JOURNAL OF ARCHITECTURAL RESEARCH AND DESIGN STUDIES
DOI: 10.20885/jars.vol8.iss1.art3

BambuFlex – a Digital Form-Finding Tool for Curved Bamboo Structure based on Indonesian Bamboo

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Article History

Received	:	January 29, 2024
Accepted	:	April 29, 2024
Published	:	May 20, 2024

Abstract

Contemporary bamboo buildings with curved structures have recently gained popularity despite their challenging nature to design and construct. The inherent material characteristic must be incorporated into the design process, often called form-finding. The typical form-finding approach in Indonesia incorporates physical mediums known to be complex and laborious. On the contrary, the digital medium is rarely used due to the lack of tools capable of performing quick and accurate form-finding while incorporating local bamboo and bending methods. This paper showcases BambuFlex, a digital tool that performs quick and accurate form-finding based on local bamboo and bending approaches in Indonesia. The algorithm's capability was validated by comparing its accuracy and real-time material feedback with the conventional physical method. The result shows that BambuFlex is able to provide accurate and materially informed form-finding, but it has some limitations. To conclude, BambuFlex can complement the conventional physical form finding, allowing architects to explore more design alternatives rapidly.

Keywords: *bending-active bamboo structure, digital form-finding, local bending method*

Introduction

Bamboo has traditionally been used in building construction in Indonesia, particularly in vernacular architecture. In addition to its traditional application, bamboo is an increasingly popular choice for more modern construction industries, with architects and designers incorporating it into various typologies, such as commercial and leisure facilities. The use of bamboo in contemporary Indonesian buildings extends beyond structural elements; it is also used in flooring, wall panels, and decorative features, embracing its aesthetic appeal and natural beauty (Lianto et al., 2019).

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Contemporary bamboo buildings in Indonesia often integrate innovative design techniques and technology. One that received massive attention is bamboo's application for curved bamboo structures. This approach, often called "Organic-Shaped Buildings," allows for the creation of unique and aesthetically pleasing structures while harnessing the unique material characteristics of bamboo culm (Nurdiah, 2016). This curvature is typically achieved by bending initially straight culm into a curve, which is then articulated and fixed in certain parts, creating a form-active structural system (Maurina et al., 2014). Several research and design projects have confirmed bamboo's suitability for such purposes due to its high flexural ductility compared to other wood types (Crolla, 2017; Seixas et al., 2021).

In contrast to its popularity, constructing a curved bamboo structure is, in fact, challenging. Raw culm commonly has a straight shape and non-uniform geometries, which is difficult to bend in its raw condition (Minke, 2022). Building a bamboo arch with a high degree of curvature is almost impossible solely using natural culm form. In order to overcome the issue, various techniques have been developed to alter culm morphology using low-tech (Maurina, 2015) or high-tech approaches (Sharma et al., 2015). Particularly in Indonesia, using raw or low-tech bending techniques such as the "split bundle technique" is still of preference due to its tool and processing simplicity and low cost.

Besides its construction challenge, the curved bamboo structure is also complicated to design. The conventional approach, where the architect can arbitrarily define form, is unworkable when designing such a type of structure. Bamboo's distinctive material characteristics and structural systems must be incorporated when defining the curvature (Maurina et al., 2014). The search process for this form based on material and structure is often termed "form-finding."

Contemporary local practices in Indonesia typically use scaled physical models made using skewers and rubber bands to assist the early form-finding process (Maurina & Prastyatama, 2016; Nurdiah, 2016; Stamm et al., 2022). The skewers can be bent to seek the proper element curvature, which is then fixed into the base on both ends to maintain the form. A rubber band temporarily secures the connection between multiple arches, allowing further modifications as the model becomes more complicated. In this way, the skewers can undergo plastic deformation or even break when the radius becomes too small. Such material feedback is valuable for architects to determine if a certain form could work on a larger scale.

