Bamboo Housing Structural Design

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Abstract

The research presented examines several topics and concerns related to construction using bamboo, as well as the design of a bamboo structure. Bamboo is a functionally graded natural material that does not present uniform properties. Nevertheless, recent efforts in the standardization of grading, testing and structural design can overcome the anisotropy limitations. In regard to durability, treatments with boron provide a safe, economical, effective and sustainable way to make a structure last, as long as durability by design measures are performed. In connections, the hollow round shape and variable section of bamboo make joining members challenging, therefore more testing is required.

In the case study, a two-level structure using Moso bamboo was designed. The response forces were obtained from the model in the computer software and compared with allowable resistances calculated according to the structural design standard ISO 22156:2021. The loads and combinations follow the Eurocode guidelines and the Portuguese National Annex. The bamboo culms were modelled as hollow tubes with an outer diameter of 0,1 m and a wall thickness of 0,01 m. The allowable capacities calculated showed low shear resistance due to the tendency to split in the longitudinal direction, and the buckling capacity of the culms compromised the compressive capacity of the longer elements. However, no stress exceeded the resistances after alterations in the structure. The dynamic analysis results indicate that bamboo is exceedingly capable of resisting the earthquakes considered. This study suggests that bamboo design has notable potential as a sustainable, durable, seismically resistant housing alternative.

Keywords

Bamboo Structural Design, Seismic Analysis, Bamboo Literature Review, Moso Bamboo, Standards

1. Introduction

The construction industry accounts for 39% of the world's CO2 emissions (*World Green Building Council*, n.d.). Using bamboo as a construction alternative can strongly contribute to the pressing need to combat climate change.

The global bamboo industry was valued at a market size of USD 68.8 billion in 2018, with expectancy to grow at a CAGR of 5.0% from 2019 to 2025 (*Grand View Research*, n.d.). This is related to the diversity of products that bamboo can provide, contributing to circular economies that are congruent to many of the Sustainable Developments Goals laid by the United Nations.

As the fastest growing plant in the world, it can sequester 50 tons of CO2 per hectare per year, 3 times as much for the same area of timber planted (Walter Liese, 2015; *Bamboo U*, 2021; Rabik & Brown, 2004). Moreover, a single clump of bamboo can hold a tremendous amount of water and release it to the surrounding vegetation. Together with its extensive canopy that protects the land from extensive sun exposure, bamboo can play an important part in restoring degraded land, preventing deforestation, control erosion and flooding.

Bamboo is harvested yearly, leaving the root system unharmed and continuingly producing more shoots (Asif, 2009). Therefore, it can also enable the communities that manage the life cycle of bamboo to thrive (e.g. *Environmental Bamboo Foundation*, n.d.)).

Acknowledging the advantages in what regards sustainability, this study's intention is to take a step towards demonstrating the capabilities of bamboo as a structural element. As an emerging material, there is still shortage of scientific documents and data on topics related to building with bamboo. Nevertheless, recent efforts in standardizing tests, grading and structural design allow for regulated practices that will lead to making bamboo a conventional material.

This work intends to firstly present a diverse state of the art, approaching topics that could possibly compromise the efficiency, safety or use of bamboo as a structural element. After providing a broader perspective through the literature review, a practical case is developed.

The case study demonstrates a static and dynamic analysis of a structure using bamboo as the only structural element. The structure is modelled in the computer software SAP2000, and the response forces are compared with the allowable resistances calculated according to the structural design standard ISO 22156:2021. The loads and combinations follow the recommendations the Eurocode, as well as the national annex for the country of Portugal.

2. Bamboo- A Functionally Graded Material

2.1. Bamboo as a plant

To better understand the behaviour of bamboo, this section introduces a description of its constitution, botany, and morphology of bamboo, as well as the topics found most relevant inherent to the bamboo plant that will impact structural behaviour.

Bamboo integrates the following physical elements: branches, culm, leaves, rhizomes, sheath, and roots (Banik, 2015).

