

Design Optimization of Tree-Shaped Structural Systems and Sustainable Architecture Using Bamboo and Earthen Materials

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Abstract: The objective of this research is to support sustainable architecture where renewable materials (such as plant-based materials and soil) are used for construction. The use of renewable materials and earthen building techniques in structural design represent important construction practices to mitigate the associated carbon footprint. In this study we propose structural systems that will be constructed using renewable materials such as bamboo, that probably is the most well-known renewable material and has long been valued as an alternative to wood. The main goal of the study is to design tree-shaped structural systems using the advanced characteristics of *Guadua angustifolia*, a clumping variety of bamboo chiefly native to South America, and to test its effectiveness by means of a structural parametric design optimization approach. For this purpose, an elliptical and a quadrangular structural system is parametrized and optimized to effectively support the design loads imposed by the roof that is supported by the proposed structural systems. DOI: 10.1061/(ASCE)AE.1943-5568.0000492. © 2021 American Society of Civil Engineers.

Introduction

Sustainable architecture has come to the fore in recent decades in the design stage and attempts to equilibrate the dialog between natural and artificial materials, in an effort to combine architectural design with sustainability. This is happening through variations imposed in the design procedure related to the concepts of low-tech, bioclimatic, eco-tech, bio architecture etc., that is, a design procedure which can reduce environmental damage. The architecture, engineering, and construction (AEC) industry is responsible for the generation of around 39% of greenhouse gas (GHG) emissions (28% for building operations and 11% for building materials and constructions) (Ahmed Ali et al. 2020). In addition, the AEC industry is responsible for 20% of all solid waste produced in developed countries (Guillaud 2014). The main construction materials that are used today (i.e., steel, concrete, and aluminum) cause around 50% of all global industrial CO₂ emissions while the demand is expected to double by 2050 (Lagaros 2018). Therefore, it is not difficult to imagine that sustainable architecture will soon become the only approach in order to continue designing new buildings and minimizing the effect on the environment. At the same time, it is expected that the world's population will increase between 3.5 and 5 billion by 2030, with 95% of the urban expansion taking place in the developing world. Meanwhile, European citizens spend

over 90% of their time indoors, which means that human health and well-being is strongly linked to the way the built environment is constructed, maintained, and renovated (Pacheco 2014).

Sustainable architecture seeks to build a combination of energy-efficient technology and innovative design using renewable materials (soil or plant-based materials such as bamboo) which can achieve the objective of creating bioclimatic and sustainable spaces for housing, community, schools, and leisure use. The utilization of bamboo in construction can contribute to sustainable management of the Earth's resources. It is an excellent eco-friendly construction material owing to its high renewable rate, low embodied energy, reduction of pollution, high strength-to-weight ratio, and low cost. Certain bamboo species hold a record of the fastest growing plant. Different species are native to diverse climates around the world. Many environmental organizations are promoting bamboo owing to its variety of excellent properties. Similarly, soil which is the main material of earthen architecture is ecological and widely available. Earthen constructions are low strength, so it is mainly used to build thick walls or timber-supported walls for a longer life cycle of the construction (Minke 2009). The combination of the two materials can give architectural paradigms of high standards. Many historical earth constructions, already part of UNESCO heritage, such as the houses of Hakas in China or the fortified rammed earth constructions in Portugal have survived despite several strong earthquakes in recent centuries due to water-resistant walls (Frangedaki et al. 2020).

The synthesis of building vaults and slabs constructed from bamboo is very promising according to traditional construction practices in many countries. These structures can become sustainable solutions through a new design approach for conventionally (masonry and wood) or earthen-built buildings. The design with natural materials and the connection of modern engineering science with traditional techniques is an approach which can lead to waste and pollution reduction but also produce low-cost dwellings, which can be an effective solution to the housing crisis. In low-cost housing, the roof structures can account for up to one third of the total building cost (Minke 2009), which can be significantly decreased with the utilization of bamboo. Materials such as soil and bamboo combine eco-friendly construction with low environmental impact, so are appropriate for use in the modern

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context (Frangedaki et al. 2018). Finally, materials such as earth, stone, bamboo, and wood, mostly taken directly from the site of the construction, reduce adverse effects from the transportation of building materials from their source to the construction site.

The design of the structural systems studied in this research focuses on an optimization framework aiming to improve construction (Lagaros 2014). The contribution of this work to sustainable architecture is to investigate alternatives of a column-beam system made of bamboo, inspired by tree-shaped (dendriform) structural systems. These systems can be described as vertical structural elements which are attached to a roof slab, able to carry the loads transferred from the roof to the foundation of the structure. The proposed tree-shaped structural systems are designed based on knowledge of traditional bamboo construction and the characteristics of *Guadua angustifolia*, which is a tropical species of giant timber bamboo native to South America (Farrelly 1984). This species was selected because it is available in many regions of the world, occurring naturally in Colombia, Ecuador, Venezuela, and also introduced to other countries in Central and South America, Europe, and Asia (García and Kleinn 2010). In this research, parametric design is used as a means to explore a large number of parameters within an AEC project that enables the designer to control the morphology of the system without neglecting the structural aspects, thus integrating architectural language and offering greater freedom of expression. The use of design numerical tools and the standardization of innovative materials can also contribute significantly to the development and application of the ecological principles, which can help lead to an inclusive transition towards a climate-neutral Europe (Lagaros 2018; Mavrokapnidis et al. 2019). The utilization of natural materials in buildings and the application of modern engineering science with traditional techniques are a promising approach for controlling and reducing construction waste.

