Encoding Bamboo's Nature for Freeform Structure Design

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Abstract

Bamboo is a construction material that is renewable, environmentally friendly and widely available. It has long been used in various projects, ranging from temporary, easily assembled, and rectilinear structures to complex freeform pavilions. Design with bamboo has never been easy to architects and engineers due to its nature of shape irregularity and round section. This prompts the need to develop a new design process that can accommodate these properties which hinder bamboo to be used by designers.

In this paper we take a close look at freeform structure design, and specifically demonstrate how systematically and algorithmically parametric modelling can be used to tackle bamboo material irregularities and bamboo-jointing challenges. A two-stage optimization process is proposed to support a fabricable freeform structure design through encoding material properties and freeform shape optimization. The approach approximates the given freeform shape using a finite set of unique bamboo elements while maintaining the aesthetical design intention. By limiting the number of bamboo elements, it will provide insight to both designers and engineers on the efficiency and cost benefits of producing required structure elements for the final assembly.

Keywords

Freeform structure design; bamboo structures; bamboo joint design; shape optimization; shape rationalization.

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1. Introduction

In contrast with conventional design practice, the propagation of digital design tools and computational design thinking allow designers to explore the parametric variability of each design and make necessary customization possible. The key to such parametric design is to establish relational dependencies between elements of design such that all elements change simultaneously as associated parts were altered. The most distinctive feature of parametric design is through articulating a generative procedure to automate form finding and form generation [1]. In the industrial age at early 20th century, mass production of identical components was the norm; yet due to irregularity of the freeform shapes, mass customization is inevitably a necessary treatment [2]. In addition, parametric design components are deemed easily adaptable to many contexts given the clearly defined boundary [3].

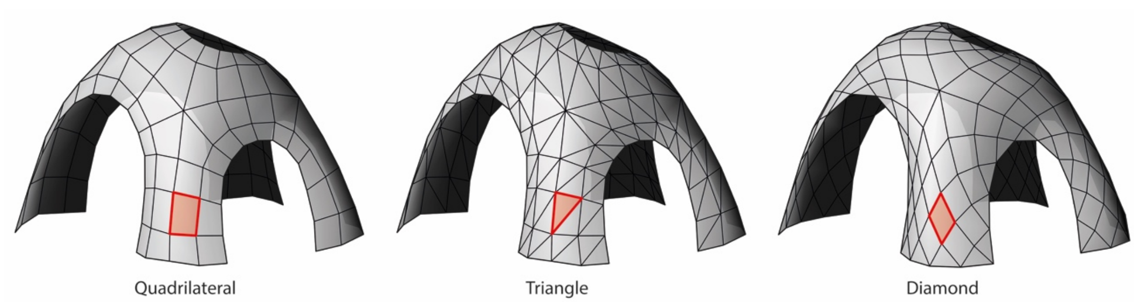


Figure 1. Freeform surface design with quadrilateral, triangle, and diamond-like tessellation patterns.

With the prevalence of digital technology and parametric design thinking, designers increasingly incorporate freeform shapes to pursue eccentric, and sometimes intricate, structures in contemporary architectural and design practice. Commonly seen examples include those from pioneering avant-garde designers such as Frank Gehry [4] and Zaha Hadid [5]. The development of manifesting freeform designs relies heavily on a core geometry, which is used from early conceptual form finding to final detailed building assembly. In design practice, the modelling and subsequent fabrication of a freeform shape require an extension of the meshing process to include considerations of constructible building components [6]. Figure 1 illustrates a freeform surface with three varied types of tessellation, namely quadrilateral, triangle and diamond-like patterns. Albeit designers can freely specify customized patterns to approximate any intended freeform shapes, the main challenge remains at how these discrete geometrical elements can be further evaluated and rationalized for fabrication.

Savill building (as shown in Figure 2) exemplifies the integration of timber into form finding technique. This project used small-sectioned timber members due to their flexibility. For centuries, the use of bamboo as a building material has been limited to the construction of scaffoldings, rural dwellings and temporary structures [7]. Bamboo is a renewable natural resource and is currently experiencing a renaissance in the building industry as a future sustainable material in construction [8].

Figure 2. The design of Savill building integrated form finding technique with timber.

Recently, there have been some emerging bamboo structures in a variety of projects. They range from temporary and easily assembled structures, like the Madasi Art Festival in Taiwan, to contemporary structures such as Bamboo housing project for Haiti designed by Saint Val Architects [9]. The success of bamboo is intrinsically linked to the development of technologies to overcome the main challenge—the complexity in the bamboo jointing design [10]. While traditional bamboo-jointing techniques struggle with the irregular geometry of bamboo, parametric technology allows irregularity to be systematically addressed in a design. As bamboo has now risen as a competitive candidate to replace timber in the future [8] [11], this paper presents an attempt to incorporate bamboo as a structural material into freeform structure design. Particularly, our main research question is how to encode physical properties from the chosen material, bamboo, into the integrated design optimization process. Through the parameterization of the design elements our objective is to examine iteratively the correlations between encoded physical attributes of the chosen material and the resulting construction of the design artifact. In this paper, a freeform surface design is therefore selected to test and demonstrate the applicability of the integrated design optimization process.