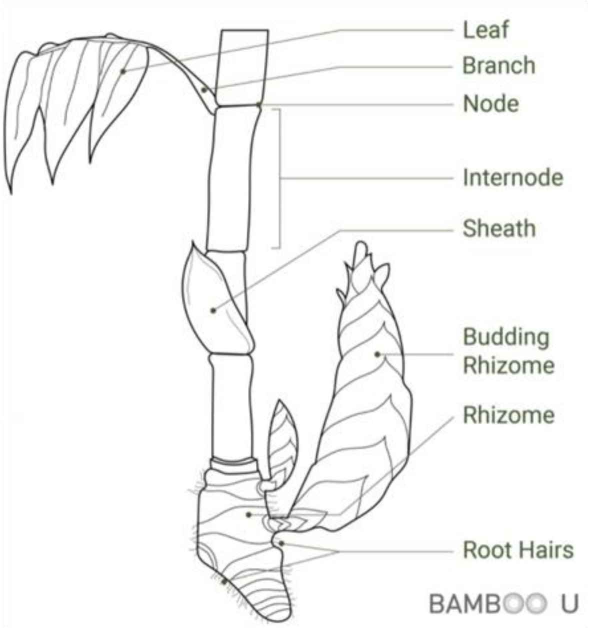


Figure 1- Sketch of the constitutional elements of bamboo (picture from *Bamboo U*, 2021)

The culm is the visible part of the plant, and it is hollow (though there are exceptions), tapered and segmented. The nodes consist of intermittent joints that manifest as a diaphragm to the interior of the culm, providing transverse interconnection of the culm walls. Their radially oriented cells help prevent buckling of the walls (Kaminski, Laurence, et al., 2016), assist straightening the culm and enable the conduct of water (Shao et al., 2010). The internodes are essentially hollow tubes with longitudinal oriented cells and have a varying wall thickness.

The bamboo inner culm wall is constituted by strong dark vascular bundles (vessels supported by fibers) that run parallel through the length of the culm, connected transversely by a weaker matrix called parenchyma (Liese, 1998; Dixon et al., 2015; D. J. Trujillo & López, 2019; Correal, 2019). Bamboo is considered a functionally graded material due to the ability to ajust its constitutional properties to respond to the stresses imposed by nature during its life course. This natural efficiency of bamboo translates in, for example, the higher concentration of vascular bundles towords the exterior of the culm wall, resulting in an increase of mechanical properties along the culm wall (Richard & Harries (2015); Habibi et al. (2015).

2.2. Material properties of Bamboo

Bamboo can grow exceptionally fast, up to more than 1 meter a day (Titilayo Akinlabi et al., 2017; Rabik & Brown, 2004). However, it is required a maturation period to enhance the physical and mechanical properties of bamboo. On the other hand, the properties of bamboo will decay after they reach their peak if the culms are not harvested (Zhou, 1981; Lu et al., 1985). Therefore, the bamboo age at harvest will largely impact its structural applicability. This relates to the hardening of the parenchyma tissue matrix which lignifies the culm, resulting in the increase of the culm's density, stiffness and strength (Liese, 1998; Kaminski et al, 2016; Harries et al, 2017).

In a similar manner to timber and other materials, density correlates to the strength of bamboo. The density of bamboo depends on fiber content, fiber diameter, and cell wall thickness (Janssen 2000). The density of most bamboo is 600 – 800 kg/m^3 but will vary with species, growing circumstances, and height (Harries et al., 2017).

The effect of moisture content (MC) of bamboo is broadly considered crucial when analysing the properties and strength of bamboo, as it affects both short and long-term performance. In a similar manner to timber, green bamboo (freshly harvested) has inferior strength than dry bamboo. The international standard for testing (ISO 22157:2019) requires testing bamboo at a dry condition ((12 ± 3) % moisture content), since it is more representative of service conditions. In addition, the structural design standard ISO 22156:2021 sorts 3 different service classes to consider the correct environment of the bamboo *in situ*. As for the variation through culm length, MC decreases from the bottom to the top, contrarily to density (e.g. Zhou (1981); Abdul Latif et al. (1990); Titilayo Akinlabi et al. (2017)), independently of the time of harvesting (Wakchaure & Kute, 2012).