Despite its success in delivering conceptual design into constructed curved bamboo structures, the current dominance of the physical-based form-finding method has several known issues. Each bamboo species' unique bending characteristics and morphological alterations are difficult to simulate using a small physical model. Moreover, this approach is also known to be complex and laborious (Crolla, 2018), making it hard to create rapid design changes or explore more design alternatives typical in the early design stage.

Conversely, the presence of digital tools in the early form-finding process is still underutilized. Only a few local projects are known to adopt digital tools (Charnele & Maurina, 2020; Ikhwan Harnomo, 2022). One issue that hinders its adoption is the absence of robust digital form-finding tools that able to incorporate the characteristics of local bamboo and artisan bending techniques in Indonesia while providing accurate and real-time material feedback on-par with the current physical form-finding.

This paper introduces BambuFlex, a digital tool that helps architects design curved bamboo structures by leveraging the unique properties of local bamboo and bending techniques in Indonesia. The tool uses algorithms that enable architects to quickly and accurately perform form-finding tasks, while providing feedback that is similar to physical models. This program also set the base for a complete digital simulation tool for designing complete bamboo structures. The Author tested the tool by form-finding several categories of curved bamboo structures and compared the results to physical form-finding. Finally, The Author reflected on how this tool can be strategically used in the current design workflow of curved bamboo structures and outlined its future development.

Literature Review

The known local bending technique in Indonesia typically incorporate bending from the initially straight culm. This method can be regarded as “bending-active” approach characterized by the presence of residual bending stress in the system (Lienhard & Knippers, 2014). As a theoretical basis for analysis, the variables proposed by the same Author were used. Four input aspects are essential for the form-finding process: boundary condition, dimension and section profile, length of the structural member, and material stiffness. The outputs for this process are two types of information, namely element curvature and stress.

1. **Boundary Conditions (Input)**

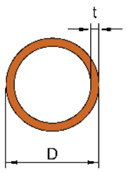
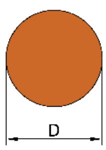
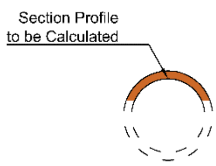
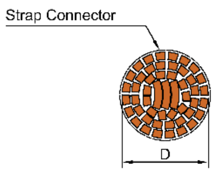
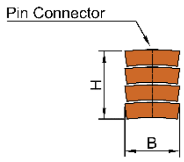
   Boundary conditions refer to any constraints applied to the structure around its boundaries. Two significant factors here are support and external loads. For support, bent bamboo structures commonly use fixed or pinned edge connections to maintain curvature under loads (Minke, 2022). However, using a free edge connection when bending is controlled using other methods, such as strain wires. The presence of external loads that affect the overall curve structure should also be incorporated, such as dead load from permanent building components such as roofing, floors, or more temporary load such as wind or rainwater.

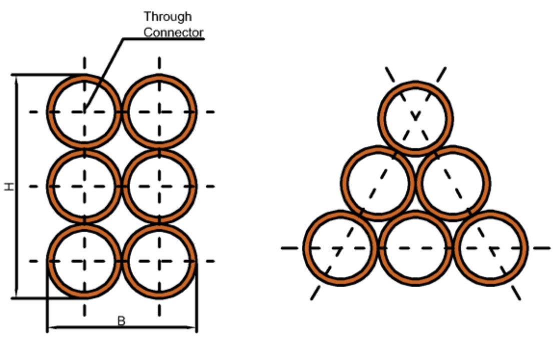
2. **Dimension and Section Profile (Input)**

   Several aspects must be considered when designing the section profile of curved bamboo structures. The first aspect relates to the varying morphology of each bamboo culm. Raw bamboo culms have hollowed and solid profiles (Chaowana et al., 2021). Hollowed culms are more common than solid profiles for local Indonesian bamboo species. The culm diameter also has varying diameters, wall thickness, and internode length (Lorenzo et al., 2020). Several approaches exist, such as using mean value (Seixas et al., 2021), lowest value (Crolla, 2017), or disregarding the variability concerning other structural members (Tahmasebinia et al., 2020).