The Objectives and Motivation

In this study, a new approach is explored for designing a structural support system for earthen buildings as described in the following. The primary interest of this study is to investigate the use of a renewable, eco-material, for an eco-structural system, in order to propose a building (walls and structure) as a design strategy towards sustainable architecture. Bamboo poles are selected for a dendriform structural system appropriate to support the roof and other floors as a central pillar. Finally, after the description of the design method, we have chosen two different cases to be studied, which can give a more in-depth understanding of their behavior. A linear and a curved structure have been designed to illustrate the application of the proposed material and to observe their conformation and characteristics after optimization.

Structural Materials and Parametric Design

Renewable Materials Selected

The selection of sustainable materials plays a vital role in a building's environmental footprint. Bamboo and soil can contribute to minimizing a building's impact. There are around 1,500 species of bamboo which are classified as herbaceous or woody plants (Desalegn and Tadesse 2014). Genus *Guadua* has many environmental benefits as a construction material owing to its high renewable rate, embodied energy, and high strength-to-weight ratio. Although bamboo represents a valuable sustainable natural resource, it is not utilized enough as a building material in modern architecture;

bamboo use is limited because of the variation in material properties, poor treatment processes, and also because of the functional difficulties in making connections between poles (Ramirez et al. 2012). One of its positive features is that it can grow in most climates and has no need of fertilizers for its growth, the use of which can cause negative environmental effects. Bamboo is found in abundance, from cold mountains to tropical areas and is found mostly in Asia, Africa, America, and has also recently been grown in Europe (Akwada and Akinlabi 2015). The purpose of the European bamboo cultivation is to mitigate the climate change by planting and managing bamboo, starting in Southern Portugal (Van der Lugt et al. 2003). Some species of bamboo are among the world's fastest growing plants and *Guadua* bamboo represents the most important species in Latin America and is used extensively in traditional construction. After the earthquake in 1999 in Armenia city (Colombia), the seismic performance of structures using *Guadua* bamboo as the main material was good. The reason for the seismic disaster was mistakes caused by improper construction techniques and the lack of design parameters for this type of structure (Luna et al. 2012). For the proper simulation of the models in this research, its elements obtain values from the range of material characteristics listed in Table 1. Bamboo has not been standardized industrially yet; however, the International Organization for Standardization published ISO 22156:2004 "Bamboo – Structural design" including guidelines that apply to the use of bamboo structures (Van der Lugt et al. 2006), that is, structures made of bamboo (round bamboo, split bamboo, glued laminated bamboo, or bamboo-based panels joined together with adhesives or mechanical fasteners), and the ISO 22157-1:2004 "Bamboo – Determination of physical and mechanical properties – Part 1: Requirements" (ISO 2004). In addition the recent ISO 22157:2019 "Bamboo structures – Determination of physical and mechanical properties of bamboo culms – Test methods," proposed guidelines for testing procedures for specimens obtained from bamboo culm, in order to examine moisture content, density, mass per unit length, strength properties, tension, and bending (Gauss et al. 2019).

Guadua poles can reach a length of 20 m and are cut into different lengths according to their cross sections. Typically the most used parts are the intermediate section called the "middle or basas," characterized by its strength in relation to its weight and the "bottom or cepa" part which has the highest diameter. Owing to the morphology of *Guadua*, the diameter of the canes is almost constant along its length, with a maximum reduction in diameter

Table 1. Material properties of *Guadua angustifolia* "Kunth" and typical dimensions of bamboo poles

Property (1)	Values (2)
Density (dry)	500–800 kg/m ³
Culm height	6–25 m
Internodal space	250–500 mm
Diameter	50–200 mm
Modulus of elasticity $E_{0.5}$	7,000–17,000 N/mm ²
Poles thickness $E_{0.5}$	10% of the outer diameter
Bending	15 MPa
Tension	18 MPa
Shear	1.2 MPa
Compression parallel to fibers	14 MPa
Compression perpendicular to axis	1.4 MPa
Poisson's ratio	0.5
Ø (diameter vertical elements)	13–15 cm
Thickness (vertical elements)	0.8–4 cm
Ø (diameter horizontal elements)	11–13 cm
Thickness (horizontal elements)	0.8–4 cm
Maximum pole length	590 cm

value by 5 mm/m and an almost stable thickness. It can work perfectly as a structural material (Ghavami 1988).

In this research, the combined use of two eco-friendly materials is examined. Bamboo for the structural system and earth for the building skin and filling elements (especially unfired, untreated, raw earth). There are many earthen construction techniques which vary related to culture, climate, local resources, and can be categorized as adobe, cob, rammed earth, wattle and daub, light straw, earth bags, earth plaster, and render. Many of the earthen building constructions gain stability with a timber framing, such as lintels, beams, or with a whole timber structural system. Most of earth houses are covered with roof tiles, or plates of rocks and in many cases they have a roof with a layer of planted or grassed earth. Such structures require multiple thick earth walls to support the earth roof which means extensive work and an increased need for material; thus, the replacement of timber with other more ecologically acceptable material is important for sustainable architecture and will be an ecological solution especially when there is a scarcity of wood.

The use of bamboo as a structural system has existed for thousands of years in countries such as Colombia, Indonesia, and China (Akwada and Akinlabi 2015). The combination of earth in construction with bamboo reinforcement has a very long history in housing, in countries such as Guatemala, where it is mainly used as a structural system for the transmission of roof loads to the walls and then to the foundation, utilizing a large number of columns fragmenting the living space into small rooms. Owing to the limited durability of bamboo when in contact with the ground, foundations, or regularly wet areas, it is primarily utilized indoors or in roof construction (Trujillo et al. 2013). European earthen buildings are usually covered with tiled pitched roofs with a timber structural system. In these two case studies (1 and 2) which are examined, the construction detail for the connection between walls and roof can follow the paradigm of existing traditional designs (Mousourakis et al. 2020).

