results to lower the range, led to the second part of the research. It incorporated the high range of values reported in the literature but was able to establish safety factors and reduction factors alongside corresponding failure rates. This work allows for a designer to use bamboo culms choosing a failure rate he/she deems appropriate for structural bamboo construction. The analyses in this work were performed using Allowable Stress Design (ASD) and Load and Resistance Factor Design (LRFD) equations applied to bamboo as well as Monte Carlo statistical analyses for verification. The raw data and statistically analyzed data of 25 publications were used for this analysis, yielding 3806 strength test values (shear strength, compressive strength, bending strength / modulus of rupture, and tensile strength). Shear strength safety factors ranged from 1.38-3.58 for failure ratios from 1:6-1:25000; compressive strength from 1.30-2.79; bending strength from 1.43-4.03; tensile strength from 1.66-7.43. No singular safety factor is suggested for design as that is due to the judgment of the designer of what failure ratio he/she deems appropriate for the specific application.

Although many compression tests have been performed on bamboo, there are no known tests which destructively test bamboo after an extended period of time after harvesting (more than ~3 months). This experiment conducted a field experiment to test the functionality of using bamboo for the application of installing bamboo wells to provide groundwater. The bamboo tested in the third part of the study was of two species, *Dendrocalamus giganteus* and *Dendrocalamus asper* half of which were 1) air-dried in a laboratory for 3.5 years and the other half of which was 2) inserted in the ground as bamboo wells. The bamboo culms (or poles) had been separately treated in three different ways right after cutting: 1/3 with a borax and boric acid solution (most conventional treatment in the industry), 1/3 with coconut oil (experimental treatment in the literature), and 1/3 air-dried, a non-treated control. Bamboo wells are said to be used in ancient times as well as in more recent applications in the 1990s in India by small scale farmers. The publication of bamboo well studies have been very few and nearly no scientific analyses had been performed on them. Therefore, six bamboo wells were assembled and installed at the University of South Florida Geopark, the first of their kind in the U.S. These wells were half of species *D. giganteus* and half of species *D. asper* and also treated individually using the three different treatments described above. The wells were monitored for pH and presence of leached boron for a 3.5-year monitoring period and then removed. Upon removal, the bamboo well casings were examined for molds present as well as by mechanical compression testing to assess degradation in comparison to each other (of different treatments) and to air-dried control samples maintained in the laboratory for 3.5 years. The mold fc. *Acrodictys* was observed to cover the entire inner portion of the bamboo (inner diameter), from the surface level up to the water table. The lab air-dried control samples had compression strength and compressive modulus of elasticity values correlating to those found in the literature, 44-90 MPa (72 MPa average) and 15-31 GPa, respectively. Removed well samples exhibited compressive strengths and compressive modulus of elasticity values of 22-61 MPa (39 MPa average) and 7-25 GPa, respectively. This study revealed that bamboo wells were feasible and although their compressive strengths lowered by around a half after being in the ground for 3.5 years, their compressive strength and compressive modulus of elasticity values were still in the range of bamboo tested in the literature.

CHAPTER 1: INTRODUCTION

1.1 Introduction

With a global rate of population increase of 1.2% (Population Reference Bureau 2011), projections of population at 2050 are 10-12 billion people (Goodwin 2011; Pimentel 2012). Accordingly, engineering materials that support community well-being and can also keep up with this growth in population will be needed (Mihelcic et al. 2007). Currently, many materials used for necessary and non-necessary needs are unsustainable and on the road to depletion if the situation remains ‘business as usual.’ The global need to identify and make use of more sustainable materials is thus clear. Sustainability, as defined by the United Nation's Brundtland Commission in 1987 is meeting the needs of the present without compromising the ability of future generations to meet their own basic needs.

One material that exhibits rapid growth, strong indicators of sustainability, and high strength properties is bamboo. Bamboo, of the grass family *Poaceae*, is a remarkable plant which offers uses for all of its parts. Its leaves can be used as animal feed, stems for basket making, young shoots for eating, and most notably for this work, its culm, or trunk, can be used as a high strength engineering material. The overall goal of this research is to advance the understanding of the engineering properties of bamboo and its potential use in construction/structural applications. While bamboo is a broad term, as there are many species of bamboo, in this work ‘bamboo’ will refer to large diameter bamboo species, used previously in bamboo applications and mechanical property testing; all species studied are specified in pages 18 and 54. This goal will be met by critically assessing the strength properties of the bamboo culm, determining average values of specific mechanical strength properties, associated safety factors, and worst-case experimental data by gathering and comparing published data as well as running field experiments. Although studies on bamboo fibers, bamboo composite materials, and non-destructive tests have been performed, this study will focus on structural species bamboo culms in their intact form tested using traditional destructive testing.

Bamboo was used, long ago, for all types of things: basket making, cups, flooring, bridges, housing, pipes, wells, insect repellent, and food with up to 1,500 archeologically marked uses (Lewington 2003). Although it is known that bamboo can be used as a building material, the mechanical properties of bamboo are not yet well understood. In the last 30 years or so, bamboo is being 'rediscovered' as scientists test bamboo scientifically for a variety of applications: biochar, cancer curing nanoparticles, structural uses, and more (e.g., Lipangile 1991; Gu et al. 2015; Xie et al. 2017). The focus of this work is to research bamboo for use in structural and engineering applications.

After an in-depth review of past and current bamboo literature, it became clear that one obstacle in using bamboo for structural purposes is there are large gaps in knowledge regarding bamboo mechanical properties. This led to the first part of the research that gathered and assessed bamboo mechanical property values obtained from researchers who represented 25+ countries from the three main bamboo publishing languages, English, Spanish, and Portuguese (Chapter 2). This purpose of this research was to obtain average mechanical property values of bamboo using a large array of mechanical property data from researchers from all over the world. Although some researchers have compared their mechanical property values to other studies, there has never been a comparison of more than five to ten studies, and in table format (this work encompassed 186 studies compared graphically). Using these comparative graphs, a range of mechanical property values were obtained. Since the ranges found per mechanical property value were quite large, a synthesis of the data was performed, comparing mechanical property values to specific variables which are stated in the literature to influence mechanical property values (i.e. age, species, density, moisture content, treatment, and testing standard employed).

The first work showed variability in mechanical property values and this variability was embraced in order to make bamboo construction feasible at the current time, by establishing appropriate safety factors and reduction factors for intact bamboo culms (Chapter 3). Bamboo design manuals mention the need to establish safety factors (Arce-Villalobos 1993; Janssen 2000) and to our knowledge no safety factors or reduction factors for undisturbed bamboo culms have as of yet been established. Design parameters for bamboo strength properties (compressive, tensile, bending, and shear strength) were calculated attaining safety factors and resistance factors, reliability indices, and failure ratios. These were calculated using design equations of Allowable Stress Design (ASD), which generate safety factors, and Load Resistance Factor Design (LRFD), which generate resistance factors and Monte Carlo statistical analyses for verification.

The original motivation of the dissertation author in working with bamboo was to use bamboo in developing countries where it is native and where it is arguably most needed because standard building materials of steel and concrete are of too high cost. Upon researching the published literature, the author encountered a little known but very useful application of bamboo: bamboo wells. Bamboo wells were used in ancient China thousands of years ago for salt mining (Arif 1978) and more recently (1900s) in India and Bangladesh with proven functionality (Rahman 1976; Arif 1978) but have not yet been reported to be in use anywhere else in the world. Therefore, a field research trial of the performance of bamboo wells was done at the University of South Florida (USF) as bamboo was cut, treated, prepared, and installed as bamboo wells at the USF Geopark (Chapter 4). The installed bamboo wells were monitored for pest infestation and water quality was monitored for pH and possibility of leaching by the two chemical treatments of the installed bamboo. The six wells installed were treated using three methods most mentioned in the literature: air-drying, borax/boric acid, and natural oil treatment. Although these different treatments are much mentioned and sometimes laboratory tested, they are seldom tested in real world settings (outdoors) for extended periods of time. The bamboo wells were removed after the 3.5-year monitoring period and were tested mechanically using a compression test. The compression test and the use of axial extensometers provided compressive strength and compressive modulus of elasticity data. These data were used to compare deterioration between differently treated wells as well as against air-dried control samples which were maintained in the laboratory for the 3.5 years. Additionally, these data are unique in bamboo mechanical testing because testing bamboo at 3.5 years of air-drying is nearly unheard of, as most researchers test the bamboo either freshly cut or after ~3 months of air-drying; neither of which provide values of how the material would behave after being in use for years in a structure. The well mechanical property tests are also interesting as they provide 'worst case scenario' data of bamboo in the ground uncovered outside and inside the water table. This type of 'worst case scenario' study has not been yet observed for bamboo.

The author, as a part of her PhD, served as a Peace Corps Volunteer in Ethiopia through the International Development Engineering program at USF (Mihelcic et al., 2006; Mihelcic, 2010; Manser et al., 2015). There, she, alongside the local people, installed a rainwater tank made mainly of natural materials called the Natural Rainwater Harvesting System (Appendix D).

Since bamboo was not a common building material in Ethiopia, the tank was made with natural materials commonly used by the local people (eucalyptus wood, rocks, mud, teff straw, etc.). This field trial is an example of how bamboo (if available in the area) alongside other natural materials could be used for sustainable projects in the Water, Sanitation and Hygiene (WASH) sector.

1.2 Research Questions

Based on the background research, the following research questions have been identified as knowledge gaps:

- ❖ Why are the mechanical properties of bamboo not yet fully understood and how can they be understood to a high enough degree so as to make bamboo a viable engineering material for current use? (*Chapters 2 & 3*)
- ❖ Why has bamboo use as the casing for groundwater well not received more widespread use and what is the expected durability for short-term use? (*Chapter 4*)

1.3 Research Topics

The specific research topics are:

- ❖ *Chapter 2*: Compilation of bamboo mechanical properties and investigate if any correlations exist between strength values and items such as age, species, density, moisture content, treatment, and testing standard.
- ❖ *Chapter 3*: Determination of safety factors and resistance factors that can be used in structural design applications for bamboo using design equations of Allowable Stress Design (ASD), and Load Resistance Factor Design (LRFD) with Monte Carlo analyses for verification.
- ❖ *Chapter 4*: Field trial of bamboo wells installed in USF GeoPark that includes

mechanical property analyses of wells after 3.5 years placement in the subsurface versus air-dried control bamboo samples.

1.4 References

Arce-Villalobos, O. A. (1993). Fundamentals of the design of bamboo structures (Doctoral dissertation, Technische Universiteit Eindhoven).

Arif, M. T. (1978). A study on bamboo tube-well for irrigation. Rural Development Academy, Bogra. Bangladesh.

Goodwin, K. (2011). Having children: Reproductive ethics in the face of overpopulation. Macalester Journal of Philosophy, 20(1), 3.

Gu, X., Wang, Y., Lai, C., Qiu, J., Li, S., Hou, Y., ... & Zhang, S. (2015). Microporous bamboo biochar for lithium-sulfur batteries. Nano Research, 8(1), 129-139.

Janssen, J. J. (2000). Designing and building with bamboo (pp. 130-133). Netherlands: International Network for Bamboo and Rattan. Technical Report no. 20. ISBN 81-86247-46-7.

Kaminski, S., Lawrence, A., Trujillo, D., Feltham, I., & Felipe López, L. (2016). Structural use of bamboo. Part 3: Design values. The Structural Engineer: journal of the Institution of Structural Engineer, 94(12), 42–45.

Lewington, A. (2003). Plants for people. Random House.

Liese, W. (1992). The structure of bamboo in relation to its properties and utilization. Proceedings of the International symposium on Industrial Use of Bamboo, Beijing, China, 7–11.

Lipangile, T.N. (1991). Manufacture and construction of bamboo water supply systems. Journal of the American Bamboo Society, 8(1&2), 191-198.

Lugt, P.V., Dobbelsteen, A. A. J. F., & Janssen, J. J. A. (2006). An environmental, economic and practical assessment of bamboo as a building material for supporting structures. Construction and Building Materials, 20(9), 648–656.

Manser, N., Naughton, C., Prouty, C., Orner, K., Verbyla, M., & Mihelcic, J.R. (2015). Improving the global competency of graduate engineers through Peace Corps partnership and long-term international service. Making value for society. Proceedings of the American Society for Engineering Education (ASEE) National Conference, Washington Convention Center, Seattle, WA.

Mihelcic, J.R., Phillips, L.D., Watkins, D.W. (2006). Integrating a global perspective into engineering education & research: engineering international sustainable development. Environmental Engineering Science, 23(3):426-438.

Mihelcic, J.R. Zimmerman, J.B., Ramaswami, A. (2007). Integrating developed and developing world knowledge into global discussions and strategies for sustainability. Part 1: Science and Technology. Environmental Science & Technology, 41(10):3415-3421.

Mihelcic, J.R. (2010). The right thing to do: graduate education and research in a global and human context. What Is Global Engineering Education For? The Making of International and Global Engineering Educators (Eds: G.L. Downey and K. Beddoes), Morgan & Claypool Publishers, San Francisco, 235-250.

Pimentel, D. (2012). World Overpopulation. Environmental, Development and Sustainability, 14, 151-152.

Population Reference Bureau. (2011). Population data sheet 2011. Washington, DC: Population Reference Bureau. http://www.prb.org/pdf11/2011population-data-sheet_eng.pdf.

Rahman, M. (1976). A preliminary report on two experimental bamboo wells in Comilla Kotwali Thana. Bangladesh Academy for Rural Development.

Xie, J., Yong, Y., Dong, X., Du, J., Guo, Z., Gong, L., ... & Zhao, Y. (2017). Therapeutic nanoparticles based on curcumin and bamboo charcoal nanoparticles for chemo-photothermal synergistic treatment of cancer and radioprotection of normal cells. ACS applied materials & interfaces, 9(16), 14281-14291.

CHAPTER 2: MECHANICAL PROPERTIES OF BAMBOO: A CRITICAL REVIEW OF HOW AGE, SPECIES, DENSITY, MOISTURE CONTENT, TREATMENT, AND TESTING STANDARD INFLUENCE STRENGTH VALUES[1]

2.1 Abstract

Bamboo is a highly renewable material that is used in some countries as a viable building construction material; however, it is not yet widely used in the U.S. since it is not included in building codes/safety standards. To develop standards, the mechanical properties of bamboo must be understood and documented. Studies have been independently conducted by different researchers in different languages all over the world which have not yet been aggregated or compared. Therefore, 43 publications (in English, Portuguese, and Spanish) presenting mechanical properties of bamboo were compiled and analyzed. The five mechanical properties reviewed were: shear strength, compressive strength, tensile strength, bending strength / modulus of rupture (MOR), and modulus of elasticity (MOE). Properties were found to have a large range, so the major variables were investigated: age, bamboo species, density, moisture content, post-harvest treatment, and testing standard employed. The findings suggest no strong correlations exist with external factors and the inherent variability in mechanical properties should be statistically embraced via use of appropriate safety factors.

[1] Reprinted from: Sánchez Vivas, L., Mullins, G., Cunningham, J.A., Mihelcic, J.R. (2019). Mechanical Properties of Bamboo: A Critical Review of how Age, Species, Density, Moisture Content, Treatment, and Testing Standard Influence Strength Values. Journal of the American Bamboo Society. In review.

2.2 Introduction

Currently, dynamic changes are occurring in the world from rapid increases in population, affluence, and associated consumption of resources (Zimmerman et al. 2008) with many natural material reserves being stressed. This has led to water scarcity, deforestation, and mineral depletion. One path forward to a more sustainable future is through wider adoption of an underutilized natural and renewable plant material: bamboo, of the grass family *Poaceae*. Bamboo is an advantageous and sustainable material mainly due to its fast growth, reaching maturity in 2 - 4 years, when some species become ready for use in engineering applications (Limay 1952; Liese 1991; Liese 2004). Cusak (1999) noted: “there could never be enough silver flutes to give one to everybody in the world. There could, easily, be enough bamboo for all 50 billion fingers on the earth to make and play their own.”

Since bamboo grows natively, is cultivated, and is naturalized in many countries, it also has the potential to improve community well-being for a variety of peoples of different cultures. Parts of many species of bamboo can be used: its shoots as a nutritious food (Zheng et al. 2013; Badwaik et al. 2014), its leaves as improved chicken and cattle feed (Ogunwusi & Onwualu 2013), and its culm (the focus of this paper), which can number 5,000–10,000 culms per hectare, as a sturdy, inexpensive, and readily available building material (Lipangile 1991). Traditionally, bamboo is also used as a home building material as well as for repelling insects, flooring, and basket making (Laha 2000; Arinasa & Bagus 2010; Teron & Borthakur 2012). Commercially, bamboo is used in part as a material to manufacture paper, clothing, corrugated roofing, and walls (Verma & Chariar 2012; Sathish et al. 2017). In fact, bamboo housing has been found to be more resistant to earthquakes than unreinforced masonry (Edwards & Doing 1995; Macdonald 1999). It has additionally been used as outdoor piping for water supply (Lipangile 1991) and as fast-producing biomass (Liese 1987). More recent science has taken a new look at bamboo, using it in research for improved wastewater treatment (Colin et al. 2007) and in its nanoparticle form for cancer research (Xie et al. 2017). Bamboo therefore presents itself as a viable material for a wide variety of uses for high-income as well as economically-marginalized areas. However, it has not received global attention as a common building material.

Compared to global use of conventional building materials of steel (56%), concrete (28%), and other forest products (16%), bamboo use makes up less than 0.1% of the total global building materials used (Trujillo 2018). Nevertheless, bamboo has large potential for use. There is a general lack of information, understanding of the material properties, and research findings to advance the use of bamboo.

Current literature demonstrates there are large gaps in knowledge regarding bamboo mechanical properties (Valero et al. 2005; Fabiani 2015). Liese (1992) stated that “a thorough understanding of the relations between structure, properties, behavior in processing and product qualities is necessary for promoting the utilization of bamboo.” Supporting this notion, Wang et al. (2014) wrote “to promote the widespread application of bamboo in construction and other engineering fields, far more knowledge and understanding of its mechanical properties is required.” This lack of knowledge extends to building codes for bamboo which are likewise in need of development (Lugt et al. 2006). Kaminski et al. (2016) noted “bamboo will be as well understood as timber is, but we have some way to go before that happens.”

Although the mechanical property values of bamboo have been tested by different researchers, the data has not been collectively synthesized. Here, mechanical property values have been compiled to obtain average values and analyzed by variable to see which and how they affect mechanical property values. Variables analyzed are: age, species, density, moisture content, post-harvest treatment, and testing standard employed. The objective of this paper therefore is to gather and graphically compare mechanical property values to establish averages and ranges as well as compare them to variables which are stated in bamboo literature to influence mechanical property values.

2.3 Methods

A critical review of the literature identified 43 publications which provided mechanical property values of bamboo to be used for this paper (see Appendix A). Criteria for inclusion in this study required: (1) focus on externally peer-reviewed publication, (2) publications that provided access to well-presented data, (3) collecting information that spanned a period of 1981 to 2018, (4) focus on collecting information that represented the diversity of global contributors (publications from authors of 25 countries are included), including papers published in English, Spanish, and Portuguese, as most studies identified were published in these three languages. The seven mechanical properties reviewed were: shear strength, compressive strength, tensile strength, bending strength / modulus of rupture, compressive modulus of elasticity, bending modulus of elasticity, and tensile modulus of elasticity. From each publication one or more average mechanical property values per study were excerpted (i.e. species of bamboo, treatment condition, etc.). These individual mechanical properties were used to derive overall averages (of the individual average) and statistical ranges as well as dependency on variables reported in the literature: age, bamboo species, density, moisture content, post-harvest treatment, and testing standard employed.

The mechanical property value data were compiled as follows: shear strength, 18 studies conducted by 9 researchers; compressive strength, 59 studies by 24 researchers; modulus of rupture, 52 studies by 18 researchers; tensile strength, 21 studies by 7 researchers; compressive MOE, 19 studies conducted by 10 researchers; bending MOE, 34 studies by 16 researchers;

tensile MOE, 10 studies by 6 researchers.

Table 2.1 presents the definitions and symbols used to represent each property. F_v, F_c, F_b, F_t and E_c, E_b, E_t, E have been adopted from timber specification for comparison and uniformity (Parker 1979).

Table 2.1 Mechanical properties studied and the definitions

Mechanical Property	Symbol	Units of Measure	Definition
Shear strength	F_v	MPa	Strength of material when fails in shear
Compressive strength parallel to grain	F_c	MPa	Maximum compressive load divided by initial cross-sectional area
Bending Strength / Modulus of rupture (MOR)	F_b	MPa	Tensile strength at bending failure
Tensile strength	F_t	MPa	Ultimate tensile strength, maximum tensile stress at failure
Compressive Modulus of Elasticity (MOE)	E_c	GPa	Compressive force per unit area divided by change in length over initial length
Bending Modulus of Elasticity (MOE)	E_b	GPa	Ratio of stress to strain in flexural deformation
Tensile Modulus of Elasticity (MOE)	E_t	GPa	Ratio of tensile stress to tensile strain
Combined Modulus of Elasticity (MOE)	E	GPa	The compressive, bending, and tensile MOE values combined

Other test methods have been performed on bamboo, such as microscopic nano-indentation and non-destructive tests (Yan-hui et al. 2012; Yang et al. 2014; Lin et al. 2006), but only conventional destructive mechanical property tests were considered for this review. Additionally, although mechanical testing has been performed on bamboo composites (*e.g.*, Huang et al. 2014; Bahari et al. 2017; Sathish et al. 2017; Wistara et al. 2017), only studies that tested the bamboo in its original whole or split culm state were assessed here.

2.4 Results

A compilation of all 43 publications that assesses the seven basic mechanical properties, the variables affecting mechanical properties, and the effects of the various standards used worldwide is presented. The main bamboo species reported were *Bambusa vulgaris*, *Guadua* *angustifolia*, and *Phyllostachys pubescens* (Moso), and less common species were *Bambusa balcooa, B. bluemeana, B. oldhamii, B. pervariabilis, B. salarkhanii, B. tulda, Dendrocalamus asper, D. giganteus, D. strictus, Gigantochloa apus, Gi. scortechinii, Guadua aculeata, Melocanna baccifera, Phyllostachys aurea, P. bambusoides, P. edulis, P. viridiglaucescens,* and *Schizostachyum brachycladum.*

2.4.1 Mechanical Properties of Bamboo

The tensile, compressive, shear, and bending strength (also called modulus of rupture) shown in Figure 2.1 (F_t, F_c, F_v and F_b, respectively). For each test type, the box represents the interquartile range of the data, the whiskers represent 1.5times the interquartile range, and the points outside of the whiskers are outliers. The middle line represents the median and the middle "x" is the mean.

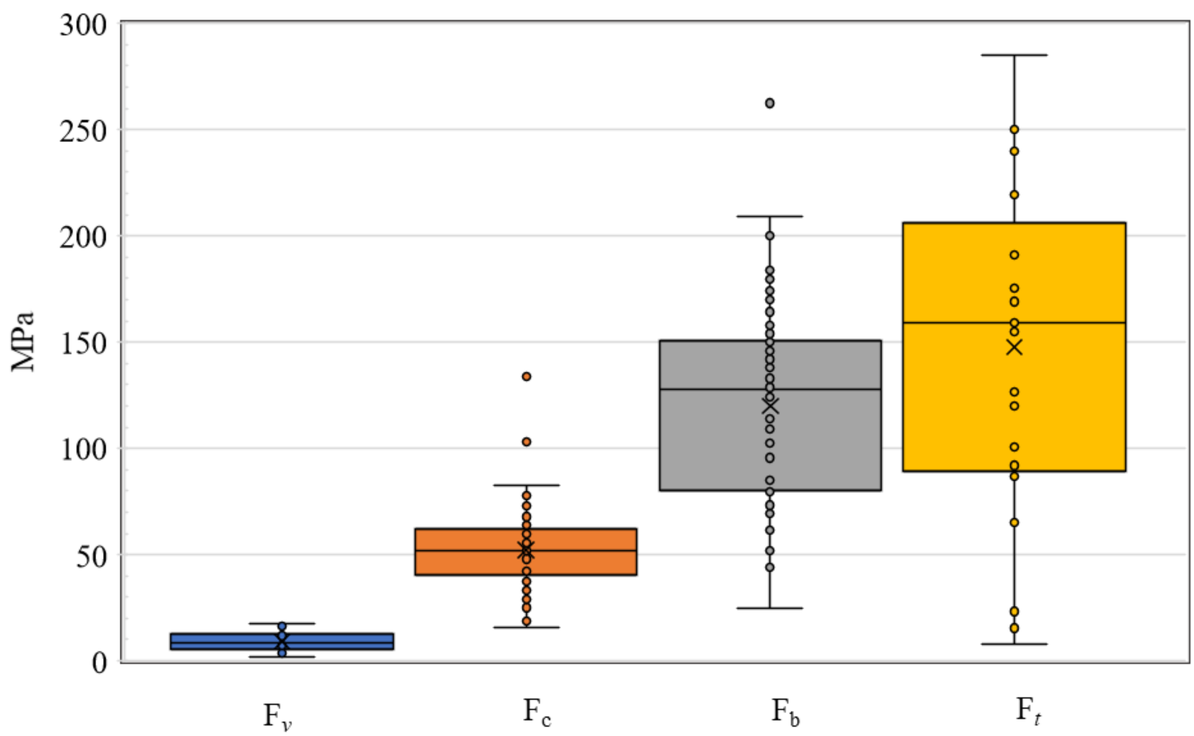

Figure 2.1 Shear strength (F_v), compressive strength (F_c), bending strength (F_b), and tensile strength (F_t) values.

The average values shown are: shear strength, 9 MPa; compressive strength, 52 MPa; bending strength, 120 MPa; and tensile strength, 159 MPa. Figure 2.1 provides the results for the modulus of elasticity, in compression (E_c), bending (E_b), and tension (E_t). The combined MOE, similar to timber, has a consistent MOE regardless of test method used to acquire it (i.e. E_c, E_b, and E_t all have consistent values). The MOE values of timber (Parker 1979) were included in Figure 2.2 for comparison. The range of values obtained were for the following timber species: California Redwood, Douglas Fir and Larch, Engelmann Spruce, and Southern Pine. The higher MOE values of bamboo are advantageous to its potential use in structural members.

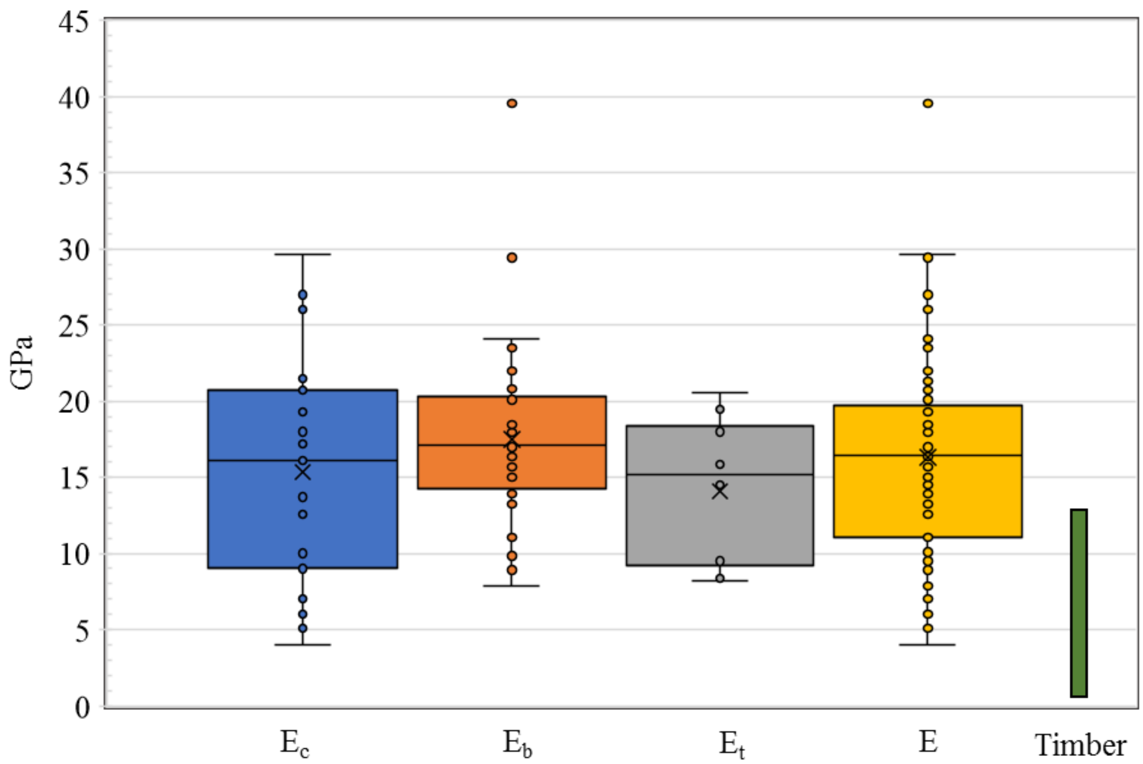

Figure 2.2 Compressive modulus of elasticity (MOE), bending MOE, tensile MOE, and combined MOE values alongside timber values for comparison.

The average values of MOE are: compressive, 16 GPa; bending, 17 GPa; tensile, 14 GPa; combined, 16 GPa. From Figures 2.1 and 2.2, it can be seen that the mechanical properties have a wide range. These studies included many species of bamboo, and similar variability exists for different species of structural timber. Although the values of bamboo range as high as 61% for shear strength, 65% for compressive strength, 60% for MOR, 90% for ultimate tensile strength, and 75% for MOE, these values are comparable to the average deviation of structural timber of different varieties: 23% for shear strength, 52% for compressive strength, 33% for ultimate tensile strength, and 20% for MOE (Parker 1979) for structural timber species, including: California Redwood, Douglas Fir and Larch, and Southern Pine.

It was also found that several mechanical properties are quite understudied for bamboo. These are: impact energy, toughness, and compression perpendicular to grain. Each was only found to be reported in 1–2 publications; those values are presented in Table 2.2. If bamboo is to be used conventionally, these understudied properties should be better understood for safer design of bamboo structures.

Table 2.2 Mechanical properties and values understudied for bamboo

Mechanical Property	Value(s)	Average Value	Publication
Compression perpendicular to the grain	1.7 MPa	1.7 MPa	Luna et al. 2014
Impact energy	7.6-8.9 J	8 J	Omobowale & Ogedengbe 2008
Poisson's Ratio	0.23-0.35	0.3	Cruz 2002; Ghavami & Marinho 2005
Toughness	17-22 J	20 J	Manalo & Acda 2009

2.4.2 Variables Affecting Properties

As one method of explaining variations in mechanical properties, the properties were separated into different bamboo variables, or factors. The variability of mechanical properties has been linked to: age, species, density, moisture content, position in culm, post-harvest treatment, and whether or not the node was included in the test specimen. These are individually explored. Although initial defects is a major variable for timber (Parker 1979), it is hardly mentioned as an explanation for bamboo variability in the literature.

2.4.2.1 Age

The literature supports cutting bamboo between 3–4 years old (y.o.) for use as an engineering material. It is stated that very young bamboo (age <1 y.o.) should never be used as it will warp significantly; young bamboo (age <2 y.o.) is more susceptible to pest attack (Dhawan et al. 2008); mature bamboo (age 3–4 y.o.) is the optimum age for the highest value of strength properties (Liese 1992; Kabir et al. 1993); and old bamboo (age >5 y.o.), becomes less dense, increasingly brittle, and lower in starches (Zhou 1981). The decrease in starches, especially for very old and flowering bamboo, is stated to render the bamboo nearly immune to post harvest pest attack (Liese & Tang 2015). Accordingly, old brittle bamboo could be used in situations that do not require high material properties (e.g., decorative items), having the advantage of natural pest resistance.

This raises the question of how to identify the age of bamboo upon cutting from wild sources or nurseries. In a nursery setting, new shoots can be labeled each year and the age of the culms accurately monitored. For bamboo acquired from wild sources, the estimation of age is less precise although there are some ways to estimate age. While there are no quantitative parameters currently established to identify the age of the bamboo (Londoño et al. 2002), there are qualitative parameters, such as outer color and presence of mold (Ubidia 2002). One study recently found the surface temperature was successful in estimating the age of the culm before cutting (Nölke et al. 2015).

Figure 2.3 shows the influence of age on four mechanical properties. Only the data which reported the age of testing were included in Figure 2.3 (30% did not report).

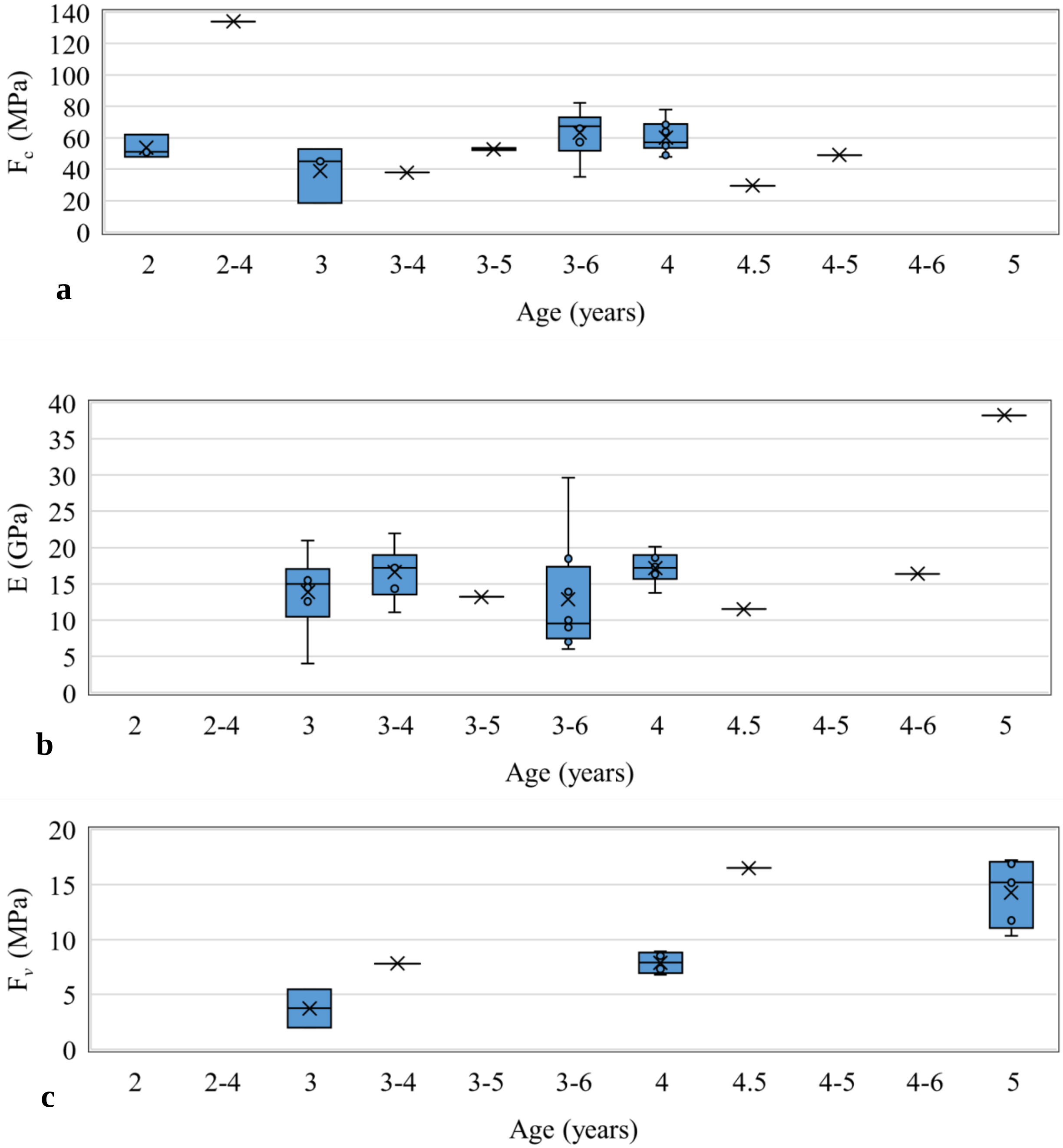

Figure 2.3 Mechanical strength data sorted by age of the tested bamboo: a) comprehensive strength (F_c), b) modulus of elasticity (E), c) shear strength (F_v), d) bending strength (F_b).

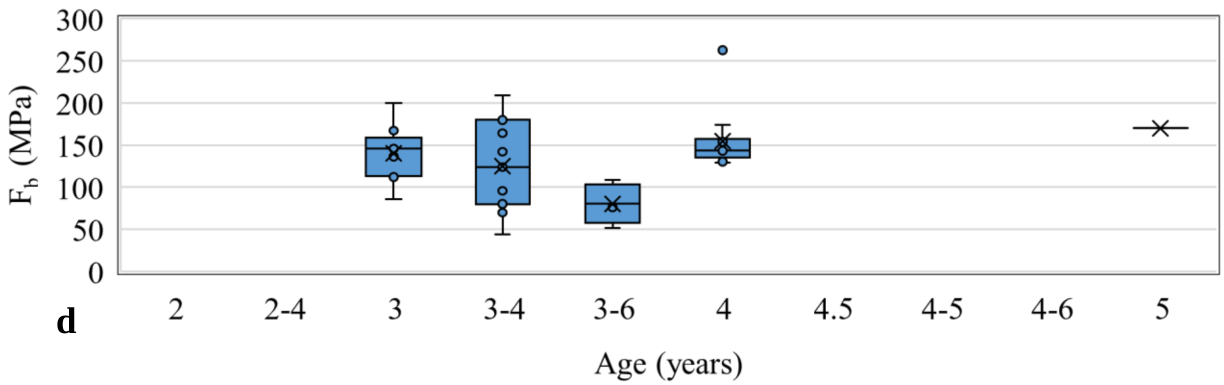

Figure 2.3 (Continued)

Only the shear strength showed appreciable effect from the age of the material when it was tested. In many cases, the age was reported vaguely (e.g. 2–4, 3–6 y.o.) which did not aid in establishing clearer trends. Additionally, in the studies which reported age, the bamboo was at an age which is recommended by bamboo literature (3–5 y.o.). Not enough data were gathered for tensile strength for a conclusive comparison.

2.4.2.2 Species

The most commonly tested species of bamboo found in the literature by species were: *Bambusa vulgaris* (pantropical), *Guadua angustifolia* (found in Latin America), and *Phyllostachys pubescens,* commonly called Moso (found in Asia). And by genera were: *Bambusa* (including species: *Bambusa balcooa*, *B. bluemeana, B. oldhamii, B. pervariabilis, B. salarkhanii,* and *B. tulda*), *Dendrocalamus* (including species: *Dendrocalamus asper, D. giganteus,* and *D. strictus*), *Guadua* (including species: *Guadua aculeata* and *G. angustifolia*), and *Phyllostachys* (including species: *Phyllostachys aurea, P. bambusoides, P. edulis,* and *P. viridiglaucescens*). Figure 2.4 shows the effect of species and genera on compressive strength, MOE, and MOR / bending strength, respectively.