   Another aspect that needs to be considered is various modification techniques that significantly alter the natural culm morphology. Two categories of bending approaches are known in Indonesia: the hot and cold (Maurina, 2015). Bamboo can also be bundled to increase its structural capacity in full culm or split. Table 1 summarizes the dimension and section profile for each bending approach. Note that for curves made using the rup-rup approach, the structural behavior might not belong purely to the bending active category due to the cut that better suited to the compression structural types.

Table 1. Various Section Profile of Bamboo Culm from Different Local Bending Technique in Indonesia

				Section of the split bundle 
Single hollowed culm profile	Single solid culm profile	Section of single rup-rup with an open gap	Section of the split bundle	Section of the split bundle



Section of combined hollow members

Source: Author

3. **Length of Structural Member (Input)**

Local bamboo species in Indonesia can reach a culm length of up to 30m. However, these raw culms are usually cut into uniform 6-meter segments for commercial distribution. Consequently, when constructing spans exceeding 6 meters, overlapping of sections may be necessary. The calculation input relies on the original length of the component in a straight configuration before any bending occurs.

4. **Material Stiffness (Input)**

The stiffness of each structural member can be calculated primarily based on the material's modulus of elasticity (E) and section moment of inertia (I). For the modulus of elasticity, data on the material properties of local bamboo species common in Indonesia were gathered based on the available scholarly literature, as shown in Table 2. The section moment of inertia value can be calculated based on the raw/morphological alteration of the culm. It is worth noting that bamboo culm exhibits non-uniform culm properties; the value used for calculation is determined using average value, and the value used in the design should be reflected in the construction process.

5. **Element Curvature and Stress (Output)**

The digital form-finding process generates two main outputs: element curvature and member stress values. The element curvature represents the overall geometry of the form that can be used by designers to determine whether it meets the functional requirements or other design criteria. On the other hand, the stress output shows the amount of stress and its position along the curve segments. This information helps designers determine whether the stress values are within the limit of the material and the curved parts that have a higher risk of failure due to the inherent residual bending stress.

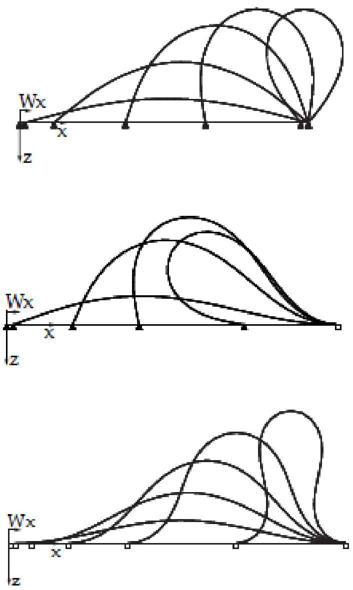
6. **Elastica Beam**

The approach of creating curve bamboo structure based on high elastic deformation of beam is in line with the criteria of the elastica beam theory introduced by Euler (1744). According to the theory, when elastica beam is bent and constrained, the system will attempt to achieve the lowest bending energy possible resulting in the form attempting to return to its straight state (Levien, 2009). Figure 1 displays several types of elastica curves based on Euler's Theory.

Table 2. Material Properties of Several Local Indonesian Bamboo Species

Bamboo Species	Age (Yrs)	Moisture Content (%)	Average Modulus of Elasticity (E) (MPa)	Average Bending Strength (MoR) (MPa)	Source
Bambu Petung *(Dendrocalamus asper)*	4	13.68	14944	62	(Junaid et al., 2022)
Bambu Apus *(Gigantochloa apus)*	3-4	16.79	17952	673	(Nugroho & Bahtiar, 2017)
Bambu Wulung *(Gigantochloa atroviolacea)*	3-5	N/A	6548	27.56	(Irawati & Wusqo, 2020)
Bambu Duri/Ori *(Bambusa blumeana)*	1-3	20	3220	91	(Mohmod et al., 1993)
Bambu Ampel/Kuning *(Bambusa Vulgaris)*	4	17.3	1120	12.24	(Nugroho et al., 2013)

Figure 1. Elastica curves based on Euler's Theory
Source: (Lienhard & Knippers, 2014)