2. Bamboo as a Construction Material

Bamboo is one of the fastest growing giant grasses in the world; it has a number of advantages when used as a construction material. Bamboos mainly grow in Asia, South America and Africa, with transportation and international trade activity developments they are now available worldwide. Bamboo is fast growing and can reach 25-30 metres in height in one year and become mature and ready for harvest within three to five years. Bamboos are generally hollow tubes with some nodes along its length, as shown in Figure 3. They are reinforced by the fibres along the length which makes bamboo a very efficient structural member in resisting axial loads. Bamboo has very high stiffness to weight ratio and strength to weight ratio [10].

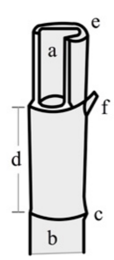


Figure 3. Bamboo Structure: Interior wall (a), exterior wall (b), node (c), internode (d), wall thickness (e) and branch (f).

There are also some shortfalls when using bamboos for construction. For example, bamboos are tapered along the length with sections being larger at the bottom and smaller on the top. The sizes of the bamboo vary significantly from species to species. Although they are strong along the grain, they are weak across the grain which results in cracks perpendicular to the fiber—a major failure mode when used in structure. Furthermore, as they are hollow tube by nature, connections become a challenge. Shape and size adaptability consequently become key constraints to be resolved when considering bamboo as the construction material. Successful use of bamboo as a building material relies heavily on the acknowledgement of its mechanical properties and in the correct distribution of forces.

2.1 Bamboo joints

In most bamboo structures, the strength of the culm could be lost due to the poor joint design [10]. It is widely accepted that the effective design of joints is essential to guarantee the structural stability of any project [2]. Using bamboo in the construction, however, introduces additional design challenges due to the uniqueness and variability of every member. The design of joints therefore becomes a critical and intensive process where a considerable amount of skill is needed [12]. The bamboo-jointing techniques have been instinctively developed through trial and error from generation to generation. It is arguable that the bamboo-jointing practice is often treated as an arbitrary process that thus cannot be efficiently rationalized [10]. We explored the utilization of various bamboo joints in practice and summarized commonly used joint types into six different categories [13]. Figure 4 illustrates these six types of commonly used bamboo joints.

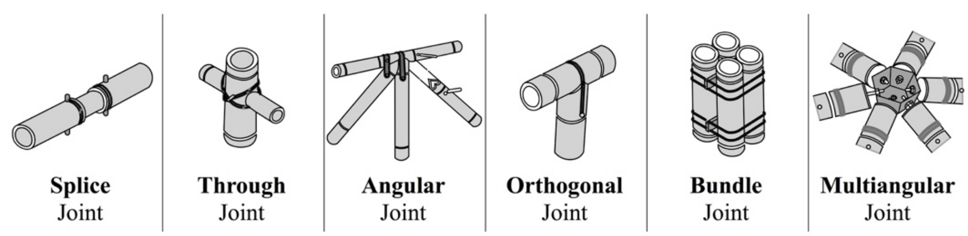


Figure 4. Types of bamboo joints in practice.

In this paper, we take a step further to investigate the integration of bamboo culms, which consist of segments in various lengths. The physical dimensional constraints will be examined and be resolved through the optimization process using a genetic algorithm approach.

2.2 The dimension restrictions for Bamboo

As previously discussed, the variations of bamboo in dimensions make adaptability of the bamboo members being the main challenge. As bamboos are tapered along their length, take Moso bamboo (Phyllostachys edulis) as an example, the lower part of the culm has an average outer diameter of 100mm with inner diameter of 80mm. The mid-height part of the culm could have an average outer diameter of 75mm with an average inner diameter 60mm, whilst the outer and inner diameters for upper part of the culm are 40mm and 30mm, respectively. The lengths of internode parts are less regular, however, they range between 150mm to 300mm. These dimensions will restrict the design and become an important parameter to be considered in the form finding process. For instance, the minimum length of the design components will then be restricted to one section of internode.

3. Discretizing Freeform Surface for Fabrication

Among various techniques for freeform shape construction, a NURBS (Non-Uniform Rational Basis Spline) surface is commonly exploited in design practice as the initial geometrical model [14]. To manifest a NURBS surface, a discrete model—namely a mesh, is often used. The meshing process is essentially to approximate a given freeform surface with a finite set of discrete elements, namely, vertices, edges and faces. Due to the design freedom of any given surfaces with arbitrary underlying conditions, the complexity of subdividing a freeform shape into a discrete set of constructible components inevitably increases. To realize such a freeform design, the pattern-based approach was adopted to articulate how faces associate with panels, edges to structural frames, and vertices to joints [15] [6]. However, varying sizes of mesh elements still present challenges to designers while translating initial freeform shapes into a mesh using a conventional top-down approach. In this paper, we have chosen the multiangular joint as shown in Figure 4 as a case study to explore a freeform surface structure that can be evaluated and optimized using Bamboo as the construction material.