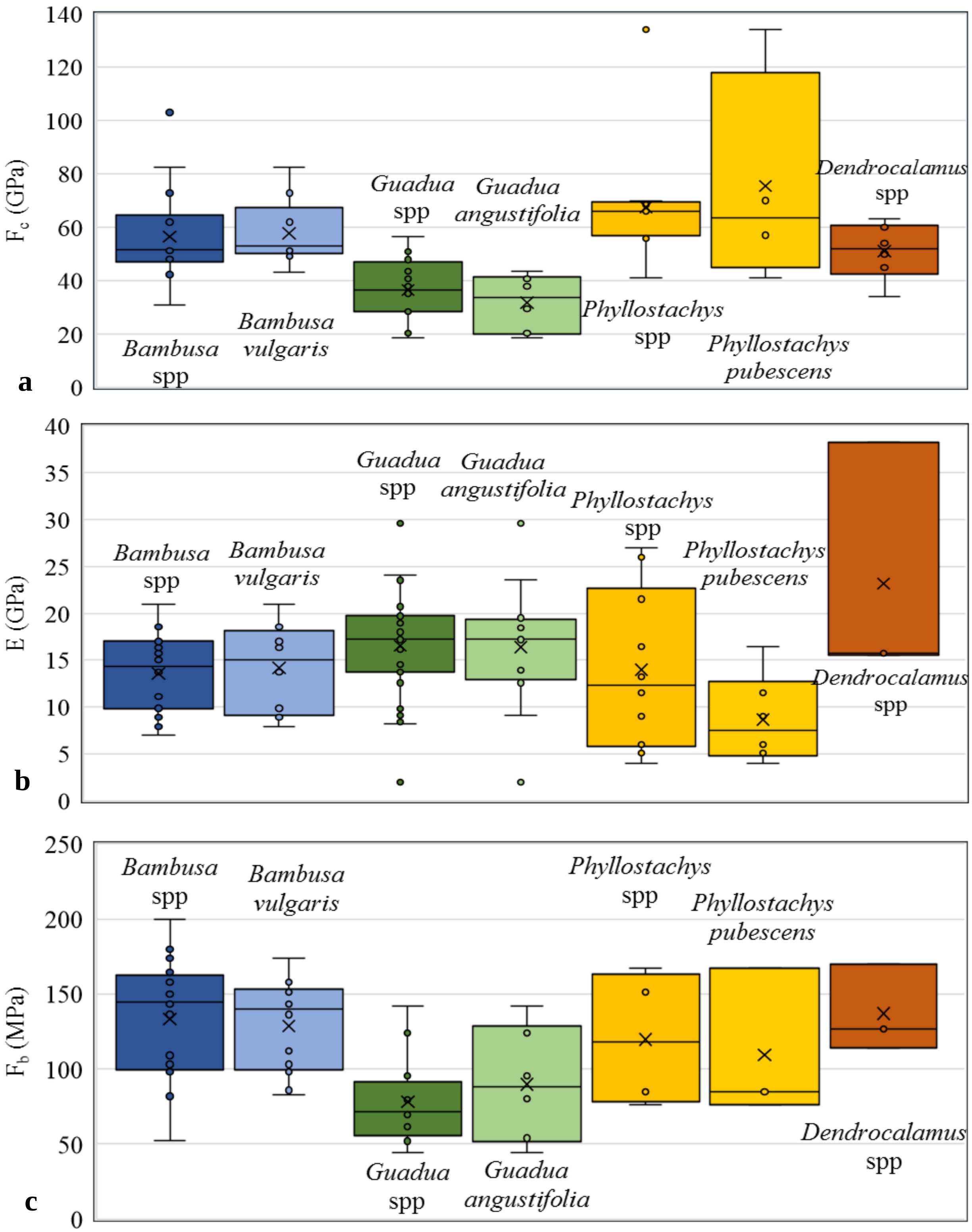

Figure 2.4 Mechanical strength data sorted by bamboo species and genera: a) compressive strength (F_c) b) modulus of elasticity (E), c) bending strength (F_b). Spp. is an abbreviation meaning two or more species.

While structural timber shows a strong dependence on species when considering mechanical properties (Parker 1979), less influence was noted with bamboo. Some bamboo studies, however, have found density to be a stronger indicator than species type for modulus of rupture in three different bamboo species of similar density (Dixon 2016).

2.4.2.3 Density

Erakhrumen & Ogunsanwo (2010) suggested that density is the major factor that influences mechanical properties of bamboo. However, the density values versus mechanical properties (Figure 2.5) show no correlation for the 91 data points plotted. Typically, a correlation (R^2) value of 0.27 is the threshold for a moderate association (Pfeiffer & Olson 1981). Higher R^2 values indicate stronger relationships; these were all significantly less.

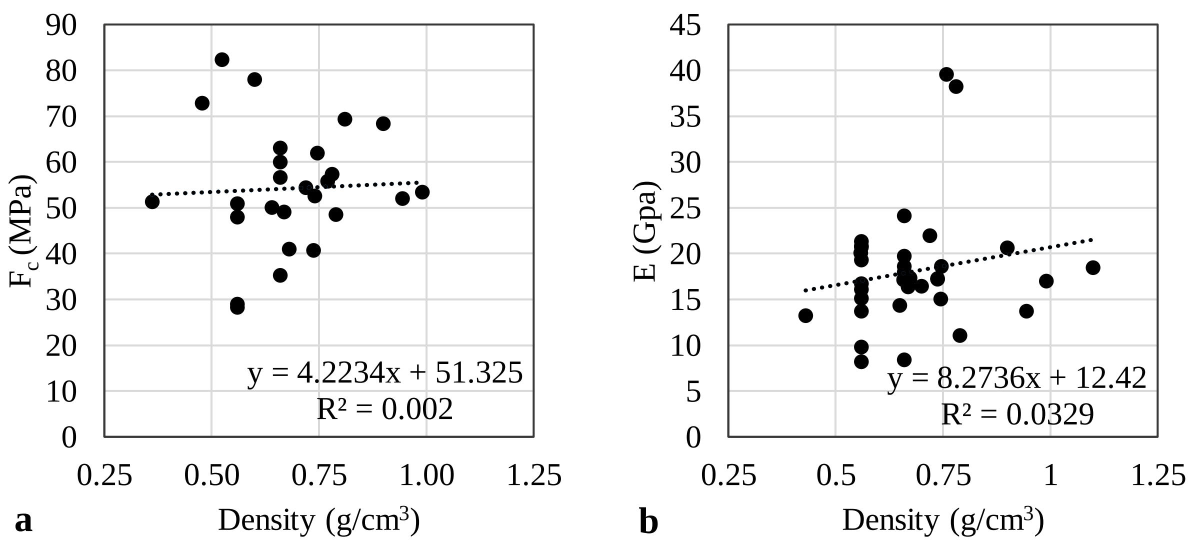

Figure 2.5 a. Density vs. compressive strength (F_c), b. density vs. bending strength (F_b), c. density vs. modulus of elasticity (E), d. density vs. tensile strength (F_t).

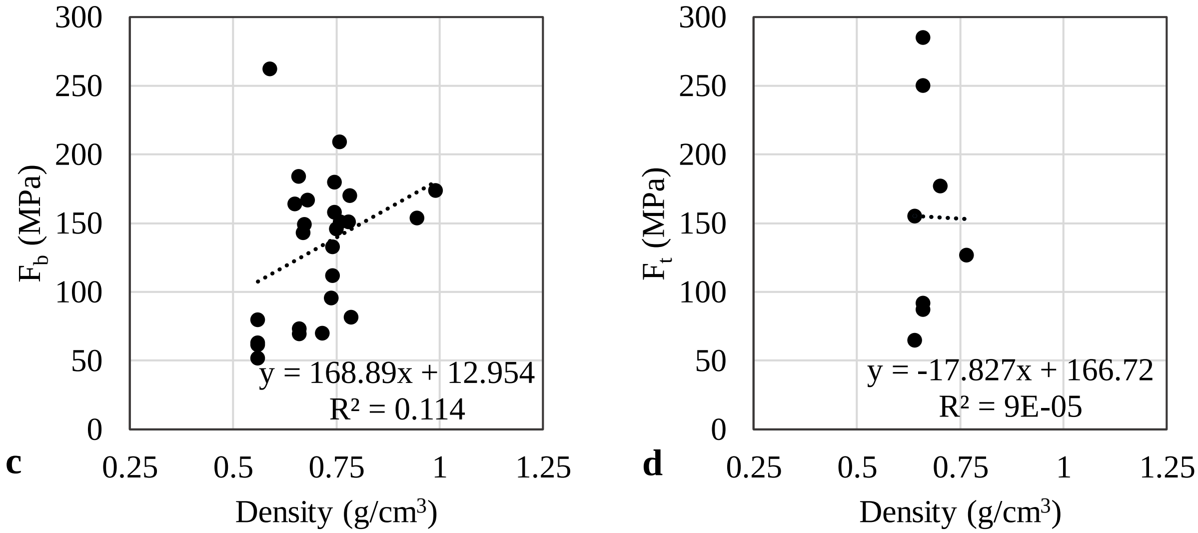

Figure 2.5 (Continued)

Research has also reported a positive linear correlation for density versus E_b and F_b values (Berndsen et al. 2013; Srivaro et al. 2018); the highest R^2 value (0.114) correlation found in this study was also for F_b. According to one study, by using density and the bamboo outer diameter, in combination, the MOR and MOE values can be estimated (Gnanaharan et al. 1994). The densities reported in this literature review study ranged from 0.36 to 1.1 g/cm^3 which is wider in range than stated in the literature, 0.5–0.9 g/cm^3 (Liese 1991; Harries et al. 2017). Additionally, density has been noted to vary along the culm height of the bamboo and generally, a positive correlation with height was seen (Sattar et al. 1990; Gnanaharan et al. 1994; Nordahlia et al. 2011).

2.4.2.4 Moisture Content

Moisture content has been reported as the most important physical property governing the mechanical properties of bamboo by Chung & Yu (2001) and as an important property by others (Limay 1952; Liese 1987; Lee et al. 1994). The collective moisture content versus property values were plotted and show that when divided into greater than or less than 15% MC, a bimodal relationship, which has been previously noted (Chung & Yu 2002; Jiang et al. 2012a), can be identified for F_b, and to some extent, for F_c, E, and F_v (Figure 2.6). The relationships were as follows: (1) for MC ~15% or less (shown circled in red) properties are fully independent of moisture, (2) for MC ~15% or higher, properties follow an increasing, decreasing, or stable relationship; which have also been reported (González et al. 2007; Okhio et al. 2011; Jiang et al. 2012a). Tensile strength data are not reported because not enough values of moisture content were available.

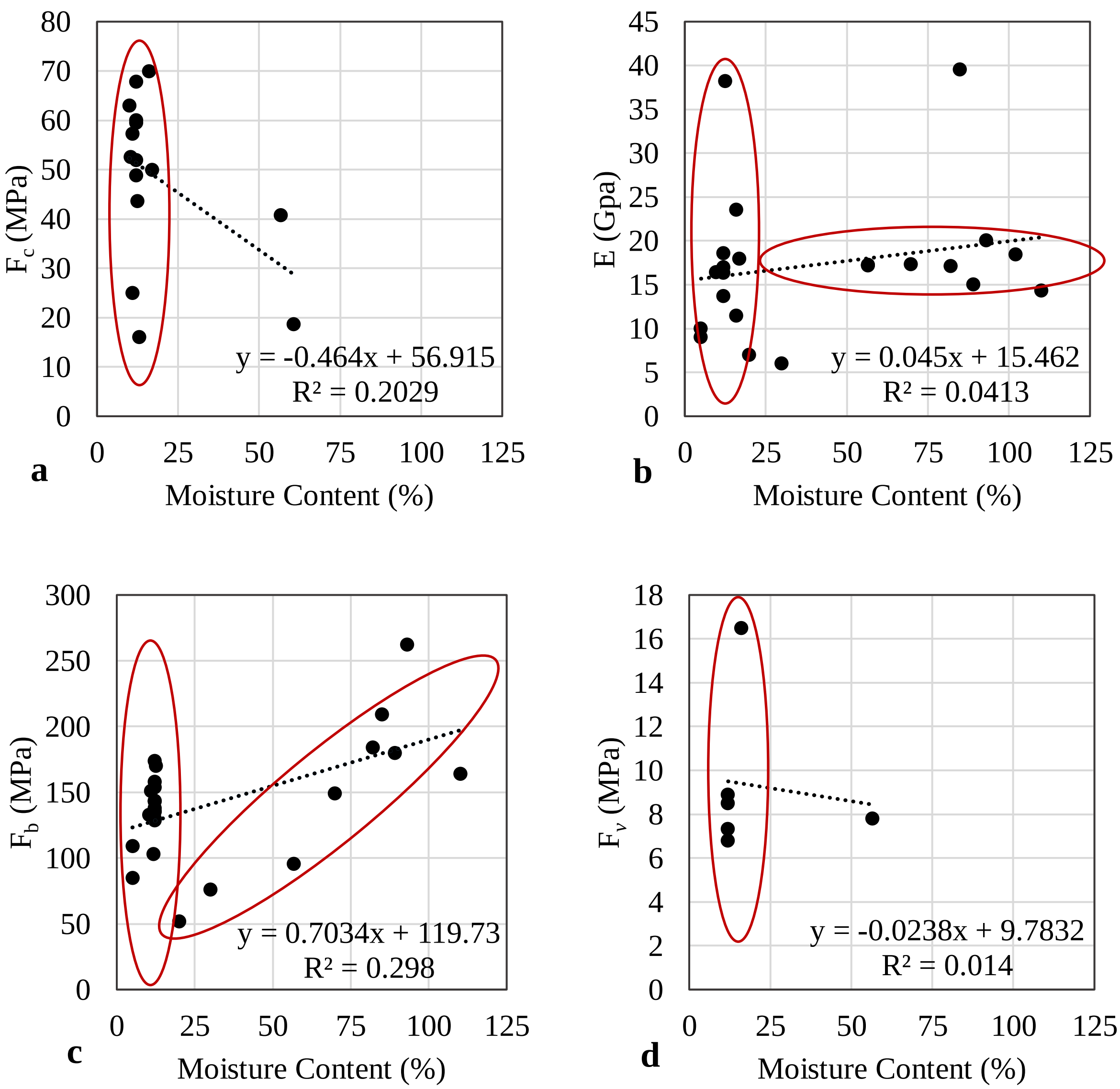

Figure 2.6 a. Moisture content vs.: compressive strength (F_c), b. combined modulus of elasticity (E), c. bending strength (F_b), d. shear strength (F_v).

Regardless of the correlation between mechanical property values and moisture content of the bamboo, it should ideally be dried to a moisture content less than 20% to prevent fungal attack (Schmidt et al. 2013; Liese & Tang 2015). Bamboo can be either air-dried or heat treated by solar drying, the latter being more effective. Improved solar dryers achieve final bamboo moisture contents of 10–22% (Ong 1996; Verma & Chariar 2012) the different values depend mainly on bamboo species and drying methods; bamboos with lower densities have higher drying rates (Tang et al. 2012).

For timber, moisture content is noted to have a significant influence on strength properties and is therefore stated that it should be dried to constant weight before testing (ASTM 143). In design, moisture content is stated to be one of the three most important properties which influence the strength of timber and a strength reduction factor for wet service conditions of 0.667–0.875 is applied to the mechanical property values (Parker 1979). Following with timber conditions and due to the currently contradictive data, moisture content and mechanical property value correlation should continue to be studied for bamboo.

Moisture content versus density was also compared for the compiled data (Figure 2.7).

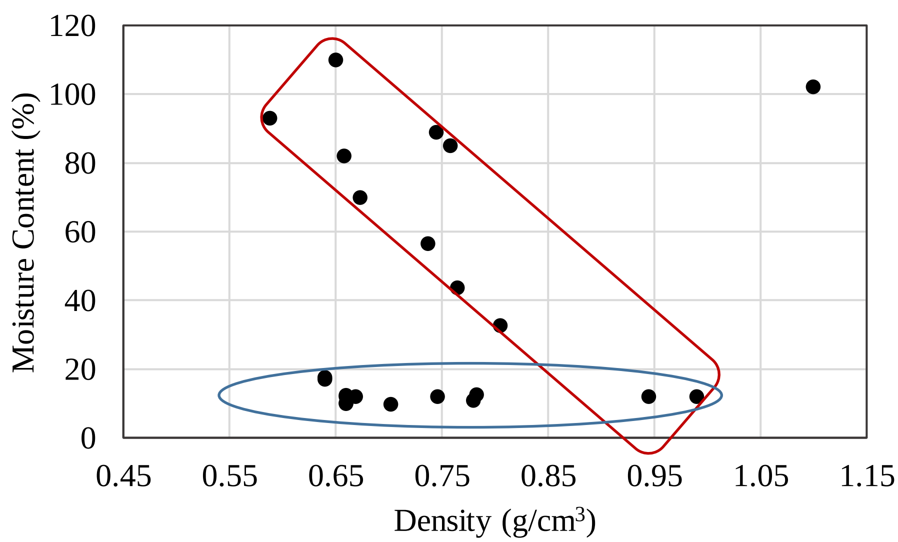

Figure 2.7 Density vs. moisture content (MC).

Similar to Figure 2.6, Figure 2.7 shows two trends: (1) for dry bamboo of MC <20% (in blue oval), and (2) for MC >20% (in red rectangle). The density and MC are inversely related for MC >20% (Figure 2.7 assumes density is reported on a dry weight basis). This again suggests the reported MC values reflect lab/dry conditions (<20%) and as-received (>20%) where specimens with higher void volumes were reflected in lower density even when still containing moisture within the voids.

2.4.2.5 Height along Culm (Base, Middle, Top)

The density and other variables have been reported to vary along the culm height of bamboo (Limay 1952; Liese 1987). Literature generally separates the bamboo culm into three parts: base, middle, and top. Once again there is conflicting evidence on the dependence of mechanical properties on the bamboo height. Many studies report increased mechanical property values from base to top of culm, specifically for compressive strength and MOR (Gnanaharan et al. 1994; Lee et al. 1994; González et al. 2008; Bahari & Ahmad 2009; Chung & Yu 2001; Tomak et al. 2012; Berndsen et al. 2013). Other studies report decreased mechanical property values from base to top of culm, specifically MOR and tensile MOE (Gnanaharan et al. 1994; Ghavami & Marinho 2005; Wahab et al. 2006; González et al. 2007). One study reports the highest tensile strength at the middle section (Wakchaure & Kute 2012). And yet others, specifically some for compressive strength and one shear study, report no difference in mechanical property values due to height (Ghavami & Marinho 2005; Correal & Albeláez 2010; Wakchaure & Kute 2012; Zaragoza-Hernandez et al. 2015). If height produces a difference in mechanical property values, it is an easy variable to control practically. The data presented in all of the graphs in this study generally use a 1/3 top, 1/3 middle, and 1/3 bottom sections for mechanical property tests as required by most standards.

2.4.2.6 Post-harvest Treatment/Testing Condition

Treatment is performed to extend the service life of bamboo by protecting it from pests which attack the bamboo after cutting. The common treatments identified in the literature were borax/boric acid immersion, metal-based chemical treatments, heat treatment, natural oil treatments, and water immersion. The two conditions of bamboo at the time of mechanical property testing were green (raw) state and air-dried state. The treatment or testing condition is plotted versus mechanical property values (Table 2.3 and Figure 2.8) and the results seem inconclusive with regard to correlating trends between mechanical property values and post-harvest treatment.

Table 2.3 Statistical data of bamboo treatment mechanical property values. Values reported: maximum value (max.), minimum value (min.), average value (avg.), standard deviation (STD), coefficient of variation (COV)

		Air-dried	Green	Borax	Chemical	Heat	Oil	Water
F_c (MPa)	Max.	134	82.4	-	63.7	68	52	68.5
	Min.	18.6	16	-	48.8	68	49	45
	Avg.	54.1	42.7	-	56.2	68	50.5	56.8
	STD	21.9	18.5	-	7.5	-	2.1	16.6
	COV	0.41	0.43	-	0.13	-	0.04	0.29
E (GPa)	Max.	39.6	18.6	29.6	15.7	26.0	21.0	21.5
	Min.	1.9	9.5	23.5	15.7	26.0	7.9	5.1
	Avg.	15.9	16.1	26.6	15.7	26.0	14.2	13.3
	STD	7.9	2.6	4.3	-	-	4.5	11.6
	COV	0.50	0.16	0.16	-	-	0.3	0.9
F_v (MPa)	Max.	17.2	8.5	5.5	-	4.5	7.3	9.2
	Min.	4.2	7.8	5.5	-	4.5	6.8	3.5
	Avg.	12.2	8.1	5.5	-	4.5	7.1	6.4
	STD	4.5	0.5	-	-	-	0.4	4.0
	COV	0.37	0.06	-	-	-	0.05	0.63
F_b (MPa)	Max.	262.5	209.2	-	135.3	-	200.0	-
	Min.	44.0	51.9	-	126.4	-	83.0	-
	Avg.	120.4	122.4	-	130.2	-	134.6	-
	STD	50.5	61.1	-	3.8	-	39.6	-
	COV	0.42	0.50	-	0.03	-	0.29	-

Table 2.3 (Continued)

F_t (MPa)	Max.	285.0	169.1	-	-	-	-	250.0
	Min.	8.1	15.4	-	-	-	-	250.0
	Avg.	153.6	77.1	-	-	-	-	250.0
	STD	72.7	72.4	-	-	-	-	-
	COV	0.47	0.94	-	-	-	-	-

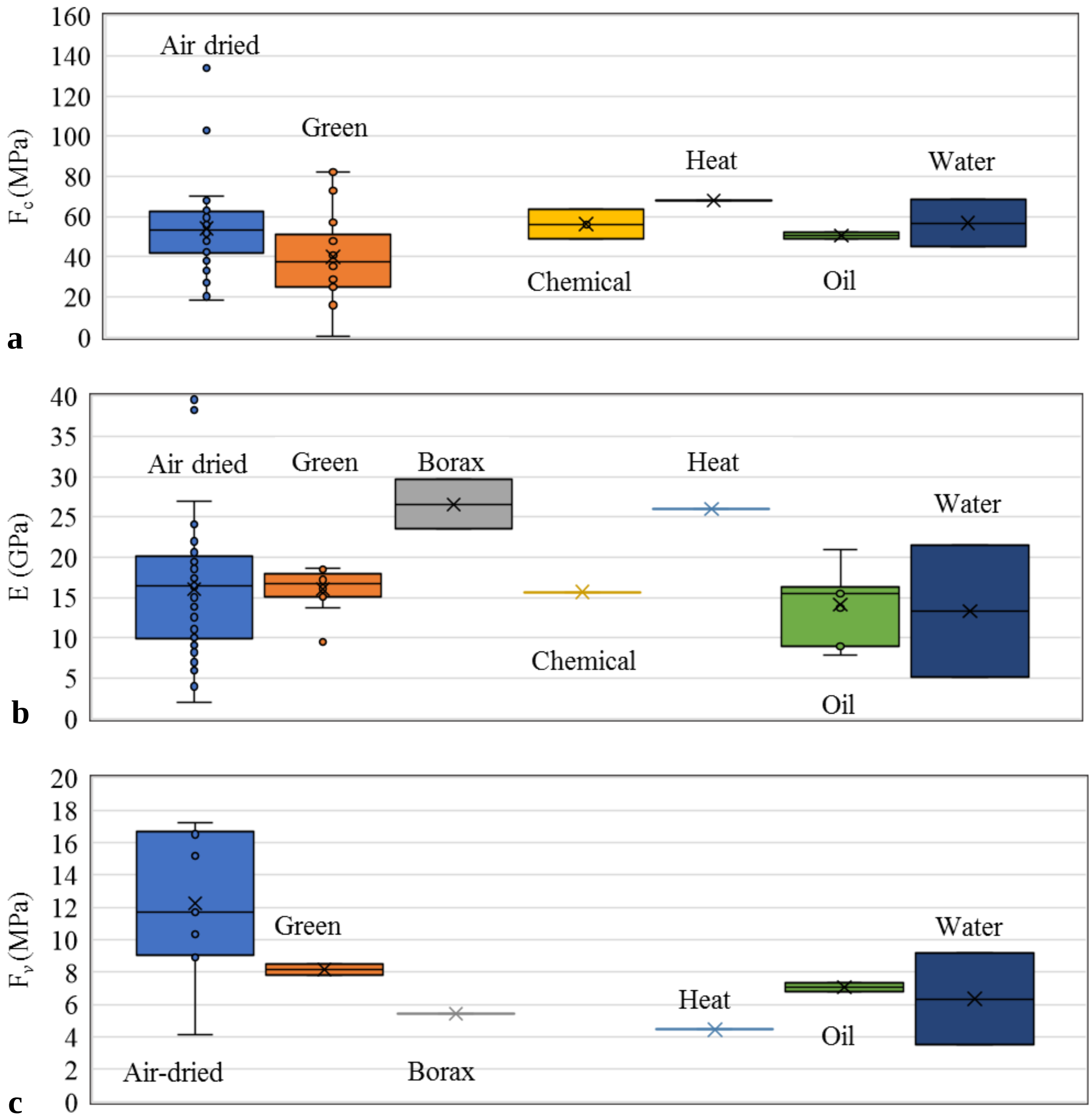

Figure 2.8 Property vs. treatment a. compressive strength (F_c), b. modulus of elasticity (E), c. bending strength (F_b), d. shear (F_v), e. tensile strength (F_t).

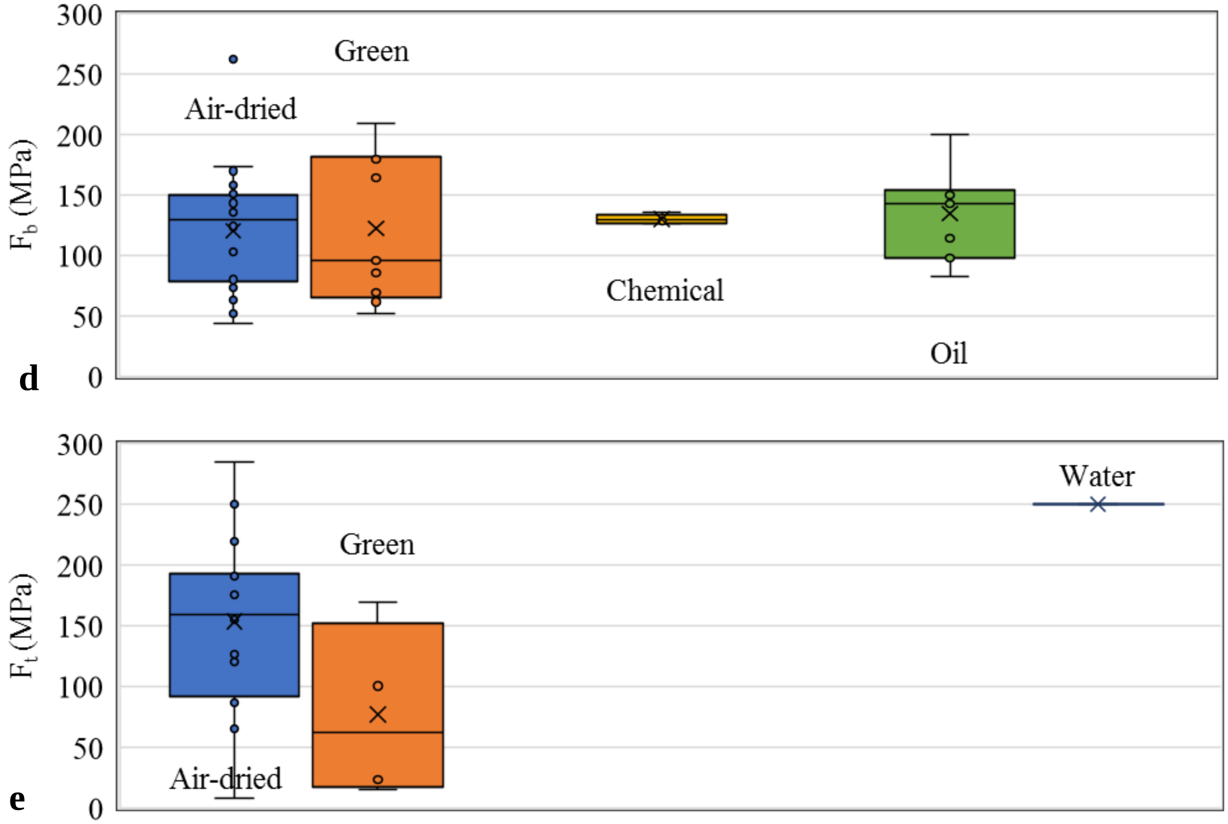

Figure 2.8 (Continued)

A trend observed in Figure 2.8 is that green bamboo mechanical properties are consistently less than or equal to those of the air-dried bamboo samples. However, it should be noted that it is never recommended to use green bamboo because it shrinks radially over time as it dries (Kaminski et al. 2016c). Additionally, any green bamboo used will eventually dry, and therefore, mechanical property values of air-dried bamboo should be assumed. Yet, a large percentage of the data found in the literature (used herein) of bamboo mechanical property testing was performed on green, or raw, bamboo. Similar to these statistical findings, others have concluded that type of bamboo treatment did not significantly change the mechanical property values of the bamboo (Gupta et al. 2015).

In contrast, other studies have found a correlation between bamboo mechanical property values and post-harvest treatment and are as follows, from highest to lowest mechanical property values: (1) green or water treated bamboo samples (Wahab et al. 2007; Amatosa & Loretero 2016), (2) air-dried samples (Manalo & Acda 2009; Wahab et al. 2007; Erakhrumen 2010), (3) oil treated samples (Manalo & Acda 2009). For samples treated with oils, the higher the treatment oil temperature, the lower the mechanical property values (Wahab et al. 2007; Erakhrumen & Ogunsanwo 2010; Colla et al. 2011; Jiang et al. 2012b).

Regarding the effectiveness of bamboo post-harvest treatments: (1) metal-based chemical treatments such as copper compounds are the most effective treatments, although they present environmental concerns. (2) Borax/boric acid treatment is the current conventional treatment used in the industry with proven effectiveness yet has the disadvantage of being water-soluble (Trujillo 2018) which limits its use in outdoor settings because environmental moisture and rain can leach it away. Additionally, the concentration of borax/boric acid is different in many bamboo guides and one publication reports that it did not adequately protect from fungi and bamboo borers (Jayanetti & Follet 1998), (3) Natural treatments, such as camphor oil, bamboo vinegar (Lin & Shiah 2006; Shiah et al. 2006), camphor and resin treatments (Xu et al. 2013), coconut oil (Manalo & Acda 2009), neem oil (Erakhrumen 2009), cedar oil, and *Lantana* and *Jatropha* leaves (Perminderjit et al. 2014), have also been shown to function effectively although have mainly been used in scientific studies and scarcely in practical applications.

2.4.2.7 Node vs. Internode

Although most bamboo mechanical property tests are performed on bamboo internodes, with the exception of tensile tests, there is mention in the scientific literature of how the presence of nodes impacts mechanical properties. Some studies report that the presence of a node in mechanical property tests did not vary the mechanical property values significantly (Gnanaharan et al. 1994; Ghavami & Marinho 2005; González et al. 2008). Other studies reported that having a node in the mechanical property test did reduce the mechanical property values (Lee et al. 1994; Omobowale & Ogedengbe 2008; Bahari & Ahmad 2009; Tomak et al. 2012). Despite this, it has also been noted that the presence of nodes is the least important factor from a practical point of view (Limay 1952; Prawirohatmodjo 1990). Although the presence of nodes affects the end-product of bamboo, it is not technically or economically feasible or justifiable to remove the nodes (Nordahlia et al. 2011).

2.4.3 Testing Standards

The formal testing of mechanical properties of bamboo is limited when compared to materials such as concrete or steel. Testing standards are still not widely adopted/unified for bamboo and, in this review, it was found the testing fell under the guidelines of 18 different standards: some timber standards, some plastic standards, and some relatively recently established bamboo standards. The most commonly used and recently established bamboo standards are ISO 22157 (2004) and NTC 5525 (2007). Bamboo standards have been previously documented and compared as it is known that changes in the standard testing procedure used will influence the resulting mechanical property values (Gnanaharan et al. 1994; Harries et al. 2012; Trujillo 2018). Accordingly, average data were compared for common testing standards over nine studies done for each (Figure 2.9). The results show reported measurements can vary by up to 29% for compressive strength, 19% for MOE, 23% for MOR, and 31% for shear strength.

Figure 2.9 generally shows that the highest mechanical property values were for the following standards from highest to lowest: (1) N/A (no testing standard used); (2) ISO 22157: International Standards Office, determination of physical and mechanical properties of bamboo; (3) ASTM 143: standard methods of testing small clear specimens of timber; and (4) NTC 5525: Norma Técnica Colombiana (Colombian Technical Standard), determination of physical and mechanical properties for the *Guadua angustafolia* Kunth.

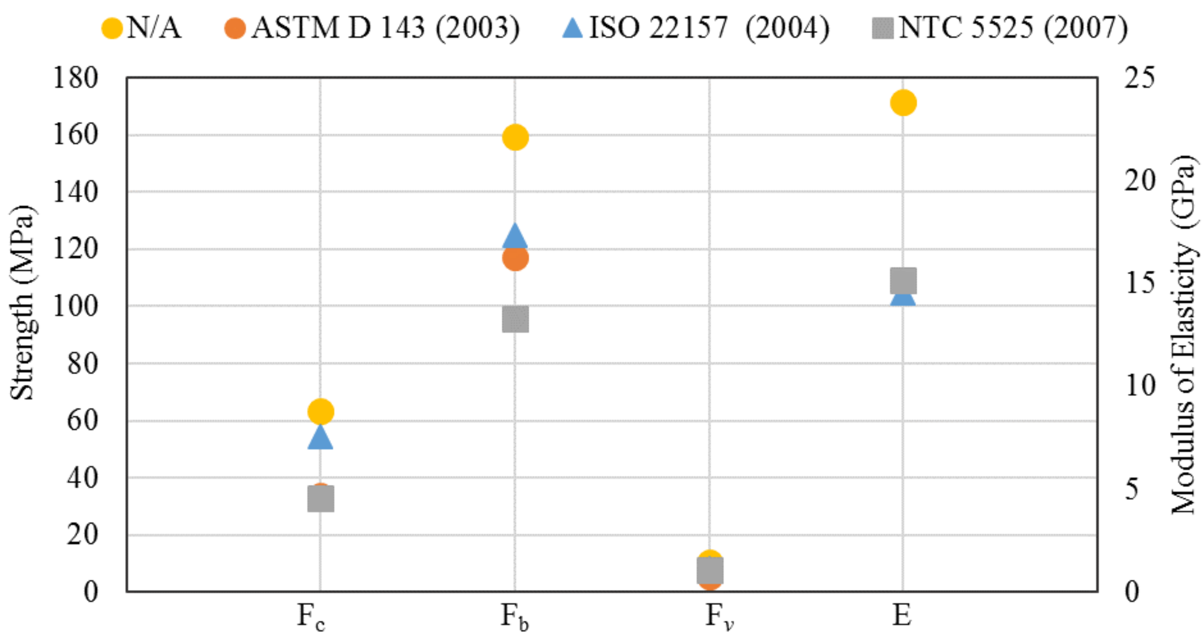

Figure 2.9 Common bamboo testing standards vs. mechanical properties: compressive strength (F_c), combined modulus of elasticity (E), modulus of rupture (F_b), and shear strength (F_v).

Compression testing information comparing the different most common testing standards are presented in Table 2.4. The ASTM 143 standard which used a possibly longer sample (depending on how the researcher adapted the standard to fit bamboo) helps to explain the lower compressive strength value. Compression failures are classified according to criteria in standards for wood (ASTM 2003), and these criteria are not present in the recently established bamboo testing standards.

Table 2.4 Compression test data. Length is reported as L, diameter as D

	Loading Rate	**Length**	**Node vs. Internode**	**Misc.**
ASTM 143	N/A	50 * 50 * 200 mm	N/A	No intermediate layer
NTC 5525	0.01 mm/s	L = D	Internode	Intermediate layer
ISO 22157	0.01 mm/s	L = D	internode	Intermediate layer

Bending test information comparing the different most common testing standards is presented in Table 2.5. The large variation in testing standards can be mainly explained due to the different sizes of bamboo used (whole culm vs. split piece) as well as to performing 3-point or 4-point bending tests. The ideal full culm 4-point bending test is also the most cumbersome to perform in a traditional material testing laboratory and has been seen to produce lower MOR values than the split test specimen values (Gnanaharan et al. 1994). This explains why the ISO 22157 average MOR values (Figure 2.9) result in much lower values than the N/A tests which used no specific standard (generally used a split specimen test for simplicity). The primary and secondary labels in ASTM 143 refer to using a larger, primary specimen if available, but if not, using a smaller, secondary specimen. In wood standards, such as ASTM 143, there are types of failures shown to help understand and classify the material which are not present in bamboo standards.

Table 2.5 Bending test data. Diameter is reported as D

	Loading Rate	**Length**	**Node vs. Internode**	**Misc.**
ASTM 143	Primary: 0.0416 mm/s, Secondary: 0.0216 mm/s	Primary: 50 * 50 * 760 mm. Secondary: 25 * 25 * 410 mm	N/A (wood standards)	3-point test
NTC 5525	0.5 mm/s	30 * D; whole culm	whole culm; node & internode	4-point test
ISO 22157	0.5 mm/s	30 * D; whole culm	whole culm; node & internode	4-point test

Tensile testing information comparing the different most common testing standards used are presented in Table 2.6. The tensile test in the ISO 22157 and NTC 5525 standards require a dog-bone shape of a node cut from split bamboo; bamboo is not easy to shape into a dog-bone which explains why few of these tests have been conducted. The node section is required for testing as it results in significantly weakening the bamboo, only 30% of the internode value (Arce 1993). For the ASTM 143 standard, the dog-bone shape has a thinner 'neck' and there is no specification about node or internode (as it is an adapted wood standard). Some of the other less commonly used standards (N/A) test the bamboo using just a split piece which is much easier to cut. There were not enough data to compare tensile strength in Figure 2.9.

Table 2.6 Tensile test data

	Loading Rate	**Length**	**Node vs. Internode**	**Misc.**
ASTM 143	0.016 mm/s	'dog-bone' shape (Primary: 925mm Secondary: 476mm thin section)	N/A (wood standards)	'special grips' used
NTC 5525	0.01 mm/s	'dog-bone' shape (10-20mm thin section)	node	N/A
ISO 22157	0.01 mm/s	'dog-bone' shape (10-20mm thin section)	node	Clamped at grips, no friction layer

Shear testing information comparing the different most common testing standards used is presented in Table 2.7. The ASTM 143 timber standard states to use a 2*2*2.5-inch specimen cut in a way that is not feasible for bamboo, therefore, there must have been variations in using this test once adapted to bamboo by the researchers reporting its use.

Table 2.7 Shear test data. Length is reported as L, diameter as D

	Loading Rate	**Length**	**Node vs. Internode**	**Misc.**
ASTM 143	0.01 mm/s	50 * 50 * 63 mm	N/A (wood standards)	'notched' in a way not easily possible for bamboo
NTC 5525	0.01 mm/s	L = D	50% node; 50% internode	'bow tie'
ISO 22157	0.01 mm/s	L = D	50% node; 50% internode	'bow tie'

The combined MOE values (Figure 2.9) were measured using 3 different types of tests: compression, bending, and tension, so perhaps the variation is so great that no clear trend was found. Additionally, the NTC 5525 standard is only used for the bamboo species *Guadua angustifolia*, which therefore has the additional variable of bamboo species.

From this comparison it was found that the testing standard greatly influenced the bamboo mechanical property values. This is logical as the test setup can vary greatly for the different standards, such as using bamboo split pieces versus whole length culms.

2.5 Conclusion

Numerous studies have attempted to correlate the mechanical properties of bamboo to a wide range of variables. The findings support single mechanical property values representing all structural bamboo species should be used but with an understood variability (Table 2.8). In Table 2.8, the number in parentheses next to the average value is the number of studies from which the data were collected.

Table 2.8 Average bamboo mechanical property values

Mechanical Property	**Symbol**	**Average Value (N)**	**Interquartile Range (IQR)**	**Full Range**
Shear Strength Parallel to Grain	F_v	9 MPa (18)	6.8–11.7 MPa	2.5-16.5 MPa
Compressive Strength	F_c	52 MPa (59)	40.7–61.9 MPa	18.6-134.0 MPa
Bending strength / Modulus of Rupture (MOR)	F_b	120 MPa (52)	79.6–149 MPa	25.0 – 262.5 MPa
Tensile Strength	F_t	159 MPa (21)	89.5–206 MPa	8.1 – 285.0 MPa
Compressive Modulus of Elasticity (MOE)	E_c	16 GPa (19)	9–20.7 GPa	4.0 – 29.6 GPa
Bending Modulus of Elasticity (MOE)	E_b	17 GPa (34)	14.3–20 GPa	8.4 – 20.6 GPa
Tensile Modulus of Elasticity (MOE)	E_t	14 GPa (10)	9.5–18 GPa	7.9 – 39.6 GPa
Combined Modulus of Elasticity (MOE)	E	16 GPa (63)	11.8–19.7 GPa	4.0 – 39.6 GPa

From the comparative analyses of 43 peer-reviewed publications, it was found three variables influence bamboo mechanical property values: the test standard, moisture content and, to a lesser extent, bamboo species. Variability should be rationally addressed in the use of bamboo with appropriate safety factors. This was supported by contradicting findings in the literature regarding the mechanical properties of bamboo; this shows that additional research and practice with bamboo is necessary.