As seen, bamboo does not present uniform properties. Nevertheless, the variations are not particularly substantial and therefore do not compromise the structural use of bamboo. It just evidences the significance in registering all of these relevant characteristics to properly grade the culms, enabling the safe use of this natural element.

3. Durability and Treatments

The evolution of bamboo treatments is one of the most consequential reasons why bamboo is now leaning towards becoming a conventional material. It is common understanding in the referenced literature that if untreated, bamboo will not last. It is a vulnerable material, and can deteriorate in as little as less than half a year (e.g Kaminski, 2018). Bamboo’s lack of natural toxins, high levels of starch and thin walls make it more susceptible to decay than timber (Kaminski et al., 2020). Despite there being an immense diversity in pests and diseases that can damage bamboo (described in Shu & Wang, 2015), the three main causes of decay are beetles, termites and fungal attack (rot) (e.g Kaminski et al. 2016). These attacks emerge immediately after harvesting, depreciating the properties and applicability of bamboo (Titilayo Akinlabi et al. (2017)).

Any treatments using Arsenic, as some older copper-based preservatives, are now highly unrecommended as they cause major health and safety risks, and have been banned from most countries (Kaminski et al., 2020). Painting with conventional paint is also unadvised, since although it reduces the water absorbed from the rain, water will eventually infiltrate due to splits or deterioration of the paint and get trapped on the inside, making it more favourable to rot (Kaminski, 2018).

Boron is the chemical element that is the most popular and appropriate by virtue of its efficiency, cost, low toxicity and easy applicability. Furthermore, it proves to be competent (Kaminski, 2013). It has both insecticidal and fungicidal properties, yet boron treated bamboo (or treated with any of the boron-containing compounds) cannot be exposed to rain since the preservative will eventually dissolve (Kaminski, 2018). Liese & Tang (2015) also declare it to be ineffective against soft rot.

Modern copper-based preservatives no longer have arsenic and chromium, and therefore are no longer as toxic as previous forms. Unlike boron, they are chemically relatively well-fixed into the bamboo, meaning it can more easily be utilised externally or in contact with the ground Kaminski et al. (2016). Although it is quite effective, this applying this preservative comes out quite expensive, as not only it implies semi-industrial pressure treatments, but also because the bamboo must be kiln-dried beforehand (Kaminski et al. (2016)).

Regarding the treatment methods, bamboo does not have ray cells that provide a radial transportation system through the wall thickness, contrarily to timber (Correal, 2019; Liese & Tang, 2015). Thus, the penetration of chemicals into bamboo is not as easy. From the several existent treatment methods, soaking, vertical soak diffusion and the modified boucherie are used for treating with boron. Pressure treating is between the best to preserve bamboo, yet it is quite expensive because it needs specialized equipment to apply the pressure (Correal, 2019).

Seasoning of bamboo consists in drying the culms in order to lower the moisture content closer to the equilibrium moisture content in service (e.g Kaminski et al. (2016)). This is extremely relevant since not only bamboo is stronger and less susceptible to decay when dry, but also because shrinkage is directly corelated to moisture content (Liese & Tang, 2015).

Durability by design means designing a structure with characteristics that improve its durability. Kaminski et al. (2020) states this is the single most important way to preserve the durability of a bamboo structure, arguing it might even be more relevant than the durability treatments. This is because no treatment allows bamboo to really last without preventing it from rotting, therefore bamboo needs to be fully protected from the rain. Kaminski et al. (2020) argues bamboo can last a lifetime (50+ years). This of course if all cautious steps are taken:

- Selecting mature bamboo;
- Harvesting at appropriate times (when starch and MC levels are lower);
- Seasoning;
- Modern methods of preservation;
- Durability by design;

4. Connections

Connections are crucial for the integrity and safety of any structure. The joints in bamboo are particularly challenging due to its round, hollow, tapered, and thin-walled constitution. This makes it hard to find reliable connections in the construction process, more than in other materials as timber (Correal, 2019; Hong et al., 2019).