3.1 Parametric design system for multiangular joint design

A multi-angular joint holds together a number of bamboo pieces that rotate around a central point in multiple angles. Given its flexible configuration, this joint can be applied in a variety of projects, for instance, the construction of curvilinear structures, space frames, geodesic domes as well as planar grids. Figure 5 illustrates three different multi-angular joint types that are suitable and commonly deployed in Bamboo structures.

Figure 5. Design configurations of multiangular joints.

The flexibility and versatility of this type of the joint present advantages while considering curvilinear structures using bamboo. A parametric design system proposed to tackle such a multi-angular joint design from our previous research is adopted [13]. Figure 6 illustrates the generative steps of the parametric modelling system. In this system, design considerations of the multiangular joint include:

- A central joint holds together all pieces, rotating around the centroid of the joint
- Reduction of bamboo ends is advisable for a better load transference
- An external anchor system is used to fix bamboo pieces inside the central joint
- Reinforcement of every bamboo member is needed at its ends

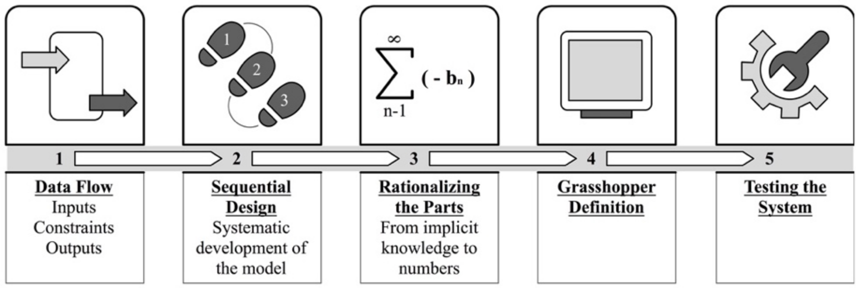


Figure 6. Generative steps of the parametric modelling system.

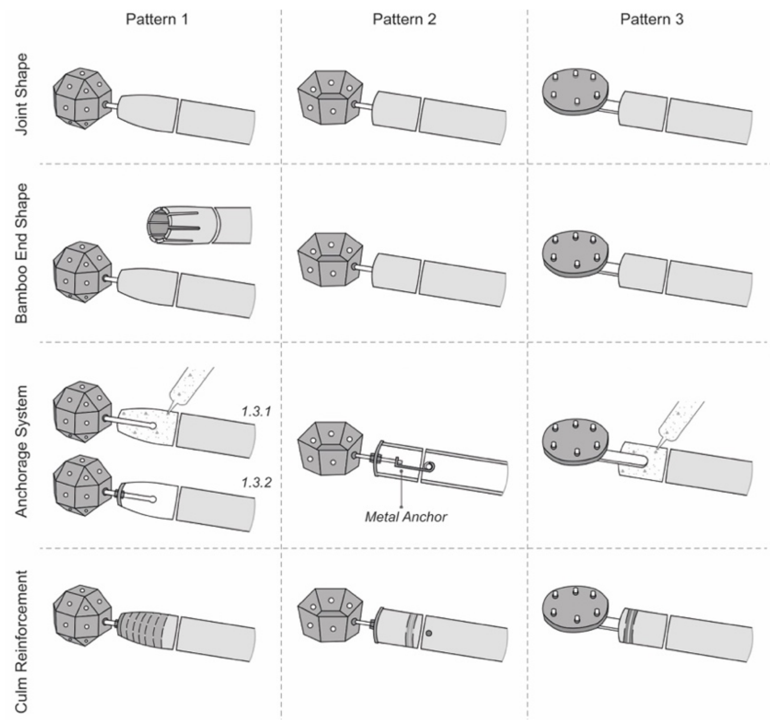


Figure 7. Multi-angular joint design considerations.

Figure 7 illustrates multi-angular joint developments using four major design considerations: (1) joint shape, (2) bamboo end shape, (3) anchorage system, and (4) culm reinforcement. One of the main advantages of this joint is the fact that, its flexible and versatile configuration enables the construction of organic structures to cover large spans. Pattern 1 in Figure 7 is the most flexible approach for this type of joint. The multiplanar shape of the joint offers the addition of numerous bamboo pieces arranged in different angles. Pattern 2, on the other hand, holds a reduced number of pieces at fixed angles. Its application appears to be limited to the construction of prism-like structures. Pattern 3 is the joint with the less flexibility mainly because the bamboo pieces can only be arranged on a single plane. Consequently, they are mostly common on the construction of horizontal or vertical frames.

Figure 8 illustrates the data flow diagram of the parametric multi-angular joint system. Five input parameters are encoded with material properties to form the parametric jointing system. These five parameters include (1) exterior diameter, (2) interior diameter, (3) node distance, (4) total segment length and (5) angle configurations. Through resolving constraints in the parametric joint design, a customized multiangular joining system for the freeform structure will be produced.