2.6 Recommendations for Research and Practice

In order to truly establish bamboo as a conventional building material, it must have established mechanical property values and ranges for designers to incorporate into practice. Once established, these values will make designing with bamboo similar to designing with conventional materials in having more predictable factors of safety, or strength reduction factors.

The effect of the changing diameter of bamboo per culm length has not been addressed by the literature on how to design despite this irregularity. Because of this, bamboo cannot be treated as a uniformly shaped material in design. This natural variability renders bamboo as a non-uniform material thereby making it harder to design with as the dimensions change. This issue must be addressed prior to bamboo being adopted globally as a serious alternative building material.

Options of post-harvest treatment of bamboo are still in experimental stages by researchers. Although many possibilities are available, none have been formally established as best practice. The mechanical property values which have been cited for bamboo are nearly all obtained from green or dry bamboo which were untreated. Thorough research on how treatment of bamboo affects the mechanical properties of bamboo has yet to be addressed. Additionally, experiments which test the effect of bamboo post-harvest treatment are all analyzed in laboratory conditions. More efforts should be made to test these treatments after real-world outdoor exposure.

Although the connections for timber construction are well understood (Parker 1979), these rules do not hold true for bamboo. Anecdotally, bamboo should never be drilled but rather should be tied in order to achieve highest performance. Although some efforts have been made to study fiber and metal connection joints for bamboo (Awaludin & Andriani 2014; Trujillo & Wang 2015), connection using traditional tying methods should also be studied.

2.7 References

Aladín, M.F.G., García, H., Mosquera, J.M., & García, J. (2014). The importance of shear in the deflection of bamboo beams. Key Engineering Materials, 600, 87–96.

Amatosa Jr, T. A., & Loretero, M. E. (2016). Analytical behaviour in mechanical properties of *Dendrocalamus asper* bamboo as construction building materials in the Philippines. Global Journal of Engineering and Technology Review, 1(1), 114–121.

Arce, O. (1993). Fundamentals of the design of bamboo structures. Thesis Eindhoven University, 260pp. ISBN: 90-6814-524-X. Also available from the website www.lue.nl.

Arinasa, I. B. K., & Bagus, I. (2010). Bamboo diversity and utilization in Balinese rituals at Angsri Village, Bali, Indonesia. Bamboo Science & Culture: The Journal of the American Bamboo Society, 23(1), 29–37.

Ashby, M. F. (2012). Materials and the environment: eco-informed material choice. Elsevier.

Askarinejad, S., Kotowski, P., Shalchy, F., & Rahbar, N. (2015) Effects of humidity on shear behavior of bamboo. Theoretical and Applied Mechanics Letters, 5, 236–243.

ASTM (American Society of Testing Materials, Standard methods of testing small clear specimens of timber, Annual Book of ASTM Standard Des. (ASTM), ASTM D 143-94 (Reapproved 2000), Vol 4.10, Philadelphia, 2003.

Awaludin, A., & Andriani, V. (2014). Bolted bamboo joints reinforced with fibers. Procedia Engineering, 95, 15–21.

Badwaik, L. S., Choudhury, S., Borah, P. K., Sit, N., & Deka, S. C. (2014). Comparison of kinetics and other related properties of bamboo shoot drying pretreated with osmotic dehydration. Journal of food processing and preservation, 38(3), 1171-1180.

Bahari, S. A. & Ahmad, M. (2009). Effects of culm height levels and node presence on mechanical properties and fracture modes of *Gigantochloa scortechinii* strips loaded in shear parallel to grain. Bamboo Science and Culture: The Journal of the American Bamboo Society, 22(1), 41–44.

Bahari, S. A., Grigsby, W., & Krause, A. (2017). Thermal stability of processed PVC/bamboo blends: effect of compounding procedures. European Journal of Wood and Wood Products, 75(2), 147–159.

Berndsen, R.S., Klitzke, R.J., Batista, D.C., Nacimento, E.M., & Ostapiv, F. (2013). Pesistência à flexão estática e à compressão paralela do bamboo-mossô (*Phyllostachys pubescens*). Floresta, Curitiba, PR, 43(3), 485-494.

Chung, K. F., & Yu, W. K. (2001). Mechanical properties of structural bamboo for bamboo scaffoldings. Engineering structures, 24(4), 429–442.

Colin, X., Farinet, J. L., Rojas, O., & Alazard, D. (2007). Anaerobic treatment of cassava starch extraction wastewater using a horizontal flow filter with bamboo as support. Bioresource Technology, 98(8), 1602–1607.

Colla, W.A., Beraldo, A.L., & Brito, J.O. (2011) Effects of thermal treatment on the physiochemical characteristics of giant bamboo. Cerne, Lavras, 17(3), 361–367.

Correal, D., Francisco, J., & Arbeláez, C. (2010). Influence of age and height position on Colombian Guadua angustifolia bamboo mechanical properties. Maderas Ciencia y tecnología, 12(2), 105–113.

Cruz, M. (2002). Caracterização física e mecânica de colmos inteiros do bambu da espécie *Phyllostachys aurea*: comportamento à flambagem. 2002. 114 f (Doctoral dissertation, Dissertação (Mestrado em Engenharia Civil) Pontifícia Universidade Católica do Rio de Janeiro, Rio de Janeiro).

Cusak, V., Stewart, D. (1999). Bamboo world: clumping bamboos & how to use them.

Dhawan, S., Mishra, S.C., & Dhawan, S. (2008). Influence of height and age on natural resistance of bamboos against termites. The Indian Forester, 134(5), 697-702.

Dixon, P. G., Semple, K. E., Kutnar, A., Kamke, F. A., Smith, G. D., & Gibson, L. J. (2016). Comparison of the flexural behavior of natural and thermo-hydro-mechanically densified Moso bamboo. European Journal of Wood and Wood Products, 74(5), 633–642.

Edwards, K., Doing, H. (1995). The importance of bamboo and housing construction: a case study in Flores. The Flores Bamboo Development Foundation, Maumere, Flores, NTT, Indonesia, 33–37.

Erakhrumen, A. A. (2009). Tensile strength properties of wild grown *Bambusa vulgaris* treated with neem seed oil in Southwest Nigeria. Journal of Bamboo and Rattan, 8(1/2), 95–102.

Erakhrumen, A. A., & Ogunsanwo, O. Y. (2010). Influence of neem (*Azadirachta indica A. Juss*) seed oil-treatment on static bending strength properties of wild grown split-bamboo (*Bambusa vulgaris* Schrad.) in south-west Nigeria. American-Eurasian Journal of Agricultural and Environmental Science, 8(1), 73–79.

Erakhrumen, A.A. (2010). Assessing the effectiveness of need seed oil treatment for split-bamboo (*Bambusa vulgaris*) against *Pycnoporus* sanguineus based on tensile strength properties. Bamboo Science and Culture: The Journal of the American Bamboo Society, 27(1), 36–48.

Espiloy, Z. B., Ella, A. B., & Floresca, A. R. (1986). Physico-mechanical properties and anatomical structure relationships of two erect bamboo species. Philippine lumberman, 4(32), 25–27.

Fabiani, M. (2015). Physical and mechanical properties of Italian bamboo culms. 10th World Bamboo Congress, Korea.

Ghavami, K., & Marinho, A. B. (2005). Propriedades físicas e mecânicas do colmo inteiro do bambu da espécie do bambu da espécie *Guadua angustifolia*. Revista Brasileira de Engenharia Agrícola e Ambiental, 9(1), 107–114.

Gnanaharan, R., Janssen, J.J.A. & Arce, O. (1994). Bending strength of *Guadua* bamboo: comparison of different testing procedures. International Network for Bamboo and Rattan: INBAR Working Paper No. 3. International Development Research Centre, Canada & Kerala Forest Research Institute, India.

González, E.G., Osorio, J.A.S., Garcia, E.A.G. (2002). Resistencia a la flexion de la *Guadua angustifolia kunt* a escala natural. Rev. Fac. Nal. Agr. Medellín, 5(2), 1555–1572.

González, H.A.B, Montoya, J.A., Bedoya, J.R. (2006). Esfuerzo de tension y la influencia de la humedad relativa del ambiente y la Altura a lo largo del tramo en la especie de bambú *Guadua angustifolia* Kunth. Scientia et Technica Año XII, 32, 445–450.

González, H.A.B., Arango, J.A.M., Sánchez, J.R.B. (2007). Resultados del ensayo a flexion en muestras de bambú de la especie *Guadua angustifolia* Kunth. Scientia et Technica Ano XIII, 35. Universidad Tecnológica de Pereira. ISSN: 0122-1701.

González, H.A.B., Montoya, J.A.A., & Bedoya, J.R. (2008). Comportamiento de muestras de *Guadua angustifolia* Kunth con diafragma y sin diafragma sometidas a esfuerzo de compression. Sciencia et Technica, XIV, 38, 449–454.

Gupta, A. K., Ganguly, R., & Mehra A. S. (2015). Bamboo as green alternative to steel for reinforced concrete elements of a low-cost residential building. EJGE, 20, 6.

Gyansah, L. Akinwonmi, A.S., & Affam, M. (2010). The fracture behaviour of fresh bamboo under uniaxial compressive loading condition. Research Journal of Applied Sciences, Engineering and Technology, 2(8), 720–726.

Harries, K. A., Sharma, B., & Richard, M. (2012). Structural use of full culm bamboo: the path to standardization. International Journal of Architecture, Engineering and Construction, 1(2), 66-75.

Harries, K. A., Bumstead, J., Richard, M., & Trujillo, D. (2017). Geometric and material effects on bamboo buckling behaviour. Proceedings of the Institution of Civil Engineers-Structures and Buildings, 170(4).

Huang, X. D., Hse, C. Y., Shupe, T. F. (2014). Evaluation of the performance of the composite bamboo/epoxy laminated material for wind turbine blades technology. BioResources, 10(1), 660–671.

International Standards Office (ISO) (2004). ISO 22157-1. Bamboo: Determination of physical and mechanical properties. Part 2: Laboratory manual. Geneva, ISO.

Jayanetti, D.L. & Follet, P.R. (1998). TRADA and INBAR for DFID: Bamboo in Construction: An Introduction.

Jiang, Z., Wang, H., Tian, G., Liu, X., Yan, Yu. (2012a). Sensitivity of several selected mechanical properties of moso bamboo to moisture content change under the fibre saturation point. Bioresources, 7(4), 5048–5058.

Jiang, Z., Chen, F., Wang, G., Liu, X., Shi, S.Q., Cheng, H. (2012b). The circumferential mechanical properties of bamboo with uniaxial and biaxial compression tests. BioResources, 7(4), 4806–4816.

Kabir, M.F., Bhattacharjee, D.K., & Sattar, M.A. (1993). Effect of age and height on strength properties of *Dendrocalamus langispathus*. Bamboo Information Centre India Bulletin, 3, 11–15.

Kaminski, S., Lawrence, A., Trujillo, D., Feltham, I., & Felipe López, L. (2016). Structural use of bamboo. Part 3: Design values. The Structural Engineer: journal of the Institution of Structural Engineer, 94(12), 42–45.

Kamruzzaman, M., Saha, S. K., Bose, A. K., & Islam, M. N. (2008). Effects of age and height on physical and mechanical properties of bamboo. Journal of Tropical Forest Science, 211–217.

Kusak, V. (1999). Bamboo World: The growing and use of clumping bamboo.

Laha, R. (2000). Bamboo uses for housing by the different tribes of Northeast India. Bamboo Science and Culture, The Journal of the American Bamboo Society, 14(1): 10–14.

Lakkad, S. C., Patel, J. M. (1981). Mechanical properties of bamboo, a natural composite. Fibre Science and Technology, 14(4), 319–322.

Lee, A. W., Bai, X., & Peralta, P. N. (1994). Selected physical and mechanical properties of giant timber bamboo grown in South Carolina. Forest Products Journal, 44(9), 40.

Liese, W. & Tang, T.K.H. (2015). Preservation and drying of bamboo. Springer International Publishing. Switzerland. Bamboo, Tropical Forestry 10(9), 257–297.

Liese, W. (1987). Research on bamboo. Wood Science and Technology, 21(3), 189–209.

Liese, W. (1991). Progress in bamboo research. Journal of the American Bamboo Society, 8(1&2).

Liese, W. (1992). The structure of bamboo in relation to its properties and utilization. Proceedings of the International symposium on Industrial Use of Bamboo, Beijing, China, 7–11.

Liese, W. (2004). Preservation of bamboo structures. Ghana Journal of Forestry, 15(1), 40–48.

Limay, V. D. (1952). Strength of bamboo (*Dendrocalamus strictus*). Indian Forester, 78(11), 558–575.

Lin, C. J., Tsai, M. J., & Wang, S. Y. (2006). Nondestructive evaluation techniques for assessing dynamic modulus of elasticity of moso bamboo (*Phyllosachys edulis*) lamina. Journal of wood science, 52(4), 342.

Lin, H. C., & Shiah, T. C. (2006). Evaluation of fungi resistance of moso bamboo materials using bamboo vinegar with smoking process. QJ Forest Res. Taiwan, 28(2), 51–66.

Lipangile, T.N. (1991). Manufacture and construction of bamboo water supply systems. Journal of the American Bamboo Society, 8(1&2), 191–198.

Londoño, X., Camayo, G.C., Riaño, N.M., López, Y. (2002). Charactirazation of the anatomy of *Guadua angustifolia* (Poaeae: Bambusoideae) culms. Bamboo Science and Culture, 16(1), 18–31.

Lugt, P.V., Dobbelsteen, A. A. J. F., & Janssen, J. J. A. (2006). An environmental, economic and practical assessment of bamboo as a building material for supporting structures. Construction and Building Materials, 20(9), 648–656.

Luna, P., Lozano, J., & Takeuchi, C. (2014). Determinación experimental de valores caracteristicos de Resistencia para *Guadua angustifolia*. Maderas, Ciencia y Tecnologia, 16(1), 77–92.

Macdonald, J. (1999). The Quindío, Colombia Earthquake of 25 January 1999. SECED Newsletter 13/2, 1–3.

Manalo, R. D., & Acda, M. N. (2009). Effects of hot oil treatment on physical and mechanical properties of three species of Philippine bamboo. Journal of Tropical Forest Science, 19–24.

Matsuoka, J. H., & Beraldo, A. L. (2013). Evaluation of preservative treatment of bamboo strips with pyroligneous acid [avaliação do tratamento preservativo de taliscas de bambu com ácido pirolenhoso]. Floresta, 44, 11–20.

Mota, I.O., Pereira, M.A., Damacena, P.C., Santos, L.C.B. (2017). Estudo das propriedades físicas e mecânicas do bambu brasileiro (*Bambusa vulgaris* vittata) para aplicação de sistemas hidráulicos alternativos de distribuição de água à baixa pressão. Revista de Estudos Ambientais, 19(1), 18–26.

Nölke, N., García, J.C.C., Kleinn, C., & Polle, A. (2015). Changes in culm surface temperature with maturity of the bamboo species *Guadua angustifolia.* Journal of Forest Resources, 27(2), 419–425.

Nordahlia, A.S., Anwar, U.M.K., Hamdan,M., Abd Latif & Mahanim S.M.A. (2011). Anatomical, physical and strength properties of *Shizostachyum brachycladum* (Buluh lemang). Journal of Bamboo and Rattan, 10(3&4), 111–122.

Norma Técnica Colombiana (2007). NTC 5525, Determinación de las propriedades físicas y mecánicas de la *Guadua Angustafolia Kunth*, Instituto Colombiano de Normas Técnicas (ICONTEC).

Nurmadina, Nugroho, N., Bahtiar, E.T. (2017). Structural grading of *Gigantochloa apus* bamboo based on its flexural properties. Construction and Building Materials, 157, 1173–1189.

Ogunwusi, A.A., Onwualu, A.P. (2013). Prospects for multi-functional utilization of bamboo in Nigeria. Chemistry and Materials Research, 3(8), 58–71.

Okhio, C.B., Eng, C., Waning, J.E., Mekonnen, Y.T. (2011). An experimental investigation of the effects of moisture content on the mechanical properties of bamboo and cane. Multidisciplinary Journals in Science and Technology, Journal of Selected Areas in Bioengineering (JSAB), 8–14.

Omobowale, M.O. & Ogedengbe, K. (2008). Trends in fiber characteristics of Nigerian grown bamboo and its effect on its impact and tensile strengths. Bamboo Science & Culture: The Journal of the American Bamboo Society, 21(1), 9–13.

Ong, K. S. (1996). Experimental investigation of a solar bamboo dryer. Drying technology, 14(10), 2411–2417.

Parker, H. (1979). Simplified Design of Structural Wood. USA: John Wiley & Sons, Inc.

Perminderjit, K., Pant, K., Satya, S., Naik, S. (2014). Comparison of decay resistance of bamboo treated with plant extracts and oil cakes. International Journal of Emerging Technology and Advanced Engineering. Volume 4, Issue 1.

Pfeiffer, K. & Olson, N. J. (1981). Basic statistics for the behavioral sciences. Holt Rinehart Winston. New York, New York.

Prawirohatmodjo, S. (1990). Comparative strength of green and air-dry bamboo. In International Bamboo Workshop. Cochin, India. 14-18 November 1988 (p. 218).

Purushotham, A. (1953). Preservative treatment of green bamboos under low pneumatic pressures. The Indian Forester, 79(12), 652–672.

Ramírez, E. B. R., Villamizar, N. I., González, L. M., & Tovar, A. K. A. (2018). Análisis comparativo de las propiedades mecánicas de la guadua angustifolia kunth como material estructural de eje para protesis transtibial. Revista de Investigación Agria y Ambiental (RIAA), 9(2), 5.

Sánchez-Echeverri, L.A., Aita, G., Robert, D., & Garcia, M.E.R. (2014). Correlation between chemical compounds and mechanical response in culms of two different ages of *Guadua angustifolia* Kunth. Madera y Bosques, 20(2) 87–94.

Sathish, S., Kumaresan, K., Prabhu, L., & Vigneshkumar, N. (2017). Experimental investigation on volume fraction of mechanical and physical properties of flax and bamboo fibers reinforced hybrid epoxy composites. Polymers & Polymer Composites, 25(3), 229.

Sattar, M. A., Kabir, M. F., & Bhattacharjee, D. K. (1990). Effect of age and height position of muli (*Melocanna baccifera*) and borak (*Bambusa balcooa*) bamboos on their physical and mechanical properties. Bangladesh Journal of Forest Science, 19(1&2), 29–37.

Schmidt, O., Wei, D. S., Tang, T. K. H., Liese, W. (2013). Bamboo and fungi. Journal of Bamboo and Rattan, 12(1-4), 1–14.

Shiah, T. C., Wu, S. K., Huang, J. C., Lin, H. C. (2006). The fungi resistance of bamboo materials treated with bamboo vinegar using soaking treatment. Journal of Agriculture and Forestry, NCYU, 3(1), 1–22.

Srivaro, S., Rattanarat, J., & Noothong, P. (2018). Comparison of the anatomical characteristics and physical and mechanical properties of oil palm and bamboo trunks. Journal of wood science, 64(3), 186-192.

Takeuchi, C., Durate, M., & Erazo, W. (2013). Análisis comparativas en muestras de *Guadua angustifolia* Kunth solicitadas a compression paralela a la fibra. Revista Ingeniería y Región, 10, 117–124.

Tang, T. K. H., Welling, J., Ho, T. D., & Liese, W. (2012). Investigation on optimization of kiln drying for the bamboo species *Bambusa stenostachya*, *Dendrocalamus asper* and *Thyrsostachys siamensis*. Bamboo Science & Culture, 25(1).

Teron, R., & Borthakur, S. K. (2012). Traditional uses of bamboos among the Karbis, a hill tribe of India. Bamboo Science & Culture, 25(1).

Tomak, E. D., Topaloglu, E., Ay, N., Yildiz, U.C. (2012). Effect of accelerated aging on some physical and mechanical properties of bamboo. Wood Science Technology, 46, 905–918.

Trujillo, O. E., & Wang, T. H. (2015). Parametric Modeling of Bamboo Pole Joints. In International Conference on Computer-Aided Architectural Design Futures, 272–290. Springer, Berlin, Heidelberg.

Trujillo, D. (2018). Developments in structural design standards with bamboo. World Bamboo Congress Keynote Presentation. Xalapa, Mexico.

Ubidia, J.A.M. (2002). Traditional bamboo preservation methods in Latin America. International Network for Bamboo and Rattan – INBAR. Faculty of Architecture, University of Guayaquil, Ecuador.

Valero, S.W., Reyes, E., Contreras, W. (2005). Estudio de las propiedades físicas y mecánicas des bambú (*Bambusa vulgaris*), de tres años de edad y proveniente de las plantaciones ubicadas en la ribera de la margen derecho del rio Chama, municipio Francisco Javier Pulgar, estado Pulgar, estado Zuilia, Venezuela. Revista Forestal Latinoamericana, 37, 87–107.

Verma, C.S. & Chariar, V.M. (2012). Development of layered laminate bamboo composite and their mechanical properties. Composites: Part B, 43, 1063–1069.

Wahab, R. Moktar, J., Sudin, M., Samsi, H.W. (2006). Strength properties of preservative treated *Gigantochloa scortechinii* after vacuum impregnation process. International Journal of Agricultural Research, 1(1), 8–13.

Wahab, R., Samsi, H.W., Sulaiman, O., Salim, R. & Hashim, R. (2007). Properties of oil-cured cultivated *Bambusa vulgaris*. International Journal of Agricultural Research, 2(9), 820–825.

Wakchaure, M.R. & Kute, S.Y. (2012). Effect of moisture content on physical and mechanical properties of bamboo. Asian Journal of Civil Engineering (Building and Housing), 13(6), 753–763.

Wang, H., Li, W., Ren, D., Yu, Z., Yu, Y. (2014). A two-variable model for predicting the effects of moisture content and density on compressive strength parallel to the grain for moso bamboo. Journal of wood science, 60(5), 362–366.

Wistara, N. J., Purnamasari, D. A., & Indrawan, D. A. (2017). The properties of bamboo and old corrugated containers pulp mixture. Journal of Tropical Wood Science and Technology, 10(2), 112–121.

Xie, J., Yong, Y., Dong, X., Du, J., Guo, Z., Gong, L., ... & Zhao, Y. (2017). Therapeutic nanoparticles based on curcumin and bamboo charcoal nanoparticles for chemo-photothermal synergistic treatment of cancer and radioprotection of normal cells. ACS applied materials & interfaces, 9(16), 14281–14291.

Xu, G., Wang, L., Liu, J., Hu, S. (2013). Decay resistance and thermal stability of bamboo preservatives prepared using camphor leaf extract. International Biodeterioration & Biodegradation, 78, 103–107.

Xu, Q., Harries, K., Li, X., Liu, Q., & Gottron, J. (2014). Mechanical properties of structural bamboo following immersion in water. Engineering Structures, 81, 230–239.

Yang, X., Tian, G., Shang, L., Lv, H., & Yang, S. (2014). Variation in the cell wall mechanical properties of Dendrocalamus farinosus bamboo by nanoindentation. BioResources, 9(2), 2289–2298.

Yan-hui, H., Ben-hua, F., Yan Y., & Rong-jun, Z. (2012). Plant age effect on mechanical properties of moso bamboo (*Phyllostachys heterocycle var. pubescens*) single fibers. Wood and Fiber Science, 44 (2), 196–201.

Yu, H. Q., Jiang, Z. H., Hse, C. Y., & Shupe, T. F. (2008). Selected physical and mechanical properties of moso bamboo (*Phyllostachys pubescens*). Journal of Tropical Forest Science, 20(4), 258–263.

Zaragoza-Hernández, I., Ordóñez-Candelaria, V. R., Bárcenas-Pazos, G. M., Borja-de la Rosa, A. M., & Zamudio-Sánchez, F. J. (2015). Propiedades físico-mecánicas de una guadua mexicana (*Guadua aculeata*). Maderas. Ciencia y tecnología, 17(3), 505–516.

Zheng J., Zhang, F., Song, J., Lin, M., & Kan, J. (2013). Effect of blanching and drying treatments on quality of bamboo shoot slices. International Journal of Food Science and Technology, 49, 531–540.

Zhou, F.C. (1981). Studies on physical and mechanical properties of bamboo woods. Journal of Nanjing Forest University, 2: 1–32.

Zimmerman, J. B., Mihelcic, J. R., & Smith, J. (2008). Global stressors on water quality and quantity. Environmental Science & Technology, 42(12), 4247–4254.

CHAPTER 3: DETERMINATION OF SAFETY FACTORS FOR STRUCTURAL BAMBOO APPLICATIONS[2]

3.1 Abstract

Use of bamboo as a construction material has world-wide potential given it is highly-renewable / fast-growing. The pitfall lies largely in the variability of the material properties reported by numerous investigators. Previous research has sought to correlate various material properties to external factors but results are conflicting. This paper outlines the significance of a common set of material properties with the goal of identifying the necessary safety factors designers can incorporate to ensure a given level of reliability and an acceptable failure rate. These results thus provide a rational approach to selecting structural design strength values for bamboo applications worldwide.

3.2 Introduction

Bamboo, of the grass family *Poaceae*, is one of the fastest growing plants on earth (Liese 1992), certain large diameter species having mechanical property values which are in the range of or surpass those of structural timber. Bamboo has a competitive advantage of achieving its highest structural properties in only 3 years and being connected to an underlying root network which replenishes itself and prevents soil erosion (Tu et al. 2013). As bamboo and timber are

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similar materials, it is reasonable to adopt some of the same design parameters used in the timber industry for its benefit and expanded use.

Historically, research dealing with the material properties of bamboo has strived to develop correlations to external factors to better explain what appeared to be inexplicable variations. The most commonly explored factors include: moisture, density, age, treatment methods and species. Unfortunately, no strong link to any of these factors has been universally established. Sánchez Vivas et al. (2019) highlighted the need to ignore the many external variables potentially impacting the strength of bamboo. Instead that study recognized the inherent variability and focused on applying a single set of mechanical property values for shear, tensile, bending, and compressive strengths.

This study addresses the variability of bamboo by applying the same approaches previously applied to other structural materials (i.e. concrete, steel, and timber) when identifying appropriate safety factors or strength reduction factors (ACI 2004; AISC 1986; AWC 2014). Accordingly, while this type of analysis has been applied to steel, concrete, and timber, it has not yet been applied to bamboo. To this end, this article first presents a brief overview of design principles followed by the statistical evaluation of test results of mechanical strength properties obtained from twenty-five publications. The results provide recommended safety factors (or strength reduction factors) when applying bamboo to structural applications depending on the design philosophy adopted.

3.3 Background

A critical review of global bamboo research reporting mechanical strength properties showed conflicting findings regarding what specific bamboo mechanical properties to use in design and the factors that might influence the strength (Sánchez Vivas et al. 2019). These studies focused on relationships between mechanical properties and external factors such as: moisture content, density, species, node and internode sections, base to top of culm location, bamboo treatment, and testing standards employed. The most conflicting references dealt with last five factors: presence or absence of nodes, location along the length of the culm, treatment method, and the test standard.

Regarding node vs. internode sections, Gnanaharan et al. (1994), Ghavami & Marinho (2005) and González et al. (2008) reported the presence of nodes in test specimens did not vary the mechanical property values significantly. Conversely, others reported the presence of nodes related to a reduction in mechanical property values (Lee et al. 1994; Omobowale & Ogedengbe 2008; Bahari & Ahmad 2009; Tomak et al. 2012). For example, tensile strength at nodes has been reported to be only 30% of internode values (Arce 1993) and bamboo testing standards (ISO 22157 and NTC 5525) state tensile tests should be conducted on a node to account for the lowest possible values.

Regarding location along culm, where some studies report increased strength from base to the top of culm (Lee et al. 1994; González et al. 2008; Bahari & Ahmad 2009; Chung & Yu 2001; Tomak et al. 2012; Berndsen et al. 2013), others report the opposite, decreasing strength with height above the base of the culm (Ghavami & Marinho 2005; Wahab et al. 2006; González et al. 2007). Yet another study reports the highest tensile strength at the middle section

(Wakchaure & Kute 2012). Finally, Correal & Albeláez (2010) and Zaragoza-Hernandez et al. (2015) report no difference in strength with regards to height along culm.

Regarding bamboo treatment, where one study concluded that bamboo treatment did not significantly change the mechanical property values of bamboo (Gupta et al. 2015)019). Others did find an effect with the highest strength properties for green or water treated samples (Wahab et al. 2007; Amatosa & Loretero 2016). Green samples however are not feasible to use for structural applications as bamboo shrinks radially as it dries. Second highest strength values have been reported for air-dried bamboo (Ghavami & Marinho 2005; Correal & Albeláez 2010; Wakchaure & Kute 2012; Zaragoza-Hernandez et al. 2015). The lowest strength values were attributed to oil treatments with higher oil temperatures during treatment resulting in lower strength values (Wahab et al. 2007; Manalo & Acda 2009; Erakhrumen & Ogunsanwo 2010; Colla et al. 2011; Jiang et al. 2012a).

Regarding testing standards, the noted effect of a testing methods on results has led most industries to issue standardized testing methods. For bamboo no singly, accepted standard exists for measuring mechanical properties. Gnanaharan et al. (1994), Harries et al. (2012), and Trujillo (2018) all cite variations in strength values stemming from differences in the test methods. In addition, Sánchez Vivas et al. (2019) showed the testing standard was the most significant variable influencing bamboo mechanical property values.

The wide variation in findings reviewed above highlights the lack of interconnectivity of the factors influencing bamboo strength. Given that the bamboo scientific community has yet to come to a consensus as to the effect of these factors, this paper addresses the variability by combining bamboo strength values from numerous sources regardless of external factors to develop safe design approaches for bamboo as a structural material.

3.4 Design Philosophies

Over the past 50 years there has been a transition from empirical to statistically based design methodologies. The underlying fundamental premise of all designs is simple: the load on a structure should always be less than the strength of the structure. Elements within a structure can be exposed to compression, tension or shearing forces or can be subjected to bending which is technically not a force, but is caused by forces. Depending on the material type, the strength (breaking stress) may vary for these types of loads. For instance, the tensile strength of concrete is on the order of 1/10 the compression strength and shear strengths are often ¼ - ½ the axial strength.

Empirical design methods are often called Allowable Stress Design (ASD) or Working Stress Design. This method identifies the yield stress or ultimate breaking strength of a material and then applies a safety factor such that the imposed stress stays below a safe threshold (the allowable stress). Determination of the safety factor and allowable stress are typically based on experience and calibrated to ensure failures were reasonably infrequent. The selection of a failure ratio varies by application or the philosophy of the owner balancing cost and risk. The ASD design equation (Equation 3.1) sums all loads stemming from self-weight (or dead load, DL), moving or temporary loads (referred to as live loads, LL), and external forces such as wind, snow, rain, etc. (referred to as other loads) and compares that summation to the allowable load carrying capacity. Equation 3.2 shows the same basic formulation but for bending moments caused by various load types.

$$DL + LL + other\ loads \leq P_{allowable} = F_{allowable} A_{cross\ section} = \frac{F_{ult}}{SF} A_{cross\ section} \quad \text{Eq. 3.1}$$

$$M_{DL} + M_{LL} + M_{other\ loads} \leq M_{allowable} = F_{allowable} S = \frac{F_{ult}}{SF} S \quad \text{Eq. 3.2}$$

where:

DL = the dead load (self-weight) or M_{DL} = moment caused by dead load

LL = the live load (living or movable loads within the structure) or M_{LL} = moment caused by live load

$P_{allowable}$ = the computed allowable load carrying capacity

$F_{allowable}$ = the allowable stress that can be applied to the structural element

F_{ult} = the ultimate strength of the material in tension, compression, shear (or bending)

$A_{cross\ section}$ = the area over which the loads are distributed causing stress (load divided by area)

S = section modulus

SF = the empirically derived safety factor to limit the usable/allowable stress to a safe fraction of the breaking strength

More recently statistically based design methods have emerged. The most common is referred to as Load and Resistance Factor Design, LRFD (or limit state design). In this design, each load type is assigned a "load factor" on the basis of how well it can be predicted. Where DL is easier to estimate knowing the exact material type and shape, it has a lower load factor. Furthermore, more difficult to estimate loads such as LL which may vary by occupant and/or application are assigned higher load factors. Concrete design introduced an early version starting in 1963 called ultimate strength design, USD, which assigned load and resistance factors on the basis of experience, calibrated to previously successful ASD projects (ACI 2004). Steel design offered a new LRFD option in 1986 (AISC 1986), and timber made the transition in 2014 (AWC, 2014).

This approach further assigns a strength reduction factor (resistance factor) to the predicted design capacity on the basis of the reliability of the method to accurately predict the actual capacity. All combined, LRFD addresses the reliability of predicting different types of loads and the resisting strength supporting these loads. This translates into individual safety factors of sorts. Equations 3.3 and 3.4 show the most common formulation of the design equation when using LRFD.

$$1.2DL + 1.6LL \leq \Phi_i P_n = \Phi_i F_i A_{cross\ section} \qquad \text{Eq. 3.3}$$

$$1.2M_{DL} + 1.6M_{LL} \leq \Phi_b M_n = \Phi_b F_b S \qquad \text{Eq. 3.4}$$

where:

Φ_i = the resistance factor assigned to a given type of loading where *i* varies from tension, compression or shear (t, c, or v respectively).

F_i = ultimate strength in tension, compression or shear (bending design equation is slightly different)

P_n = the computed capacity (often ultimate capacity) of the element for the given type of loading.

M_n = the computed bending capacity

While not discussed herein, the magnitude of the load factors shown in Equations 3.3 or 3.4 as 1.2 (for DL) and 1.6 (for LL) can be changed to accommodate different load combinations and reflect how probable the load is likely to be when combined with other types of forces (i.e., snow loads, rain loads, wind loads, etc.). The most common combination (Equation 3.3) implies DL is more safely predicted when compared to LL (1.2 vs 1.6) where the larger 1.6 multiplier is intended to account for errors in predicting the severity of the possible loads.

3.5 Safety Factors (ASD) And Strength Reduction Factors (LRFD)

Where early strength reduction factors (circa 1960s) were calibrated from experience and previously successful ASD case studies, modern values are based on statistical evaluations of load and strength variations, and a prescribed level of reliability. This reliability translates into an acceptable failure ratio where significantly higher than average loads rarely coincide with lower than average strength (or resistance).

Figure 3.1 shows the probability density functions for example load and resistance values. The area under each curve is 1.0 meaning the entire population of loads (or resistance) possibilities lies under the respective curve. Where the two curves intersect represents the probability of failure which for the left case has an area of 0.0025 or a 1 in 400 chance of failing (where load > resistance). The ASD safety factor is 2.3 defined by the ratio of the average resistance (23) to average load (10). The shape of the two curves is dictated by the average value (central tendency) and the standard deviation where taller, thinner curves indicate highly predictable values and shorter wider curves indicate more variability / less predictable. In this example, the load is more predictable than the resistance (or strength). Note by increasing the safety factor slightly from 2.3 to 2.8 (Figure 3.1 right) the failure ratio can be cut by a factor of ten.

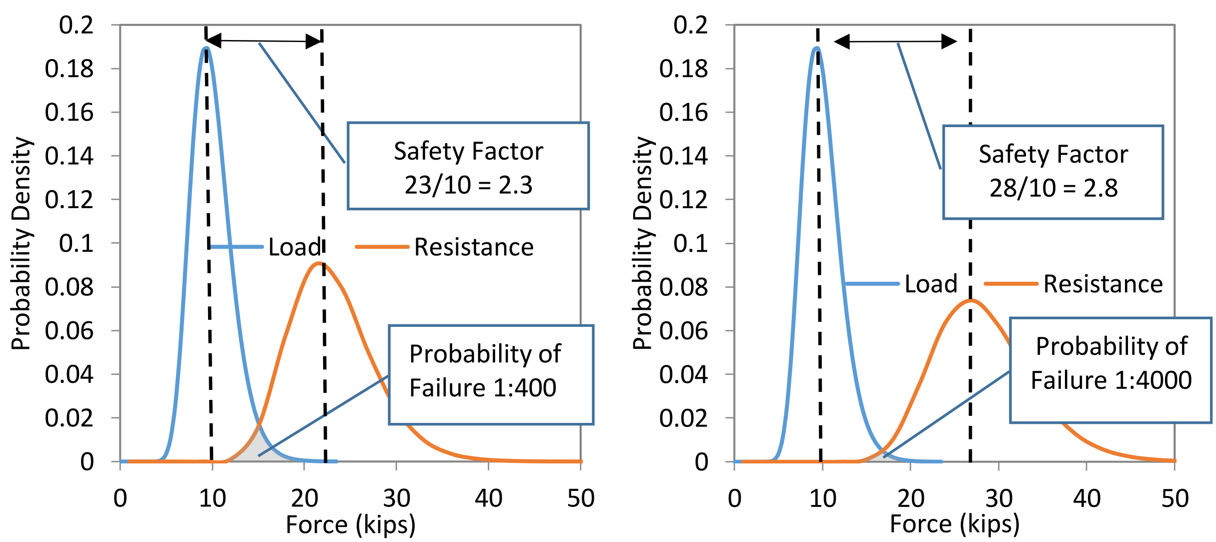


Figure 3.1 Safety factor and probability of failure for example load and resistance values.

For LRFD applications, the variability of the load, the magnitude of the load magnifier, and the value of the strength reduction factor all contribute to a given level of reliability (Equations 2a and 2b). Using this type of statistical evaluation, a prescribed level of confidence for a given loading and element strength can be established without empiricism and on the basis of a permissible/acceptable failure ratio.

Assignment of safety factors for ASD applications can use the same statistical approach as LRFD where the ratio of dead and live loads (DL/LL) is used to define a single / effective load factor for all service loads. The safety factor is then simply the ratio of the single load factor and the computed resistance factor. In this way, the same level of confidence can be assigned to both ASD and LRFD philosophies with the exceptions: the individual assignment of load factors is removed and the DL/LL ratio is assumed and constant. Resistance factors are determined by closed-form expression where numerous statistical input parameters are required.

Equation 3.5 from Darwin (1998) defines the most commonly used expression in determining the LRFD strength reduction (resistance) factors for concrete design and which is applicable to most structures other than perhaps bridges (significantly different loads compared to buildings). It makes use of known dead load and live load predictability terms called bias values or the measured load divided by the predicted load. Where the load bias is larger than 1.0, the load estimate is unconservative. Similarly, on the resistance side of the equation the resistance bias is the measured/predicted ratio but now for the predicted capacity. A resistance bias larger than 1.0 implies a conservative design. However, on both sides of Equation 3.5, the average bias values for loads and resistance are accompanied by variability defined by the coefficient of variation (CoV of bias = stdev/avg bias). Larger CoV values indicate poor predictability and in turn result in higher failure ratios for a given safety factor (ratio of avg resistance and avg load).

$$\Phi_i = \frac{\bar{r}}{\bar{q}} e^{-\left(V_r^2 + V_{\phi q}^2\right)^{1/2} \beta} \qquad \text{Eq. 3.5}$$

where:

V_r = coefficient of variation of resistance, r (or CoV_r)

$V_{\varphi q}$ = coefficient of variation of loading, q (or CoV_q)

$\bar{q}$ = mean value of random loading variable

$\bar{r}$ = mean test-prediction ratio

β = reliability index

i = subscript associated with different types of strength prediction

In Equation 3.5 the reliability index, β, is prescribed on the basis of the acceptable failure ratio. Table 3.1 provides common values of β and the associated failure ratios (Gunaratne, 2014).