Besides its dimensional characteristics, bamboo’s dominant tendency to split (Mitch et al., 2010) and low allowable shear stress make connections regarded as the weakest parts in bamboo constructions (e.g Awaludin & Andriani, 2014). Bamboo structural members are also more efficient in axial loading due to the difficulty to provide moment-resisting connections in bamboo. Thus, no moment transmission between connected culms should be considered (only pin-connected), unless for continuous elements (Correal, 2019; Kaminski, Laurence, & Trujillo, 2016).

Bolted connections are the most broadly adopted for their simplicity, efficiency and cost (Hong et al., 2019), although using solely bolted connections may cause brittle behaviour (Paraskeva et al., 2019).

There are many ways to connect bamboo through steel members, from simpler ways to more complex prefabricated solutions that try to meet the mechanical and architectural requirements. Although prefabricated solutions are accurate, durable, and have all the advantages inherent to steel, the fabrication process is expensive and most likely not universal, which makes it difficult to connect with such a variable material as bamboo (Hong et al., 2019).

Infilled bamboo connections have become a very popular solution. Cement mortar is the most common filling material, as it is economic and easy to obtain (Correal, 2019).

Connections have not yet reached a preferable level of investigation. The peer-reviewed research on bamboo connections remains limited (Paraskeva et al., 2019), and joints are in nearly all cases the most vulnerable parts in bamboo structures (Kaminski, Lawrence, & Trujillo, 2016). The weight, strength, ductility, cost, reliability, efficiency and durability of the connections are all relevant and vary between proposals.

5. Case Study – Structural Analysis

To analyse the structural behaviour of the design, the structure was modelled in SAP2000 (*CSI Portugal | SAP2000*, n.d.). This program was chosen due to its selection by several engineering and academic organizations.

A bamboo nursery based in Alentejo, Portugal was contacted to find if one of the species known to be fit for structural use existed, and Phyllostachys Edulis (Moso bamboo) was guaranteed to grow there.

The design of the structure was mostly conditioned by the nature of the material. Not only in terms of the properties of bamboo as a structural element, but also due to the implications of the causes of decay of this organic material. Moreover, the fact that there would be no bending moment transferred between horizontal and vertical elements resulted in a clear necessity of a strong bracing system.

The core idea was to design a residential structure and test its safety according to the recommendations of the new version of the ISO22156 (published 03/06/2021), while implementing all of the good practices found in the literature review.

The model developed holds the following assumptions, amongst others referenced in the IS (International Standard):

- Bamboo is modelled as a linear elastic material through the allowable stress;
- Bamboo culms are conservatively modelled as hollow tubes having cross section dimensions equal to the smallest dimension of the culm;
- Second order effects resulting from imperfect members are considered;
- All joints are assumed to be pinned (hinged);

5.1. International Standards

For an emerging anisotropic material as bamboo, the standards are largely responsible for enabling the confidence in using it as a reliable alternative, and a variety of thorough international standards are now available.

In 2004, the first bamboo international standard was released by the International Organization for Standardisation (ISO) in cooperation with the International Network for Bamboo and Rattan (INBAR). A strongly revised testing standard was further published in 2019 (ISO 22157:2019- Bamboo structures - Determination of physical and mechanical properties of bamboo culms - Test methods (ISO, 2019)). The process of testing, together with grading the culms to use in construction will greatly minimize the risk of building with bamboo. Grading can be done in compliance to ISO 19624:2018- Bamboo structures- Grading of bamboo culms- Basic principles and procedures (ISO, 2018).

In 2021, it was published a strongly revised and more detailed structural design document (ISO 22156:2021 (*ISO*, 2021)). It contains complete design equations and is up to date with the new revisions of normative references (ISO 22157:2019 and ISO 19624:2018) (Kaminski et al., 2020).