Bamboo, as a sustainable local building material, also gives added value to traditional earthen construction, in many Asia and Latin American countries, such as tensile strength and the ability to afford weights over long spans such as roofs, wide doors, and windows. Many architectural firms such as CRU! Architects, Chiangmai Life Architects, and Studio Anna Heringer, contribute to the minimization of the effect on the environment through the application of appropriate design concepts and eco-friendly

materials and focus on how to bring bamboo and earth architecture into the 21st century [Fig. 1(a)] In this research, we examine the use of bamboo for flat roof structures filled with lightweight loam which is commonly tile covered. If the roof is filled with lightweight loam and the ceiling made of timber boards, it reaches a density of 600 kg/m^3 and the roof achieves a U value of $0.8 \text{ W/m}^2\text{K}$.

State of the Art on Tree-Shaped Structural Systems

The design approach for the structural elements is made with the application of biomimicry, a field which is about the use of nature as a guide for creating new types of structures and gave rise to a series of designs, such as the “dendriform” structures, inspired by the shape of the trees (Rian and Sassone 2014). According to Pollack (Pollack 2005) “Trees are organisms that stand by themselves, and therefore their shape has an inherent structural rationality.” They are exposed mainly to the wind load, therefore trees have a configuration that can cope with wind load and the corresponding bending moments. The self-weight of a tree represents the axial load (compression) that is sustained by their stems and trunks. When trees are exposed to the wind (bending conditions) the stresses developed vary: from the traction on the convex side to the compression on the concave side. These schematic forces which act on the tree shape play a major role in the implementation on buildings design such as TOD’S Omotesando Building by Toyo Ito (Turnbull 2012).

The configuration of trees permits the distribution of uniform loading, so the structural system of trees can be considered as *optimized* with respect to the distribution of the loads (Rian and Sassone 2014). According to the principle of the minimum lever arm, larger branches increase the chances of breaking. To avoid breaking, trees have a compromise point by exposing a larger number of leaves, limiting however the length of the branch (Mattheck 1995). The branched structures, known as “dendriforms,” first had a decorative role in architecture, though later their use as a structural system was found to be a very successful construction practice, starting from ancient Greek structures of Corinthian style in architecture until post modern architecture constructions such as the Gardens by the Bay in Singapore (Davey 2011).

Over time the shape of the dendriform structures changed as new materials were used in architectural design. Through the new materials, the sections of the supporting columns have thinned bringing the tree-column structures to increasingly resemble the



(a)



(b)

Fig. 1. Tree-shaped structural system: (a) Chiangmai Life Architects and Construction Co. Ltd (reprinted from CLA 2021, with permission); and (b) Mushroom structures (image courtesy of Giorgio Baroni, “Baroni’s Tree,” 1938).

typical structure of trees. During the last century the forms of nature continued to attract the interest of architects and engineers, so in movements such as art nouveau, the plant world in general and especially their morphology played a primary role, not only in defining decorative but also structural elements (Howard 1996).

The combination of concrete and steel has been widely applied in tree design structures with much experimentation searching for solutions that minimize the use of steel. One of the first examples was Giorgio Baroni's studies in which he experimented with double-inverse curvature thin reinforced concrete roofs. Among his experiments was a design in 1938, the "mushroom" inverted umbrella structure known as the "Baroni tree" [Fig. 1(b)]. This had a double advantage: less steel with a better distribution of forces, close to the field of structural optimization (Greco 2001).

During the 1950s, dendriform structures took on another meaning due to an interest in biomimetics (derived from the Greek words *Bios* and *Mimesis*, meaning life and imitating) expressed in the work of Otto Schmidt. In this approach, Schmidt utilized forms of nature and their transfer to technological ideas defined through artificial applications (Eggermont 2007) which produced good design. The term "biomimetics" became increasingly popular in the 1980s. Between 1950 and 1960, Felix Candela designed a series of thin shell structures supported by umbrella-type columns. This design combined engineering with biomimetics. A column structural system inspired by the shape of the trees not only acts as a support system for the roof, but also acts as a roof itself. The stability of the "umbrella" depends solely and exclusively on the proportions of the structure itself and the optimum rise, which depends on the area covered by the umbrellas (Rian and Sassone 2014). Felix Candela has also designed the famous hypars and umbrella column shell: a hyperbolic paraboloid with curved edges and additionally one with straight edges. His second experimental umbrella was constructed in Vallejo, Mexico, 1953 (Draper et al. 2008b). The success of these structures depended on the simple proportions of the structure (Draper et al. 2008a).

Lastly, many designers have experimented with nature-inspired dendriform structures including well-known works such as Frei Otto's large-scale structures of modern architecture (Nerdinger and Barthel 2005) in the 1970s.

Parametric Design

A parametric design approach is selected for the study of the two dendriform structural systems for constructions mainly incorporating earth. Earthen buildings are vulnerable to water, so the main concern, especially in countries with high levels of rainfall, is how to protect them with stabilized soils for coatings and with extended roofs. The structure must provide a roof overhang to prevent rain from coming into contact with the earthen walls. Owing to the difficulty in assessing the mechanical properties of earthen buildings in order to guarantee an adequate structural safety, the walls are counted as only self-load-bearing systems. This criterion for the design definition is very important mainly in countries without guidelines and regulations for constructions made of earth. In addition, the bamboo structural support system should maintain an adequate distance from the peripheral walls because it is susceptible to damage from excessive humidity. Bamboo is more resistant to water than to moisture (Bui et al. 2017). The last criterion that must be considered is that soil has relatively good strength in compression and generally poor strength in shear and tension; therefore, the layout of the structural support system needs to be able to transfer roof loads directly to foundations and provide protection to the walls. For the implementation of the proposed method, two roughly symmetrical structures are designed and simulated. According to

dendriform structures, the design definition has a symmetrical distribution of elements, placed approximately equally balanced around the z-axis to create the quadrilateral and the elliptical structure. The use of *Guadua angustifolia* is selected for its physical and mechanical properties and potential for industrial use, especially with regards to its strength. Although it is characterized with heterogeneous results from research conducted up to the present, it is considered that it has some general characteristics that are adopted for the identification of the elements of the structural system's simulation (Table 1) (Luna et al. 2012). These characteristics are implemented in the numerical model considering that material has anisotropic behavior (Chand et al. 2007). A circular hollow section based on the standard dimensions of bamboo (Table 1) is used for simulating the bamboo rod elements. Two different cross sections are adopted for the two types of elements: a larger one for the vertical elements and a smaller one for the horizontal elements (Table 1).