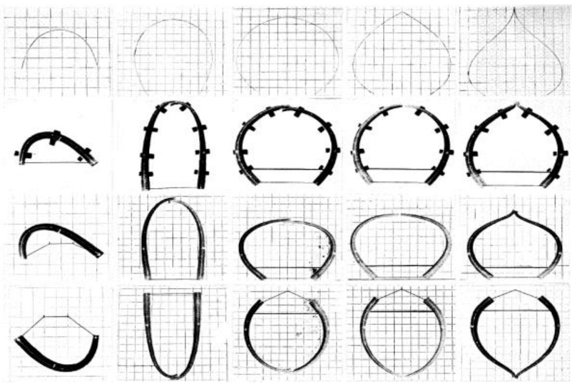
Methodology

In order to test the BambuFlex algorithm, The Author conducted experiments on the algorithm and the physical model to perform form-finding of curved bamboo structures. Several bamboo arch typologies, as described by Fritz et al. in Gass et al. (1985) were set as target forms as shown in Figure 2, including:

- Articulated single rod arch
- Articulated two-rod arch
- Restrained two-rod arch
- Restrained pointed arch
- Restrained onion-shaped arch

The Author performed an early validation of the accuracy of the digital form-finding results by comparing the curvature similarity to the physical method. Since the target typologies are similar to elastica beams, which are known to be independent of material properties, scale, and mechanical constraints (Lienhard & Knippers, 2014), the Author could perform the validation of the curvature without having to use identic input data for both the digital and physical. The process began with creating digital forms, which were later followed by the physical models with the same form target. After that, the results from both approaches were overlaid and the similarity was measured using the discrete Fréchet distance calculations. Finally, a diagram was drawn to show the similarity of the segments, which were color-coded based on their respective distance.

Figure 2. Target form in the analysis based on various typologies of bamboo arch
Source: (Gass et al., 1985)



The accuracy were calculated using Frechet's distance function (Eiter & Mannila, 1994) which then converted to percentage value against the culm's total length as follows:

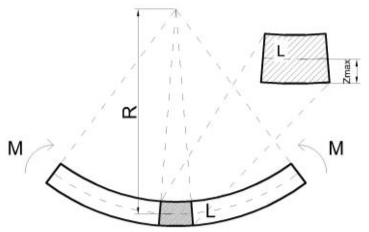
Given two curves f : [a,b] →V and g : [a',b'] →V

$$\delta_F(f,g) = \inf_{\alpha,\beta} \max_{t\epsilon\,[0,1]} d\big(f(\alpha(t)), g(\beta(t))\big)$$

$$accuracy\ (\%) = \frac{\delta_F(f,g)}{\Sigma_{(f,g)} x100}\%$$

In addition, BambuFlex was also tested for its capability to provide real-time material feedback during the form-finding process. This was done by showcasing information if the bending radii was close to the material limit. The calculations was based on the relationship between the Modulus of Elasticity (E), the section depth of each member, and the calculated stress theorized by Gengnagel et al. (2013). The Author modified the formula to enable the determination of the minimum bending radius for different bamboo species based on the Modulus of Rupture (MOR) value using the following equation. The calculation results were also plotted as gradient color assigned along the arch showing the exact position of the segment with lowest bending radius.

Figure 3. Relationship Between the Stress, Radius of Curvature, and Section Depth in a Deflected Beam.
Source: (Gengnagel et al., 2013)



$$\sigma(z) = E.z.\frac{1}{R} \qquad R_{max} = E.z_{max}.\frac{1}{\sigma_{max}}$$

Where:
σ(z) = Material stress at point (z)
E = Modulus of Elasticity
z = Distance of reference point z to the neutral axis
R = Bending radius at the neutral axis

BambuFlex adopt Dynamic Relaxation (DR) technique using Modified Kangaroo Engineering physics (Piker, 2013) inside Mc Neel's Rhinoceros® and Grasshopper® and following workflow introduced by Crolla (2017). The bamboo curve was represented as a discretized polyline with a particular curvature. Each segment was simulated in two mechanisms: rod and bar. As rod elements, each segment was set to have bending stiffness and zero-degree target curvature with its adjacent segments. For the bar elements, segments were assigned as poles with specific axial stiffness. Cusp control was also introduced by adding a break point with a hinged joint. The algorithm then tried to iteratively adjust the curvature by minimizing the degree of each segment closer to zero.