5.2. Loads

The identification of the actions was made using Eurocode 1 (Portuguese Norm NP EN 1991-1-1, 2009). the structure is subjected to the following dead and live loads:

- Self-weight of the bamboo poles – automatically considered in the program;
- Steel plate self-weight – approximately 0,05 kN/m^2;
- Roof live load, q_k – 0,4 kN/m^2 distributed by the roof;
- Roof live load, Q_k– 1 kN/m^2 in the least favourable point;

The roof live loads q_k were introduced in the program as punctual loads at the end nodes of the bamboo elements.

To consider wind action, the European codes were used to find the corresponding loads and combinations to apply. Since the roof area was designed considerably large when compared to the base of the structure, the wind effect is extremely important to consider. All of the expressions used were found in the work of Mendes & Oliveira Pedro, 2020 or directly from the Eurocode (*Eurocode 1: Wind Actions*, 2005).

The peak velocity pressure at height z ($q_\mathrm{p}(z)$), which includes mean and short-term velocity fluctuations, was determined, and resulted in 771,6 N/m^2. To infer the external pressures (c_{pe}), the Eurocode advises a specific distribution of pressures for each type of shape. Since the roof design is hipped, the load distribution is sorted in the separated areas. After sorting the pressures in the respective areas, they were multiplied by the peak velocity pressure, obtaining the external wind pressure values in kN/m^2.

The protruding roof corners were also considered, which is equal to the pressure for the zone of the vertical wall that is directly connected to the protruding roof.

As for the internal pressures, the upward value taken was +0,2, adding to the remaining wind loads.

5.3. Design Values

Previous research shows that a diameter of 100 mm with a wall thickness of 10 mm is reasonable to consider, therefore, those were the values chosen for the analysis.

This study uses characteristic values of MOE from the work of Gauss et al. (2020), similarly to the characteristic values of the strengths regarded further. This, because the result of the mean characteristic compressive MOE in this study (Ec = 18,040 MPa) was established with 75% confidence and the compression test according to the ISO 22157, as it is required by the standard.

As for the density, the value considered was 8 kN/m^3, also taking into consideration average values from the available literature.

5.4. Allowable Strength Verifications

The design methodology approached by the ISO 22156:2021 to ensure the safety and performance of a structure is based on allowable stress design (ASD). Using the characteristic strengths (f_{ik}) from the study mentioned and the standard's formulas, the allowable strengths resulted in the following:

Table 1- Maximum stress values of compression, tension, bending and shear for instantaneous and permanent loads. The stresses multiplied by the cross sectional area results in the values in kN.

fi	fik	Permanent		Instantaneous	
	MPa	MPa	KN	MPa	KN
fc (compression)	49.5	12.25	34.63	18.93	53.53
ft (tension)	220	54.45	153.93	84.15	237.89
fm (bending)	183	45.29	128.04	70.00	197.88
fv (shear)	15.4	1.91	5.39	2.95	8.33

The verifications performed are described below:

Table 2- Summary of verifications implemented.

Compression	Shear	Bending
$N_{ed} < N_{cr} = \frac{P_c + P_e}{2c} - \sqrt{\left(\frac{P_c + P_e}{2c}\right)^2 - \frac{P_c P_e}{c}}$	$V_{ed} < V_{rd} = f_v \times A$	$M_{ed} < M_{rd} = f_m \times A$
Compression + Bending	Tension	Tension + Bending
$\frac{N_{cd}}{N_{cr}} + \frac{BM_{cd}}{M_r} \leq 1{,}0$	$T_{ed} < T_{rd} = f_t \times A$	$\frac{N_{td}}{N_{tr}} + \frac{M_{cd}}{M_r} \leq 1{,}0$

The maximum values of compression and shear were, as expected, the most critical amongst the remaining. In compression, the longer elements had a lower buckling capacity that lowered their compressive capacity. Therefore, some of these elements suffered alterations to decrease the length between points of lateral restraint. Another solution that was taken not just for compression but also for shear, was to add culms in the critic elements, dividing the forces by a higher number of culms.