Table 3.1 Common values for the reliability index and associated failure ratio values

Reliability Index, β	Failure Ratio
1	1:6
2	1:44
2.33	1:100
3	1:736
3.5	1:4149
4	1:25000

For bamboo design applications Equation 3.5 can be directly used to determine the necessary resistance factors using published strength values where the CoVr is simply the ratio of the standard deviation and the average of all published strength values for a particular parameter (i.e. tensile, compressive, shear or bending strength). Without knowing the acceptable failure ratio, a range of resistance factors would then be needed. However, the failure ratio used by other design materials and codes could be used.

3.6 Research Methodologies

This study used literature reported values of bamboo strength to determine safety and resistance factors for structural design applications. Correctness of the factors were verified using Monte Carlo analyses.

3.6.1 Bamboo Material Properties

Bamboo is not a timber product and technically falls under a family of a grass, but the strength parameters nomenclature for timber has been adopted for convenience. These include the tension strength (F_t), bending strength (F_b), compression strength (F_c), and the shear strength (F_v). These parameters are all parallel to the grain. Strength values perpendicular to the grain are not discussed.

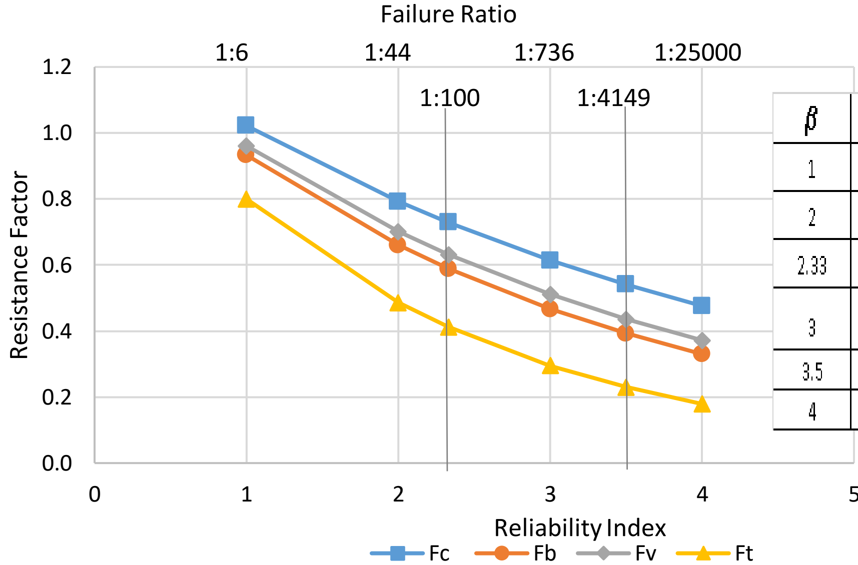
Most of the 25 studies combined for this study provided individual test results totaling 6,035 mechanical property test values (for seven properties) and were from the 43 studies analyzed by Sánchez Vivas et al. (2019); an additional four studies were included to increase the number of tensile tests and ensure statistical significance (Table 3.2 shows the number of test specimens for each data type). The data included tests of the following bamboo species: *Bambusa balcooa, Bambusa blumeana, B. oldhamii, B. pervariabilis, B. salarkhanii, B. tulda, B. vulgaris, Dendrocalamus asper, D. giganteus, D. strictus, Gigantochloa apus, Gi. scortechinii, Guadua angustifolia, Melocanna baccifera, Phyllostachys bambusoides,* and *P.pubescens.* The average and coefficient of variation were computed separately for each test type (Table 3.2). Modulus of elasticity values, while not used herein, are presented for completeness. Table 3.2 also includes values from the only in-depth bamboo design guideline found at the time of this study: IL-31 (Dunkelberg & Fritz 1985). However, these values could not be directly incorporated into this study without knowing the individual data values or the number of tests the values represent along with the respective standard deviations.

Table 3.2 Average mechanical property values of bamboo (parallel to the grain)

Mechanical Property	**Symbol**	**IL-31**	**Study Data Averages**	**Study Data Range**	**Coefficient of Variation (CoV)**	**Number of Specimens**
Shear Strength (MPa)	F_v	14-23	14.2	5-24	0.29897	154
Compressive Strength (MPa)	F_c	62-85	53.2	17-155	0.23296	1673
Bending Strength (MPa)	F_b	75-270	117.7	30-813	0.33054	1136
Tensile Strength (MPa)	F_t	145-376	114.6	2-347	0.48822	843
Compressive Modulus of Elasticity (GPa)	E_c	15-19	16.9	2-16	0.06641	448
Bending Modulus of Elasticity (GPa)	E_b	13-32	12.9	5-78	0.25765	1271
Tensile Modulus of Elasticity (GPa)	E_t	14-31	13.5	2-22	0.29977	510

3.6.2 Design Parameters

Using the statistical values provided in Table 3.2, the resistance factor was determined for each mechanical strength property using Equation 3.5. As the reliability index is required for this computation, a range of reliability indices were selected so a user can select a prescribed failure ratio. Figure 3.2 shows the trends for resistance factors versus reliability index and failure ratio. The exact resistance factor values are also tabularized for direct use in design.



β	Fc	Fb	Fv	Ft
1	1.02	0.93	0.96	0.80
2	0.80	0.66	0.70	0.49
2.33	0.73	0.59	0.63	0.41
3	0.61	0.47	0.51	0.30
3.5	0.54	0.39	0.44	0.23
4	0.48	0.33	0.37	0.18

Figure 3.2 Required resistance factor for each test of bamboo mechanical property as a function of reliability index (and failure ratio).

Hence by using the appropriate resistance factor (Figure 3.2) the engineer can provide a safe design for bamboo applications. For example, to provide a failure ratio of approximately 1:100 for a tension application, the formulation of the design equation shown previously as Equation 2a would be as shown in Equation 3.6.

$$1.2DL + 1.6LL \leq 0.41\ (114{,}600KPa)A_{cross\ section} \qquad \text{Eq. 3.6}$$

where DL and LL are input in units of kN, F_t = 114,600kPa (Table 3.2), the resistance factor is 0.41 (Figure 3.2 using F_t), and the equation can then be solved for the required cross-sectional area (in m^2). The computed cross-sectional area would be expressed in cm^2 or mm^2 that could then be used to decide on the number of individual bamboo elements needed. The cross-sectional area for bamboo refers to the annular area of the bamboo, i.e. between the outer and inner diameters. The same equation applies to compression and shear applications by inputting values of Fc or Fv, respectively in place of Ft and Equation 3.4 is used for bending.

As some designers prefer the ASD method, safety factors were also determined by first assuming a DL/LL ratio (often 2.0), computing the effective load factor using Equation 3.7, and then combining the effects of the load and resistance factors where the safety factor is the ratio of the effective load factor (Equation 3.7) and the resistance factor (Figure 3.2).

Using Equation 3.7, a DL/LL ratio of 2.0, g_{DL} =1.2 and g_{LL} = 1.6, the effective/prorated load factor g_{eff} is 1.33. Table 3.3 summarizes the safety factor required for a given failure ratio using this method.

$$\gamma_{eff} = \frac{\gamma_{DL}+\frac{\gamma_{LL}}{(DL/LL)}}{1+\frac{1}{(DL/LL)}} \qquad \text{Eq. 3.7}$$

Table 3.3 Safety factors required for each strength parameter at selected failure ratios (DL/LL=2.0)

Strength Parameter (MPa)	**Failure Ratios**					
	1:6	**1:44**	**1:100**	**1:736**	**1:4146**	**1:25000**
Shear Strength, F_v	*1.38*	*1.90*	*2.11*	*2.60*	*3.05*	*3.58*
Compressive Strength, F_c	*1.30*	*1.68*	*1.82*	*2.17*	*2.46*	*2.79*
Bending Strength, F_b	*1.43*	*2.02*	*2.26*	*2.85*	*3.38*	*4.03*
Tensile Strength, F_t	*1.66*	*2.74*	*3.23*	*4.51*	*5.78*	*7.43*

Analogous to the Equation 3.6 example, the same level of confidence using the ASD method would now incorporate the safety factors from Table 3.3 in Equation 3.8 and again solve for the total required cross-sectional area of bamboo that individual pieces would need to achieve.

$$DL + LL \leq (114{,}600KPa/3.24)A_{cross\ section} \qquad \text{Eq. 3.8}$$

While not presented, Table 3.3 can be easily reproduced for a wide range of DL/LL ratios other than that used to populate the table.

3.7 Monte Carlo Simulations

To verify the reliability of the safety (and resistance) factors, Monte Carlo simulations were performed. These simulations are used in cases where closed-form expressions such as Equation 3.5 are not available and can assess the probability of success or failure prior to an event. For this study, the numerical simulations randomly assigned 1 million values of load and resistance and tallied the number of times the load exceeded the resistance. Figure 3.3 shows both the probability density plots and the results of a Monte Carlo simulation for the Equation 3.6 and 3.8 example. For this case, the DL/LL ratio was 2, $\gamma_{DL} = 1.2$, $\gamma_{LL} = 1.6$, $\varphi = 0.41$ which also corresponds to a safety factor of 3.23 (Table 3.3). Variations in load were assigned on the basis of a typical load variation $CoV_q = 0.1$ (coefficient of variation of loading) from Darwin (1998); variation in resistance was determined from the Table 3.2 value of CoV_R. Again, this case imposed a target failure ratio of 1:100. Monte Carlo failure counts showed 11359 failures (points below the 1-to-1 line) in 1 million trials (1:88).

The Monte Carlo simulation showed the computed resistance factor (0.41) to be slightly unconservative and resulted in a safety factor of 2.94 (29.213/9.949; Figure 3.3 right)) instead of the target value of 3.23. By rerunning the simulation with a resistance factor of 0.4, the failure ratio dropped to 1:103 which is acceptable. Also, note the effect of the poorly predicted tension capacity (CoVr = 0.488) relative to the more confident prediction of load (CoVq = 0.1) whereby the width of the load prediction was very narrow and the resistance very wide. Of all the strength parameters (Table 3.2) tension has the largest variability which is also shown in Figure 3.3 by the narrower probability density plots for the F_c, F_v and F_b.

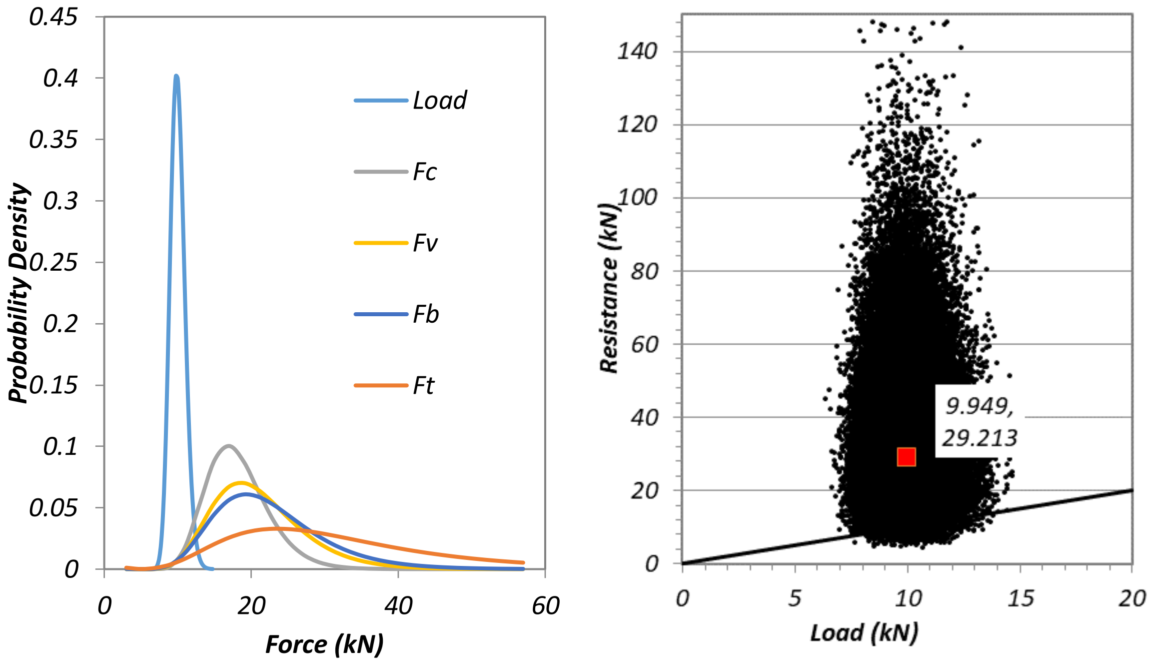


Figure 3.3 Probability density and Monte Carlo results for tension applications of bamboo showing safety factor 2.93.

Simulations were also performed on the other strength parameters and reliability indices again using DL/LL =2. Table 3.4 shows the actual number of Monte Carlo simulated failures for each strength parameter and target failure ratio using the Figure 3.2 resistance factors (or Table 3.3 safety factors).

Table 3.4 Monte Carlo predicted number of failure ratios

Strength Parameter	**Target Failure Ratios**					
	1:6	**1:44**	**1:100**	**1:736**	**1:4146**	**1:25000**
$\mathbf{F_v}$	1:5.7	1:40	1:94	1:694	1:3509	1:30303
$\mathbf{F_c}$	1:6.8	1:38	1:95	1:818	1:4831	1:27778
$\mathbf{F_b}$	1:5.6	1:39	1:86	1:622	1:4292	1:31250
$\mathbf{F_t}$	1:5.2	1:35	1:88	1:574	1:4366	1:33333

3.8 Discussion

The resistance factors computed for this study were expressed to two decimal places ranging from 0.18 to 1.02. Typically, resistance factor values are expressed by rounding down to the nearest 0.05 and was shown to provide a more appropriate lower failure ratio (0.41 to 0.40 for tension with 1:100 failures). If these values are adopted universally, the same rounding down protocol would most likely be applied.

Selection of a reliability index is often difficult to justify. Variables affecting this value include: importance of the structure, redundancy / number of load carrying elements, potential for loss of life, and/or cost versus risk evaluations. For concrete design the reliability index is usually 3.5 (1:4149) (Darwin, 1998); for redundant foundation elements such as piles 2.33 (1:100) is often used (Gunaratne, 2014). This provides a reasonably restricted range in which structural bamboo applications should use.

Of the four strength properties analyzed (compression, shear, tension, and bending), tensile strength had the highest variability. Upon examination of the bamboo literature the reason for this may stem from the test procedures which are not standardized. Tensile testing of bamboo is difficult to perform due to the dog-bone shape which is cut from a section of the culm which may or may not include large portions of the weaker interior material. Tensile testing performed on only a radial split piece of bamboo has demonstrated variability in strength relative to the radial position; values being highest at the outer diameter and lowest at the inner diameter (Gas et al. 1985; Li and Shen 2011). Additionally, while compressive, shear, and bending tests specific to bamboo all require a full culm of bamboo be used for testing, only the tensile test allows for only a split piece of bamboo be used. Like bending testing of bamboo which migrated from only split pieces of bamboo to the entire bamboo culm, tension testing should be similarly improved.

3.9 Conclusion

Bamboo is a quickly renewable and sustainable material currently underutilized in infrastructure due to lack of universal strength properties and design parameters. Of the 6036 test results reviewed for bamboo strength and moduli, 3806 were strength tests directly used to determine safety (and resistance) factors for tension, bending, compression, and shear strengths. Where closed-form solutions were used to determine resistance factors, Monte Carlo simulations suggest subtle refinement of these values could be entertained that may be as simple as rounding down to the nearest 0.05 resistance factor increment. Nevertheless, these findings allow an individual to design with bamboo with greater confidence based on a range of failure ratios from which an appropriate value can be selected. These results thus provide a rational approach to selecting structural design strength values for bamboo applications worldwide.

3.10 References

ACI. (2004). A century of progress, concrete international. American Concrete Institute, 26, (3).

AISC, American Institute of Steel Construction. (1986). Manual of Steel Construction: Load and Resistance Factor Design Manual of Steel Construction.

AWC. (2014). National Design Specifications (NDS) for Wood Construction, 2015 Edition, American Wood Council.

Amatosa Jr, T. A., & Loretero, M. E. (2016). Analytical behaviour in mechanical properties of Dendrocalamus asper bamboo as construction building materials in the Philippines. Global Journal of Engineering and Technology Review, 1(1), 114–121.

Arce, O. (1993). Fundamentals of the design of bamboo structures. Thesis Eindhoven University, 260pp. ISBN: 90-6814-524-X. Also available from the website www.lue.nl.

Bahari, S. A. & Ahmad, M. (2009). Effects of culm height levels and node presence on mechanical properties and fracture modes of *Gigantochloa scortechinii* strips loaded in shear parallel to grain. Bamboo Science and Culture: The Journal of the American Bamboo Society, 22(1), 41–44.

Berndsen, R.S., Klitzke, R.J., Batista, D.C., Nacimento, E.M., & Ostapiv, F. (2013). Resistência à flexão estática e à compressão paralela do bamboo-mossô (*Phyllostachys pubescens*). Floresta, Curitiba, PR, 43(3), 485-494.

Chung, K. F., & Yu, W. K. (2001). Mechanical properties of structural bamboo for bamboo scaffoldings. Engineering structures, 24(4), 429–442.

Colla, W.A., Beraldo, A.L., & Brito, J.O. (2011). Effects of thermal treatment on the physiochemical characteristics of giant bamboo. Cerne, Lavras, 17(3), 361–367.

Correal, D., Francisco, J., & Arbeláez, C. (2010). Influence of age and height position on Colombian *Guadua angustifolia* bamboo mechanical properties. Maderas Ciencia y Tecnología, 12(2), 105–113.

Darwin, D. Idun, E. Zuo, J. and Tholen, M. (1998). Reliability-based strength reduction factor for bond, ACI Structural Journal, 95 (4), 434-443.

Dunkelberg, K., & Fritz, J. (1985). Bambus als Baustoff. Bauen mit pflanzlichen Stäben = Bamboo as a building material: Building with vegetal rods. Stuttgart: Karl Krämer.

Erakhrumen, A. A., & Ogunsanwo, O. Y. (2010). Influence of neem (*Azadirachta indica* A. Juss) seed oil-treatment on static bending strength properties of wild grown split-bamboo (*Bambusa vulgaris* Schrad.) in south-west Nigeria. American-Eurasian Journal of Agricultural and Environmental Science, 8(1), 73–79.

Gnanaharan, R., Janssen, J.J.A. & Arce, O. (1994). Bending strength of Guadua bamboo: comparison of different testing procedures. International Network for Bamboo and Rattan: INBAR Working Paper No. 3. International Development Research Centre, Canada & Kerala Forest Research Institute, India.

Ghavami, K., & Marinho, A. B. (2005). Propriedades físicas e mecânicas do colmo inteiro do bambu da espécie do bambu da espécie *Guadua angustifolia*. Revista Brasileira de Engenharia Agrícola e Ambiental, 9(1), 107–114.

González, H.A.B., Arango, J.A.M., Sánchez, J.R.B. (2007). Resultados del ensayo a flexion en muestras de bambú de la especie *Guadua angustifolia* Kunth. Scientia et Technica Ano XIII, 35. Universidad Tecnológica de Pereira. ISSN: 0122-1701.

González, H.A.B., Montoya, J.A.A., & Bedoya, J.R. (2008). Comportamiento de muestras de *Guadua angustifolia* Kunth con diafragma y sin diafragma sometidas a esfuerzo de compression. Sciencia et Technica, XIV, 38, 449–454.

Gunaratne, M. (ed.), (2014). "The Foundation Engineering Handbook," CRC Press, Taylor and Francis Group, Boca Raton, FL pp. 588-589.

Gupta, A. K., Ganguly, R., & Mehra A. S. (2015). Bamboo as green alternative to steel for reinforced concrete elements of a low-cost residential building. EJGE, 20, 6.

Harries, K. A., Sharma, B., & Richard, M. (2012). Structural use of full culm bamboo: the path to standardization. International Journal of Architecture, Engineering and Construction, 1(2), 66-75.

International Standards Office (ISO) (2004). ISO 22157-1. Bamboo: Determination of physical and mechanical properties. Part 2: Laboratory manual. Geneva, ISO.

Jiang, Z., Chen, F., Wang, G., Liu, X., Shi, S.Q., Cheng, H. (2012a). The circumferential mechanical properties of bamboo with uniaxial and biaxial compression tests. BioResources, 7(4), 4806–4816.

Lee, A. W., Bai, X., & Peralta, P. N. (1994). Selected physical and mechanical properties of giant timber bamboo grown in South Carolina. *Forest Products Journal*, *44*(9), 40.

Li, H., & Shen, S. (2011). The mechanical properties of bamboo and vascular bundles. *Journal of Materials Research*, *26*(21), 2749-2756.

Liese, W. (1992). The structure of bamboo in relation to its properties and utilization. Proceedings of the International symposium on Industrial Use of Bamboo, Beijing, China, 7–11.

Manalo, R. D., & Acda, M. N. (2009). Effects of hot oil treatment on physical and mechanical properties of three species of Philippine bamboo. Journal of Tropical Forest Science, 19–24.

Norma Técnica Colombiana (2007). NTC 5525, Determinación de las propriedades físicas y mecánicas de la *Guadua Angustafolia* Kunth, Instituto Colombiano de Normas Técnicas (ICONTEC).

Omobowale, M.O. & Ogedengbe, K. (2008). Trends in fiber characteristics of Nigerian grown bamboo and its effect on its impact and tensile strengths. Bamboo Science & Culture: The Journal of the American Bamboo Society, 21(1), 9–13.

Sánchez Vivas, L., Mullins, G., Cunningham, J., Mihelcic, J., R. (2019). Mechanical properties of bamboo: a critical review of how age, species, density, moisture content, treatment, and testing standard influence strength values. Journal of the American Bamboo Society. *In Review.*

Tomak, E. D., Topaloglu, E., Ay, N., Yildiz, U.C. (2012). Effect of accelerated aging on some physical and mechanical properties of bamboo. Wood Science Technology, 46, 905–918.

Trujillo, D. (2018). Developments in structural design standards with bamboo. World Bamboo Congress Keynote Presentation. Xalapa, Mexico.

Tu, Z., Chen, L., Yu, X., & Zheng, Y. (2013). Effect of bamboo plantation on rhizosphere soil enzyme and microbial activities in coastal ecosystem. *J. Food Agricul Environ*, *11*(03), 2333-2338.

Wahab, R. Moktar, J., Sudin, M., Samsi, H.W. (2006). Strength properties of preservative treated *Gigantochloa scortechinii* after vacuum impregnation process. International Journal of Agricultural Research, 1(1), 8–13.

Wahab, R., Samsi, H.W., Sulaiman, O., Salim, R. & Hashim, R. (2007). Properties of oil-cured cultivated *Bambusa vulgaris*. International Journal of Agricultural Research, 2(9), 820–825.

Wakchaure, M.R. & Kute, S.Y. (2012). Effect of moisture content on physical and mechanical properties of bamboo. Asian Journal of Civil Engineering (Building and Housing), 13(6), 753–763.

Zaragoza-Hernández, I., Ordóñez-Candelaria, V. R., Bárcenas-Pazos, G. M., Borja-de la Rosa, A. M., & Zamudio-Sánchez, F. J. (2015). Propiedades físico-mecánicas de una guadua mexicana (*Guadua aculeata*). Maderas. Ciencia y tecnología, 17(3), 505–516.

3.11 References: Data Included in Monte Carlo Analyses

Ahmad, M., & Kamke, F. A. (2005). Analysis of Calcutta bamboo for structural composite materials: physical and mechanical properties. Wood science and technology, 39(6), 448-459.

Amatosa Jr, T., & Loretero, M. (2016). Analytical behaviour in mechanical properties of *Dendrocalamus asper* bamboo as construction building materials in the Philippines. Global Journal of Engineering and Technology Review, 1(1), 114-121.

Berndsen, R. S., Klitzke, R. J., Batista, D. C., do Nascimento, E. M., & Ostapiv, F. (2013). Resistência à flexão estática e à compressão paralela do bambu-Mossô (*Phyllostachys pubescens*). Floresta, 43(3), 485-494.

Chung, K. F., & Yu, W. K. (2002). Mechanical properties of structural bamboo for bamboo scaffoldings. Engineering structures, 24(4), 429-442.

Daud, N. M., Nor, N. M., Yusof, M. A., Bakhri, A. A. M. A., & Shaari, A. A. (2018, February). The physical and mechanical properties of treated and untreated *Gigantochloa scortechinii* bamboo. In AIP Conference Proceedings (Vol. 1930, No. 1, p. 020016). AIP Publishing.

Erakhrumen, A. A., & Ogunsanwo, O. Y. (2010). Influence of neem (*Azadirachta indica A. Juss*) seed oil-treatment on static bending strength properties of wild grown split-bamboo (*Bambusa vulgaris* Schrad.) in south-west Nigeria. American-Eurasian Journal of Agricultural and Environmental Science, 8(1), 73–79.

González, E.G., Osorio, J.A.S., Garcia, E.A.G. (2002). Resistencia a la flexion de la *Guadua angustifolia* kunt a escala natural. Rev. Fac. Nal. Agr. Medellín, 5(2), 1555–1572.

Gyansah, L., Akinwonmi, A. S., & Affam, M. (2010). The fracture behaviour of fresh bamboo under uniaxial compressive loading condition. Research Journal of Applied Sciences, Engineering and Technology, 2(8), 720-726.

Jiang, Z., Wang, H., Tian, G., & Yu, Y. (2012b). Sensitivity of several selected mechanical properties of moso bamboo to moisture content change under the fibre saturation point. BioResources, 7(4), 5048-5058.

Kamruzzaman, M., Saha, S. K., Bose, A. K., & Islam, M. N. (2008). Effects of age and height on physical and mechanical properties of bamboo. Journal of Tropical Forest Science, 211-217.

Lee, A. W., Bai, X., & Peralta, P. N. (1994). Selected physical and mechanical properties of giant timber bamboo grown in South Carolina. Forest Products Journal, 44(9), 40.

Li, H., & Shen, S. (2011). The mechanical properties of bamboo and vascular bundles. Journal of Materials Research, 26(21), 2749-2756.

Lima, H. C., Willrich, F. L., Barbosa, N. P., Rosa, M. A., & Cunha, B. S. (2008). Durability analysis of bamboo as concrete reinforcement. Materials and Structures, 41(5), 981-989.

Nurmadina, Nugroho, N., Bahtiar, E.T. (2017). Structural grading of Gigantochloa apus bamboo based on its flexural properties. Construction and Building Materials, 157, 1173–1189.

Ramírez, E. B. R., Villamizar, N. I., González, L. M., & Tovar, A. K. A. (2018). Análisis comparativo de las propiedades mecánicas de la guadua angustifolia kunth como material estructural de eje para protesis transtibial. RIAA, 9(2), 5.

Sánchez-Echeverri, L.A., Aita, G., Robert, D., & Garcia, M.E.R. (2014). Correlation between chemical compounds and mechanical response in culms of two different ages of *Guadua angustifolia* Kunth. Madera y Bosques, 20(2) 87–94.

Sapuyes, E., Osorio, J., Takeuchi, C., Duarte, M., & Erazo, W. (2018). Resistencia y elasticidad a la flexión de la *Guadua angustifolia* Kunth de Pitalito, Huila. Revista de Investigación, 11(1), 97-111.

Shao, Z. P., Fang, C. H., Huang, S. X., & Tian, G. L. (2010). Tensile properties of Moso bamboo (*Phyllostachys pubescens*) and its components with respect to its fiber-reinforced composite structure. Wood Science and Technology, 44(4), 655-666.

Srivaro, S., Rattanarat, J., & Noothong, P. (2018). Comparison of the anatomical characteristics and physical and mechanical properties of oil palm and bamboo trunks. Journal of Wood Science, 64(3), 186-192.

Takeuchi, C., Durate, M., & Erazo, W. (2013). Análisis comparativas en muestras de Guadua angustifolia Kunth solicitadas a compression paralela a la fibra. Revista Ingeniería y Región, 10, 117–124.

Takeuchi, C., Duarte, M. T., Alarcón, G., & Olarte, J. F. (2014). Estudio multifactorial de resistencia ultima a tensión paralela a la fibra en muestras de *Guadua angustifolia* Kunth. Ingeniería y Región, (11), 85-90.

Tomak, E. D., Topaloglu, E., Ay, N., Yildiz, U.C. (2012). Effect of accelerated aging on some physical and mechanical properties of bamboo. Wood Science Technology, 46, 905–918.

Wahab, R. Moktar, J., Sudin, M., Samsi, H.W. (2006). Strength properties of preservative treated *Gigantochloa scortechinii* after vacuum impregnation process. International Journal of Agricultural Research, 1(1), 8–13.

Xu, Q., Harries, K., Li, X., Liu, Q., & Gottron, J. (2014). Mechanical properties of structural bamboo following immersion in water. Engineering Structures, 81, 230-239.

Zhang, Y. M., Yu, Y. L., & Yu, W. J. (2013). Effect of thermal treatment on the physical and mechanical properties of *Phyllostachys pubescens* bamboo. European Journal of Wood and Wood Products, 71(1), 61-67.

CHAPTER 4: EVALUATING THE MECHANICAL PROPERTIES OF BAMBOO GROUNDWATER WELLS USED IN A FIELD TRIAL

4.1 Introduction

Twelve percent of people worldwide lack access to safe drinking water (UN 2018). In rural areas, eight of ten people still lack basic services, nearly half of them living in the world's least developed countries (JMP, WHO and UNICEF 2019). Therefore, the need for water in many places is evident and accessing groundwater using wells in a small self-supply system is one way to attain a low-cost water supply. Conventional well casing materials such as PVC and metal piping are often unattainable for segments of the global population because of their high cost and sometimes inaccessibility. These materials may also lead to less environmentally preferred methods to secure water (Held et al. 2013). Therefore, bamboo, a typically tropically available material to construct wells, is studied here. Bamboo, of the grass family *Poaceae*, is naturally abundant and available, natively found in all continents except Europe [and Antarctica] (Liese 1987). The use of bamboo has been recently explored for construction in a variety of engineering applications such as housing, bridges, flooring, and basket making (Laha 2000; Arinasa & Bagus 2010; Teron & Borthakur 2012; Kumar et al. 2013). One reason for the relatively recent focus on bamboo is because of its sustainability, being a very fast-growing plant, a construction material that grows in only 3-4 years and replenishes itself without re-planting (Liese 1991; Liese 2004). With a fast-growing world population, bamboo is now being assessed to be used as a conventional building material.

The idea of using bamboo for installation of groundwater wells is not new; it was used in ancient China thousands of years ago for salt mining (Arif 1978). In 1968, a bamboo well, or tubewell, was constructed in India by a farmer. His 'invention' gained considerable interest when the government placed funds for sanctioning loans to small farmers for sinking bamboo wells. As a result, over 19,000 bamboo wells were installed in a water table which ranges between 20 and 80 ft below the ground surface and up to 100 ft deep (Appu 1974; Dommen 1975; Shakya 2009). The bamboo wells were only one third the cost of conventional wells (and the least expensive form of irrigation for a small farmer in the area) as they were locally constructed using bamboo without inner nodes as tubing and split bamboo, coconut coir, and old cans for the water intake and powered by a mobile diesel or electric pump (Pant 1984).

A study which measured the operability of these bamboo wells was done 30 years after installation and found 51% of the wells to be still operational (Jha 2004). Unfortunately, other studies done on bamboo wells installed for accessing groundwater are scarce, mainly just government assessments particularly to find cost benefits of the bamboo wells and economic studies (Clay 1980; Jha 2004). Additionally, there is no evidence of that any of the bamboo wells were treated in any way prior to installation to prevent degradation, except for some mention of coal-tar being used (Arif 1978). Creosote (CASRN 8001-58-9) which is manufactured by the distillation of coal tar is classified by the U.S. Environmental Protection Agency Integrated Risk Information System (IRIS) as a B1, probable human carcinogen.

The bamboo well is installed similarly to other hand drilled wells, the main difference between the bamboo well and other wells is that the well casing is constructed out of bamboo (instead of commonly used PVC or galvanized iron). A schematic of a bamboo well is shown in Figure 4.1.

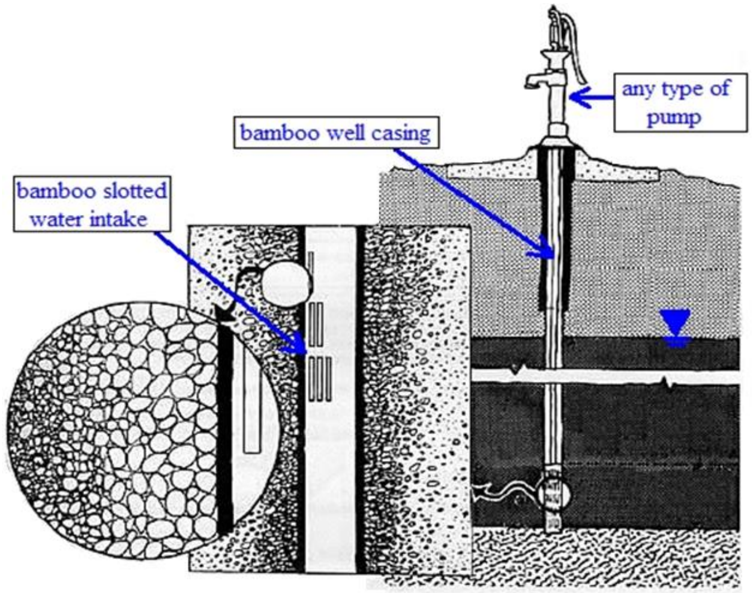


Figure 4.1 Schematic of the bamboo well (Technical Brief No.5 1985). Reprinted from Technical Brief No. 5/Slotted Bamboo Tubewell Screen, with permission of Practical Action Publishing Ltd.

Some benefits of a bamboo well include its extremely low cost and sustainable design, being made of a renewable material. Additionally, because bamboo is an organic material, once the well reaches the end of its lifetime, the well can be capped, the internal or preferably external above ground pump removed, and the bamboo well casing can be allowed to naturally decompose in the ground; leaving no foreign material in the ground. Construction, drilling and installation of the bamboo tube well does not require much technical skill and as such it is easier for understanding at the farmer's level (Arif 1978) providing an excellent example of intermediate technology (Jha 2004). Specifically, in high water table areas, bamboo wells are a very viable option as intermediate technology due to their low cost (Chandna 2004). Additionally, the need to manually dig the well was expressed due to the surplus labor found in many developing countries, and comparative high cost of mechanical drilling (Rahman 1976).

One study even used bamboo wells successfully drilled using the manual sludge-boring method (Orr 1991) which might make bamboo wells compatible with low cost methods of hand drilling wells or lifting water assessed in our research group (e.g., MacCarthy et al. 2013a, 2017).

Some of the problems identified with bamboo wells were damage by pests and the unreliability of a pump. The main pests identified were, rodents (Rahman 1976), rotting due to fungi, and white ants (Jha 2004); specific scientific names of the fungi and ants which infest bamboo wells are not published. Possibilities of treating the bamboo before installation should thus be explored to deter pest infestation. Furthermore, to increase the reliability of the bamboo well, “attempts should be made to develop manual devices for pumping water” as the imported pumps which have been used have a high cost and the skills to run and maintain it are beyond the skills of the farmers (Rahman 1976) as well as being diesel powered (Arif 1978). Having a manual pump (described in Mihelcic et al. 2009) installed on the bamboo well would also increase its reliability since in many developing countries the availability of diesel or electricity to run pumps is scarce (MacCarthy 2017). In fact, one unique manual foot operated pump called the ‘treadle pump,’ made of *B. vulgaris* bamboo was used in Bangladesh for *B. balcooa* and *Bambusa tulda* wells (Orr 1991).

Despite these findings and current research on the benefits of bamboo and possibility of bamboo wells, there has not been a scientifically monitored experiment conducted on bamboo wells, save the two done in Bangladesh (Rahman 1976; Arif 1978) that did not assess their structural integrity after placement in the ground. Therefore, a first in its kind scientifically monitored experiment of bamboo wells is presented here. The bamboo wells were prepared similarly to previous installed bamboo wells and were exposed to chemical treatments identified in the literature; 1/3 of the wells were air-dried without chemical addition, 1/3 were treated with coconut oil, and 1/3 were treated with borax/boric acid. Although these treatments have been previously studied in the literature (Manalo & Acda 2009; Kaminski et al. 2016), few studies in real outdoor conditions have been performed and no study was identified which assessed the durability of bamboo wells dependent on treatment. The bamboo wells were left in the ground at a well testing site for 3.5 years and upon the end of the monitoring period removed and assessed using mechanical compression testing.

4.2 Methods

4.2.1 Selection and Preparation

The species of bamboo selected for this experiment were *Dendrocalamus giganteus* and *Dendrocalamus asper* due to their common growth and previous use in engineering applications. Culms of mature *D. giganteus* (diameter ~ 3.25 in; 8.3 cm) and *D. asper* (diameter: ~ 2.5 in; 6.5 cm) approximately 3-4 years of age, as determined by examination (Ubidia 2002), were chosen as these ages have been correlated to highest mechanical strength properties (Liese 1992; Kabir et al. 1993; Sanchez et al. 2019).

First, the bamboo culms were formed as bamboo well casings by piercing the inner nodes of the bamboo with a spear tip of a welded piece of steel rebar. All of the inner nodes were pierced except the last one which makes a ‘pipe’ enclosed at one end (so that the well casing is sealed at its lower end).

4.2.2 Treatment

Prior to insertion in the ground as bamboo wells, some bamboo culms of ~3 m length were treated to attempt to avoid pest infestation and therefore extend the lifetime. The treatment of the bamboo well culms was as follows: 4 were air-dried, 4 were treated with borax/boric acid, 4 were treated with coconut oil. Half were randomly selected to be installed in the ground as bamboo wells and the other half were left to air-dry in the USF IDR Suite 107 laboratory at room temperature as control samples.

These treatments were chosen because: (1) they are the most common method of storage and of testing of bamboo samples for mechanical properties, (2) they are the most common methods used by industry to treat bamboo sold commercially, and (3) oils of different types such as neem oil, palm oil and coconut oil, have been experimentally tested and proven effective to some extent (Wahab et al. 2007; Erakhrumen 2009; Manalo & Acda 2009). Regarding borax/boric acid treatment, although it has been cited as the most effective treatment by some (Liese & Kumar 2003; Kaminski et al. 2016), it has also been seen to be experimentally ineffective in preventing pest attack, specifically the powder post beetle (Olic & Lorenzetti 2013) and the recommended concentration in water has not been established. The treatment was done using vertical soak diffusion (Liese 1998) due to its simplicity and therefore potential for easy replication in a rural or development setting. The method was further simplified using a tree to lean the bamboo on during treatment. The borax & boric acid mixture treated culms were of a solution of 3 kg of borax, 2 kg of boric acid in 45 L of water (10% solution) as reported in a manual (Garland 2003) which is similar to the quantities reported in other manuals and published literature (Singer 2010; Hartwich 2012; Tiburtino et al. 2015). This solution was used filling the inner bamboo entirely daily for 12 days, topping off the bamboo daily as some of the solution was absorbed through the inner bamboo walls. The brand of borax used was 20 Mule Team borax which is the most common brand sold in the U.S., and the brand of boric acid used was Zap-a-Roach and Ant Killer (100% boric acid). The filling of the bamboo culms was done by using a bucket elevated higher than the culms on the tree using the branch as a pulley and using plastic tubing to siphon the solution into the culms. The coconut oil treated culms were treated using USDA (United States Department of Agriculture) food grade organic extra virgin refined coconut oil (Tresomega Nutrition brand). Daily, for 7 days, the outside of the culms were coated with liquid coconut oil using a paintbrush and ~250 mL of oil was poured inside of the bamboo, while rotating, attempting to cover the inner bamboo entirely in many days.