In this study, a parametric design framework is applied, aiming to improve bamboo contemporary designs using this eco-friendly material mostly found in traditional architecture. In particular, dendriform structural systems are studied within an algorithm-aided design (AAD) procedure, that is, an optimization process is implemented based on the designed dendriform structural systems (Sardone et al. 2020): (i) one with quadrangular morphology (Fig. 2) and (ii) one with elliptical morphology (see Fig. 4), utilizing curved bamboo poles for column and truss elements. The methodology and algorithm workflow adopted for the analysis of the tree structures involve the use of specific tools that allow the calculation times for every possible model to be accelerated and the search of the shape and the cross-section of the horizontal and vertical elements of the tree structure to be combined. The analysis and optimization process involve the use of software and plugins in the following order.

- i. Rhinoceros 6 (Version 6.33) for the 3D computer-aided design modeling application, based on free modeling using NURBS.
- ii. Grasshopper, which is a visual programming language and environment and runs within Rhinoceros 3D, for the mathematical description and expression of the parameters. This parametric design tool is used to build generative algorithms. Most of Grasshopper's components create geometries and with the included Maths tab allows the specific domain and build matrix to be set and mathematical operations to be performed, expressions to be written, and functions evaluated with the possibility of including Python, C#, and VB script.
- iii. Karamba3D, which is a parametric structural engineering tool that allows accurate finite element analysis (FEA) of structural elements or systems such as trusses, shells, and frames. The application is developed to work in a Grasshopper environment with the direct visualization of the structural elements.
- iv. Octopus, which is a Grasshopper plugin based on the SPEA-2 and HypE multiobjective evolutionary algorithms (Bader and

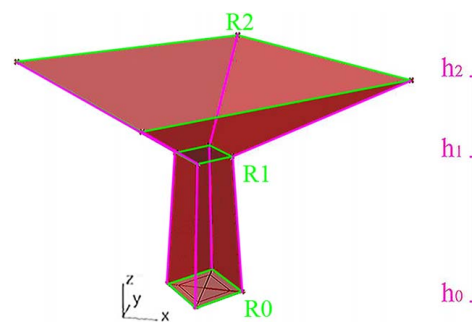


Fig. 2. Design domain of variables (height and radius) and definition of the geometry of the tree-column structure.

Zitzler 2011). The Octopus application introduces the Pareto principle for multiple goals (MOOPs). It allows different solutions to be retrieved from the trade-off achieved after the optimization process, giving different design possibilities.

Case Studies: Tree-Column Structural Systems

The models for this case study are exemplified as the determination of distribution of the loads in a finite sequence for two completely different structural shapes of bamboo. The mechanical properties considered for bamboo are presented in Table 1. In particular, the designs are a quadrangular (linear) dendriform, called test case 1, and an elliptical (curved) dendriform, called test case 2. Both are examined with respect to their effectiveness to form a structural system. For both design approaches the simplified loading cases which are considered during the implementation of the parametric design frameworks are

$$\begin{aligned} S_G &= 1.35 \times G + 1.50 \times Q \\ S_E &= G + \psi \times Q + E_d \end{aligned} \quad (1)$$

where G , Q , and E_d denote the permanent, live, and accidental actions (i.e., seismic, wind, or snow loading), respectively, and ψ is the combination coefficient for the quasi-permanent variable action, here taken equal to 0.30. The vertical load is taken equal to 1.48 kN/m^2 where the accidental actions taken into account for the needs of the current study (wind and snow) are defined according to the Eurocode [i.e., Eurocode EN 1991-1-3 (snow) and EN 1991-1-4 (wind)]. These actions in the Mediterranean areas are defined as follows: characteristic area of the snow load “B,” $s_k = 0.80 \text{ kN/m}^2$; basic value of the wind reference speed $v_0 = 33.0 \text{ m/s}$; kinetic reference pressure $q_b = 0.68 \text{ kN/m}^2$.

Definition of the Structural Systems’ Geometries

Starting with the definition of the quadrangular design, the variables are h_0 , h_1 , h_2 which represent the height of the structure and the radius R_0 , R_1 , R_2 of the polygons; the corresponding design domains (in meters) are defined as follows:

$$\begin{aligned} h_0 &\in [0, 0](m), & h_1 &\in [0, 6](m), & h_2 &\in [0, 6](m) \\ R_0 &\in [0, 2](m), & R_1 &\in [0, 4](m), & R_2 &\in [0, 6](m) \end{aligned} \quad (2)$$

Variables h_1 , h_2 , used for defining the quadrangular geometry, take values from the same design domain on the z -axis as indicated in Eq. (2); this means that the height of R_1 and R_2 belonging to the quadrangular geometry are independent on the z -axis from 0 (m) up to 6 (m). After defining the geometry of the model using the parameters and criteria described previously, the structural elements, vertical and horizontal, were positioned by connecting them to the reference polysurface; then these structural elements are discretized in order to effectively simulate the behavior of the bamboo poles respecting the maximum lengths and connecting the poles through the joints. The components of the model are converted into an equivalent number of finite elements associated with nodes. After this stage of the approach, the main horizontal and vertical elements connected to the polysurface are determined as seen in Fig. 2. The structure previously analyzed, as seen from the results of FEA simulation (Table 3), is characterized by regular shapes and shows good structural response.