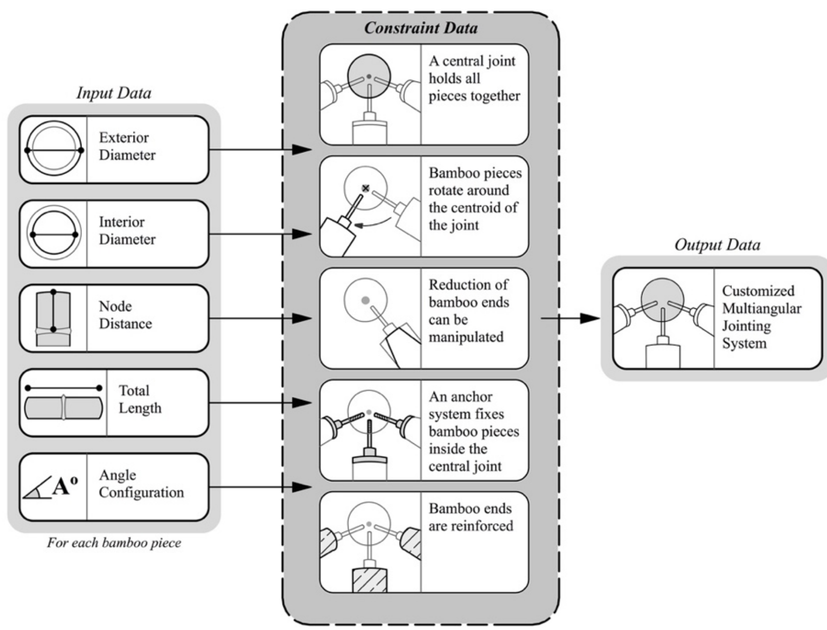


Figure 8. Data flow diagram of the parametric multiangular joint system.

Figure 9 illustrates the constructive operations using this parametric design system. The initial stage identifies the location of the joint and this serves as the reference for configuring bamboo geometry connecting at this joint location. This step uses the underlying topological vertex-to-edge connectivity to sort out all connecting edges. Following this, the anchor system for each bamboo segment is developed further with node-end reinforcement. This generative process was executed iteratively until all connected edges at this coincided vertex were visited.

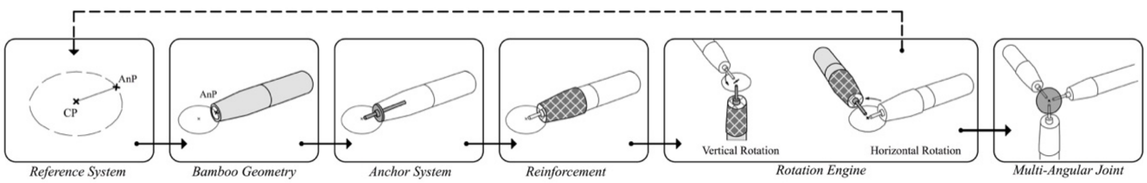


Figure 9. The parametric system for multi-angular joint development.

In this system, parametric components of the multiangular joint include (1) Reference System, (2) Bamboo Geometry, (3) Anchor System, (4) Reinforcement Membrane, (5) Rotation Engine and (6) Central Joint.

3.2 A Freeform design case study using the mesh representation and its implementation

For the demonstration purpose, we took a freeform surface as an example and deploy a diamond-like pattern, as shown in Figure 10. The dimensions of the proposed freeform structure are respectively 10000mm in Width, 8000mm in Depth, and 6000mm in Height. At the first look of the proposed design, the initial mesh model consists of 224 faces (in total 160 quadrilateral diamond-like faces and 64 triangular faces on the boundaries) and 448 different edges, ranging from 380 mm to 1490 mm.

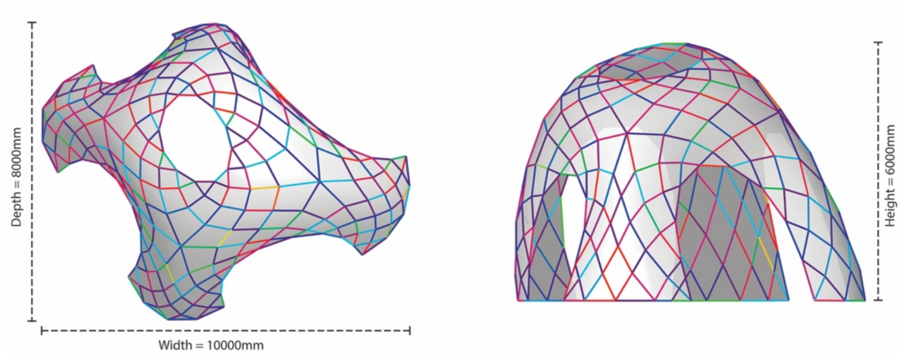


Figure 10. Initial freeform surface design.