4.2.3 Water Intake System (Well Screen)

The bamboo slotted water intake (illustrated in Figure 4.1) was made by first adding slits (i.e. 'well screen slots') using a rotary drill bit as used for previously made bamboo wells in India (Allison 1978). This rotary drill bit can be made mechanically from a bicycle pedal and therefore can be made anywhere with reused materials and does not require electricity. The drilled slots are too large to prevent sediment from clogging the water intake system; therefore, coir rope, made of coconut husk, was wrapped around all of the slots made in the bamboo to serve as a natural filter as has been done previously for bamboo wells (Arif 1978). The bamboo slits being wrapped by coconut coir is presented in Figure 4.2 and the finished prepared bamboo well pre-installation is shown on Figure 4.3.

Figure 4.2 Bamboo slits being wrapped with coconut coir which acts as a well filter/screen

Figure 4.3 Completed bamboo well. Bamboo slits first drilled and then coconut coir wrapped around slits to act as a filter/screen

Twelve bamboo culms (six of the two species type) were treated by the above three methods in equal proportions. Six of those culms were stored in laboratory conditions at room temperature as control samples and the other six culms were inserted into the ground as bamboo wells.

4.2.4 Drilling Well Installation

The bamboo wells were installed at the University of South Florida (USF) Geopark in December 2015 and remained in the ground for a monitoring period of 3.5 years (removal occurred in June 2019). Six wells, three of *Dendrocalamus giganteus* (~75 mm; ~3.25-inch outer diameter) and three of *D. asper* (~65 mm; ~2.5-inch outer diameter) were installed at a well depth of ~3.65 m; 12 ft. Figure 4.4 shows the components of how the completed wells were constructed. The first well was installed manually using the EMAS 'standard' hand manual method (MacCarthy et al. 2013a) and remaining five wells installed using conventional mechanical drilling. Figure 4.5 shows the exact placement of the bamboo wells.

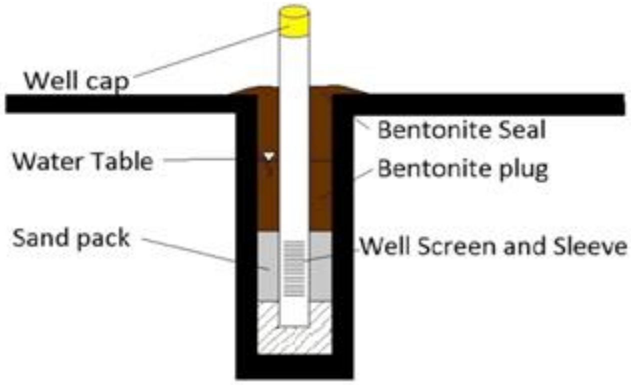


Figure 4.4 Schematic of installed well components for bamboo well field installation

Figure 4.5 Map showing location of six bamboo wells placement at USF Geopark, University of South Florida, Tampa, Florida, USA

4.2.5 Monitoring

Water quality monitoring was done periodically during the entire installed 3.5-year period with greater monitoring during the first 8 months and the final 8 months. Monitoring consisted of pH readings (using a Oakton pH 510 series meter), visual inspection for coconut oil in the water samples, and investigation of leaching of borax/boric acid treatment through testing of boron concentrations in the water. Both borax and boric acid are boron compounds. Borax (e.g., $Na_2B_4O_7$)$10H_2O$ is the salt of boric acid which crystallizes in dry places from the evaporation of salt lakes. Boron concentrations are measured in the water because boron is the elemental form of borax and boric acid ($B(OH)_3$) before it reacts with other compounds. Boron readily hydrolyzes in water and is commonly found dissolved in natural waters, primarily from leaching from surrounding geology, as the undissociated boric acid or as borate ions. Some examples of measurable concentrations in U.S. groundwater that provide drinking water are: (1) 12 µg/L to 1,100 µg/L in Sacramento Valley, (2) a median concentration of 46 µg/L in Minnesota, and (3) a median concentration of 47 µg/L in a national study of public utility groundwater sources (EPA 2008). Higher concentrations in surface waters have been associated with wastewater discharges (WHO 1998; U.S.EPA 2008). Boron was therefore analyzed in groundwater samples to determine the presence/absence of this chemical treatment. Boron was tested in water samples collected on July 20, 2016 from 4 out of the 6 wells (two wells were dry at the time of sample collection, so water could not be collected from them) and prepared by EPA method 200.2 and analyzed by EPA method 200.7 that employs inductively coupled plasma-mass spectrometry (Martin et al. 1994). Analysis was performed by Jupiter Environmental Laboratories, Inc. (Jupiter, FL)

4.2.6 Well Removal: Mold Identification and Mechanical Property Testing

At the end of the study duration, wells were removed carefully, taking care not to damage the bamboo. Two assessments were performed upon removal: identification of molds present and destructive compression mechanical property testing. Mold specimens were examined with a phase contrast microscope (Accuscope). Specimens were stained to increase visibility, using ammonia congo red, cresyl blue, phloxine a, and KOH. Keys from literature (Barnett & Hunter 1972; Watanabe 2010) were used to determine the highest taxa level possible. Mold type and placement on the bamboo was also measured (Table 4.1). A compression parallel to grain test was performed on the bamboo specimens in accordance with the International Standards

Organization (ISO-22527 2004). A compression parallel to grain test for bamboo takes a section of bamboo of length equal to the external diameter and compresses this section on a compressive test instrument. Nodes and internodes were tested. Axial extensometers (MTS 632.27E) were used for testing. From this test, the ultimate compressive strength (F_c) and the compressive modulus of elasticity (E_c) were determined. Tests were performed on the 3.5-year air-dried (control) bamboo and removed bamboo wells (3.5 years in the ground). Specimens were collected consistent distances from the ground down for equality in comparison (e.g. for each well, collected from well casing points that were of equal depths from the ground surface).

4.3 Results and Discussion

In addition to the water quality measurements, several other parameters were monitored throughout the 3.5-year monitoring phase that the bamboo wells were installed (Table 4.1). These parameters were water depth, saturation, and presence and identification of molds.

Table 4.1 Well monitoring parameters (treatment, type, depth, soil type, water depth, pH, oil presence, saturation, boron concentration, and pests/mold present) for Dendrocalamus specimens

Well No.	Treatment	Bamboo type	Well depth (ft)	Soil type	Water depth from ground (ft)	pH		Visually see presence of oil? (yes or no)		Saturated? (yes or no)	Boron Concentration July 20, 2016		Mold Presence	
						Initial year of installation	8 months before removal (3.5 years later)	Initial 8 months of installation	8 months before removal (3.5 years later)		1st sample (µg/L Boron)	2nd sample (µg/L Boron)	At installation	At removal (more details in section 4.3.2)
1	Air-dried	*D. giganteus*	10.9	Gray fine sand	5.05-9.8 (7.57) (9)	7.12 (4)	6.34 (2)	no	no	yes	44*a*[1]	24*a*[1]	no	yes
2	Air-dried	*D. asper*	6.2	Gray fine sand	4.75-5.4 (5.08) (2)	-	-	no	no	intermittently dry	-	-	no	yes
3	Coconut oil	*D. asper*	9.35	Gray fine sand	5.5-9.15 (7.47) (9)	7.14 (4)	6.54 (2)	yes	Yes (very little)	yes	9600	750	no	yes
4	Coconut oil	*D. giganteus*	6.85	Gray fine sand	4.2-6.8 (5.32) (5)	7.15 (4)	4.91 (1)	yes	Yes (a lot)	intermittently dry	910	630	no	yes
5	Borax/ boric acid	*D. giganteus*	7.4	Gray fine sand	4.4-6.6 (5.76) (8)	-	6.95 (1)	no	no	Nearly always	-	-	no	yes
6	Borax/boric acid	*D. asper*	9.7	Gray fine sand	3.8-9.1 (5.70) (9)	7.15 (4)	6.41 (2)	no	no	yes	260	110	no	yes

[1]The *a* represents that the reported value is between the laboratory method detection limit (MDL) and the practical quantitation limit (PQL).

4.3.1 Water Testing: Borax/Boric Acid Residue and pH

Regarding borax/boric acid testing, because 2 of the wells were treated with borax/boric acid prior to insertion, all of the well casing samples which were saturated (i.e. those that were under the water table at time of boron measurements) were monitored for boron levels in the water; as borax/boric acid is known to be water soluble. Only Wells No. 5 and No. 6 were treated with borax/boric acid, yet, boron was measured in all wells examined (Table 4.1). Refer to map of the placement of bamboo wells (Figure 4.5).

The results of this study were not conclusive in regards to whether the borax/boric acid treated samples leached significantly into the groundwater. The furthest well (Well No. 1) away from the borax/boric acid treated wells had some measurable boron, one that was close by (Well 3) had the highest concentrations of boron detected. This could suggest that the boron migrated out of the well. Knowledge of the hydrology of that area suggests that groundwater moves in varying directions at this site depending on the time of the year and rainfall patterns (Parker 1992) and it is known that boron is water soluble (Gaulé 2013). This made it difficult to interpret the chemical analyses as groundwater could be migrating back and forth between different wells. Alternatively, the boron being detected could be naturally occurring in the water as it is known that natural boron concentration vary between 0.3 – 100 mg/L in different parts of the world (WHO 2003) and in Florida one study found boron concentrations in springs to range from 19 µg/L to 90 µg/L with a median concentration of 39 µg/L (Carriker et al. 1976). The presence of naturally occurring boron may thus account for the presence of this chemical in all wells, though the higher concentrations measured in Well No. 3 and No. 4 (treated with coconut oil) were the highest measured values.

Regarding pH testing, it appears that the pH of all of the groundwater obtained from the bamboo wells dropped slightly in all wells (and more significantly in Well No. 4) (see Table 4.1), yet the reason for this is currently not clear (pH: 4.19-7.19). A nearby monitoring well was tested for pH at the end of the monitoring period (May 17, 2019) and it was found to be 7.11. This suggests the pH of the groundwater did not change in the area, it was the water within the bamboo wells that experienced a decreased pH. Knowing that it was only the water in the bamboo wells that changed then the difference might be attributed to: 1) the borax and boric acid leaching from Well No. 5 and Well No. 6 or, 2) the microbial degradation of organic material within the bamboo wells as bamboo is a natural material which in an oxygenated environment (expected of shallow groundwater) would produce gaseous CO_2 which can dissolve to form carbonic acid. Interestingly, bamboo Well No. 4 which was treated with coconut oil and had the highest physical presence of oil also had the lowest pH (4.91). Complete data regarding pH values can be found in Appendix C1.

4.3.2 Evaluation

After the 3.5-year monitoring period in the ground, the six bamboo wells were physically removed for evaluation. Evaluation consisted of compressive mechanical property testing and microscopic evaluation.

Upon inspection of control samples that were not installed in the ground but instead were stored for 3.5 years in an air-conditioned laboratory under favorable conditions, one type of degradation was specifically noticed: splitting. Splitting had occurred in 50% of the stored pre-cut length equal-width samples and 50% of the stored whole culm samples (3 of 6 culms). The pre-cut samples were split only once and the whole culm samples were split on each side throughout the full length (only held together still by some nodes which were not split). They had been air-drying horizontally, and all their inner nodes been pierced so that the reported effect due to air pressure inside of the bamboo could not have been the cause of splitting. Additionally, of the whole culm air-dried samples, only one species of bamboo had split. All three treated culms of the *D. giganteus* had split and none of the 3 *D. asper* culms had split. Only a small part of the literature mentions splitting as a major problem; and no publication mentions that splitting is species-dependent. Splitting is possibly a larger problem than cited due to the scientific community's seeming unwillingness to publish failure data. Due to the nearly complete splitting damage during air-drying, no samples of not-installed *D. giganteus* (i.e., the control) were acceptable for compression in their intact form.

Upon the removal of the wells, it was found that the main variable determining bamboo well durability is diameter of the bamboo. The two wells inserted of lowest average outer diameter (1.6-1.8 inches) both degraded nearly completely into the ground, rendering no bamboo well casing to be able to be removed and tested (Well No. 1 that was only air-dried and No. 6 that was treated with borax and boric acid). Although these wells received different treatments and were of different species, *D. giganteus* and *D. asper*, respectively, they both degraded nearly completely which was believed to be due to their smaller diameter. The wells that were removed from the ground and still had structural stability (Wells Nos. 2-5) were of average outer diameters 2.2 – 3.6 inches. Wells No. 2-5, which did not degrade after being in the ground for 3.5 years, are shown of Figure 4.6.

Figure 4.6 Removed bamboo Wells Nos. 2-5 after being in the ground for 3.5 years

Visually, one could observe consistently for all wells (regardless of treatment or species) that the bamboo closest to the surface suffered the highest degradation to the elements. The bamboo which was lower in the ground and in the water table by appearance looked much better, still looking like freshly cut bamboo.

Regarding molds and pests, there was a mold identified that infested the inside of the bamboo wells. All wells were infested by the mold fc. *Acrodictys* (Figure 4.7) throughout the inner bamboo, from the surface level up to the water table level. The abbreviation fc. means the mold identified is suspected to be *Acrodictys*, but not yet confirmed (molds are very difficult to correctly identify). This mold has previously been found in bamboo (Hyde et al. 2002; Cai et al. 2013).

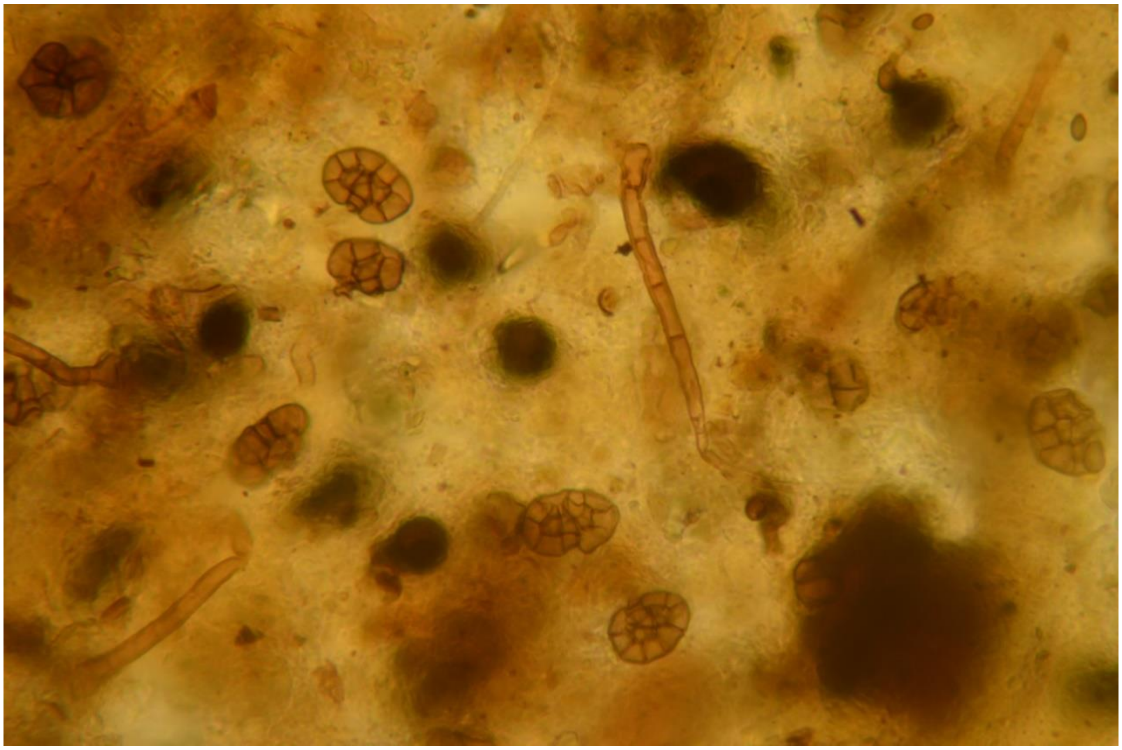


Figure 4.7 Mold identified inside the bamboo wells, fc. Acrodictys

Moisture content of the control bamboo and the removed wells was calculated using Equation 4.1 and averaged values are presented in Table 4.2.

$$\frac{m_i - m_f}{m_i} * 100\% = moisture\ content \qquad \text{Eq. 4.1}$$

where:

m_i = the initial mass of the sample

m_f = the final mass of the sample after drying for more than 24 hours in a 103˚C oven until completely dry

Table 4.2 Averaged moisture content values per bamboo culm

Sample	Bamboo Species	Treatment	Moisture Content (%)
Control 1	*D. asper*	Coconut oil	7.79
Control 2	*D. asper*	Borax & boric acid	9.13
Control 3	*D. asper*	Air-dried	8.45
Well No. 2	*D. asper*	Air-dried	29.92
Well No. 3	*D. asper*	Coconut oil	28.95
Well No. 4	*D. asper*	Coconut oil	29.06
Well No. 5	*D. giganteus*	Borax & boric acid	26.28

4.3.4 Material Property Tests

Compression parallel to culm tests were performed on control bamboo samples and on removed bamboo wells following the ISO-22527 (2004) standard which obtained a compressive modulus of elasticity, E_c, and compressive strength, F_c. Control samples which had been in an air-conditioned lab for 3.5 years had compressive strength values which were approximately double the values of those of the removed bamboo wells which had been subject to the elements of weather, soil, etc. Still, compressive strength values for both control and well specimens fell within the range of compressive strength values of bamboo found in Chapters 2 and 3 (18-134 MPa, 17 – 155 MPa, respectively). Control samples had values of compressive strength and modulus of elasticity of 44-90 MPa (72 MPa average) and 15-31 GPa, respectively. Bamboo wells had values of compressive strength and modulus of elasticity of 22-61 MPa (39 MPa average) and 7-25GPa, respectively. Although both nodes and internodes were tested, modulus of elasticity data was only calculated for internode specimens as node specimens have inconsistent surface areas. Variables graphically analyzed to find correlations between bamboo compressive strength values were moisture content, outer diameter/cross-sectional area, height along culm, treatment (air-dried, borax & boric acid, and coconut oil), and species (*D. asper and D. giganteus*) (all data not shown). No clear relation was found between compressive strength values and cross-sectional area, as shown in Figure 4.8. Higher compressive strength values were exhibited by the control samples (in black) in contrast to the well samples (in gray).

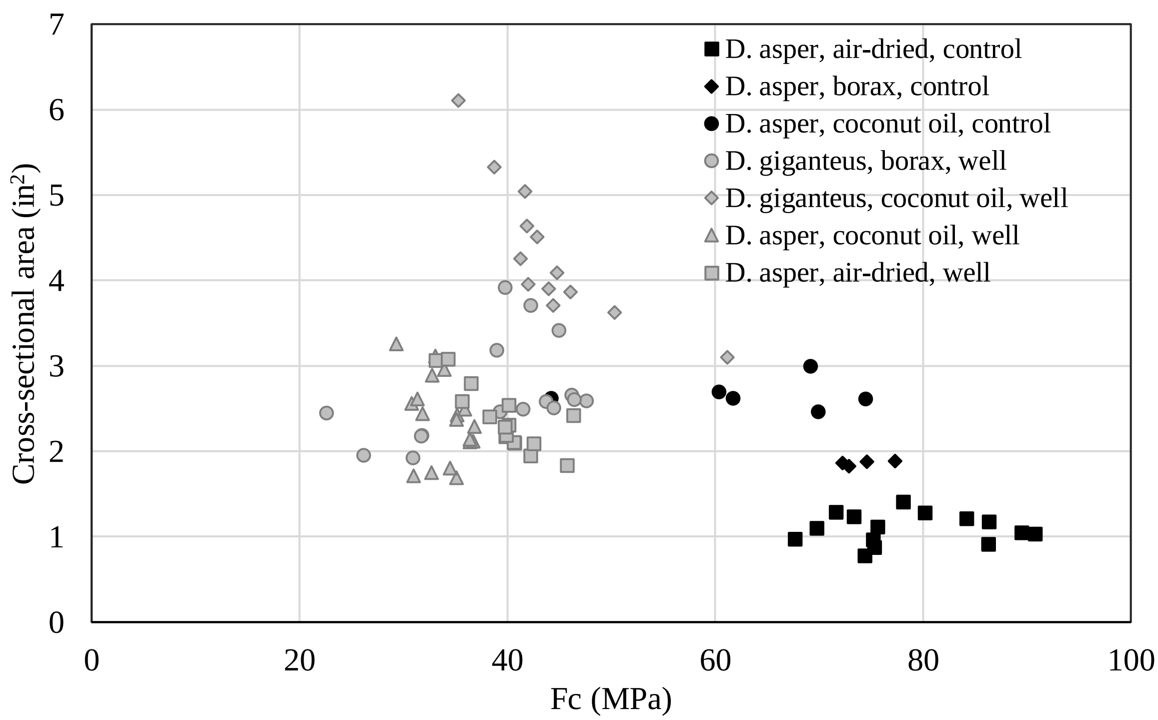


Figure 4.8 Compressive strength vs. bamboo cross-sectional area of all bamboo specimens tested.

Compressive strength versus moisture content graphs for all control samples (in black) and well samples (in gray) are shown in Figure 4.9. Control samples were of low moisture content (under 10%) and exhibited a large range of compressive strength values yet a very low variation in moisture content. Well samples, on the other hand, had high variability in moisture content yet a lower range of compressive strength values. Both Figure 4.8 and Figure 4.9 show how control samples had roughly double the compressive strength values of the well samples. Both Figure 4.8 and Figure 4.9 also show how there is no apparent relationship seen between bamboo species (*D. asper* or *D. giganteus*) or treatment type (air-dried, coconut oil, or borax & boric acid) to compressive strength values.

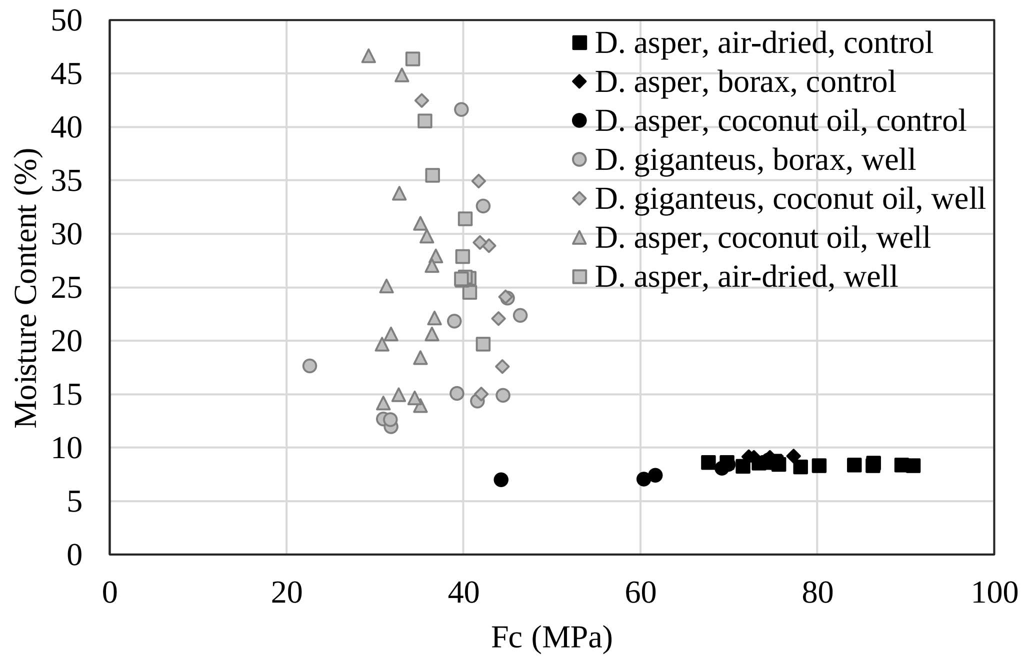


Figure 4.9 Compressive strength vs. moisture content of all bamboo specimens tested.

All compressive strength values (for control and removed well samples) are within the range of normal bamboo compressive strength values established in Chapters 2 and 3. The findings that compressive strength values do not correlate to bamboo cross-sectional area, treatment type, or bamboo type is supported by the findings in the literature summarized in Chapter 2. The finding that compressive strength values exhibit a bi-modal relationship dependent on moisture content (Figure 4.9) is consistent with the findings in the literature presented in Chapter 2, Figure 2.6. For raw compression test data of select bamboo specimens, see Appendix C2. Complete data of all bamboo specimens used for Table 4.2, Figure 4.8 and Figure 4.9 is presented in tabular form in Appendix C3.

4.3.5 Other Observations

For this study, a simple above-ground manual suction pump ('pitcher pump' style, Simmons part #1160) was installed on top of the bamboo well casing as it does not require electricity, can be locally manufactured (MacCarthy et al. 2013b), and is of low cost. It was attached to the bamboo well using a metal fitting which was tightly screwed into the bamboo and covered with 100% silicone leakproof sealant. However, it was found that the continuous pressure caused by the weight of the pump as well as environmental factors such as degradation of the bamboo caused microcracks in the bamboo and caused the pump to no longer be air tight and seize to work. This situation was first observed a few months after installation of the bamboo wells. A way to prevent this issue would be to install a concrete apron that would absorb the mechanical stress from the functioning above-ground suction pump.

The coconut coir suggested as a natural water intake filter for bamboo wells was ineffective in keeping out sand. One reason for this is that the coconut coir was fitted on the bamboo while it was in a freshly cut raw 'green' condition, and bamboo is known to shrink radially as it dries, whereby leaving a small gap between the bamboo wall and the coconut coir after radial shrinking. Additionally, as coconut coir is an imperfect natural material, perhaps wrapping a second or third layer of the coconut coir around the bamboo well may prove to be a more effective filter. The coconut coir impressively appeared to be in very good shape, with no visual degradation seen when the wells were removed, after 3.5 years of being in the water table (Figure 4.10).

Figure 4.10 Coconut coir around removed bamboo well

4.3.6 Comparison to Other Well Materials

In order to assess the functionality of bamboo wells in comparison to other well materials, material costs and durability were compared in Table 4.3.

Table 4.3 Well material comparison with conventional well materials and bamboo

Material	Cost per foot, 3-inch diameter	Cost per 12-ft well, 3-inch diameter	Durability
PVC	$5	$60	50-100 years[3]
Steel	$20	$230	20-70 years[4]
Bamboo	Potentially free	Potentially free	At least 3.5 years and 1 study found 50% of bamboo wells to still be operational after 30 years (Jha 2004)

Bamboo is here listed on cost as 'potentially free' as bamboo wells are suggested to be used by people who have bamboo growing natively in their fields. Although a price of bamboo can be attained in the US, this price is irrelevant when comparing to the price of bamboo in low-income countries where bamboo is of very low cost or potentially free. The cost, or time, of

[3]https://www.mcgarryandmadsen.com/inspection/Blog/Entries/2015/9/28_What_is_the_average_life_expectancy_of_PVC_pipe.html
[4] https://foundationtechnology.com/wp-content/downloads/technical_engineering_manual/Chapter_7_Corrosion_Considerations.pdf

potentially having to re-drill wells every several years if using bamboo versus PVC or metal piping must be considered.

4.4 Conclusion

Bamboo wells were successfully made and installed in the subsurface at the University of South Florida. The difference in treatment revealed that borax/boric acid may have leached into the water table and therefore care should be taken when considering its use for a bamboo wells application, despite the fact that it is the most common treatment method for above-ground structural applications. The experimental coconut oil treated wells were also observed to not be ideal as they leached coconut oil into the water collected from the well that was present as solid oil clumps. Air-dried bamboo culms installed as wells had the same functionality as those of the treated bamboo wells in terms of inspections and mechanical strength testing and therefore are recommended.

Mechanical testing of the air-dried control bamboo using compressive strength and compressive modulus of elasticity values showed the strength of the bamboo after the field trial was very close to the average values established for these bamboo properties in Chapters 2 and 3. Of the variables graphically analyzed to influence compressive strength values, moisture content, outer diameter / cross-sectional area, height along culm, treatment (air-dried, borax & boric acid, and coconut oil), and species (*D. asper and D. giganteus*), only moisture content was found to affect the compressive strength values. This finding is consistent with what was found in the bamboo literature, summarized in Chapter 2, Figure 2.7. Bamboo wells of small diameters (i.e. less than 2 inches) degraded nearly completely into the ground over the 3.5-year test period. Therefore, based on this field research, it is recommended that if bamboo wells are to be installed, that they be of the largest diameter possible, at least 2.5 inches or greater. Bamboo wells of over 2.5 inches in external diameter did degrade somewhat while being in the ground, which was seen by the compressive strength values lowering by approximately 50% in comparison to the control samples, yet still have structural strength to prove useful as functional wells. This study confirms that bamboo wells are a possible appropriate technology for water-supply in areas where materials such as PVC or metal are of too high a cost or are unavailable.

4.5 Future Work

In order to make a suction pump atop a bamboo well fully functional, an experimental trial can be performed making a stronger base, or some sort of concrete apron, that will absorb the movement of the above-ground suction pump whereby keeping the bamboo and pump connection air-tight and functional for a longer time period.

As this is still one of the few outdoor scientifically monitored experiments of bamboo, more experiments assessing how differently treated bamboo samples degrade and their resistance to molds and pests in an outdoor setting, below-ground should be performed and published to advance the understanding of appropriate bamboo construction options.

4.6 References

Allison, S. V., Sternberg, Y. M., Knight, R. (1978). Well casings and screens from single stalks of bamboo, and a manually operated slotter. Appropriate Technology.

Appu, P. S. (1974). The bamboo tubewell: a low cost device for exploiting ground water. Economic and Political Weekly, A63-A65.

Arif, M. T. (1978). A study on bamboo tube-well for irrigation. Rural Development Academy, Bogra. Bangladesh.

Arinasa, I. B. K., & Bagus, I. (2010). Bamboo diversity and utilization in Balinese rituals at Angsri Village, Bali, Indonesia. Bamboo Science & Culture: The Journal of the American Bamboo Society, 23(1), 29–37.

Barnett, H.L. and Hunter, B.B., 1972. Illustrated genera of imperfect fungi. Illustrated genera of imperfect fungi., 3rd edition, Burgess Publishing Co., Minneapolis, 241 p.

Cai, L., Zhang, K., McKenzie, E. H., & Hyde, K. D. (2003). Freshwater fungi from bamboo and wood submerged in the Liput River in the Philippines. *Fungal Diversity*.

Carriker, N.E., Gillespie, W.T., & Brezonik, P.L. (1976). Boron and arsenic studies in Florida waters. Florida Water Resources Research Center, Research Project Technical Completion Report, 34.

Chandna, P. (2004). Increasing the productivity of underutilized lands by targeting resource conserving technologies--a GIS/remote sensing approach: A case study of Ballia District, Uttar Pradesh, in the Eastern Gangetic Plains. CIMMYT (International Maize and Wheat Improvement Center).

Clay, E.J. (1980). The economics of the bamboo tubewell. Ceres, 13(3), 43-47.

Dommen, A. J. (1975). The bamboo tube well: A note on an example of indigenous technology. Economic Development and Cultural Change, 23(3), 483-489.

Erakhrumen, A. A. (2009). Tensile strength properties of wild grown *Bambusa vulgaris* treated with neem seed oil in Southwest Nigeria. Journal of Bamboo and Rattan, 8(1/2), 95–102.

Erakhrumen, A.A. (2010). Assessing the effectiveness of need seed oil treatment for split-bamboo (*Bambusa vulgaris*) against *Pycnoporus* sanguineus based on tensile strength properties. Bamboo Science and Culture: The Journal of the American Bamboo Society, 27(1), 36–48.

Garland, L. (2003). Vertical soak diffusion. Environmental Bamboo Foundation. Bali, Indonesia.

Hartwich, F. (2012). Bamboo training manual 1: bamboo harvesting and preservation. Bamcraft – Crafting a Green Future: Bamboo in the Curio and Souvenir Industry of Kenya. Government of Japan, United Nations Industrial Development Organization, and Kenya Forestry Research Institute.

Held, R. B., Zhang, Q., & Mihelcic, J. R. (2013). Quantification of human and embodied energy of improved water provided by source and household interventions. Journal of Cleaner Production, 60, 83-92.

Hyde, K. D., Zhou, D., McKenzie, E. H. C., Ho, W. H., & Dalisay, T. (2002). Vertical distribution of saprobic fungi on bamboo culms. *Fungal Diversity*.

International Standards Office (ISO) (2004). ISO 22157-1. Bamboo: Determination of physical and mechanical properties. Part 2: Laboratory manual. Geneva, ISO.

Jha, U.M., Program Director (2004). Economics of bamboo boring: a study of the North-East Region of Bihar. Government of India, Planning Commission (SER Division), New Delhi, 92 pages.

JMP, WHO and UNISEF (2019). Progress on household drinking water, sanitation and hygiene 2000-2017. Special focus on inequalities. New York: United Nations Children's Fund (UNICEF) and World Health Organization.

Kabir, M.F., Bhattacharjee, D.K., & Sattar, M.A. (1993). Effect of age and height on strength properties of *Dendrocalamus langispathus*. Bamboo Information Centre India Bulletin, 3, 11–15.

Kaminski, S., Lawrence, A., Trujillo, D., & King, C. (2016). Structural use of bamboo. Part 2: durability and preservation. Structural Engineering, 94(10), 38-43.

Kumar, P. S., Kanwat, M., Choudhary, V. K. (2013). Mathematical modeling and thin-layer drying kinetics of bamboo slices on convective tray drying at varying temperature. Journal of Food Processing and Preservation, 37(5), 914-923.

Laha, R. (2000). Bamboo uses for housing by the different tribes of Northeast India. Bamboo Science and Culture, The Journal of the American Bamboo Society, 14(1), 10–14.

Liese, W. (1987). Research on bamboo. Wood Science and Technology, 21(3), 189-209.

Liese, W. (1991). Progress in bamboo research. Journal of the American Bamboo Society, 8(1&2).

Liese, W. (1992). The structure of bamboo in relation to its properties and utilization. Proceedings of the International Symposium on Industrial Use of Bamboo, Beijing, China, 7–11.

Liese, W. (1998). *The Anatomy of Bamboo Culms* (Vol. 18). Brill.

Liese, W. (2004). Preservation of bamboo structures. Ghana Journal of Forestry, 15(1), 40–48.

Liese, W. & Kumar, S. (2003). INBAR Technical Report 22: Bamboo Preservation Compendium, Beijing, China: INBAR.

MacCarthy, M.F., Buckingham, J.W., Mihelcic, J.R. (2013a). EMAS household water supply technologies in Bolivia. Increasing access to low-cost water supplies in rural areas, Field Note No. 2013-4, Rural Water Supply Network (RWSN), Switzerland, 12 pages. http://www.rural-water-supply.net/fr/ressources/details/518

MacCarthy, M.F., Annis, J.E., J.R. Mihelcic (2013b). Unsubsidized self-supply in eastern Madagascar. Water Alternatives, 6(3), 424-438

MacCarthy, M.F., Carpenter, J.D., Mihelcic, J.R. (2017). Low-cost water-lifting from groundwater sources: Comparison of the EMAS pump with the rope pump. Hydrogeology Journal, 25 (5), 1477–1490.

Manalo, R. D., Acda, M. N. (2009). Effects of hot oil treatment on physical and mechanical properties of three species of Philippine bamboo. Journal of Tropical Forest Science, 21 (1), 19–24.

Martin, T.D., Brockhoff, C.A., Creed, J.T. (1994). Method 200.7 determination of metals and trace elements in water and wastes by inductively coupled plasma-atomic emission spectrometry. EMMC Methods Work Group - Method 200.7, revision 4.4

Pant, N. (1984). Community Tubewell: An Organisational Alternative to Small Farmers' Irrigation. Economic and Political Weekly, A59-A66.

Parker, J.W. (1992). Surficial Aquifer Hydrogeology in A Covered-Karst Terrane. Masters Thesis, University of South Florida.

Mihelcic, J.R., E.A. Myre, L.M. Fry, L.D. Phillips, B.D. Barkdoll. (2009). Field Guide in Environmental Engineering for Development Workers: Water, Sanitation, Indoor Air, American Society of Civil Engineers (ASCE) Press, Reston, VA.

Olic, A. B. & Lorenzetti, E. R. (2013). Tratamentos preservativos em bambu (*Dendrocalamus giganteus*) no controle de oranismos xilófagos. VI Fórum Regional de Agroecologia, 36-41.

Orr, A., Islam, N., Barnes, G. (1991) The Treadle Pump: Manual irrigation for small farmers in Bangladesh. Rangpur Dinajpur Rural Service, NGO. Dhaka, Bangladesh. Printing funded by PACT Bangladesh/PRIP with assistance from USAID.

Rahman, M. (1976). A preliminary report on two experimental bamboo wells in Comilla Kotwali Thana. Bangladesh Academy for Rural Development.

Shakya, S. K., Singh, S. R., Anjaneyulu, B., Vashisht, A. K. (2009). Design of a low-cost bamboo well. Groundwater, 47(2), 310-313.

Singer, T. (2010). Preserving bamboo with borates. A Regional Supplement to ECHO Development Notes Issue 4, Rain Tree Foundation, Chiang Mai, Thailand.

Technical Brief No5 (1985). Technical Brief No5/Slotted bamboo tubewell screen. Waterlines, 4(1). Retrieved from http://www.jstor.org/stable/24678025.

Teron, R., & Borthakur, S. K. (2012). Traditional uses of bamboos among the Karbis, a hill tribe of India. Bamboo Science & Culture, 25(1).

Tiburtino, R. F., Paes, J. B., Beraldo, A. L., Arantes, M. D. C., & Brocco, V. F. (2015). Tratamento preservativo de duas espécies de bambu por imersão prolongada e boucherie modificado. Floresta e Ambiente, 22(1), 124-133.

Ubidia, J.A.M. (2002). Traditional bamboo preservation methods in Latin America. International Network for Bamboo and Rattan – INBAR. Faculty of Architecture, University of Guayaquil, Ecuador.

Wahab, R., Samsi, H.W., Sulaiman, O., Salim, R. & Hashim, R. (2007). Properties of oil-cured cultivated *Bambusa vulgaris*. International Journal of Agricultural Research, 2(9), 820–825.

Watanabe, T., 2010. Pictorial atlas of soil and seed fungi: morphologies of cultured fungi and key to species. CRC press.

WHO (2003). Boron in drinking-water. Guidelines for Drinking-Water Quality. 2nd ed. Geneva: World Health Organization.

CHAPTER 5: SUMMARY AND CONCLUSIONS

5.1 Problem Statement

Although bamboo is a sustainable and viable material for construction because of its high growth rate, prevalence in many parts of the world, and high strength properties, it is not commonly used for many engineering applications. A primary reason for this lack of use identified in this dissertation research was lack of agreement in mechanical property variables which influence properties and lack of design data. The strength properties of bamboo have been determined by individual researchers located in numerous regions of the world but are published in different languages (namely English, Spanish, and Portuguese) and derived using different testing standards (some developed specifically for bamboo, some developed for wood, some for plastics). These items and others have resulted in a large range of reported mechanical property values, which had not yet been aggregated, compared, or synthesized for common variables. This lack of uniformly collected data and understanding of the strength performance data has caused bamboo to not be considered as a suitable building material for many designers.

Additionally, few published experiments have been conducted in the field which assess the durability of bamboo with time. Many bamboo mechanical property tests are performed on freshly cut bamboo; the values attained are unrealistic as bamboo inevitably dries and shrinks radially over time. No mechanical property tests which assess air-dried bamboo after several years of use have previously been reported, to our knowledge, including as related to the proposed use as a groundwater well placed below the land surface.

5.2 Findings

In Chapter 2, it was determined that the strength properties of bamboo are sufficient for construction and in fact are comparable to those reported for timber. The seven mechanical properties reviewed in this chapter were shear strength, compressive strength, tensile strength, modulus of rupture (MOR), compressive modulus of elasticity (MOE), bending modulus of elasticity (MOE), and tensile modulus of elasticity (MOE). Strength properties were found to have a very large range of values mainly due to differences in the mechanical property testing standard employed. Parameters which had a small effect on mechanical property values were moisture content and bamboo species. Other parameters assessed (i.e., post-harvest treatment and density) were not seen to highly influence bamboo properties.