For the tree structure defined with the elliptical design, the same workflow as in the quadrangular tree-column structural system is implemented, considering the previous geometry process, so the initial shapes are delimited with variable radius placed at different heights. In this model, a mesh base with curved vertical elements is

applied (see Fig. 4). The three elliptical sections called R_0 , R_1 , R_2 (lower, middle, upper section) are conceived parametrically. The goal is to find the positions and dimensions of elements by setting the geometric constraints in the 3D physical space ($\mathbb{R}^3$). The equation of the orbital ellipse is

$$\overline{PF_1} + \overline{PF_2} = 2a \quad (3)$$

With P we indicate a generic point of the orbital ellipse (that will represent the section of the elliptical tree structure) and with F_1 and F_2 two fixed (and arbitrary) points, called foci (Fig. 3).

After considering the previous equation [Eq. (3)], the algebraic condition in which the major axis of the generic ellipse is horizontal ($2a$) is represented by the sum of the distances between the arbitrary point tangent to the ellipse (P) and the two respective foci F_1 and F_2 .

The domains F_1 and F_2 for each transverse section (R_0 , R_1 , R_2) are structured as follows:

$$\begin{aligned} F_1, F_2 &\in R_0 = [\hat{i} = (0, 2), \hat{j} = (0, 2), \hat{k} = (0)] \\ F_1, F_2 &\in R_1 = [\hat{i} = (0, 5), \hat{j} = (0, 5), \hat{k} = (0, 3)] \\ F_1, F_2 &\in R_2 = [\hat{i} = (0, 7), \hat{j} = (0, 7), \hat{k} = (2, 5)] \end{aligned} \quad (4)$$

in which the parameters i, j, k belong to the sections of the elliptical geometry in the 3D physical space. We use k to define the height of the sections R_0 , R_1 , R_2 belonging to the equation of ellipse [Eq. (3)], with i and j the design domain on the x - and y -axes of the model, respectively, which belong to $R_{[0,1,2]}$.

In order to be able to obtain the best-performing structural shape based on the structural requirements, the shape of the bamboo tree column structure is designed in a circular or elliptical cross section and the developed model is obtained setting in the algorithm the following conditions (design variables):

$$\text{dom } \hat{l} = \text{dom } \hat{j} \quad \forall F_1, F_2 \in R_0, R_1, R_2 \quad (5)$$

or

$$\text{dom } \hat{l} \neq \text{dom } \hat{j} \quad \forall F_1, F_2 \in R_0, R_1, R_2 \quad (6)$$

If

$$\begin{aligned} \hat{i} = \hat{j} &\rightarrow (x - x_c)^2 + (y - y_c)^2 = r^2 \\ \hat{i} \neq \hat{j} &\rightarrow \sqrt{(x - x_1)^2 + (y - y_1)^2} + \sqrt{(x - x_2)^2 + (y - y_2)^2} = 2a \\ \hat{i} \neq \hat{j} &\rightarrow \sqrt{(x - x_1)^2 + (y - y_1)^2} + \sqrt{(x - x_2)^2 + (y - y_2)^2} = 2b \end{aligned} \quad (7)$$

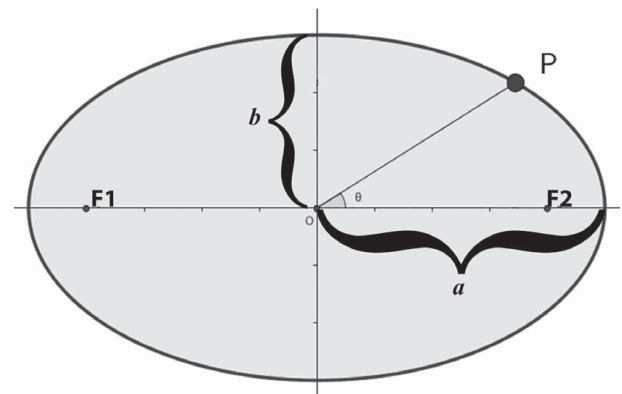


Fig. 3. Parametric development of the orbital ellipse.

If the length of the axes of the ellipse is equal ($\hat{i} = \hat{j}$) a circumference is obtained, but contrariwise (if $\hat{i} \neq \hat{j}$) an ellipse is obtained with the major horizontal axis ($2a$) or with the major vertical axis ($2b$).

With the intention to determine the positions of the structural elements from the elliptical geometry, the isolines which define the geometry were extrapolated from the elliptical scheme; they represent two other design variables, that is, the number of segments in the v direction (number of vertical elements) and the number of segments in the u direction (number of horizontal elements); in this case, the domain is defined as

$$(v) = [4, 20]; \quad (u) = [3, 20] \quad (8)$$

The Optimization Problem and its Formulation

The Multiobjective Optimization Problem

The evaluation of the two tree column structural systems is completed by comparing designs that emerged after optimization. The behavior of the two geometries chosen is defined according to the properties of bamboo (Table 1). The characteristics of vertical and horizontal elements (bamboo poles) after optimization are presented in Table 2. One of the objectives is to have a design that is resistant in shape and also meets the characteristics of structural bamboo. The amount of material for the structural use is a parameter set for optimal cost of the construction and minor effect on the environment (i.e., shorter transport distances, less bamboo). A specified genetic algorithm is used to work out the best combination for applicable bamboo elements and to identify an optimal structure morphology taking into account the geometric constraints imposed. In these case studies the genetic algorithm is repeatedly modifying the quantity of the individual elements which shape the structural system.