Given the substantial difference between the results of the bending moments applied and the moment capacity, the combined verification of axial and bending loads did not show critical frames in the structure. The tensioned elements were also far from reaching tension capacity.

5.5. Deflections

One of the reasons for including a floor was to understand how bamboo culms would behave as a flooring structural element. The model was composed of continuous beams in the direction of smallest span (3m) and pinned in the perpendicular direction (same direction as the black line in Figure 2). The design reference for maximum allowable displacement was L/200 = 3/200 = 0,015 m or 1,5 cm.

Some iterations were done on the distance between continuous beams, reaching a final separation of 0.25m. In the perpendicular direction, the pinned culms were separated by 0.375m. To further decrease vertical displacements, vertical elements were inserted along the beam represented in black until the maximum displacement was inferior to the allowable.

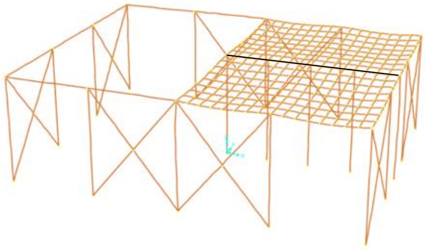


Figure 2- Ilustration of vertical displacements with four culms supporting the middle beam.

5.6. Seismic Analysis

The seismic analysis was performed using the computer program SAP2000, as it has the option to run dynamic analysis considering the Eurocode (2004) and using the characteristics of the seismic action for Portugal, specifically.

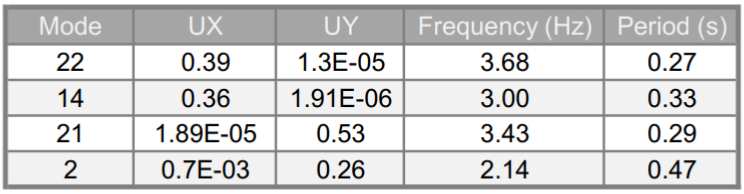
The software analyses the structure through a modal analysis with multiple degrees of freedom, using the response spectra and the correspondent design peak ground accelerations. There are two types of earthquakes in Portugal (Type 1 and Type 2), distinguished by different surface wave magnitudes and geographic origins.

To define the functions of the response spectrums, the value of the peak ground accelerations was taken from the Portuguese norm for Eurocode 8 (NP EN 1998-1, 2010). The combinations for the seismic action were defined by the European standard (NP EN 1998-1, 2010).

The number of modes was increased until the sum of modal participating mass ratios reached 90%, as recommended. For 75 modes, participation values came at 91,12% for Ux and 92,9% for Uy.

The table below presents the characterization of the two modes that represent a higher participation ratio for Ux and Uy in the structure.

Table 3- Higher modal participating mass ratios of the structure.



Mode	UX	UY	Frequency (Hz)	Period (s)
22	0.39	1.3E-05	3.68	0.27
14	0.36	1.91E-06	3.00	0.33
21	1.89E-05	0.53	3.43	0.29
2	0.7E-03	0.26	2.14	0.47

The structure under analysis has the clear advantage of being extremely lightweight. The global force in the z direction is equal to 32,78 kN, expressing the same idea. The values of the forces in the frames for the combinations mentioned were far from exceeding the values of resistance in any type of stress.

6. Conclusions

Bamboo is a functionally graded natural material that does not present uniform properties. Nevertheless, recent efforts in the standardization of grading, testing and structural design overcome the anisotropy limitations. In regard to durability, treatments with boron provide a safe, economical, effective and sustainable way to make a structure last, as long as durability by design measures are performed. In connections, the hollow round shape and variable section of bamboo make joining members challenging, therefore more testing is required.

The allowable capacities calculated showed low shear resistance due to the tendency of longitudinal splitting, and the buckling capacity of the culms compromised its compressive capacity of the longer elements. Nevertheless, no stressed exceeded the resistances after alterations in the structure. The dynamic analysis results indicate that bamboo is exceedingly capable of resisting the earthquakes considered. This study suggests that bamboo design has notable potential as a sustainable, durable, seismically resistant housing alternative.

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