Bamboo species was shown to have some relation to mechanical properties, although not as much as might be expected. Although many species of bamboo exist, only ~10 species are commonly used in construction. If these ~10 species continue to be used and studied, they could each, with time, have their own specific mechanical property values, as is reported for different timber species. The advantage of grouping all species together, as is done in this work, is that, theoretically, any large diameter bamboo species can be used with confidence without the need for identification and promoting native indigenous species of bamboo for planting or conservation, whereby truly promoting sustainability and ecological cohesion.

In Chapter 3, due to the large range of mechanical strength property values identified in the Chapter 2, an all-encompassing (all common structural bamboo species, bamboo treatments, densities, etc.) statistical study was performed on compressive, shear, bending, and tensile strengths using published raw data from 25 publications which yielded 3,806 raw data values. Using common design equations used for steel, timber, and concrete applied to bamboo using the raw data, safety factors, resistance factors, and respective failure rates were established. Design equations of Allowable Stress Design (ASD), which generate safety factors, and Load Resistance Factor Design (LRFD), which generate resistance factors were calculated. Monte Carlo statistical analyses of one million randomly generated data points (derived from the bamboo raw data) was performed for verification, per bamboo structural property (i.e. compressive strength, shear strength, tensile strength, and bending strength). This analysis allows unaltered bamboo culms to be used in structural applications with the confidence of derived safety and strength reduction factors for the first time, as no safety factors for bamboo culms have been previously calculated, to our knowledge.

For Chapter 4, although many mechanical property tests have been performed for bamboo, they have nearly all been on either freshly cut bamboo or on bamboo that was recently dried (~3 months after cutting). There are also few applications of bamboo used to solve global water, sanitation, and hygiene (WASH) problems. Therefore, a field study was carried out that installed bamboo wells to assess feasibility and functionality. The installed subsurface bamboo wells were assessed by monitoring certain water quality parameters and by subsequent (i.e. after removal of bamboo wells being in the ground for 3.5 years) mechanical compression tests to obtain compressive strength and compressive modulus of elasticity data. Same quality compression tests were performed on same treated and species air-dried control bamboo samples that were in an air-conditioned lab for 3.5 years for comparison. The bamboo wells installed in the field consisted of bamboo culms that were treated with boric acid and coconut oil in an attempt to lower biological degradation of the installed well casings, as well as air-dried control wells. This study thus allowed for collection of realistic data of control air-dried dried and installed bamboo after several years of use to be gathered and compared to published bamboo data. It was found that both full culm bamboo control air-dried samples which were in a lab for 3.5 years and full culm bamboo wells which were installed in the ground for 3.5 years had compressive strength values and modulus of elasticity values within the ranges of those published in the literature and established in Chapters 2 and 3. Control samples had values of compressive strength and modulus of elasticity of 44-90 MPa (72 MPa average) and 15-31 GPa, respectively. Bamboo wells had values of compressive strength and modulus of elasticity of 22-61 MPa (39 MPa average) and 7-25 GPa, respectively.

5.3 Conclusion

In conclusion, the overall goal of this research is to advance the understanding of the engineering properties of bamboo and its potential use in construction/structural applications. This enables the practical use of bamboo in structural and water, sanitation, and hygiene (WASH) applications, whereby promoting a sustainable material to improve community well-being by meeting some of the most basic needs of people (e.g., housing and water). This research does this by establishing mechanical property value averages and ranges of bamboo (Chapter 2), determining safety and resistance factors for use of bamboo in structural applications (Chapter 3), and assessing the feasibility of bamboo serving as the underground casing in an experimental groundwater well field experiment (Chapter 4). The main author sincerely hopes that this research is a small but important stepping stone in a path forward to a more sustainable future for humanity to meet its basic needs while conserving and integrating better with nature. Bringing bamboo into the everyday lives of people does more than serve a need, it integrates and reminds humanity that it is a part of and can, in fact, live in harmony with nature, bettering lives and overall health. Enhancing the uses of natural materials such as bamboo and other sustainable bioforestry products can potentially lead to a decrease in the use of plastic materials and formaldehyde treated timber products that can release harmful chemicals to the built environment and are attributed to causing health problems (Karstadt 1976; Allsopp et al. 2000; Yu & Kim 2012). Therefore, consideration of the use of bamboo for a variety of applications such as housing and water distribution, begins with a clear understanding of its mechanical properties, allowing the material to be safely designed by architects and engineers.

5.4 Recommendations

The field of bamboo for use in structural applications is still highly understudied and efforts must continue. Bamboo offers a high strength sustainable material that can meet the needs of a growing human population. The safety factor analysis presented in this work is the first of its kind for intact bamboo culms. More simulations, analyses, and ultimately standards must be adopted and integrated into the field of construction in order for any large-scale change to take place.

Another issue that must be addressed regarding bamboo for structural use is the way in which the connecting joints will be made. Although there are studies which critically study bamboo joints (Awaludin & Andriani 2014; Trujillo & Wang 2015), they are made with current standard materials made of metals such as screws, bolts, and annular rings around the bamboo. Traditional peoples who have worked with bamboo for centuries know that bamboo should not be pierced by nails or screws because it causes splitting in the bamboo and therefore use complex tying methods with natural ropes to make secure joints (Dunkelberg & Fritz 1985). These tying methods have the additional advantage of being truly environmentally sustainable, using all natural and biodegradable materials. Efforts should be made to study these traditional tying methods scientifically.

An experimentally studied deficient and interesting field, which the main author found reviewing the published literature, is bamboo use in water provision. Although it has been proven possible, more work should be done to make this reality highly used in actuality. Bamboo is an organic material, which therefore offers a water transfer material which does not leach harmful chemicals, such as lead from metal piping and fittings, or endocrine disruptors from PVC piping (Needleman & Bellinger 1991; Latini et al. 2004), while additionally already being conveniently shaped as a pipe whereby lowering processing environmental and financial costs to make the material a functioning pipe. Based on its proven engineering properties, its low-cost, and its local availability in many places, bamboo could be used in households for self-supply water provision technologies such as rainwater harvesting systems and groundwater wells. The values of bamboo as a construction material is exacerbated in places where piped water networks do not exist, are not regularly functional, or are inaccessible to poorer households. The result could potentially be water systems that offer water free of metal or plastic residues.

Finally, bamboo post-harvest treatments, although mentioned in this work, must continue to be scientifically studied. Bamboo treatment methods are not at all standardized yet, as one sees in the timber industry where ‘pressure treated’ woods are of the norm and available for consumers to purchase. Bamboo treatment science is still in its basic stages, as even seemingly conventional bamboo treatments of borax and boric acid solutions used most commonly in the industry are still being debated as to what concentrations should be used and to what grade they preserve bamboo against pest attack and to what extent they increase the overall lifespan of bamboo. More recent experimental natural treatments of oils, vinegars, and leaf extract solutions are still only in the research stages and have still scarcely been monitored in the field although they show promising results in the laboratory. These natural treatments should continue to be studied, specifically in real-world outdoor settings (or in indoor settings for an extended period of time, if planned to be used in indoor applications).

5.5 References

Allsopp, M., Santillo, D., & Johnston, P. (2000). Hazardous chemicals in PVC flooring. Greenpeace Research Laboratories Technical Note, University of Exeter, (14/00).

Awaludin, A., & Andriani, V. (2014). Bolted bamboo joints reinforced with fibers. Procedia Engineering, 95, 15–21.

Dunkelberg, K., & Fritz, J. (1985). Bambus als Baustoff. Bauen mit pflanzlichen Stäben = Bamboo as a building material: Building with vegetal rods. Stuttgart: Karl Krämer.

Karstadt, M. (1976). PVC: Health implications and production trends. Environmental health perspectives, 17, 107-115.

Latini, G., Verrotti, A., & De Felice, C. (2004). Di-2-ethylhexyl phthalate and endocrine disruption: a review. Current Drug Targets-Immune, Endocrine & Metabolic Disorders, 4(1), 37-40.

Needleman, H. L., & Bellinger, D. (1991). The health effects of low level exposure to lead. Annual review of public health, 12(1), 111-140.

Trujillo, D. (2018). Developments in structural design standards with bamboo. World Bamboo Congress Keynote Presentation. Xalapa, Mexico.

Yu, C. W., & Kim, J. T. (2012). Long-term impact of formaldehyde and VOC emissions from wood-based products on indoor environments; and issues with recycled products. Indoor and Built Environment, 21(1), 137-149.

APPENDIX A: PUBLICATIONS OF DATA ACQUISITION FOR CHAPTER 2

Citation	**F_v**	**F_c**	**F_b**	**F_t**	**E_t**	**E_c**	**E_b**
Aladin et al. 2014.						×	×
Amatosa & Loretero 2016		×					
Askarinejad et al. 2015	×						
Bahari & Ahmad 2009	×						
Berndsen et al. 2013		×	×			×	
Chung & Yu 2001		×	×			×	
Colla et al. 2011			×				×
Correal & Albeláez 2010	×	×	×			×	×
Cruz 2002	×			×			
Erakhrumen & Ogunsanwo 2010			×				×
Espiloy et al. 1986		×			×		
Fabiani 2015		×		×			×
Ghavami & Marinho 2005	×	×			×	×	
González, E.G. et al. 2002			×				×
González, H.A.B. et al. 2006				×	×		
González, H.A.B. et al. 2008		×				×	
Gupta et al. 2015		×					
Gyansah et al. 2010		×					
Jiang et al. 2012a	×	×					×
Kamruzzaman et al. 2008			×				×
Lakkad & Patel 1981	×	×			×		
Lee et al. 1994		×		×			
Luna et al. 2014		×				×	×
Manalo & Acda 2009			×				×
Matsuoka & Beraldo 2013			×				×
Mota et al. 2017			×				
Nordahlia et al. 2011			×				×
Nurmadina et al. 2017							×
Okhio et al. 2011		×					
Omobowale & Ogedengbe 2008				×			
Ramírez et al. 2018		×					
Sánchez-Echeverri 2014			×				
Sattar et al. 1990		×	×				×
Takeuchi et al. 2013		×					
Tomak et al. 2012		×	×				
Valero et al. 2005		×	×				
Wahab et al. 2006		×	×				
Wahab et al. 2007	×	×	×				×
Wakchaure & Kute 2012		×		×			
Xu et al. 2014	×					×	
Yu et al. 2008				×	×		
Zaragoza-Hernandez et al 2015		×	×		×	×	×

APPENDIX B: EMAS DRILLING PROCEDURE USED IN CHAPTER 5

Well drilling (shown in Figure B.1) was performed according to EMAS drilling procedures that have described in detail elsewhere (MacCarthy et al. 2013).

Figure B.1 Standard EMAS drilling site at the USF Geopark.

In Figure B.1 the “A” symbol refers to jetting which requires use of a manual mud pump to supply drilling fluid that is lifted from the mud pit to the drilling handle where it flows down the borehole and exits through the drill bit. The loose sediment at the bottom of the well is lifted to the surface via the drilling fluid. The mud pump is a standard EMAS pump composed of galvanized iron pipes and fittings, glass marbles, and rubber cut from a used car tire (Buchner, 2006). The mud pump used during this study consists of an outer pipe (‘pump cylinder’ – 1.25-inch diameter galvanized iron pipe) with a one-way foot valve on its lower end, and a smaller-diameter inner pipe (‘piston pipe’ 0.75-inch diameter galvanized iron pipe) with a one-way piston valve on its lower end. A rubber gasket on the outside of the piston valve provides a seal with the pump cylinder. The upper end of the piston pipe attaches to a handle, which was constructed of 0.75-inch galvanized iron pipe. The pump is placed in the mud pit so that the piston valve and foot valve are submerged in drilling fluid. The pump cylinder remains static, and when the handle (piston pipe) is lifted, suction force causes the foot valve to open (while the piston valve remains closed), and drilling fluid enters from the mud pit into the pump cylinder. When the handle is then lowered, the foot valve closes, and compression pressure causes the piston valve to open, and water flows into the piston pipe. Continued pumping alternatively displaces water from the well into the pump cylinder then into and up the piston pipe, and the drilling fluid flows out a spout that is located on one side of the pump handle. The mud pump differs from conventional piston pumps in that the water lifted inside the ‘pump rod’ (piston pipe) rather than outside it, which avoids the problem of sealing the pump rod, and additionally results in the drilling fluid being delivered to the pump outlet at pressure (MacCarthy et al, 2013).

The drilling fluid used in this study was a bentonite slurry that was hand-mixed using powdered bentonite and freshwater from a nearby shallow well. The slurry acts as a sealant that coats the borehole and prevents the walls of the borehole from caving in on themselves. The drilling fluid also acts as a vehicle for removing sediment from the borehole while drilling.
In Figure B.1, “B” refers to *percussion drilling* where a drill bit is lifted by the rope tracking through a pulley system and is released to free fall its way back to the soil. The drill should be lifted about 30 cm during each percussion. A ‘universal drilling bit’ made of only rebar and metal pipe was used due to its ease of machinability in any part of the world with access to a welder.

In Figure B.1 “C” refers to *rotation* whereby the drill bit is rotated 90 to 180 degrees clockwise and then returned to its original position using the drilling handle. Additional rotations may be necessary.

APPENDIX C1: pH RAW DATA AND STATISTICAL ANALYSIS

Table C1.1 Raw pH data

		After Initial Well Installation				Before Well Removal	
Well No.	**Well Treatment**	**April 20, 2016**	**June 9, 2016**	**July 13, 2016**	**October 12, 2016**	**May 13, 2019**	**May 17, 2019**
1	Air-dried	7.13	7.1	7.12	7.14	6.09	6.58
2	Air-dried	dry	dry	dry	dry	Well casing plugged	Well casing plugged
3	Coconut oil	7.16	7.11	7.16	7.12	6.18	6.906
4	Coconut oil	7.19	7.13	7.12	7.16	4.19	Well casing plugged
5	Borax & boric acid	dry	dry	dry	dry	Almost dry	6.95
6	Borax & boric acid	7.18	7.14	7.13	7.15	6.37	6.45

Table C1.2 Initial well installation statistical analysis

Well No.	**1**	**2**	**3**	**4**	**5**	**6**
pH value	7.13	dry	7.16	7.19	dry	7.18
	7.1	dry	7.11	7.13	dry	7.14
	7.12	dry	7.16	7.12	dry	7.13
	7.14	dry	7.12	7.16	dry	7.15
n	4	0	4	4	0	4
Average	7.1225		7.1375	7.15		7.15
Stdv	0.017078		0.0263	0.031623		0.021602
COV	0.002398		0.003685	0.004423		0.003021

Table C1.3 Before well removal statistical analysis

Well No.	**1**	**2**	**3**	**4**	**5**	**6**
pH value	**6.09**	Clogged	6.18	4.19	Almost dry	6.37
	6.58	Clogged	6.906	Clogged	6.95	6.45
n	2	0	2	1	0	2
Average	6.335		6.543	4.19	6.95	6.41
Stdv	0.346482		0.51336			0.056569
COV	0.054693		0.078459			0.008825

APPENDIX C2: COMPRESSION TEST RAW DATA PLOTS

Selected compression raw data plots are here presented. For additional data, contact the lead author.

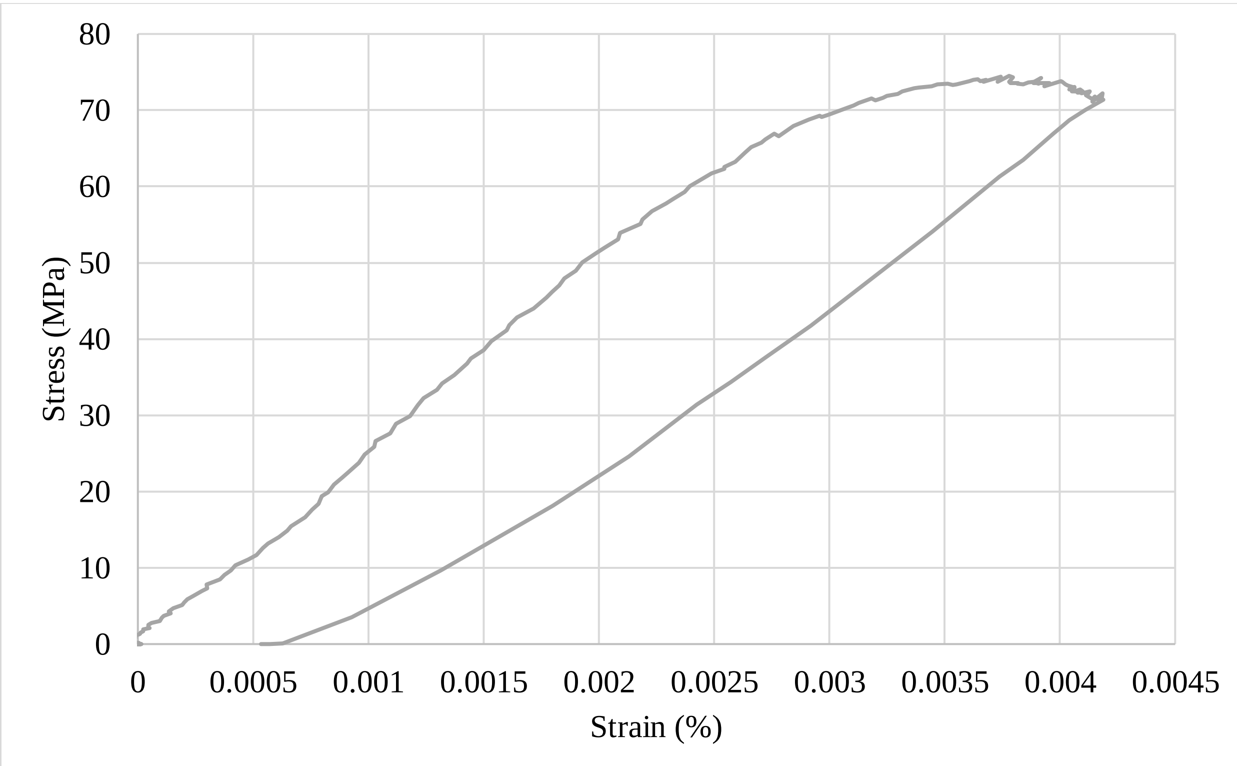


Figure C2.1 Compression raw data plot of specimen A2-37. Control, D. asper, coconut oil treated, node, cross-sectional area = 2.61 in^2, outer diameter = 2.60 in., compressive strength = 74.5.

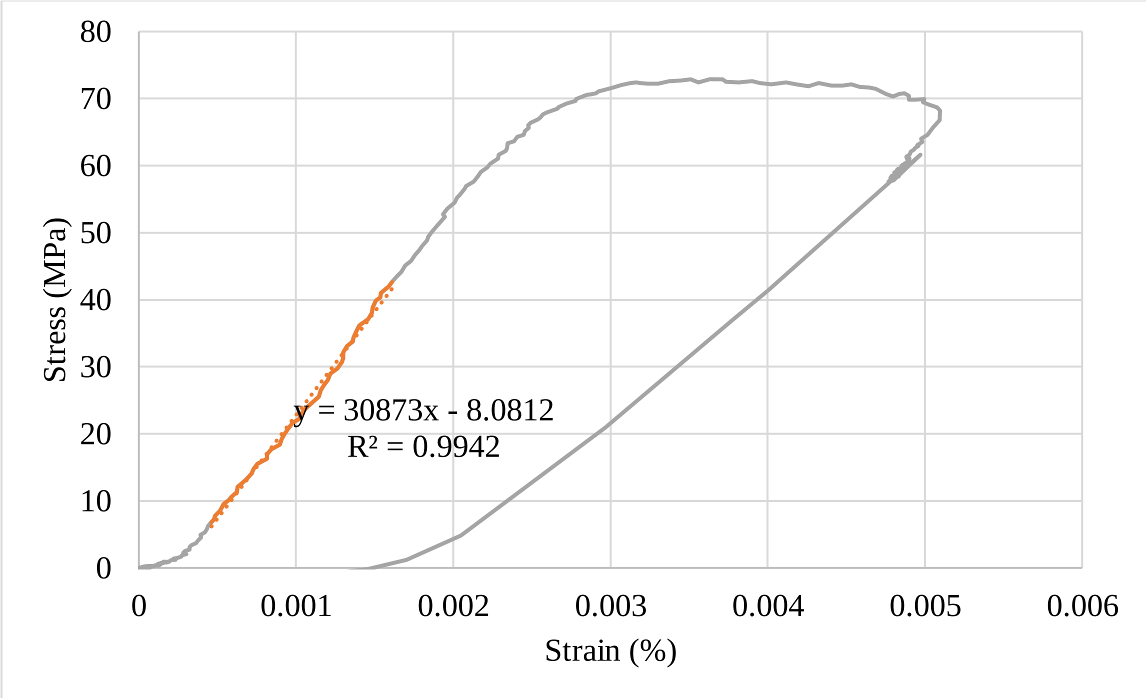


Figure C2.2 Compression raw data plot of specimen A4-31. Control, D. asper, borax &boric acid solution treated, internode, cross-sectional area = 2.83 in^2, outer diameter = 2.40 in., compressive strength = 72.9, compressive modulus of elasticity = 31.

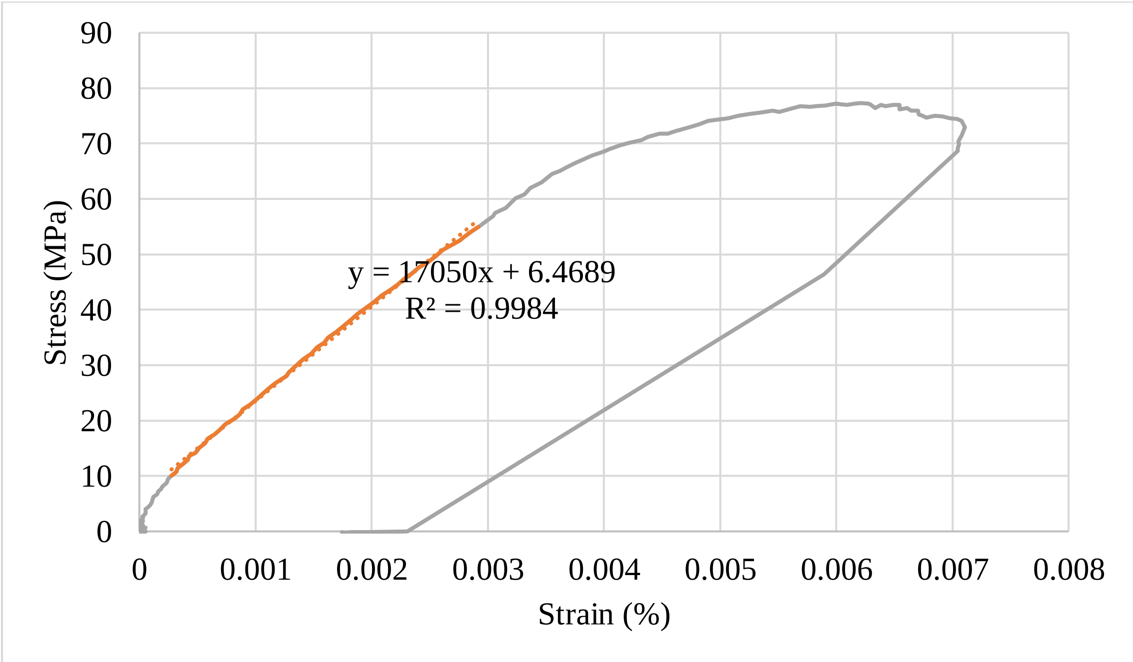


Figure C2.3 Compression raw data plot of specimen A4-34. Control, D. asper, borax &boric acid solution treated, internode, cross-sectional area = 1.89 in^2, outer diameter = 2.43 in., compressive strength = 77.3, compressive modulus of elasticity = 17.

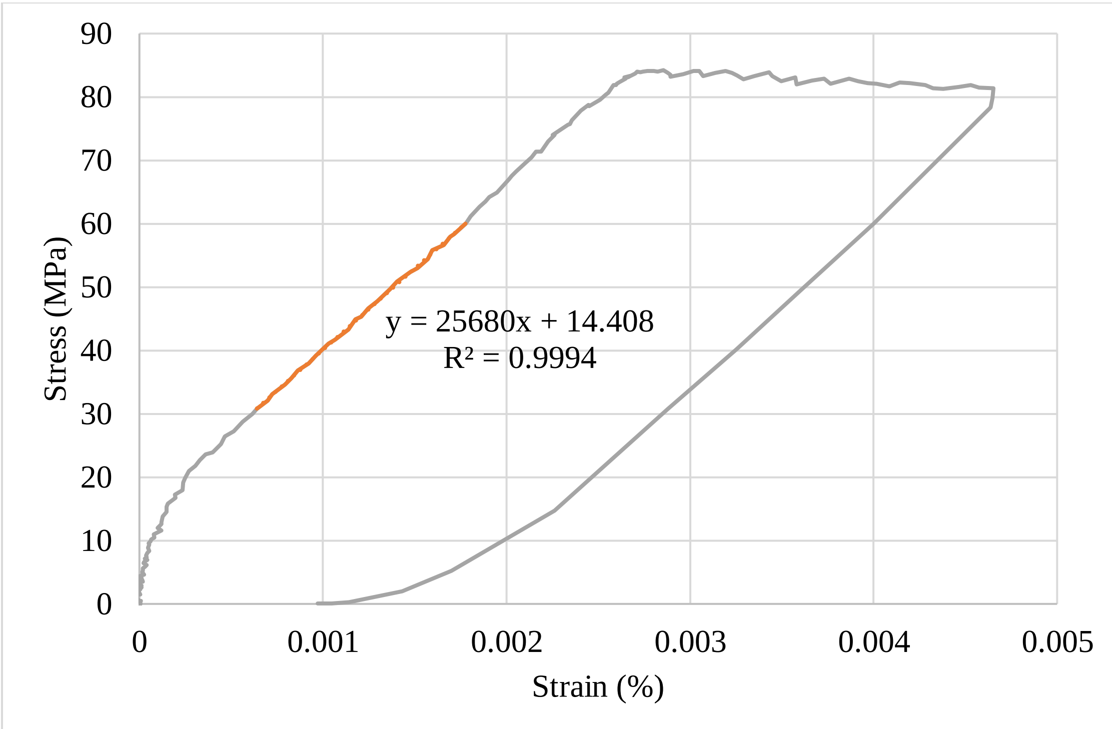


Figure C2.4 Compression raw data plot of specimen A6-64. Control, D. asper, air-dried, internode, cross-sectional area = 1.21 in^2, outer diameter = 2.14 in., compressive strength = 84.2, compressive modulus of elasticity = 26.

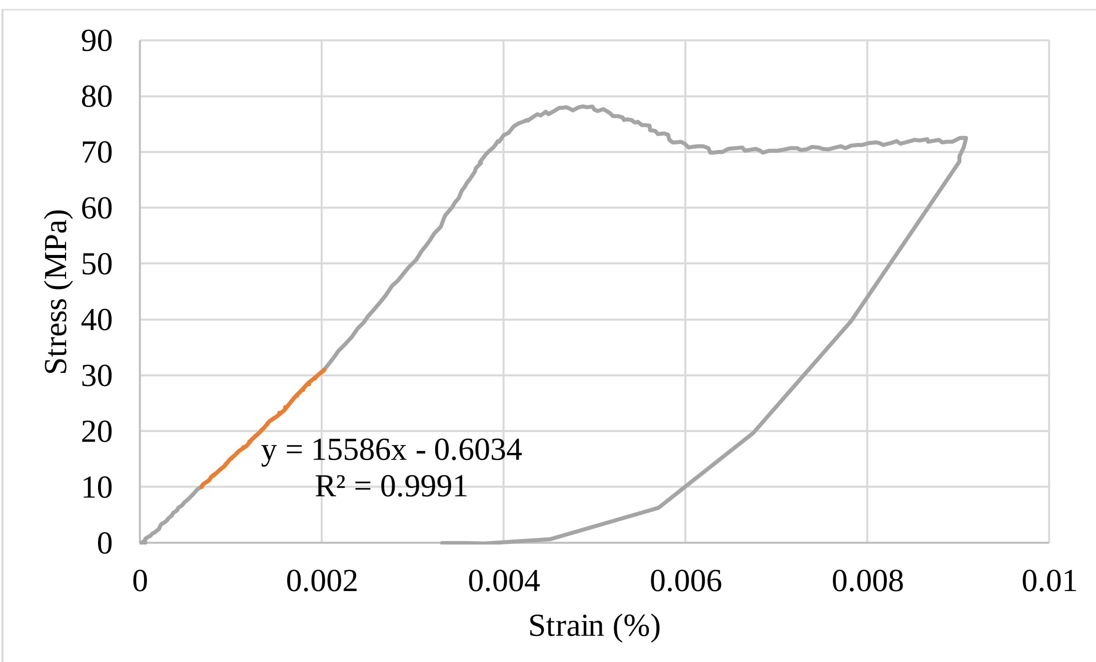


Figure C2.5 Compression raw data plot of specimen A6-67. Control, D. asper, air-dried, internode, cross-sectional area = 1.40 in^2, outer diameter = 2.10 in., compressive strength = 78.2, compressive modulus of elasticity = 16.

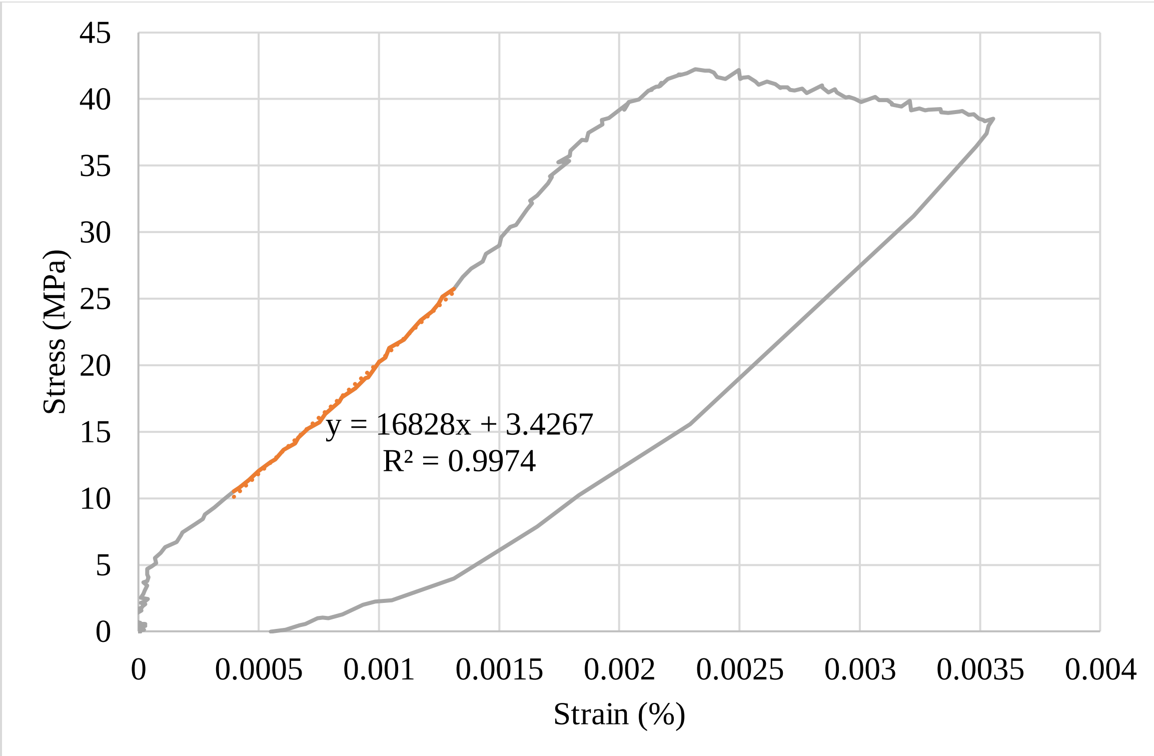


Figure C2.6 Compression raw data plot of specimen W2-2. Well, D. asper, air-dried, internode, cross-sectional area = 1.95 in^2, outer diameter = 2.18 in., compressive strength = 42.2, compressive modulus of elasticity = 17.

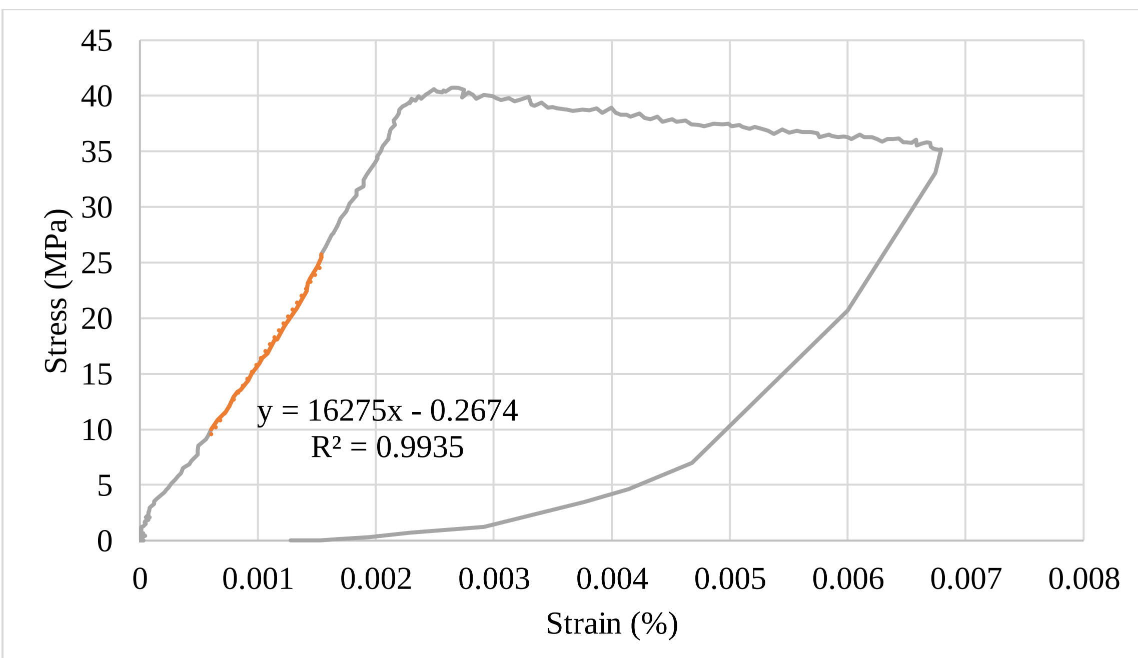


Figure C2.7 Compression raw data plot of specimen W2-4. Well, D. asper, air-dried, internode, cross-sectional area = 2.10 in^2, outer diameter = 2.21 in., compressive strength = 40.7, compressive modulus of elasticity = 16.

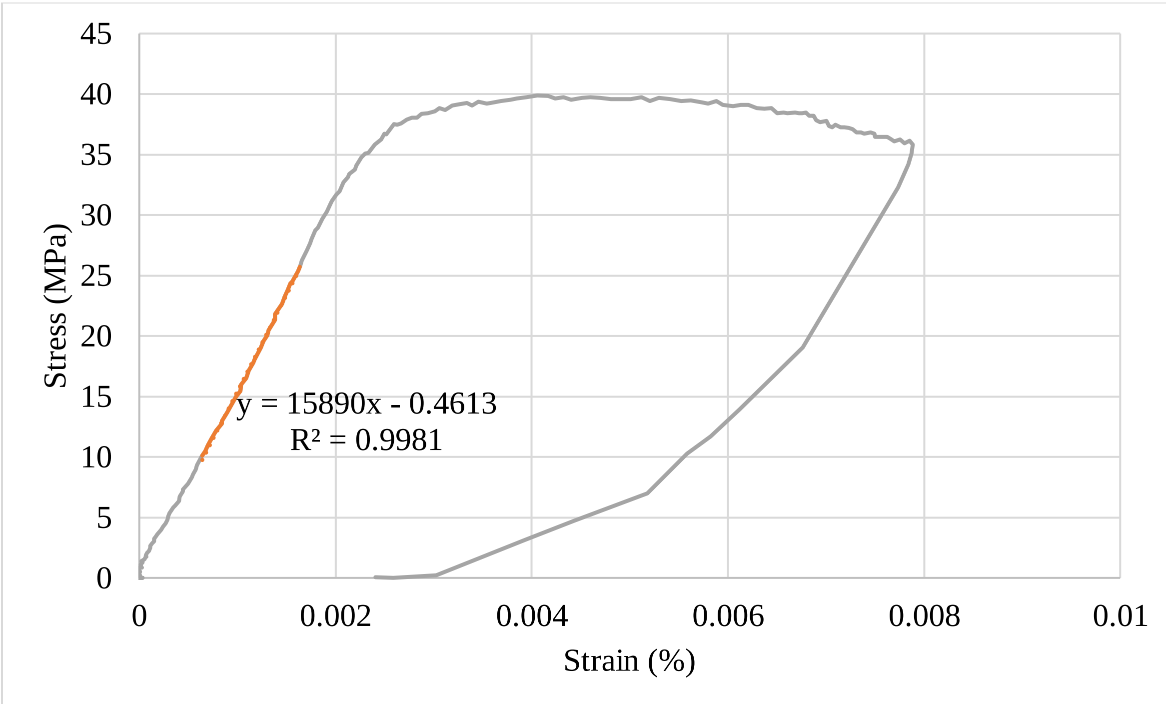


Figure C2.8 Compression raw data plot of specimen W2-5. Well, D. asper, air-dried, internode, cross-sectional area = 2.17 in^2, outer diameter = 2.22 in., compressive strength = 39.9, compressive modulus of elasticity = 16.

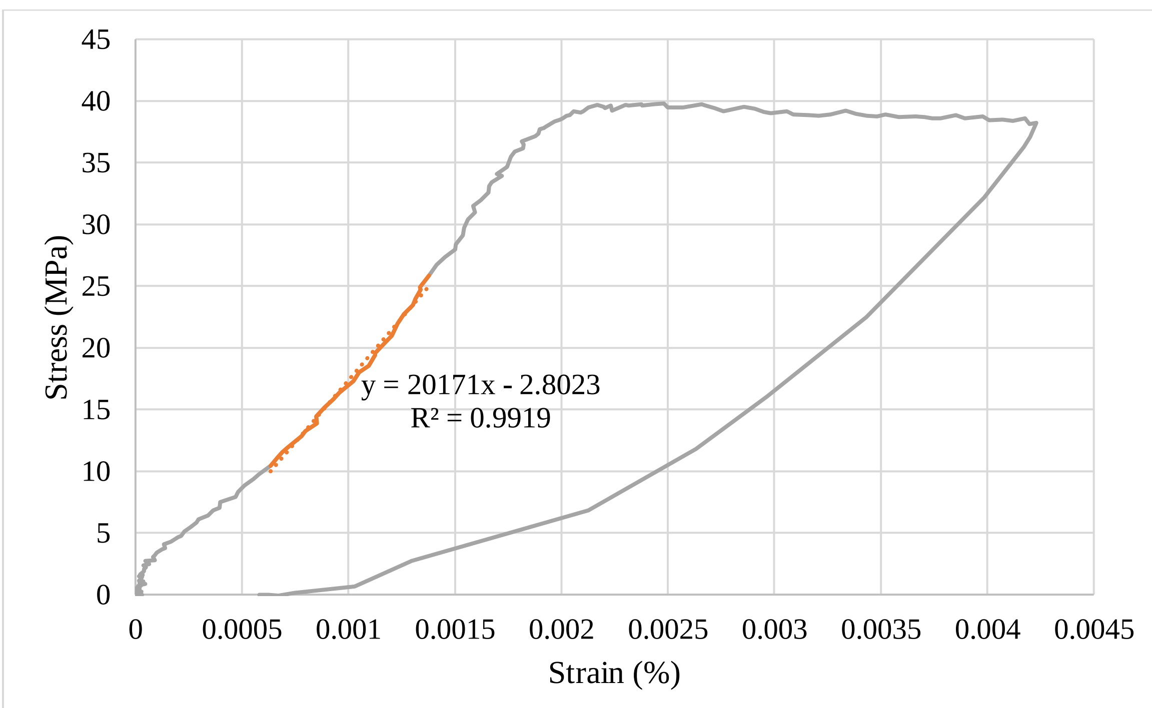


Figure C2.9 Compression raw data plot of specimen W2-12. Well, D. asper, air-dried, internode, cross-sectional area = 2.28 in^2, outer diameter = 2.24 in., compressive strength = 39.8, compressive modulus of elasticity = 20.