A typical multiobjective optimization problem can be formulated as follows:

$$\begin{aligned} &(f_1(x), f_2(x), \dots, f_m(x)) \\ &\text{subject to} \\ &h_i(x) = 0, \quad i = 1, \dots, k \\ &g_j(x) \leq 0, \quad j = 1, \dots, l \\ &x^l \leq x \leq x^u \end{aligned} \quad (9)$$

Table 2. Characteristics of vertical and horizontal elements (bamboo poles) after optimization

Characteristic	Vertical poles (cm)	Horizontal poles (cm)
$\emptyset$ (diameter – test case 1)	13.00	13.00
Thickness (test case 1)	3.90	0.80
Maximum pole length (test case 1)	590	590
$\emptyset$ (diameter – test case 2)	15.00	11.00
Thickness (test case 2)	1.90	0.8
Maximum pole length (test case 2)	590	590

Table 3. FEA and Optimization Results - Comparison

Test case	C. Length (cm)	Mass (kg)	Displacement (cm)	Compression (kN)	Tension (kN)	Moment (kNm)	Shear (kN)
1 – FEA	1,200	2,404	0.87	0.42	0.27	0.06	0.06
1 – Optimized	1,200	1,892	0.53	0.07	0.22	0.04	0.04
2 – FEA	690	3,047	2.25	11.9	9.81	0.36	0.17
2 – Optimized	690	126	0.33	1.31	0.42	0.02	0.05

where $f_i(x)$ ($i = 1, \dots, m$) are the objective functions to be optimized, $x = \{x_1, \dots, x_n\}$ is the design variable vector, x^l and x^u denote the vectors of its lower and upper bounds, respectively subject to equality $h_i(x)$ and inequality $g_j(x)$ constraints.

Table 3 lists the changed characteristics of the optimized structural system and also the values of internal forces (compression, tension, moment, shear) for both structures. The results obtained by the second structural system can vary by considering the variable number of horizontal and vertical elements. In this case, the above results consist of 13 vertical elements and 9 horizontal elements. Considering the previous equations, the optimization problem is formulated as follows:

$$[f_1(x), f_2(x)] \quad (10)$$

where $f_1(x)$ refers to the mass and $f_2(x)$ to the maximum displacement of the structural system. The design variables are defined in Figs. 2 and 4. By applying Eq. (2), in which h_0, h_1, h_2 represents the different heights of the sections of the structural system, and R_0, R_1, R_2 represent the radius of the sections of the structural system, while

$$\emptyset_0 \in [13, 15](\text{cm}); \quad \emptyset_1 \in [11, 13](\text{cm}) \quad (11)$$

where $\emptyset$ denotes the diameter of the cross sections belonging to the bamboo poles,

$$t_0 \in [0.8, 4](\text{cm}); \quad t_1 \in [0.8, 4](\text{cm}); \quad t_2 \in [0, 10](\text{cm}) \quad (12)$$

where t represents the thickness of the cross sections.

$$h_1 < h_2; \quad R_1 < R_2; \quad d_{\max} \leq \frac{1}{200}L \quad (13)$$

where $d_{\max}$ refers to maximum displacement allowed for the specific structure which is coded and solved using an algorithmic modeling plugin (Octopus). Subsequently, this process introduces the

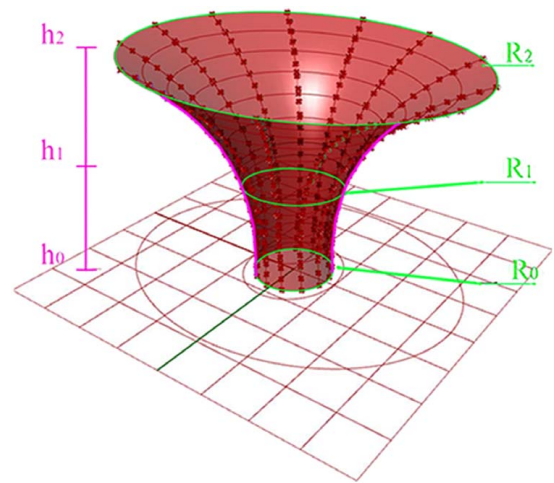


Fig. 4. Implementation of elliptical geometry and geometrical constraints in the space $\mathbb{R}^3$ (x, y, z).