We investigate a post-design rationalization process and examine two major design constraints: (1) number of structural components and (2) variable controlling threshold for each structure member connecting to multi-angular joints. These two control variables are the major evaluation criteria while considering bamboo as the construction material for the abovementioned freeform structure. In the post-design rationalization process, the objective is to examine the variations derived from the changes in the number of component types in relation to the changes of the optimized freeform shapes. The implication of using a limited number of distinct components is to reduce the potential fabrication cost by providing reusable modular components. Figure 11 illustrates these two design variables, (1) component length and (2) gap threshold, and how they are associated with the mesh edge elements. The intention to introduce the adjustable gap threshold is to investigate the flexibility through adjustable gaps. In this preliminary design, there are in total 448 different mesh edges. The potential number of different component types is therefore 448. Using the mesh model, the length of a mesh edge is equal to the component length plus two gap thresholds on both ends:

$$Length_{Mesh\_Edge} = Length_{Component} + GapT_{Start} + GapT_{End} . \quad (1)$$

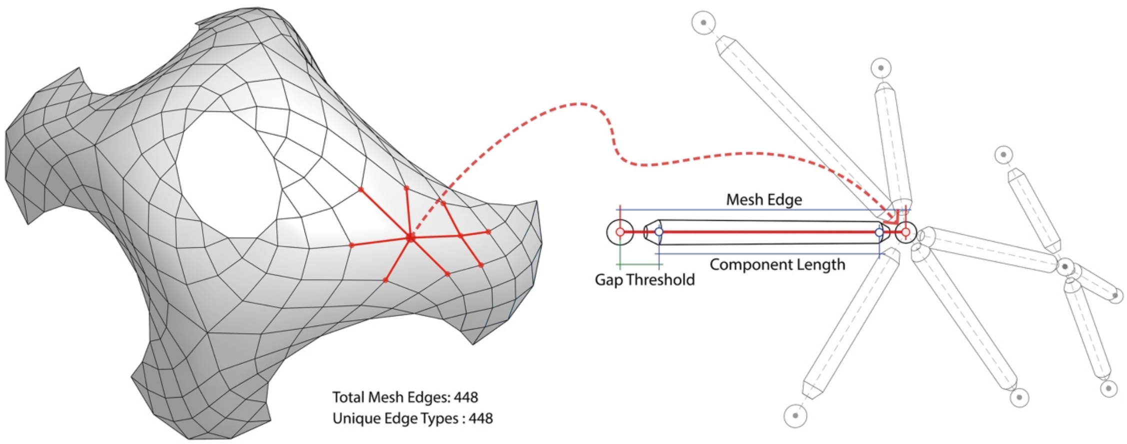


Figure 11. Two design constraints, component length and gap threshold.

The gap threshold herein is a design variable, reserved to develop the multi-angular joint, the bamboo end reinforcement system, and the secondary structure element connecting bamboo structure component to the joint. Figure 12 illustrates the translation from mesh elements, namely vertices and edges, to fabricable structure components, multi-angular joints and bamboo structure components. On the left image of Figure 11, a mesh model consists of vertices, edges, and faces. By visiting all the connecting edges per mesh vertex, a minimum angle constraint can be calculated as following:

$$Angle_{min} = 2 * \mathrm{Tan}^{-1}(\frac{R_{Bamboo}}{Gap_T}) \quad (2)$$

where R_{Bamboo} is the radius of the chosen bamboo species for selected mesh edges, and Gap_T is the gap threshold at the mesh vertex where these edges meet.

The minimum angular constraint is calculated and imposed during the post rationalization process as it provides an indicative angular criterion to fulfil while searching for a viable solution for the optimal form. The angular constraint is thus to keep the minimum gap distance from bamboo ends to connecting joints while maximizing the lengths of applicable bamboo structural components.

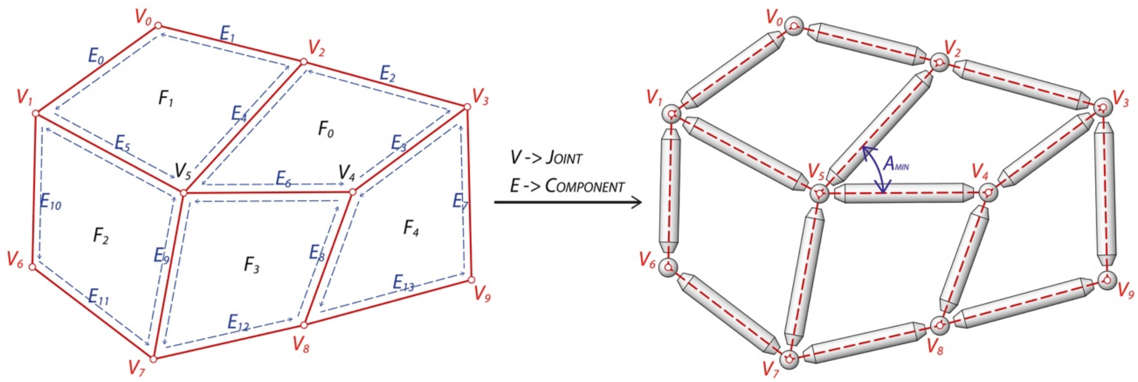


Figure 12. Translating mesh elements to constructible components.