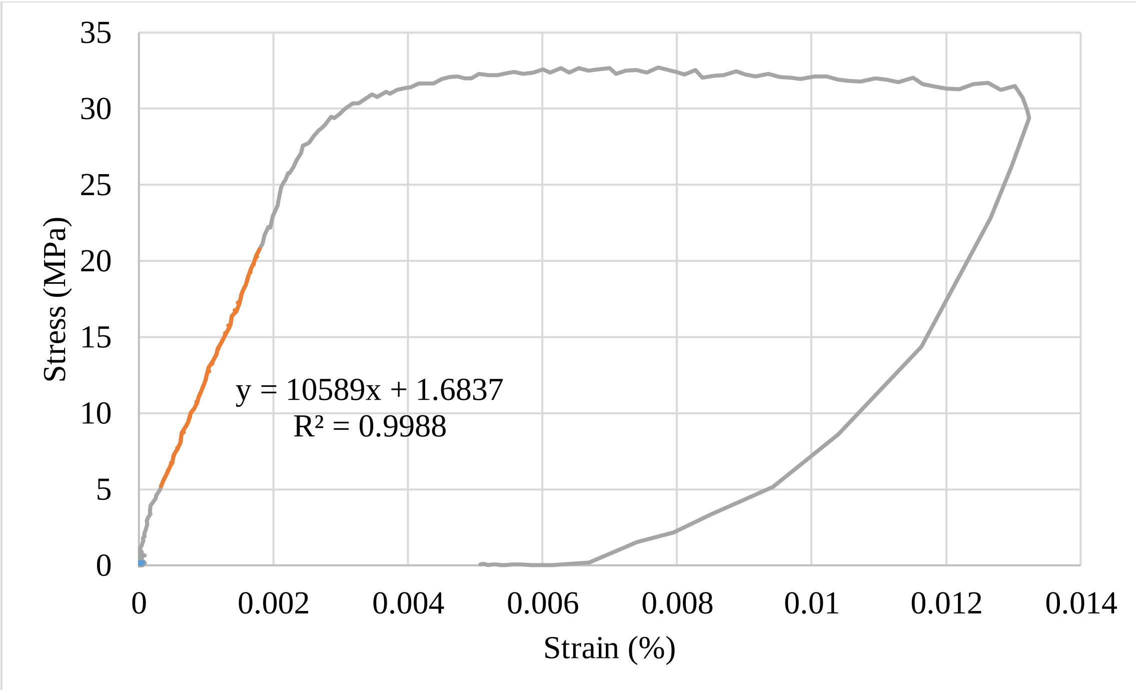


Figure C2.10 Compression raw data plot of specimen W3-1. Well, D. asper, coconut oil treated, internode, cross-sectional area = 1.75 in^2, outer diameter = 2.33 in., compressive strength = 32.7, compressive modulus of elasticity = 11.

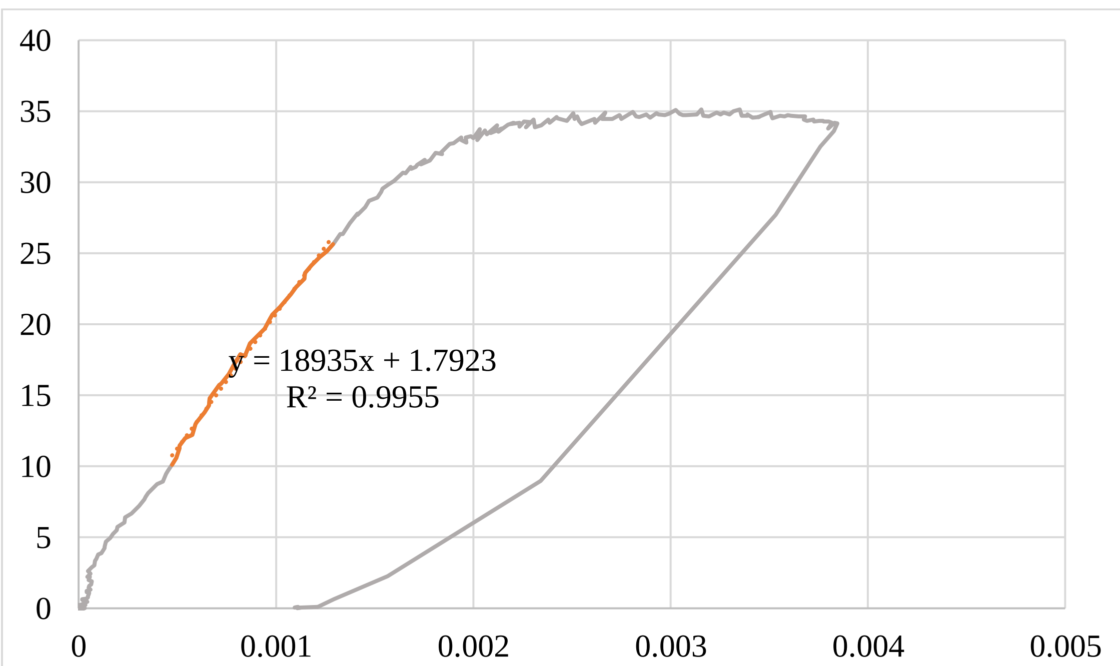


Figure C2.11 Compression raw data plot of specimen W3-3. Well, D. asper, coconut oil treated, internode, cross-sectional area = 1.69 in^2, outer diameter = 2.32 in., compressive strength = 35.1, compressive modulus of elasticity = 19.

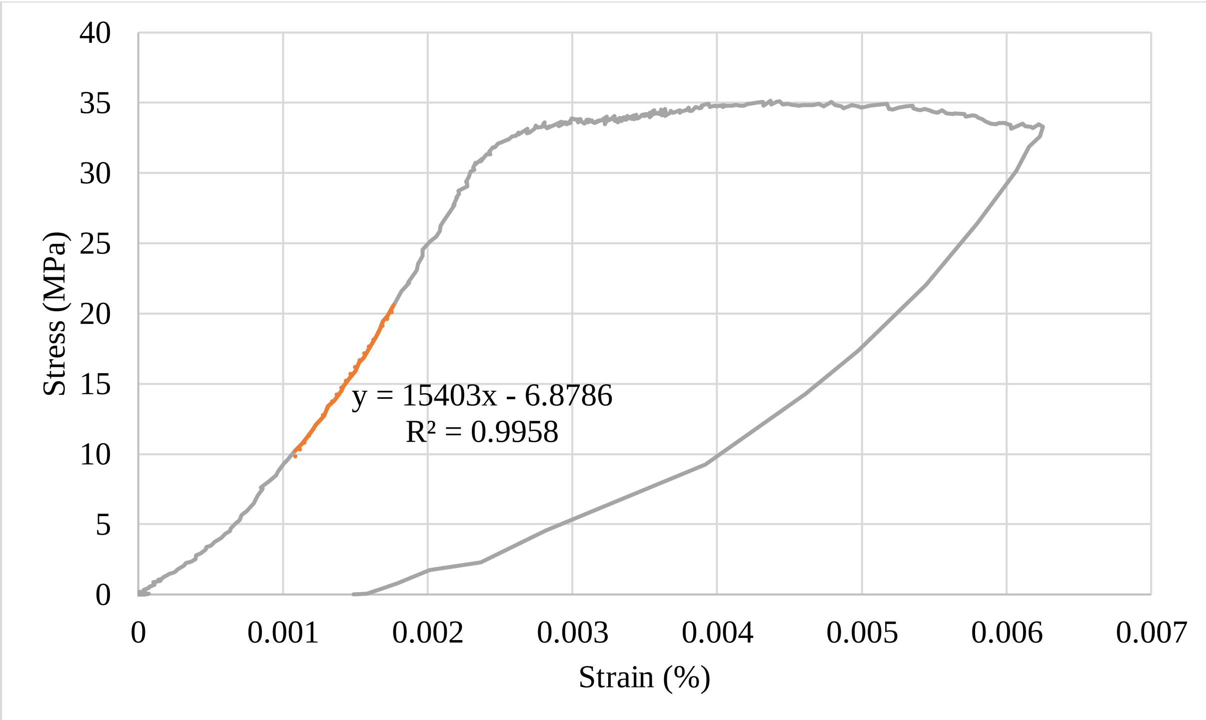


Figure C2.12 Compression raw data plot of specimen W3-24. Well, D. asper, coconut oil treated, internode, cross-sectional area = 2.37 in^2, outer diameter = 2.62 in., compressive strength = 35.1, compressive modulus of elasticity = 15.

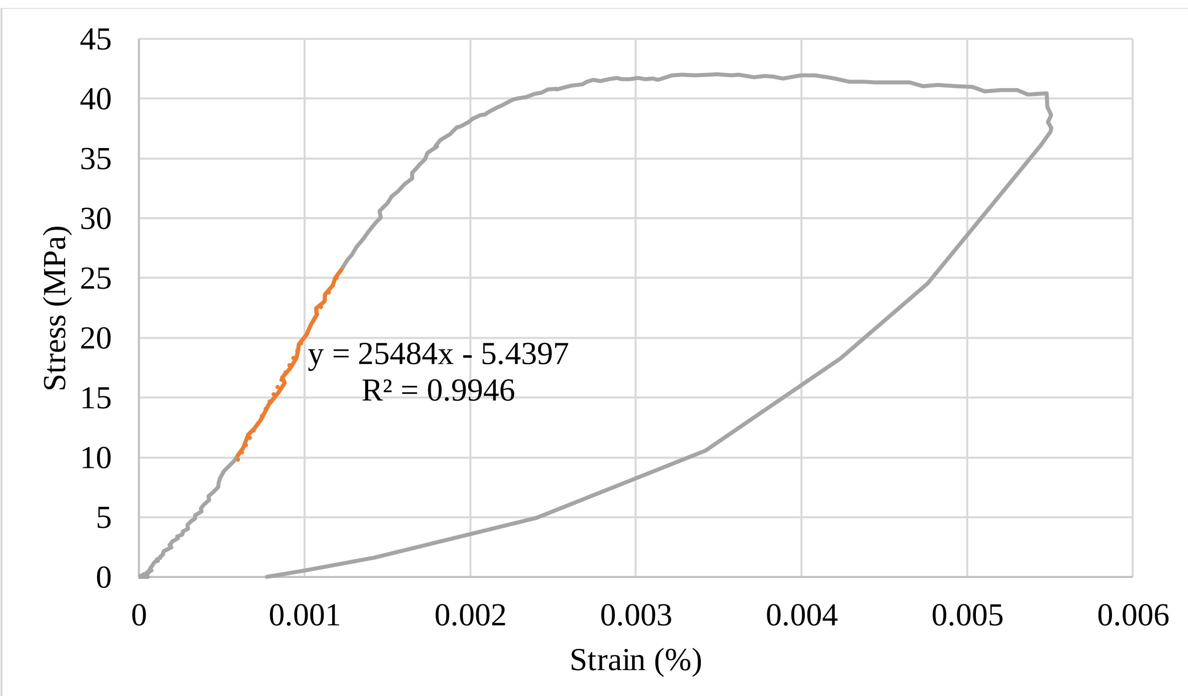


Figure C2.13 Compression raw data plot of specimen W4-1. Well, D. giganteus, coconut oil treated, internode, cross-sectional area = 3.95 in^2, outer diameter = 3.51 in., compressive strength = 42.0, compressive modulus of elasticity = 25.

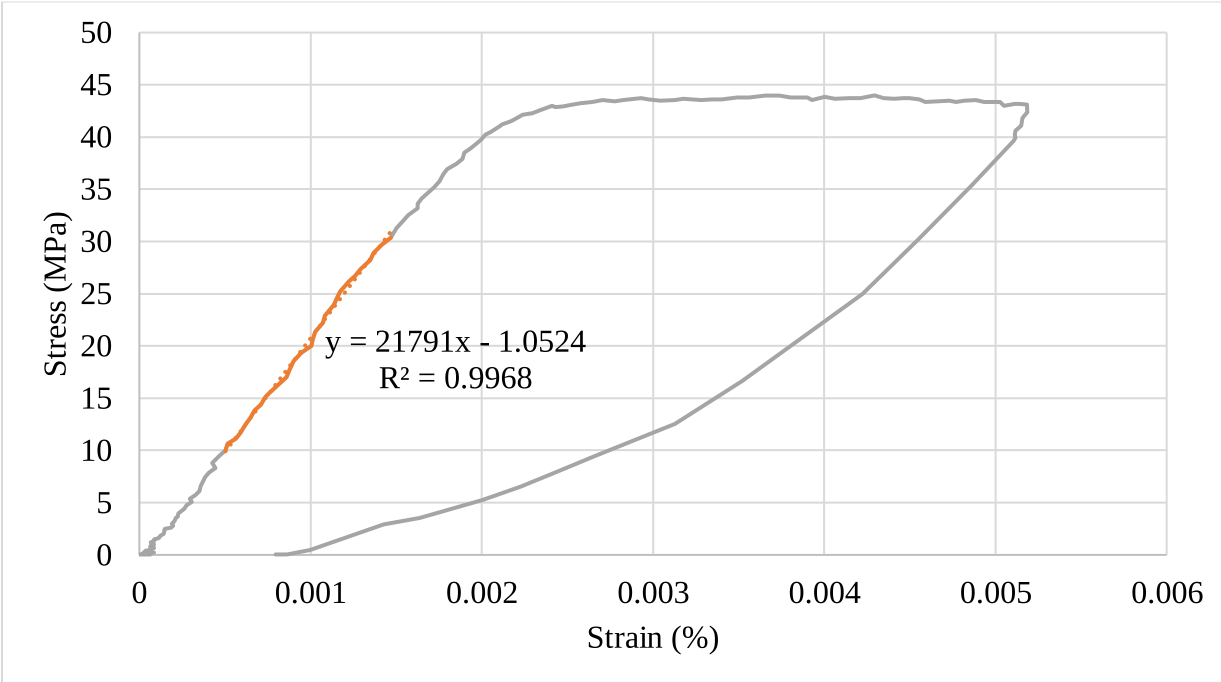


Figure C2.14 Compression raw data plot of specimen W4-4. Well, D. giganteus, coconut oil treated, internode, cross-sectional area = 3.90 in^2, outer diameter = 3.50 in., compressive strength = 44.0, compressive modulus of elasticity = 22.

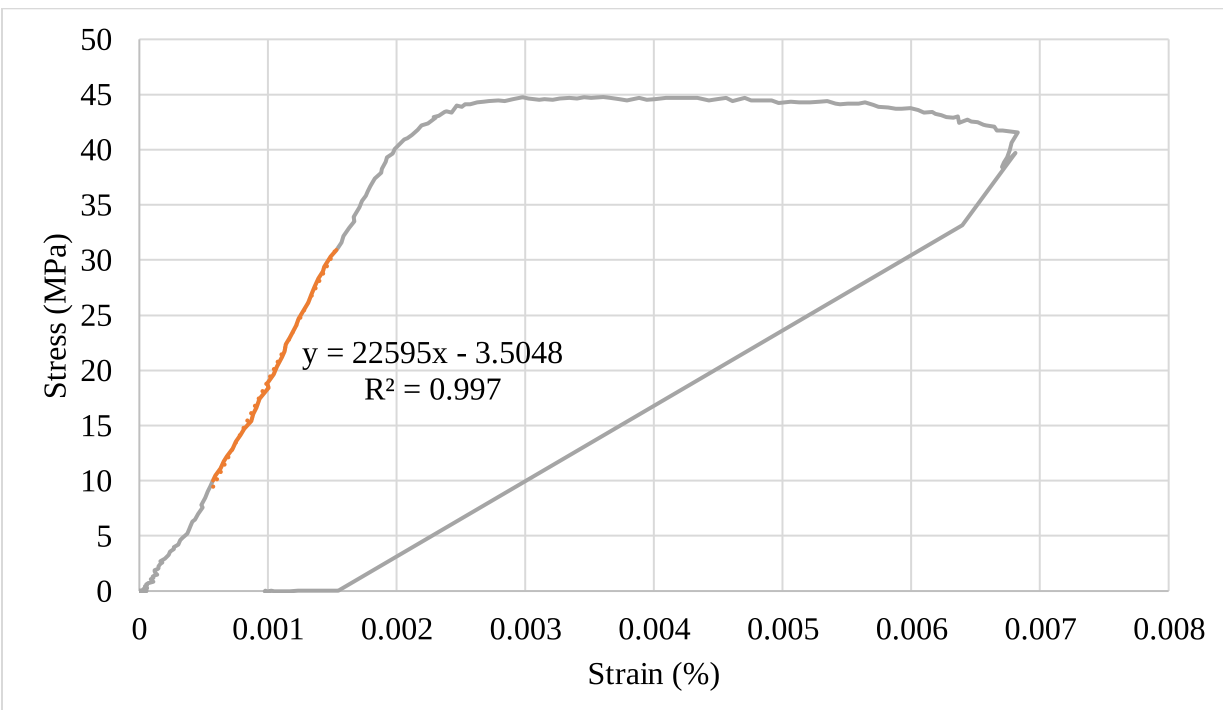


Figure C2.15 Compression raw data plot of specimen W4-6. Well, D. giganteus, coconut oil treated, internode, cross-sectional area = 4.09 in^2, outer diameter = 3.52 in., compressive strength = 44.8, compressive modulus of elasticity = 23.

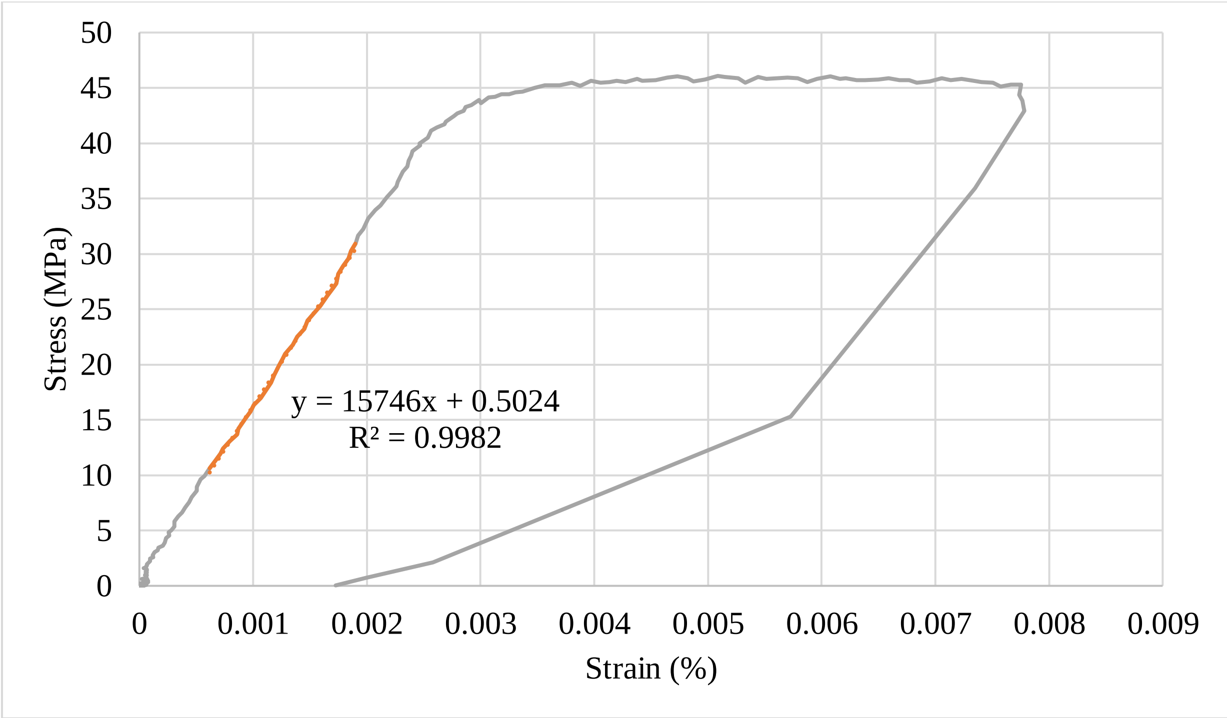


Figure C2.16 Compression raw data plot of specimen W4-7. Well, D. giganteus, coconut oil treated, internode, cross-sectional area = 3.86 in^2, outer diameter = 3.49 in., compressive strength = 46.1, compressive modulus of elasticity = 16.

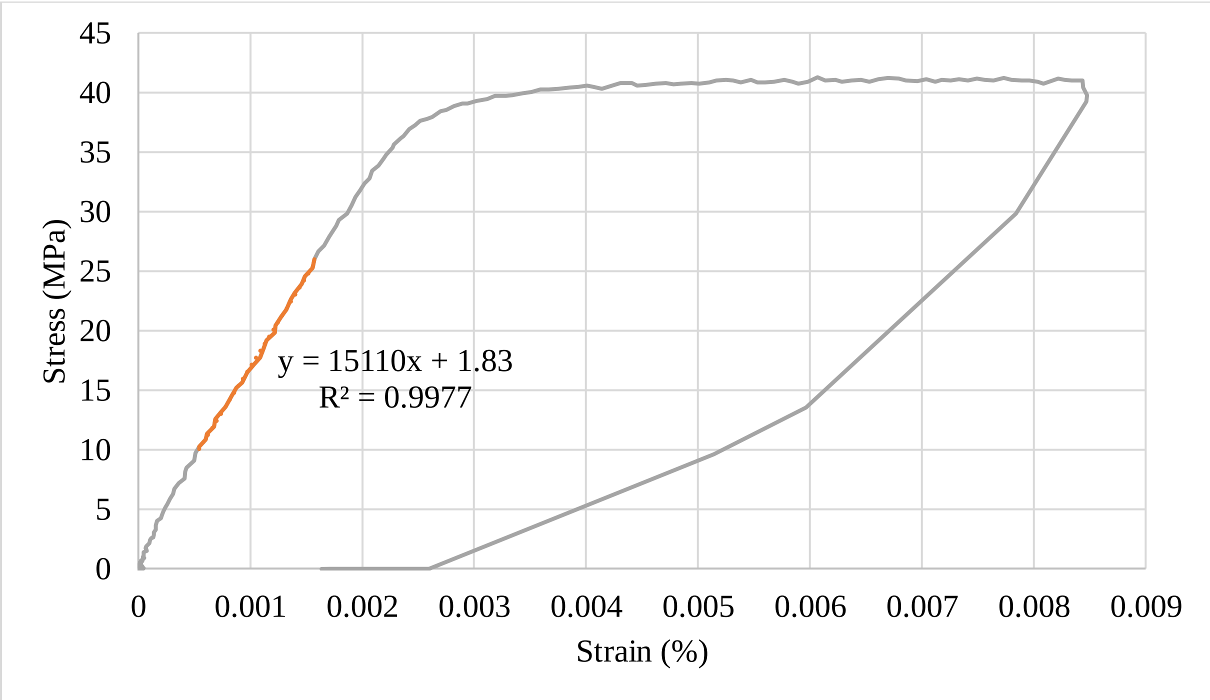


Figure C2.17 Compression raw data plot of specimen W4-8. Well, D. giganteus, coconut oil treated, internode, cross-sectional area = 4.25 in^2, outer diameter = 3.59 in., compressive strength = 41.3, compressive modulus of elasticity = 15.

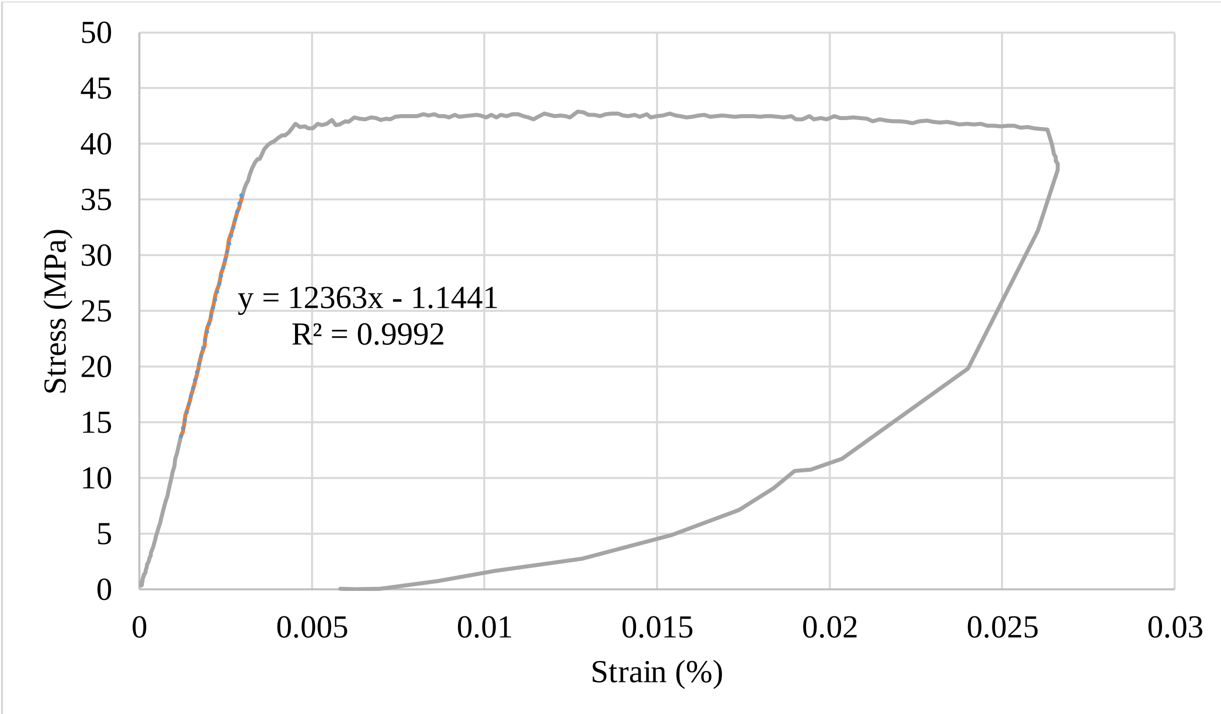


Figure C2.18 Compression raw data plot of specimen W4-10. Well, D. giganteus, coconut oil treated, internode, cross-sectional area = 4.51 in^2, outer diameter = 3.58 in., compressive strength = 42.9, compressive modulus of elasticity = 12.

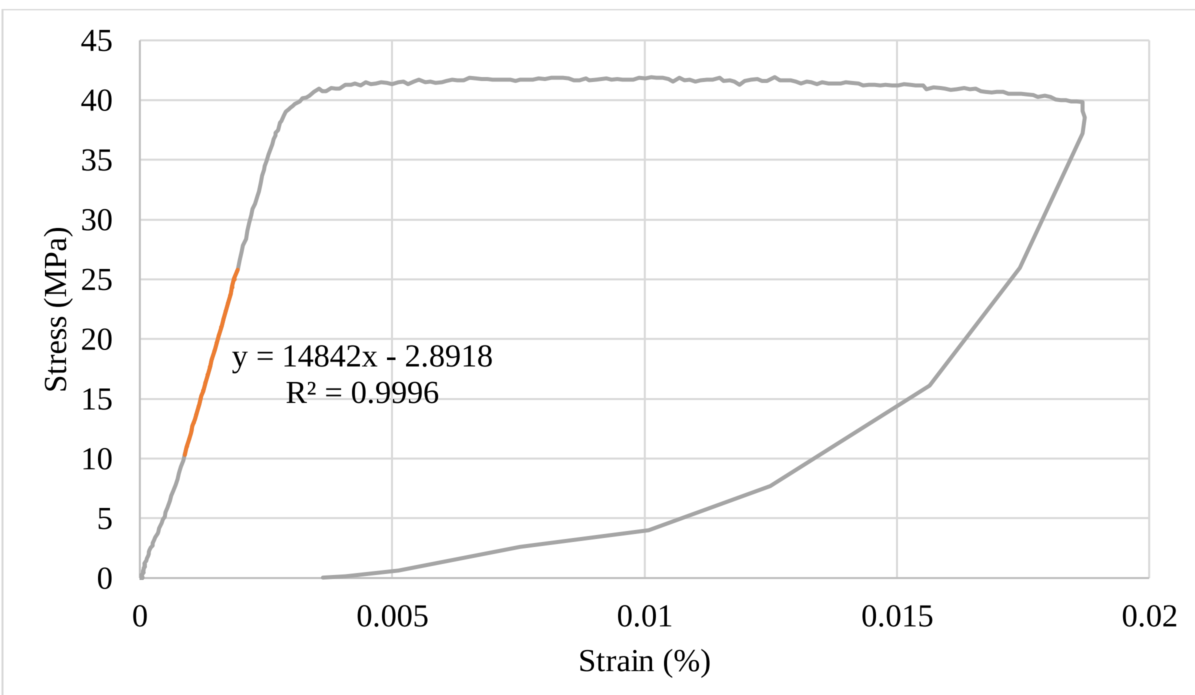


Figure C2.19 Compression raw data plot of specimen W4-11. Well, D. giganteus, coconut oil treated, internode, cross-sectional area = 4.63 in^2, outer diameter = 3.61 in., compressive strength = 41.9, compressive modulus of elasticity = 15.

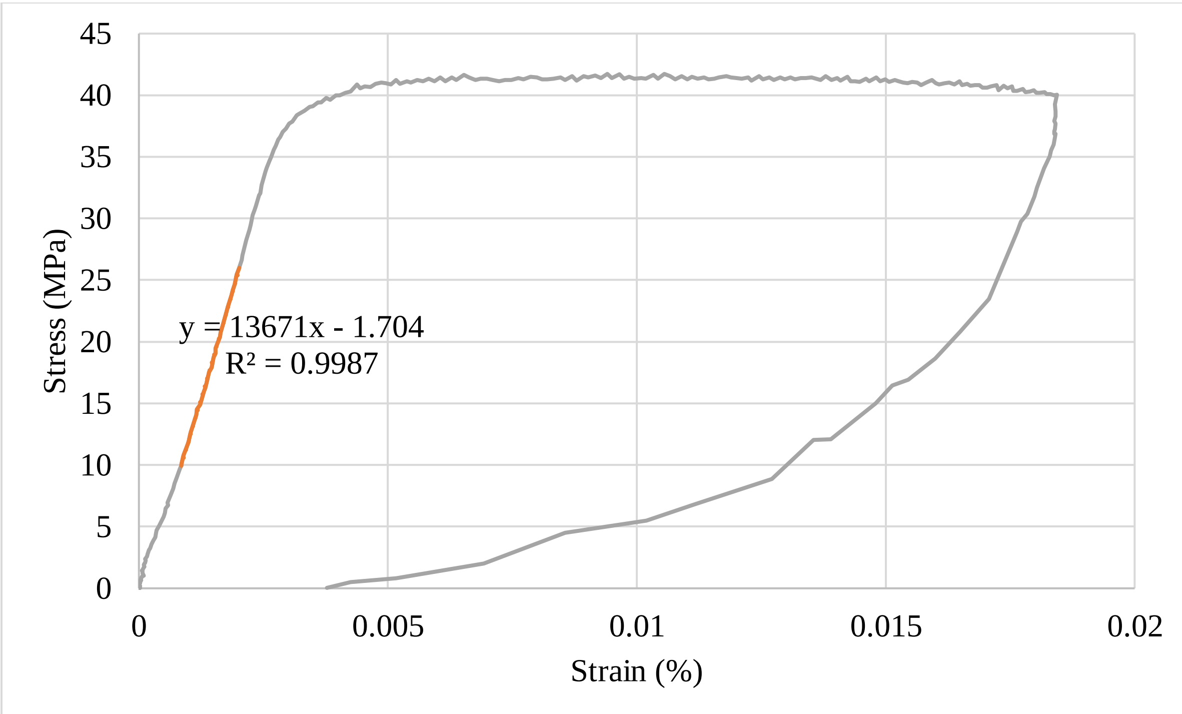


Figure C2.20 Compression raw data plot of specimen W4–13. Well, D. giganteus, coconut oil treated, internode, cross-sectional area = 5.04 in^2, outer diameter = 3.63 in., compressive strength = 41.7, compressive modulus of elasticity = 14.

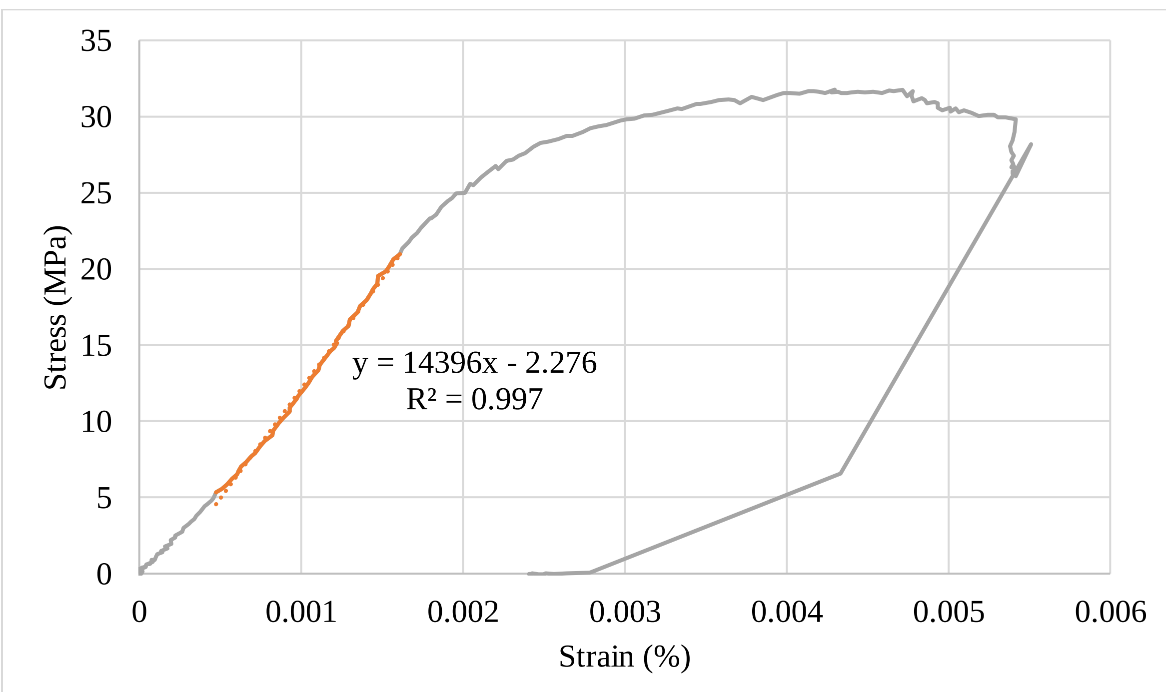


Figure C2.21 Compression raw data plot of specimen W5-5. Well, D. giganteus, borax & boric acid solution treated, internode, cross-sectional area = 2.17 in^2, outer diameter = 2.81 in., compressive strength = 31.8, compressive modulus of elasticity = 14.

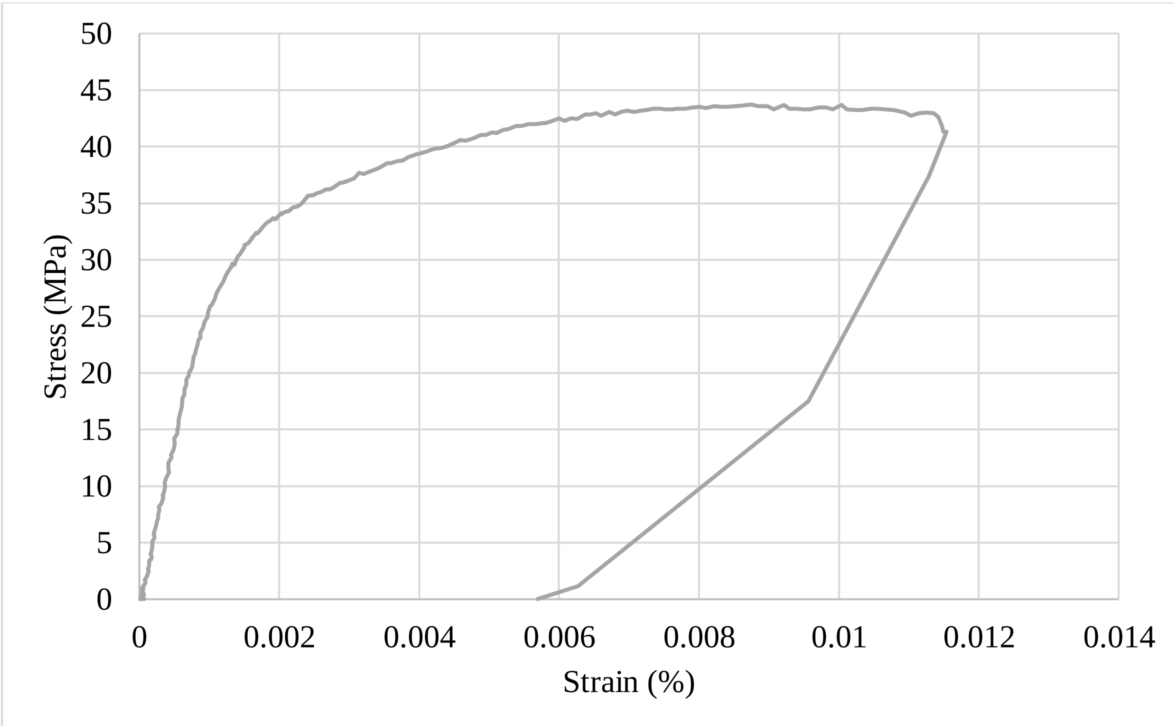


Figure C2.22 Compression raw data plot of specimen W5-10. Well, D. giganteus, borax & boric acid solution treated, node, cross-sectional area = 3.18 in^2, outer diameter = 3.06 in., compressive strength = 39.0.

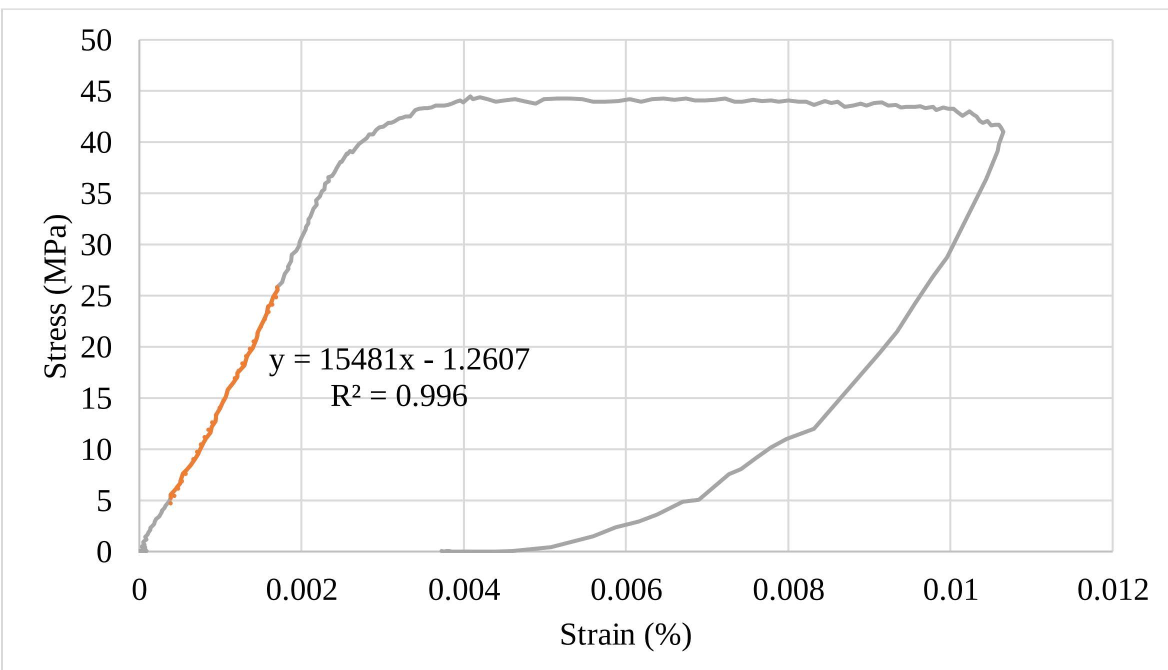


Figure C2.23 Compression raw data plot of specimen W5–13. Well, D. giganteus, borax & boric acid solution treated, internode, cross-sectional area = 2.51 in^2, outer diameter = 2.93 in., compressive strength = 44.5, compressive modulus of elasticity = 15.