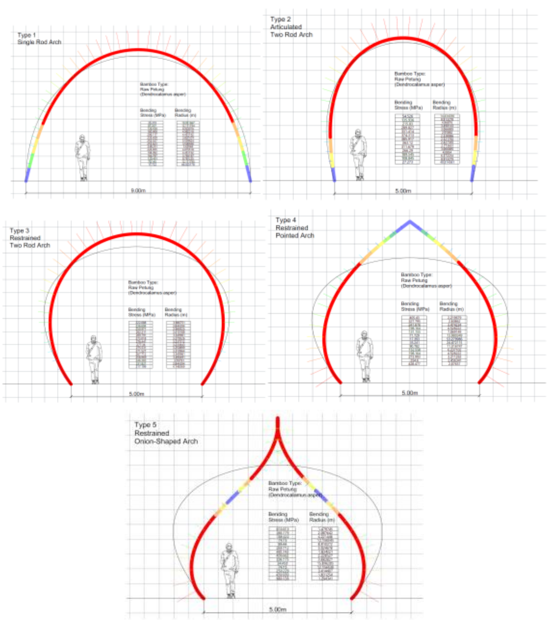
For the physical model, The Author utilized "lidi" - thin bamboo splits with a diameter of 3mm - that were procured from a local store in Yogyakarta, Indonesia. Unfortunately, The Author was unable to ascertain the specific type and characteristics of the bamboo. Each lidi was carefully placed in thick cardboard and bent using the same setup as the digital model. To ensure structural integrity, paper staples and paper tape were utilized to create joints between two pieces of lidi and secure them in the cardboard. The resultant form was then scanned to obtain the digital copy and facilitate further comparison with the digital approach.

The initial input data for BambuFlex were defined arbitrarily but consistent between the digital and physical. The Author drew planar NURBS curve in the XZ axis for the setup, enclosing a specific two-dimensional space. Both ends of the curve were used as support points that are movable manually by user input. The Author also defined two load sources, namely, self-weight and external load. Self-weight is mandatory in the calculation, while external load consisting of point or uniform load is optional. The initial member section and bamboo species were also defined randomly. These initial values were refined as the simulation ran until a specific solution was achieved.

Result and Discussion

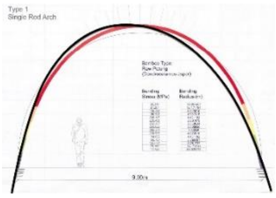
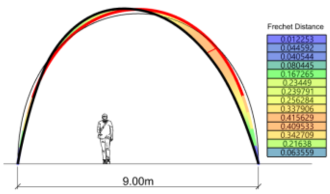
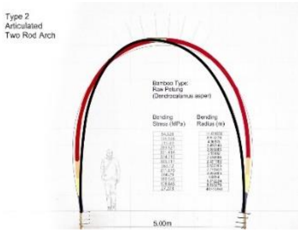
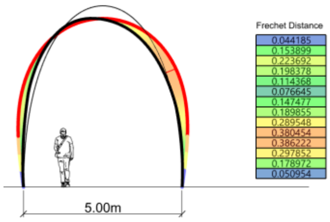
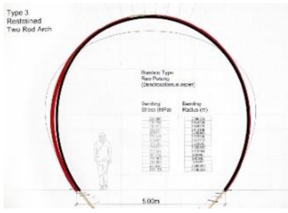
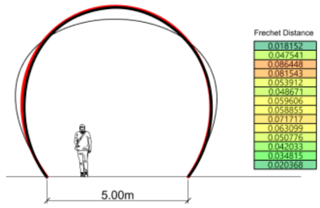
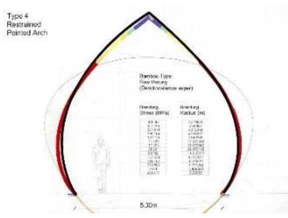
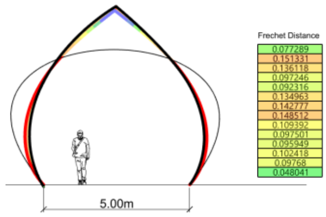
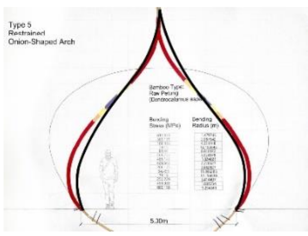
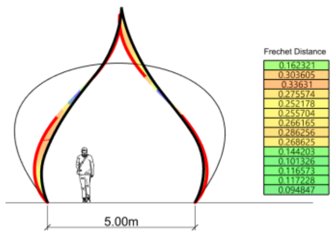
The initial curve and the form-finding result are presented below for each targeted arch typology, different configurations of local bamboo species, and bending approach. The first BambuFlex simulation run with arbitrary input configurations and simple initial curve control point modification to achieve the targeted typology, as shown in Figure 4.