4. Encoding Material Constraints for Freeform Structural Element Development

In this section, we demonstrate a two-stage optimization process, as shown in Figure 13, to explore a fabricable freeform structure design using bamboo. To begin with, we describe an encoding scheme for the bamboo structure components. This is designed to explore applicable bamboo element types taking into account constraints from internode dimensions, i.e. the varying distances from one node to the other. The objective aims to evaluate the optimal bamboo element set using four identified internode constraints, all of which should be shorter than the normal internode length ranging from 100mm to 300mm. In this paper, we take the internode lengths of 250mm, 210mm, 180mm, and 115mm as the design restriction to approximate the given freeform shape. With the specified encoding scheme for applicable bamboo element types, we employ the genetic algorithm to identify optimal set of applicable bamboo types. The filtered bamboo element types are then introduced to the second stage mesh rationalization process, in which the original mesh surface will be altered to ensure other design constraints, such as edge dimensions, gap threshold, angles between connected vertices, etc., to be fulfilled with the intended criteria.

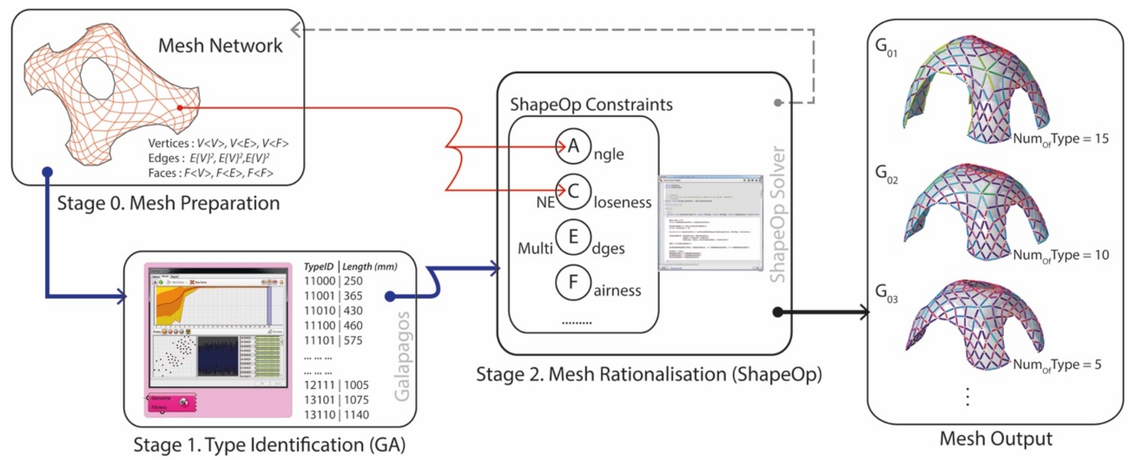


Figure 13. The two-stage optimization process.

4.1 Bamboo element type identifier (TypeID):

Element TypeID is a five-digit unique identifier and each digit represents the number of specific internode segments with specific given lengths, ranging from 115mm to 250mm. The first digit from the right contains information for the number of 115mm segments, second for 180mm, third for 210mm and forth for 250mm. The last digit of the TypeID is the unique code for the bamboo class and in this case as shown in Figure 14, this class identifier is 1. Bamboo components can therefore be described using the unique identifier with remaining four digit numbers to represent various internode patterns. In our case study, the maximum length of a bamboo element that can be specified using this representation is therefore 6,975mm in length, where last four digits of the ID are all equal to 9. An example, TypeID_10001, as shown in Figure 14, represents the bamboo element, which consists of only one 115mm segment, and thus the total length is 115mm.

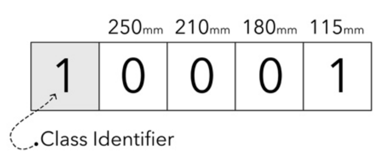


Figure 14. Bamboo element type identifier.

With the encoding scheme, we perform a bamboo element type search using genetic algorithm with a single objective function, which aims to identify the best bamboo element type using the abovementioned four different internodes. During the search, these four unit segments, 250mm, 210mm, 180mm, and 115mm, were permutated and tested with the intended freeform design. The search outcome will provide an optimal bamboo type per mesh edge using four abovementioned internode options such that a specific internode combinational pattern will be formulated with minimized gaps between bamboo segments to the joints. At this stage, the mesh input will not be changed and only analyzed with all applicable internode combinations. Figure 15 illustrates the computational workflow, in which a mesh object represents the initial freeform design (Figure 15–A) with a range of different design variables (Figure 15–B and Figure 15–C) specified for the genetic algorithm optimization. We used Galapagos, a genetic algorithm solver provided in Grasshopper3D as shown in Figure 15, to search for an optimal solution that satisfies the target fitness—a set of optimal bamboo element types using four different internode segments with minimized average gap threshold.