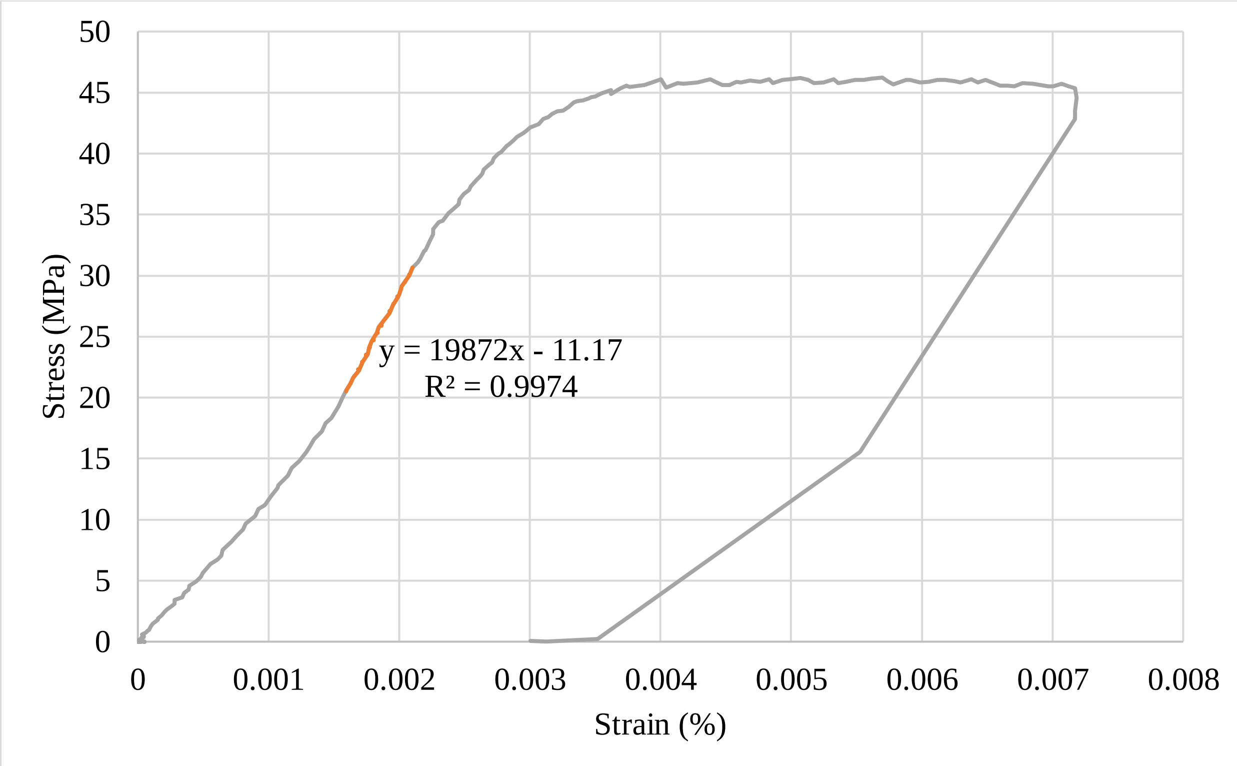


Figure C2.24 Compression raw data plot of specimen W5-14. Well, D. giganteus, borax & boric acid solution treated, internode, cross-sectional area = 2.66 in^2, outer diameter = 2.95 in., compressive strength = 46.2, compressive modulus of elasticity = 20.

From Figures C2.1-C2.24, the data suggests that bamboo exhibits plastic behaviour as is seen by the initial linear stress strain line which obeys Hook's law, the nearly consistent plateau of the graphs, and the return of the nearly parallel modulus of elasticity line after the sample is released. As is seen in Figures C2.1-C2.24, a linear slope line is only calculated for internode specimens as node specimens have inconsistent cross-sectional surface areas and therefore an accurate compressive modulus of elasticity value is unable to be calculated.

APPENDIX C3: BAMBOO SPECIMENS DATA TABLES

The detailed data of all specimens used in Figures 4.7 and 4.8 are here presented. There is a dash (-) for node sample compressive modulus of elasticity, E_c, values as a modulus of elasticity value cannot be calculated for nodes as they have an inconsistent cross-sectional surface area. A star symbol (*) is used for compressive of elasticity, E_c, or compressive strength, F_c, data which was unable to be determined due to imperfectly acquired data due to the axial extensometers making poor contact with the imperfect and irregularly shaped bamboo specimens.

Table C3.1 Laboratory control, coconut oil treated, D. asper, dimensions, compression test data and moisture content

Specimen Number	Laboratory Control or Well	Bamboo Type	Treatment	Node or Internode	E_c, Gpa	F_c, Mpa	Surface Area (in^2)	Diameter (in)	MC (%)
A2-12	Laboratory Control	*D. asper*	Coconut oil	Node	-	69.23	2.99	2.69	8.05
A2-32	Laboratory Control	*D. asper*	Coconut oil	Node	-	69.97	2.46	2.56	8.43
A2-37	Laboratory Control	*D. asper*	Coconut oil	Node	-	74.51	2.61	2.60	8.87
A2-42	Laboratory Control	*D. asper*	Coconut oil	Internode	15	60.41	2.69	2.65	7.03
A2-43	Laboratory Control	*D. asper*	Coconut oil	Internode	19	61.74	2.62	2.68	7.42
A2-44	Laboratory Control	*D. asper*	Coconut oil	Internode	*	*	2.58	2.65	7.38
A2-45	Laboratory Control	*D. asper*	Coconut oil	Internode	20	44.26	2.62	2.65	7.00

Table C3.2 Laboratory control, borax & boric acid solution treated, D. asper, dimensions, compression test data and moisture content

Specimen Number	Laboratory Control or Well	Bamboo Type	Treatment	Node or Internode	E_c, Gpa	F_c, Mpa	Surface Area (in^2)	Diameter (in)	MC (%)
A4-30	Laboratory Control	*D. asper*	Borax & boric acid	Internode	*	17.56	1.67	2.41	9.31
A4-31	Laboratory Control	*D. asper*	Borax & boric acid	Internode	31	72.87	1.83	2.40	9.08
A4-32	Laboratory Control	*D. asper*	Borax & boric acid	Internode	20	74.65	1.88	2.40	9.07
A4-34	Laboratory Control	*D. asper*	Borax & boric acid	Internode	17	77.31	1.89	2.43	9.22
A4-35	Laboratory Control	*D. asper*	Borax & boric acid	Internode	25	78.43	1.83	2.43	9.24
A4-36	Laboratory Control	*D. asper*	Borax & boric acid	Internode	29	72.30	1.86	2.43	9.14

Table C3.3 Laboratory control, air-dried, D. asper, dimensions, compression test data and moisture content

Specimen Number	Laboratory Control or Well	Bamboo Type	Treatment	Node or Internode	E_c, Gpa	F_c, Mpa	Surface Area (in^2)	Diameter (in)	MC (%)
A6-02	Laboratory Control	*D. asper*	Air-dried	Node	-	74.46	0.77	1.55	8.62
A6-10	Laboratory Control	*D. asper*	Air-dried	Node	-	75.36	0.87	1.63	8.62
A6-17	Laboratory Control	*D. asper*	Air-dried	Node	-	67.71	0.97	1.70	8.59
A6-25	Laboratory Control	*D. asper*	Air-dried	Node	-	75.21	0.96	1.77	8.70
A6-31	Laboratory Control	*D. asper*	Air-dried	Internode	*	86.34	0.91	1.78	8.30
A6-32	Laboratory Control	*D. asper*	Air-dried	Node	-	69.84	1.10	1.85	8.58
A6-39	Laboratory Control	*D. asper*	Air-dried	Node	-	75.67	1.12	1.91	8.45
A6-46	Laboratory Control	*D. asper*	Air-dried	Node	-	73.42	1.23	1.98	8.57
A6-49	Laboratory Control	*D. asper*	Air-dried	Internode	64	90.84	1.03	2.01	8.30
A6-50	Laboratory Control	*D. asper*	Air-dried	Internode	40	89.56	1.04	2.01	8.39
A6-53	Laboratory Control	*D. asper*	Air-dried	Node	-	71.64	1.28	2.05	8.28
A6-53	Laboratory Control	*D. asper*	Air-dried	Internode	65	86.41	1.17	2.14	8.52
A6-64	Laboratory Control	*D. asper*	Air-dried	Internode	25	84.23	1.21	2.14	8.36
A6-65	Laboratory Control	*D. asper*	Air-dried	Internode	*	80.21	1.28	2.12	8.32
A6-67	Laboratory Control	*D. asper*	Air-dried	Internode	16	78.16	1.40	2.10	8.21

Table C3.4 Removed Well No. 2, air-dried, D. asper, dimensions, compression test data and moisture content

Specimen Number	Laboratory Control or Well	Bamboo Type	Treatment	Node or Internode	E_c, Gpa	F_c, Mpa	Surface Area (in^2)	Diameter (in)	MC (%)
W2 - 1	Well	*D. asper*	Air-dried	Internode	-	45.78	1.83	2.18	13.18
W2 - 2	Well	*D. asper*	Air-dried	Internode	17	42.25	1.95	2.18	19.67
W2 -3	Well	*D. asper*	Air-dried	Node	-	46.43	2.41	2.26	22.94
W2 - 4	Well	*D. asper*	Air-dried	Internode	16	40.73	2.10	2.21	24.53
W2 - 5	Well	*D. asper*	Air-dried	Internode	16	39.88	2.17	2.22	25.63
W2 - 6	Well	*D. asper*	Air-dried	Internode	26	42.61	2.08	2.21	17.72
W2 - 7	Well	*D. asper*	Air-dried	Internode	12	40.64	2.11	2.21	25.86
W2 - 8	Well	*D. asper*	Air-dried	Internode	*	39.91	2.19	2.22	27.89
W2 - 10	Well	*D. asper*	Air-dried	Node	-	40.21	2.54	2.26	31.40
W2 - 11	Well	*D. asper*	Air-dried	Internode	19	40.19	2.30	2.24	25.98
W2 - 12	Well	*D. asper*	Air-dried	Internode	20	39.80	2.28	2.24	25.76
W2 - 15	Well	*D. asper*	Air-dried	Internode	26	38.31	2.40	2.26	25.53
W2 - 20	Well	*D. asper*	Air-dried	Internode	16	35.68	2.58	2.22	40.58
W2 - 22	Well	*D. asper*	Air-dried	Node	-	36.52	2.79	2.32	35.45
W2 - 30	Well	*D. asper*	Air-dried	Internode	16	33.17	3.06	2.38	38.40
W2 - 31	Well	*D. asper*	Air-dried	Internode	17	34.32	3.08	2.39	46.35

Table C3.5 Removed Well No. 3, coconut oil treated, D. asper, dimensions, compression test data and moisture content

Specimen Number	Laboratory Control or Well	Bamboo Type	Treatment	Node or Internode	E_c, Gpa	F_c, Mpa	Surface Area (in^2)	Diameter (in)	MC (%)
W3 - 1	Well	*D. asper*	Coconut oil	Internode	11	32.71	1.75	2.33	14.93
W3 - 2	Well	*D. asper*	Coconut oil	internode	*	30.98	1.72	2.32	14.18
W3 - 3	Well	*D. asper*	Coconut oil	internode	19	35.13	1.69	2.32	13.94
W3- 4	Well	*D. asper*	Coconut oil	internode	*	34.53	1.80	2.35	14.66
W3 - 6	Well	*D. asper*	Coconut oil	Node	-	36.42	2.11	2.42	20.66
W3 - 12	Well	*D. asper*	Coconut oil	Node	-	36.76	2.12	2.44	22.14
W3 - 17	Well	*D. asper*	Coconut oil	Node	-	36.87	2.29	2.51	27.94
W3 - 19	Well	*D. asper*	Coconut oil	internode	*	36.45	2.14	2.55	27.03
W3 - 21	Well	*D. asper*	Coconut oil	internode	13	35.16	2.42	2.59	31.00
W3 - 22	Well	*D. asper*	Coconut oil	Node	-	35.91	2.50	2.59	29.79
W3 - 23	Well	*D. asper*	Coconut oil	internode	19	31.84	2.44	2.62	20.64
W3 - 24	Well	*D. asper*	Coconut oil	internode	15	35.15	2.37	2.62	18.44
W3 - 25	Well	*D. asper*	Coconut oil	internode	14	30.83	2.56	2.65	19.68
W3 - 26	Well	*D. asper*	Coconut oil	internode	13	31.35	2.61	2.65	25.11
W3 - 27	Well	*D. asper*	Coconut oil	Node	-	32.77	2.89	2.72	33.77
W3 - 32	Well	*D. asper*	Coconut oil	Node	-	33.93	2.96	2.73	95.62
W3 - 37	Well	*D. asper*	Coconut oil	Node	-	33.07	3.11	2.81	44.89
W3 - 40	Well	*D. asper*	Coconut oil	internode	14	29.31	3.25	2.83	46.63

Table C3.6 Removed Well No.4, coconut oil treated, D. giganteus, dimensions, compression test data and moisture content

Specimen Number	Laboratory Control or Well	Bamboo Type	Treatment	Node or Internode	E_c, Gpa	F_c, Mpa	Surface Area (in^2)	Diameter (in)	MC (%)
W4 - 1	Well	*D. giganteus*	Coconut oil	internode	25	42.04	3.95	3.51	15.03
W4 - 2	Well	*D. giganteus*	Coconut oil	internode	18	44.45	3.71	3.47	17.58
W4 - 4	Well	*D. giganteus*	Coconut oil	internode	22	43.99	3.90	3.50	22.06
W4 - 5	Well	*D. giganteus*	Coconut oil	Node	-	50.35	3.63	3.42	25.87
W4 - 6	Well	*D. giganteus*	Coconut oil	internode	23	44.77	4.09	3.52	24.10
W4 - 7	Well	*D. giganteus*	Coconut oil	internode	16	46.08	3.86	3.49	16.05
W4 - 8	Well	*D. giganteus*	Coconut oil	internode	15	41.27	4.25	3.59	19.69
W4 - 9	Well	*D. giganteus*	Coconut oil	Node	-	61.20	3.10	3.33	29.65
W4 - 10	Well	*D. giganteus*	Coconut oil	internode	12	42.90	4.51	3.58	28.86
W4 - 11	Well	*D. giganteus*	Coconut oil	internode	15	41.92	4.63	3.61	29.21
W4 - 12	Well	*D. giganteus*	Coconut oil	Node	-	38.74	5.33	3.70	33.98
W4 - 13	Well	*D. giganteus*	Coconut oil	internode	14	41.73	5.04	3.63	34.92
W4 - 15	Well	*D. giganteus*	Coconut oil	Node	-	35.31	6.10	3.81	42.49

Table C3.7 Removed Well No.5, borax & boric acid solution treated, D. giganteus, dimensions, compression test data and moisture content

Specimen Number	Laboratory Control or Well	Bamboo Type	Treatment	Node or Internode	E_c, Gpa	F_c, Mpa	Surface Area (in^2)	Diameter (in)	MC (%)
W5 - 1	Well	*D. Gigantuous*	Borax & boric acid	internode	11	26.18	1.95	2.76	12.01
W5 - 2	Well	*D. Gigantuous*	Borax & boric acid	Internode	21	30.93	1.92	2.81	12.70
W5 - 3	Well	*D. Gigantuous*	Borax & boric acid	Internode	7	31.81	2.18	2.80	11.98
W5 - 5	Well	*D. Gigantuous*	Borax & boric acid	Internode	14	31.76	2.17	2.81	12.61
W5 - 6	Well	*D. Gigantuous*	Borax & boric acid	Node	-	22.61	2.45	2.85	17.67
W5 - 7	Well	*D. Gigantuous*	Borax & boric acid	Internode	10	39.31	2.46	2.89	15.07
W5 - 8	Well	*D. Gigantuous*	Borax & boric acid	Internode	-	41.56	2.49	2.91	14.35
W5 - 10	Well	*D. Gigantuous*	Borax & boric acid	Internode	28	43.73	2.58	2.92	14.45
W5 - 12	Well	*D. Gigantuous*	Borax & boric acid	Internode	36	47.65	2.59	2.91	14.66
W5 - 13	Well	*D. Gigantuous*	Borax & boric acid	Internode	15	44.48	2.51	2.93	14.87
W5 - 14	Well	*D. Gigantuous*	Borax & boric acid	Internode	20	46.23	2.66	2.95	18.23
W5 - 17	Well	*D. Gigantuous*	Borax & boric acid	Node	-	46.45	2.61	2.96	22.36
W5 - 22	Well	*D. Gigantuous*	Borax & boric acid	Node	-	39.02	3.18	3.06	21.86
W5 - 27	Well	*D. Gigantuous*	Borax & boric acid	Node	-	44.96	3.42	3.11	23.97
W5 - 31	Well	*D. Gigantuous*	Borax & boric acid	Node	-	42.26	3.71	3.17	32.61
W5 - 35	Well	*D. Gigantuous*	Borax & boric acid	Internode	21	39.81	3.92	3.23	41.63

APPENDIX D: ASSESSMENT OF FIELD DEMONSTRATION OF NATURAL RAINWATER HARVESTING SYSTEM (NRHS) USE IN ETHIOPIA

D.1 Introduction

Water is typically stored in rural settings of low-income countries using tanks constructed of steel reinforced brick or concrete block (Mihelcic et al. 2009), metal, and plastic. These items may not be affordable to local populations (Thayil-Blanchard & Mihelcic 2015), lead to decreased water quality depending on the tank material (Schafer & Mihelcic 2012), and/or have issues of environmental sustainability due to the embodied energy from use of less sustainable construction materials that may be manufactured large distances from their use (e.g., Green 2011; Held et al. 2013). Cost is also important because globally, the annual total capital cost to meet the Sustainable Development Goals' water, sanitation, and hygiene (WASH) targets is estimated to be as high as $US 166 billion through 2030 (Hutton & Varughese 2016).

For local people to be self-dependent, they must rely on using materials which are readily available in their local economy and environment. For these peoples, it is advantageous to use abundant and available natural materials which can be used to make systems which meet the goal of providing water. Natural and plant-based materials such as wood, mud, bamboo, straw, rocks, gravel, sand, and clay have five benefits above conventional building materials: 1) They are locally available and accessible to people who live in rural areas; 2) They are materials which people with traditional knowledge have experience using for building their own houses, fencing, etc.; 3) They may be in some societies considered 'waste' materials, having no current use and when given value may improve their local economy; 4) They do not have to be shipped, imported, or brought in on trucks which are perhaps non-accessible and roads which may be non-existent; 5) They are naturally regenerative in the short term and therefore sustainable.

Rainwater catchment is the most practically simple way to relieve water scarcity in many locations, is a sustainable type of water usage, is ideal for self-supply, and can provide high quality water (Helmreich & Horn 2009). It has also been reported that in regards to the risk for gastrointestinal disease, rainwater is safer than water obtained from unimproved water supplies (Dean and Hunter, 2012). In places in the world where conditions lend themselves to collecting rainwater, i.e. it rains more than 1 meter/year and there are no city air contaminants, rainwater collection should be considered as a viable solution to water supply problems.

However, though hand washing stations can be constructed from wood and discarded containers (e.g., Naughton et al., 2015) little information was identified in the literature of water or sanitation projects constructed almost entirely with natural plant-based materials. In fact, a literature review identified only one water storage tank which employed a bamboo structure to support an internal polythene sheet (Development Technology Unit, 2001).

Accordingly, in a rural village in South Ethiopia, with high amounts of water inaccessibility, a first of its kind rainwater tank named the Natural Rainwater Harvesting System (NRHS) was designed and constructed nearly completely of natural plant-based and earthen materials (wood, mixture of soil and teff straw, local plant-based *Goola* rope, rocks, long grass, and clay) was built and is currently in use. The feasibility of the NRHS was assessed for its operational ability to hold water, economics, and structural durability using finite element modeling.

D.2 Methods

The Natural Rainwater Harvesting System (NRHS) was made using local available materials of the village or rural South Ethiopia where it was constructed and are provided in Table D.1. The NRHS was constructed alongside the local community, using local knowledge integrated with engineering theory.

Table D.1 Materials used to construct the Natural Rainwater Harvesting System (NRHS)

Item	Material
1	Eucalyptus wood (*Eucalyptus globulus*)
2	Eucalyptus leaves (*Eucalyptus globulus*)
3	Rocks
4	Concrete (1:1 ratio, by volume, cement and sand)
5	*Goola* 'rope' from the false banana plant (*Ensete ventricosum*)
6	*Chika*: soil and teff straw (a by-product of harvesting the Ethiopian grain, *Eragrostis tef*)
7	Clay
8	Long grass
9	Metal piping
10	Plastic piping

Eucalyptus wood, *Eucalyptus globulus*, was cut fresh from a tree of diameter of 5-8 cm at the base and 3-5 cm at the top. It was locally attained, cut only ~30 meters from where the prototype was constructed. Eucalyptus wood grows very commonly throughout Ethiopia and is used as a main building material for housing. When compared to other plants, it has the feasible advantage of naturally growing back from its stump when cut over 11 times. The outer covering of the eucalyptus wood was immediately removed; it comes off easily when fresh and its removal is believed to prevent pest damage. The next day the peeled eucalyptus was 'painted' in a strong mixture of its own young leaves and water as pest prevention. First, a strong mixture of water and eucalyptus leaves, (saturated eucalyptus leaf water) was boiled for ~20 minutes on a traditional 3 stone fire fueled by local wood (Figure D.1). The mixture was then applied warm to the eucalyptus wood by brush (Figure D.2).

Figure D.1 The saturated young eucalyptus leaves and water mixture, being heated.

Figure D.2 Application of warm saturated eucalyptus leaf water to fresh eucalyptus wood by brush.

The wood was left to dry in an outside partly covered concrete slab for 1 week. Dry wood was used for the structure after natural shrinkage had taken place. Next, a hole was dug in the shape of circle ~0.5 m deep and 1.7 m wide (outer diameter). The soil, mainly clay based, was hand compacted in the middle and sides of the circle (Figure D.3). Rocks of different sizes, which were used for the base, were collected from the surrounding area as it is a naturally rocky environment (Figure D.4).

Figure D.3 Initial dug and compacted hole employed to strengthen base of the Natural Rainwater Harvesting System.

Figure D.4 Naturally rocky environment of the study site of Zaminenare, Wolayita, SNNPR, Ethiopia.

To make the base of the NRHS, a concrete mixture and different diameter sized rocks were used as in a masonry style building. The cement used was produced in Dangote (Ethiopia), close to the central location of the capital of the country, approximately 414 km from the demonstration site. It is sold only 30 km away from the town where this project was demonstrated. The community is accustomed to using cement as the local houses use concrete commonly as a raised concrete flooring; additionally, there are some concrete buildings in the small city center.

The concrete used for the base was made of cement and sand in a 1:1 ratio (by volume); this may seem like a high cement to sand ratio; however, the locals usually use a 1:4 ratio in other building projects. The water used to make the concrete was obtained from a nearby large diameter well which is not clean (it was brown) but no better water source was available nearby. Then, the cement was combined with the local rocks and dry eucalyptus wood were inserted into the previously dug 0.5 m. deep hole, whereby the poles were inserted fully with rocks and concrete surrounding and supporting (Figure D.5).

Figure D.5 Base of NRHS; with eucalyptus wood, concrete, and rock added.

The next day, additional cement rock mixture was added to the middle of the structure to make a ~0.4m elevation of this mixture. Very little concrete was used as it was used only to adhere the rocks and wood together; this was done due to the high cost of cement and difficulty of transporting to the village (only four 50kg bags were used). The cement was allowed to dry while putting daily water on it for 2 days (the same turbid well water). Next, a horizontal layer of split eucalyptus wood and of small diameter was added and tied to the vertical poles by using a locally naturally made rope called '*Goola*' (Figure D.6). The horizontal layers were added first from the outside and then the inside and spacing between horizontal layers was ~10 cm, as determined by the local people as it is done for their traditional houses.

Figure D.6 Eucalyptus wood of small diameter attached to the eucalyptus wood base.

Goola (Figure D.7) is a natural fiber made in the village and sold by the villagers at weekly market to make the traditional houses in the same way this structure was built. *Goola* comes from the false banana plant, or *Ensete ventricosum* (Figure D.8) trunk. It is useful byproduct of the outer and inner core of the plant trunk which is stripped by a split piece of bamboo of its pulp and is then fermented, then cooked to make traditional foods. The inner and outer core of the plant trunk is left only with fresh fibers which are then dried and become the useful *Goola* ‘rope.’

Figure D.7 Traditional Goola rope, made locally of the false banana, or Ensete ventricosum.

Figure D.8 False banana or Ensete ventricosum.

Chika, a dirt, water and teff straw (a by-product of harvesting the Ethiopian native grain, *Eragrostis tef*) mixture was used to construct the outer walls of the structure; just as it is done traditionally by the local people. The *Chika* is made a week before it is used and covered by false banana leaves to retain moisture as is done traditionally to enhance its strength and adhesive properties. Right before use water is added to the *Chika* mixture and it is re-mixed by foot (Figure D.9).

Figure D.9 The traditional building material to make walls of buildings, Chika, being re-mixed ready for use.

The mixture is surprisingly strong as the teff straw and mud act as a composite material, much like carbon fiber, holding the wall together. The ratio of teff straw, water, and dirt used was determined by the local people as is done to make their traditional houses (Figure D.10) and is roughly calculated by adding enough teff straw to make it present through the Chika, yet not over concentrated, and enough water to make a smearable consistency that will adhere to the wall without falling. The *Chika* was added by hand all around the structure of the NRHS, first from the inside and bottom of the base, then, once dry (the next day), from the outside (Figure D.11). Enough Chika was added to cover the eucalyptus wood completely, resulting in an outer diameter thickness of ~15 cm.

Figure D.10 Traditional house of Wolayita with walls made of Chika: dirt, water, and teff straw (a by-product of harvesting the grain, Eragrostis tef) mixture.

Figure D.11 The Chika being applied.

On the third day a final thin smooth coat of *Chika* is added in a special way. It is first smoothed by hand, then patted by teff straw, then smoothened by a wet wooden pallet. The final product of the outer *Chika* layer is seen on Figure D.12.

Figure D.12 The final Chika layer placed on the NRHS.

Before the placement of all layers of the *Chika*, in certain locations, a water inlet (plastic), outlet (metal), and overflow pipe (metal) were added (Figures D.13 and D.14). The water outlet was added ~ 5 cm above the bottom of the tank to improve the exit water quality by; allowing natural sedimentation to take place. Under the water outlet, a simple soak pit was constructed to relieve the users of water puddling for malaria prevention (Figure D.14).

These three pipes, and the cement used, were the only two materials which were not locally produced, and non-plant based. However, both materials are available by the local people, being bought at the nearby cities and produced in Ethiopia. The metal pipe was used (instead of plastic) as the tank was to be burnt in the inside after the final clay layer was applied. The plastic water inlet tube was used as it was already a part of the building (Kindergarten school) and was just re-adapted to fit the NRHS. Although no natural plant-based substitute was thought of as substitutable for the water outlet by the dissertation author, the author would like to, for the next prototype, substitute the overflow pipe and water inlet pipe for bamboo.

Figure D.13 Water inlet and overflow pipe.

Figure D.14 Water outlet (blue) and basic soak pit (red).

The cover of the NRHS was modeled after the roofs of the traditional local houses (seen previously in Figure D.10). This was done by first cutting a specific native leguminous tree which grows in a way that all branches split from one node and is cut there which once inverted becomes the top of the house roof.

To this leguminous tree top, eucalyptus wood is added to reinforce and elongate the cover, tied with traditional *Goola* rope. The cover is completed by adding long grass, more eucalyptus wood, and *Goola* as ties (Figure D.15).

Figure D.15 The top, or roof, of the NRHS being built.

The walls of the NRHS that were constructed of traditional *Chika* were left to dry for 2 days before the next step, adding clay to the inside of the NRHS. The clay was brought from the nearby environment dry and worked at the project location. First, the raw dry clay was pound by hand using eucalyptus wood by hand to decrease the particle size (Figure D.16). It was then sifted using a traditional natural sieve made of straw (Figure D.17).

Figure D.16 Dry raw clay being pounded by wood by hand as it is done by the local people traditionally.

Figure D.17 Traditional straw sifter used to segregate small particles used to make the clay.

After sifting an attaining a smaller particle size, mostly powder but larger particles of ~2mm in diameter pass through the sieve, the dry clay is mixed with by hand with water (Figure D.18); nearby turbid well water was used. Well water was then added and mixed by hand until it reached the right consistency as determined by the local experienced people (Figure D.19).

Figure D.18 The clay after being pounded, sieved, and mixed with water.

Figure D.19 The clay completely mixed and ready for use.

The prepared clay was then passed using a double ladder system and 4 people to the inside of the NRHS (Figure D.20). The ladders were on site by the people of local eucalyptus wood and nails attained from the nearby town.

Figure D.20 Passing the clay up by hand using the double ladder system.

Two people inside of the NRHS added the prepared clay to the inside of the NRHS by hand and using a cut out plastic spatula from an old jerry can (Figures D.21 and D.22).

Figure D.21 Application of clay to the inside of the NRHS.

Figure D.22 Completed application of clay to the NRHS.

Once the clay covered the entire inside of the NRHS, it was left to dry. All aspects of the clay were made as according to the local people who work with the clay and produce traditional clay pots and the traditional coffee pot, or *Jebuna* (Figure D.23), of Ethiopia.

Figure D.23 The Jebuna, or common traditional coffee clay pot.

The NRHS was painted on the outside as is more recently culturally done in the traditional houses and for beauty and added pest prevention. On one side of the NRHS its title was written (Figure D.24) and on the other side, its name in the local language was written (Figure D.25). Its name in the local language of Wolaitatua, '*Hattaa Kettaa*' means water house, as this name was easily understood by the local people as the NRHS resembles their traditional houses.

Figure D.24 The completed Natural Rainwater Harvesting System (NRHS).

Figure D.25 The other side of the NRHS with its local name in the local language of Wolaitatua, 'Hatta Kettaa,' or water house.

D.3 Final Thoughts

D.3.1 Feasibility Assessment / Operational Analyses

Although the clay was expected to be cured (burnt) as is done traditionally for the community clay pots after five days, upon return to the NRHS after five days the clay was dry and cracked as can be seen on Figure D.26.

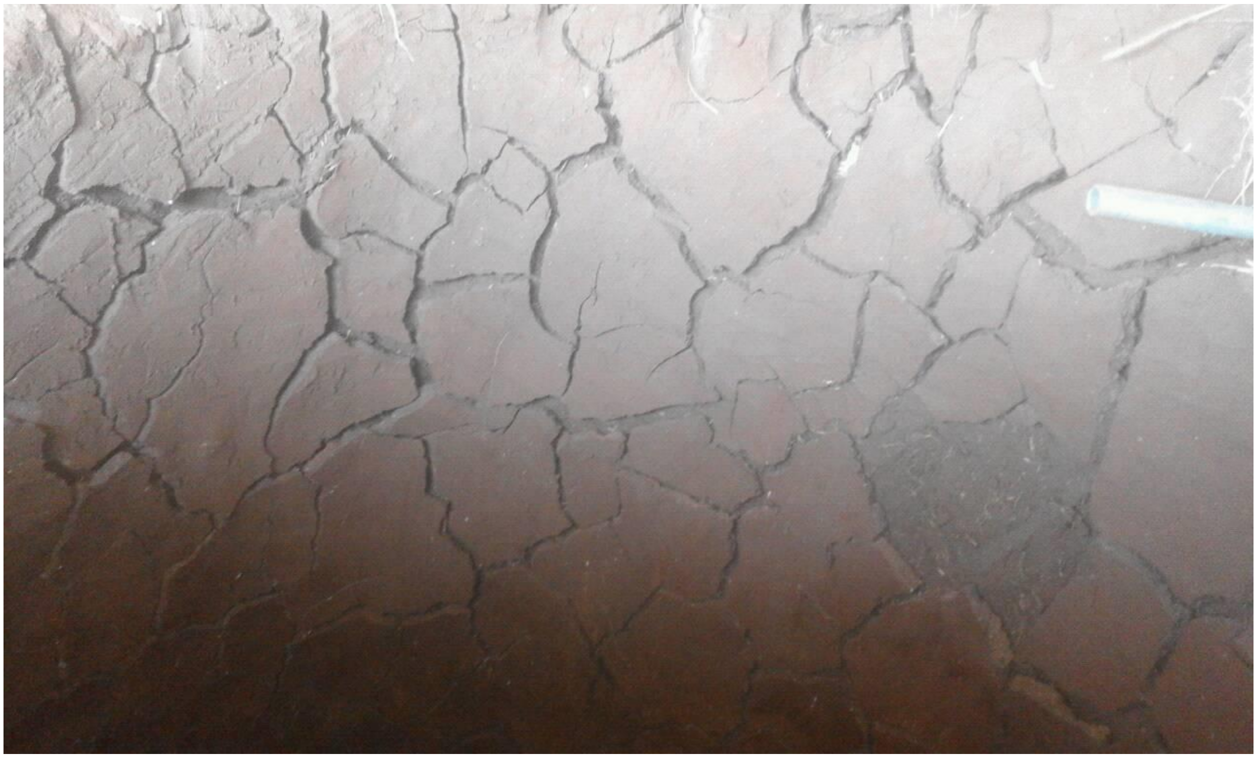


Figure D.26 Inner clay layer which dried and fell, unexpectedly making poor contact with the Chika.

This type of clay rainwater tank had never been attempted before and was therefore done experimentally although the results were unknown. To mitigate this problem, the falling clay could be removed, and an inner layer of concrete added to hold the water inside impermeably. This kind of *Chika* to cement contact is commonly done in the area to coat the outside of houses for weather protection of the *Chika* which is known to dissolve in water.

D.3.2 Economics

An economic assessment on the Natural Rainwater Harvesting System (NRHS) is presented in Table D.2.

Table D.2 Economics of NRHS in the South of Ethiopia

Item	Material	Quantity	Cost per Unit	Total Cost
1	Eucalyptus wood (*Eucalyptus globulus*)	42 logs	No Cost	No Cost
2	Eucalyptus leaves (*Eucalyptus globulus*)	Leaves of 1 log	No Cost	No Cost
3	Rocks	~1 m^3	No Cost	No Cost
4	Cement	4 bags of 50 kg	125 Birr (4.34$)	500 Birr (17.36$)
5	Sand	~ 0.06 m^3	No Cost	No Cost
6	*Goola* 'rope' from the false banana plant (*Ensete ventricosum*)	1bundle	50 Birr (1.74$)	50 Birr (1.74$)
7	*Chika*: soil and teff straw (a by-product of harvesting the Ethiopian grain, *Eragrostis tef*)	~ 2 m^3	No Cost	No Cost
8	Clay	~1 m^3	200 Birr (6.94$)	200 Birr (6.94$)
9	Long grass	~1.5m^3	No Cost	No Cost
10	Metal piping	1 m	100 Birr (3.47$)	100 Birr (3.47$)
11	Plastic piping	Included	Included	Included
12	Total Cost			850 Birr (29.51$)

D.4 Conclusions

A nearly all-natural material rainwater tank was made in the South of Ethiopia, alongside the local people. The local people were enthusiastic about the project and understood the idea of the project, some even stating they would try to make something similar in their own homes. Rainwater catchment is a new concept in this area as people attain their water from either wells or rivers. The structure of the tank being much like the traditional houses much helped with understanding of the project and allowed for the local people to do the project alone for many parts, whereby taking ownership of the project. The functionality of the project was unfortunately compromised at the end due to unexpected high shrinkage of the clay inside of the tank which caused the layer of clay to fall off. A simple and locally appropriate remediation to this problem would be to remove the inner clay layer and replace with a cement sand mixture, as is done on the outside of the local houses for added waterproofing. As the main author had left the country by the time this problem was identified, it is up to the local people to resolve this issue in whichever way they see best.

D.5 References

Dean, J., & Hunter, P. R. (2012). Risk of gastrointestinal illness associated with the consumption of rainwater: a systematic review. Environmental science & technology, 46(5), 2501-2507.

Green, Kaitlin Elinor. (2011). Embodied energy assessment of rainwater harvesting systems in primary school settings on La Peninsula Valiente, Comarca Ngobe Bugle, Republic of Panama. Graduate Theses and Dissertations. <https://scholarcommons.usf.edu/etd/3127>.

Held, B.R., Zhang, Q., Mihelcic, J.R. (2013). Analysis of embodied human and materials energy associated with provision of improved water through source and household interventions. Journal of Cleaner Production, 60(1):83-92, 2013.

Helmreich, B., & Horn, H. (2009). Opportunities in rainwater harvesting. Desalination, 248(1-3), 118-124.

Hutton, G. and Varughese, M. (2016). The costs of meeting the 2030 Sustainable Development Goal targets on drinking water, sanitation, and hygiene. The World Bank.

Mihelcic, J. R., Fry, L. M., Myre, E. A., Phillips, L. D., Barkdoll, B. D. (2009). Field guide to environmental engineering for development workers: water, sanitation, and indoor air. American Society of Civil Engineers (ASCE).

Mihelcic, J.R., (2010). The right thing to do: graduate education and research in a global and human context. What Is Global Engineering Education For? The Making of International and Global Engineering Educators (Eds: G.L. Downey and K. Beddoes), Morgan & Claypool Publishers, San Francisco, 235-250.

Mihelcic, J.R., Phillips, L.D., Watkins, D.W. (2006). Integrating a global perspective into engineering education & research: Engineering International Sustainable Development. Environmental Engineering Science, 23(3):426-438.

Naughton, C. C., Sissoko, H. T., & Mihelcic, J. R. (2015). Assessing factors that lead to use of appropriate technology handwashing stations in Mali, West Africa. Journal of Water, Sanitation and Hygiene for Development, 5(2), 279-288.

RWSN Rural Water Supply Network (2019). Self-supply. <http://www.rural-water-supply.net/en/self-supply>.

Schafer, C.A., Mihelcic, J.R. (2012). Impact of storage tank material and maintenance on household water quality. Journal American Water Works Association, 104(9): E521-E529.

Thayil-Blanchard, J., Mihelcic, J.R. (2015). Chapter 7: Potential of self supply in Uganda's Rakai District: Assessing domestic rainwater harvesting storage cost and geographic availability. Alternative Water Supply Systems, (Eds: F. Memon, S. Ward). IWA Publishing, London, UK.

APPENDIX E: REPRINTING PERMISSION, FIGURE 4.1

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Lorena Sánchez Vivas was born in Caracas, Venezuela, from a Venezuelan mother and Cuban father, and moved to Florida as a child (1998). She has a Bachelor of science & Master's in mechanical engineering from Florida State University (FSU) (2008-2014). There she worked on a senior design project on microalgae photobioreactors in the, Federal University of Parana (UFPR) in Curitiba, Brazil (2012). She worked as a research assistant several labs thanks to National Science Foundation Research Experience for Undergraduates program: National High Magnetic Field Laboratory (NHMFL), Carnegie Mellon University Materials Science Research, University of Chicago Materials Science Research, and University of Idaho Physics Department Research (2008-2014). She served as a Peace Corps Environment Volunteer in ኢትዮጵያ Ethiopia (2016-2018). She has worked as a teaching assistant at Florida State University and University of South Florida teaching courses of thermodynamics, fluid mechanics, surveying, and environmental engineering laboratory (2013 – 2015; 2018 - 2019).

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