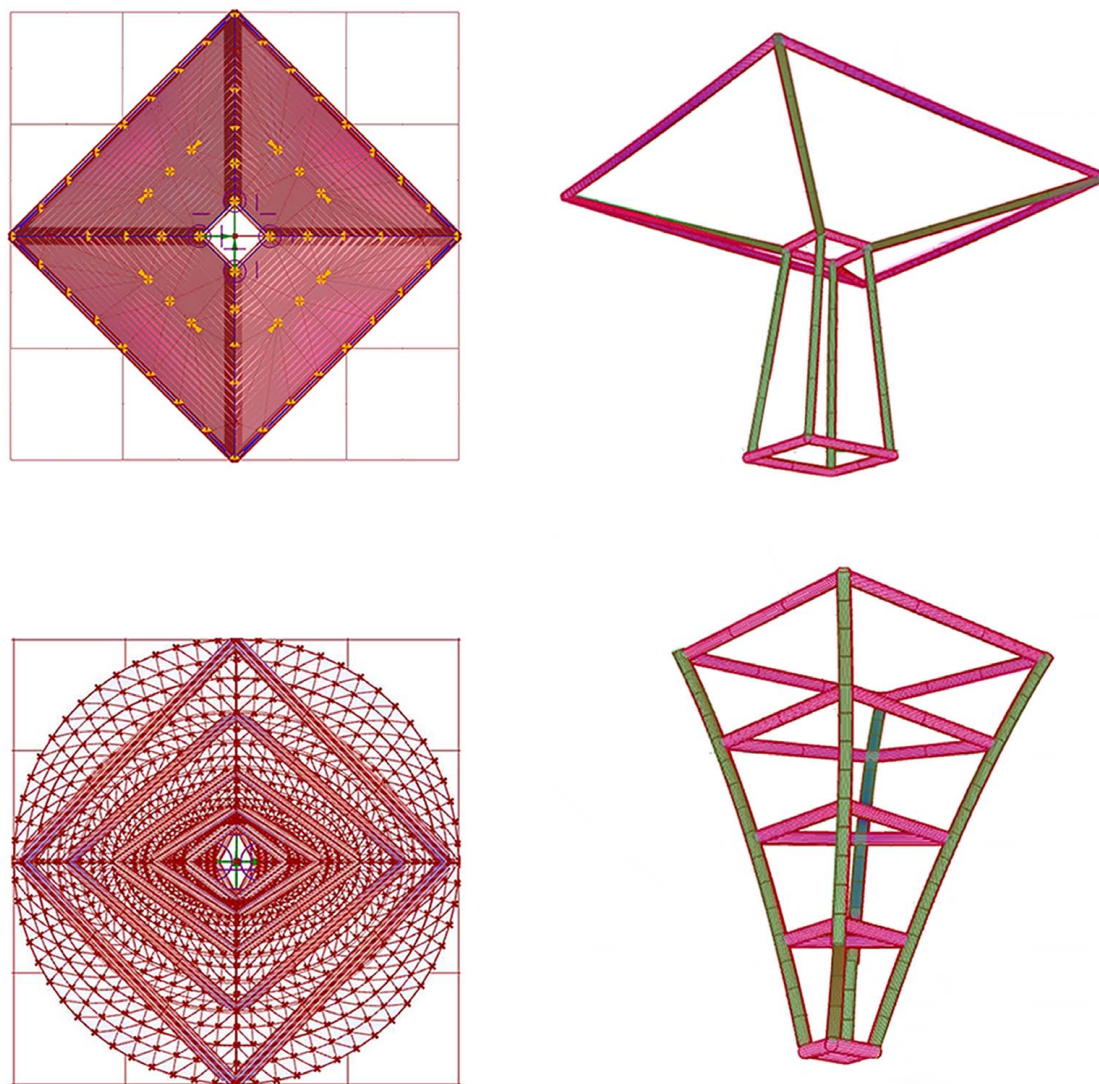


Fig. 5. Optimized morphology of test case 1 and optimized morphology of test case 2.

multiple fitness values (multiobjective) to the optimization process which is based on the SPEA-2 multiobjective evolutionary algorithm (strength Pareto evolutionary algorithm for multiobjective optimization—core algorithm).

Optimization Results

In the specific process, design relatives are obtained according to a set of prioritized criteria (mass and displacement) while taking into account other constraints related to shape (position of each element) of the structural system. The goal of the optimization process is to reduce the material consumption and increase the efficiency of the system by minimizing displacement. After applying the optimization problem to the quadrangular and the elliptical system, a new geometry is obtained after 2,000 generations in each case study resulting (see Fig. 5) in the characteristics/dimensions listed in Tables 2 and 3. The solutions which are nondominated, are called “Pareto efficient,” that is, there are multiple solutions of the problem that can simultaneously optimize every single objective. In these cases the objective functions can also be “conflicting” with the consequent existence of different feasible solutions which might improve one objective while penalizing another.

The Pareto front (see Fig. 6) represents a set of nondominated solutions which ensure the optimal compromise between design objectives. The dark cubes in Fig. 6 indicate the nondominated Pareto front; the transparent cubes indicate the dominant solutions belonging to the elite (better individuals who will undergo other mutations) and the cubes in the circle represent elite solutions from previous generations. The chosen solutions after 2,000 generations in each case study are the most balanced among the solutions identified in the Pareto front. The values after optimization are presented in Table 3. For both cases, the displacement begins to increase as the mass decreases and vice versa. As mentioned, the feasible solutions are multiple but there exists a limited choice in order to minimize the mass and the displacement, considering the initial values. In conclusion, the nonselected solutions penalize one of the two values: less displacement means more mass and vice versa, despite that they could be considered equally good structural systems because all solutions included in the Pareto front respected the imposed constraints (see Fig. 6).

The optimization problem is formulated for both the elliptical and the quadrangular case studies [Eq. (9)]. Considering Eq. (3) where F_1 and F_2 represents the foci of the ellipse on the x , y , z

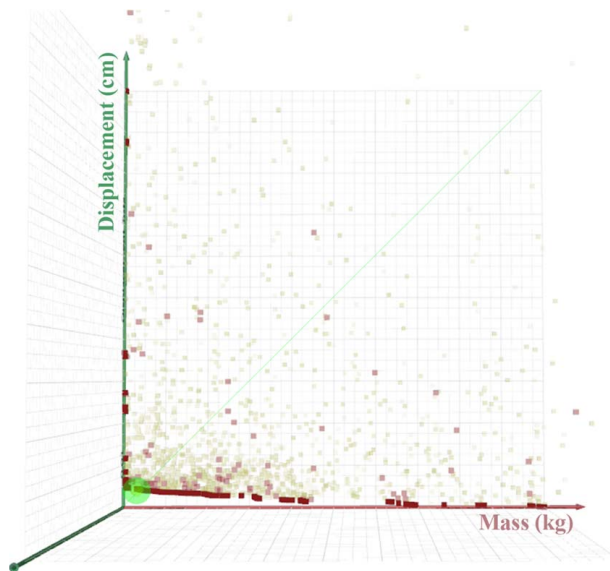


Fig. 6. Pareto front (nonunique solution): test case 2 (nondominated 106; dominated 91).

plane, we have

$$\emptyset_0 \in [13, 15](\text{cm}) \quad \emptyset_1 \in [11, 13](\text{cm}) \quad (14)$$

and $\emptyset$ refers to the diameter of the cross sections belonging to the bamboo poles.

$$T_0 \in [0.8, 4](\text{cm}) \quad T_1 \in [0.8, 4](\text{cm}) \quad T_2 \in [0, 10](\text{cm}) \quad (15)$$

where T identifies the thickness of the cross sections, subject to the maximum displacement allowed [Eq. (12)].