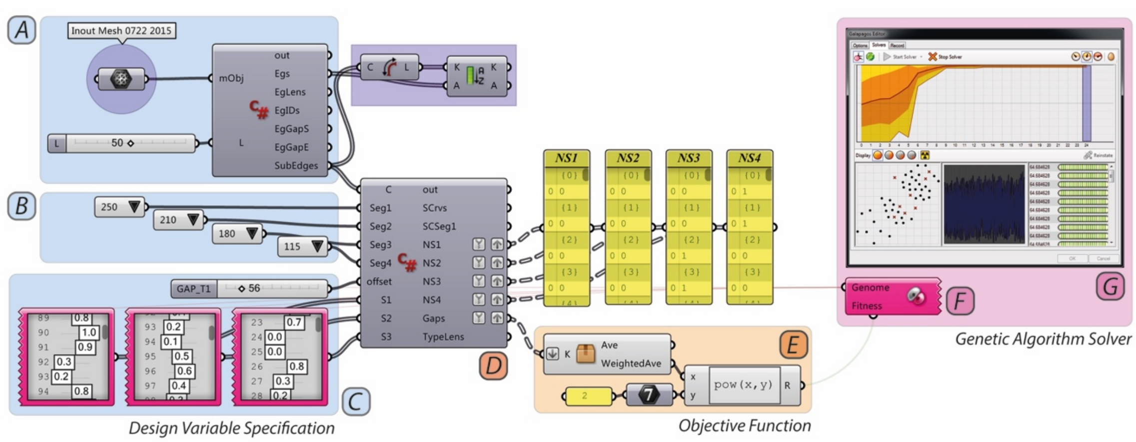


Figure 15. The computational workflow using Genetic Algorithm (Galapagos in Grasshopper3D).

4.2 An integrated optimization and post-design rationalization process

After the first stage filtering process a number of unique bamboo element types are determined. Due to the nature of non-uniform mesh edges, it is inevitably that selected bamboo element types will not always be desirable as, in some cases, they might induce the violation in a larger gap threshold between bamboo ends to the connecting joints. these vary according to the discrete combinations from limited internode options available from chosen bamboo species. As such the second stage rationalization process is proposed to further process the initial freeform shape (mesh) to investigate a better approximation that can be fulfilled with intended physical properties from bamboo. In addition to modify the initial mesh to ensure the initial design constraints are fulfilled, we also examine the number of different bamboo element types as another optimization criterion during this process. By limiting the number of bamboo element types, we intend to investigate the deviation from the refined shape to the original design and to understand better the trade-off between the limited bamboo type numbers with the ultimate aesthetic design appearance.

During the second stage rationalization process, we use ShapeOp [16], an open source dynamic mesh optimization engine to dynamically adjust the input mesh model to find the optimal solution for all given constraints. Specifically, we optimize the mesh shape by modifying its vertex positions while fixing its connectivity, which translates to optimizing the joint positions of the bamboo structure. During the optimization we consider four major design constraints:

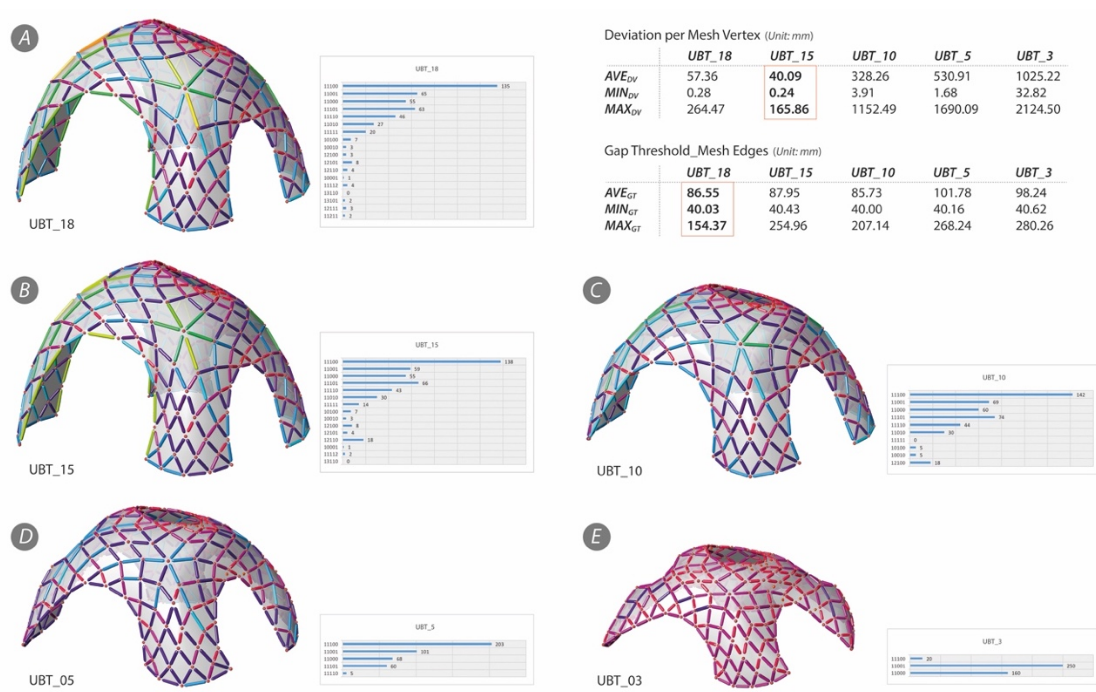
- The angle between two neighboring edges is no smaller than the minimum angle determined from the intended bamboo species radius and the default gap threshold, as specified in Equation (2). This constraint ensures the final structure is fabricable using multi-angular joints.
- The optimized mesh vertex positions are close to their initial positions before the optimization. This helps to prevent large changes in the overall shapes and respect the design intention.
- A fairness constraint that requires each vertex to be close to the centroid of its neighboring vertices. This constraint improves the aesthetics of the mesh.
- A multi-length constraint that requires the length of each edge belongs to a set of ranges, each of which represents the feasible distance between the two end joints of one bamboo element type. This enables us to specify which bamboo element types can be used in the optimized structure.