The results after 2,000 generations are summarized in Tables 2 and 3. The geometry obtained after optimization shows the following characteristics in Fig. 5.

$$\begin{aligned} F_1, F_2 \in R_0 &= [\hat{i} = 0.21, \hat{j} = 0.41, \hat{k} = 0] \\ F_1, F_2 \in R_1 &= [\hat{i} = 1.55, \hat{j} = 1.27, \hat{k} = 3] \\ F_1, F_2 \in R_2 &= [\hat{i} = \hat{j} = 2, \hat{k} = 4] \end{aligned} \quad (16)$$

From the geometry described above, the transversal sections used at a height of less than 3 m correspond to an ellipse, over 3 m correspond to a circular section according to Eqs. (4) and (5).

The structural system of case study 2 consists of four vertical supports and five transverse elements after optimization, including the bottom element of the structure. The results concerning the structural morphology are that the transversal elements act as internal connection rather than being positioned in the centerline of the mesh panel. This configuration makes the structure more rigid allowing the external geometry to have free shapes. As the vertical supports are increased, the horizontal elements will also be increased by assuming the configuration of the external mesh panel in a directly proportional way, increasing the total weight. The solution is not unique, so there will be different morphological solutions capable of satisfying the constraints imposed in the optimization process, (Pareto front) (see Fig. 6). The useful surface for a building which is produced as a floor plan between the columns, has a width of two radius R_3 ; according to dendriforms design, the column has a narrow base and spread over a large surface area at the top (a small diameter base (at h_0) and a longitudinal diameter at the top (at h_2)).

Functional Morphology: Comparison

After achieving the best design relative to the set of prioritized criteria and constraints, a clear difference of weight is observed between the two optimized structural systems chosen from the corresponding two Pareto fronts. Table 3 lists the optimization results achieved for the two structural systems. The difference in terms of structural performance is due to the distribution of material; concerning the tubular cross sections of the bamboo poles, the thickness of the connection mesh between the structural elements, the total length of the structural system, and, most important, the morphology of the structure. For test case 1 the ratio, length to mass is 0.498 and the optimized design ratio is 0.633, whereas for test case 2 the ratio was 0.225 and after optimization changed to 5.475. With respect to the mass to length ratio of the quadrangular system, the elliptical structure would result to weigh 1,087 kg for a length of 690 cm, following the quadrangular ratio of: Length : Mass = 1,200 : 1,892 = 690 : x and the elliptical would result to $x = 1,087$ kg (for a length which is almost half of the length of test case 1) while the optimized elliptical has reached a weight of only 126 kg.

On the other hand if the structural systems are evaluated according to the elliptical morphology (i.e., Test Case 2: 1,200 : $x = 690$: 126), then the obtained total length of 1,200 cm would weigh 219 Kg, which is near to 1/6 to the current weight of 1,200 Kg after optimization. It is noticed that the elliptical system performs better than the quadrangular one. The structural conformation of the two models after optimization is observed in Fig. 6. According to the optimized results, a common morphology of the structural system has been produced which is going back to the family of quadrangular polygons; these structures with polygonal shapes enable an even better performance in comparison to circular structures. Structural systems with linear geometric shapes like polygons can give better structural performance with less material consumed.

Conclusions

The use of fast-growing, renewable materials such as bamboo can help to meet the increasing demand in materials for sustainable architecture. Although traditional houses made of bamboo are common in some countries, the lack of regulations and industrialization has limited their use for contemporary constructions in many countries. In this study, a new design approach has been presented for designing modern bamboo-based structural systems which can contribute to a more sustainable future for the AEC industry. Two dendriform structural systems have been examined as case studies and then optimized. According to the formulated optimization problems for the quadrangular and elliptical tree-shaped structural systems, two generated designs were selected as the ideal design solutions that simultaneously optimize all the objectives being considered. In both case studies, mass and displacement were the criteria selected for the formulation of the optimization problem. After comparing the two models presented, the benefits of utilizing the quadrangular bamboo structural systems are clear. In conclusion, symmetry and simplicity in shape, are of fundamental importance for the design process of bamboo-framed structures. As was observed from the two optimized designs selected from the corresponding Pareto fronts, the weight of the bamboo structural system and the total length of the poles are important parameters, contributing to the effectiveness of the optimal morphology. The use of bamboo and soil in architecture is a topic for further research and according to the insights of this study, the dendriforms can be an eco-friendly solution for the structural needs of earthen buildings. Bamboo is an effective renewable construction material which can contribute to sustainable architecture and the

construction industry. For further research on optimized morphology, construction codes for bamboo need to be developed in order to have standardized structural design procedures.

Data Availability Statement

Information on the algorithmic workflow and the Rhinoceros models is listed here.

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Notation

The following symbols are used in this paper:

- F_1, F_2 = foci of the elliptical transverse section (m);
- R_0 = radius of the lower transverse section (m);
- R_1 = radius of the middle transverse section (m);
- R_2 = radius of the upper transverse section (m);
- T_0, T_1, T_2 = poles thickness (cm);
- disp = maximum displacement allowed (cm);
- $\text{dom } \hat{l}, \text{dom } \hat{J}$ = domain belongs to the foci of the ellipse (m);
- h_0 = height of the lower transverse section (m);
- h_1 = height of the middle transverse section (m);
- h_2 = height of the upper transverse section (m);
- u = variables segment in horizontal direction (number of horizontal poles);
- v = variables segment in vertical direction (number of vertical poles); and
- $\varnothing_0, \varnothing_1$ = poles diameter (cm).

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