The first three constraints are already provided by the ShapeOp library. Thus we only need to extend ShapeOp to incorporate the multi-length constraint. More precisely, for a bamboo element of length L, the feasible distance between its two end joints is from $L - 2 * Gap_{min}$ to $L + 2 * Gap_{max}$, where Gap_{min} and Gap_{max} are the minimum and maximum allowable gaps from the ends of the bamboo element respectively. Then given a set of allowable bamboo element types with length $L_1, L_2, \ldots, L_m$, the last constraint requires that the length of each mesh edge is within one of the following ranges $[L_1 - 2 * Gap_{min}, L_1 + 2 * Gap_{max}]$, $[L_2 - 2 * Gap_{min}, L_2 + 2 * Gap_{max}]$, …, $[L_m - 2 * Gap_{min}, L_m + 2 * Gap_{max}]$. Examples of optimization using a finite set of bamboo element types can be found in Figure 16.

5. Discussions and Conclusion

In this paper, we described a two-stage optimization process, as shown in Figure 13, to demonstrate how a freeform shape can be evaluated and rationalized to a finite set of fabricable bamboo components, through which a design-to-fabrication process is formulated. By limiting the number of bamboo component types chosen, we further examine the deviation from the initial freeform design to the modified design output, as shown in Figure 16. The objective is to elucidate how the proposed two-stage optimization changes the original design while fulfilling the intended fabrication constraints.

In Figure 16, we demonstrate how the ShapeOp optimization can be used to reduce the number of the unique bamboo types (UBT). Specifically, we iteratively run the ShapeOp optimization, using fewer and fewer bamboo types to refine the multi-length constraint. Before each run of the optimization, we analyze the initial mesh to find out the number of edges associated with each bamboo types. Then we rank the bamboo types based on the numbers of their associated edges, and pick a subset of types at the top of the ranking to define the multi-length constraint. By doing so, mesh edges corresponding to less common bamboo types will be replaced by more bamboo elements at the top of the ranking, which effectively reduces the UBT. In Figure 16, we use this approach to gradually decrease the UBT in five runs of optimization. During the stage-one filtering process before the optimization, we have first identified 18 unique components out of total 10^4 = 10,000 possible combinations (given that each digit of the TypeID has 10 variations). From these 18 options, we gradually reduce the number of bamboo component types for the multi-length constraint, to evaluate the impact on the freeform shape deviation. The final optimized shape (as shown in Figure 16E) only uses three unique bamboo types and as a result, the initial shape can no longer be kept intact. The size of the mesh is therefore reduced drastically, while underlying topological relationships are kept unchanged—namely same number of vertices, edges and faces given from the original design input. Although the proposed approach is capable of taking into consideration how number of different types of bamboo components can be used to optimize the input freeform shape, the optimized result may not necessarily meet the aesthetics criteria that the designer originally conceives. Future development will be required, for instance, to introduce a remeshing strategy that can change the number of vertices and edges, to retain the required height so as to keep close to the original freeform design.



Deviation per Mesh Vertex (*Unit: mm*)

	UBT_18	*UBT_15*	*UBT_10*	*UBT_5*	*UBT_3*
AVE_{DV}	57.36	**40.09**	328.26	530.91	1025.22
MIN_{DV}	0.28	**0.24**	3.91	1.68	32.82
MAX_{DV}	264.47	**165.86**	1152.49	1690.09	2124.50

Gap Threshold_Mesh Edges (*Unit: mm*)

	UBT_18	*UBT_15*	*UBT_10*	*UBT_5*	*UBT_3*
AVE_{GT}	**86.55**	87.95	85.73	101.78	98.24
MIN_{GT}	**40.03**	40.43	40.00	40.16	40.62
MAX_{GT}	**154.37**	254.96	207.14	268.24	280.26

Figure 16. Mesh optimization results using different numbers of bamboo component types.

This paper demonstrates an integrated two-stage design optimization workflow that incorporates natures of bamboo as design constraints into the form finding and rationalization process. In particular, we focus on the dimensional constraint of bamboo components and the configurational constraint from the underlying surface tessellation pattern. Through encoding these physical and geometrical attributes, we demonstrate how an integrated design optimization process could facilitate the form finding process systematically and iteratively. In addition to dimension and geometric irregularity challenges with bamboo, we intend to investigate further the strength of the bamboo connection design to justify the structure design and introduce this strength constraint into the rationalization process to fine-tune the optimal shape. This will ensure both material and structural constraints to be satisfied while searching for the optimal design solution.

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