Figure 4. The First Simulation Results Using Arbitrary Initial Setup and Target Arch Topology.
Source: Author



To evaluate the results, The Author conducted similarity comparisons between the digital and physical models, as shown in Table 3. The initial analysis indicates that the algorithm was able to accurately replicate the form of the physical model, achieving an average similarity percentage of 98% across all predefined target forms. The algorithm's accuracy tend to be higher in forms with higher bending radius. The largest Fréchet distance measured was 0.41m in the articulated single rod arch, which highlights the algorithm's inability to fully replicate the varying geometrical and material properties of natural culm with tip and base sides. Although the preliminary analysis showed high accuracy, the low number of samples increases the potential for inaccuracy in larger test scenario. To ensure reliable results from the tool, more tests is required with a higher number of samples.

Table 3. Similarity Analysis Between Digital and Physical Form-Finding

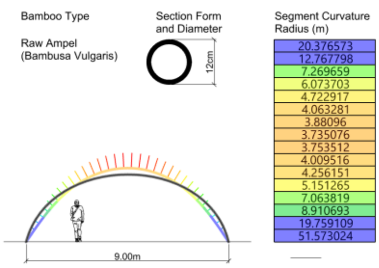
Target Form	Overlaid Digital – Physical Result Digital (colored); Physical (thick black)	Discrete Fréchet Distance Diagram	Similarity Percentage
Articulated single-rod arch			97.45%
Articulated two-rod arch			97.06%
Restrained two-rod arch			99.44%
Restrained pointed arch			98.86%
Restrained onion-shaped arch			97.65%

Source: Author

In the following analysis, The Author tested the algorithm's capability to provides real-time feedback on material during the form-finding process. The Author began with arbitrary initial input values, which were adjusted in subsequent iterations. The results in Table 4 demonstrate the step-by-step updates in the calculated output as the input values were modified. The span, culm length, and load inputs directly affect the minimum bending radius in the system. When this value exceeds the minimum radius, the algorithm can identify which parts are at risk of failure. Conversely, when the material, section profile, and dimensions are changed, the script adjusts the minimum allowable bending radius limit and rechecks the model's current curvature. This process yields similar information about the weak parts in the culm. The overall arch curvature were also continuously updated during the simulation. All of these information is on par with feedback from the real scaled model.

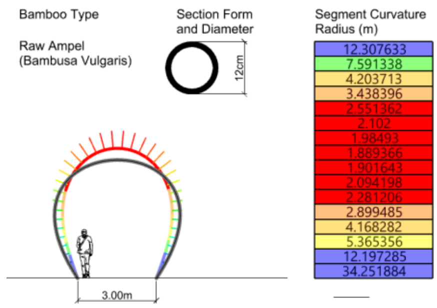
Table 4. Form-Finding Iteration with Real-Time Material Feedback

Initial Input Curvature



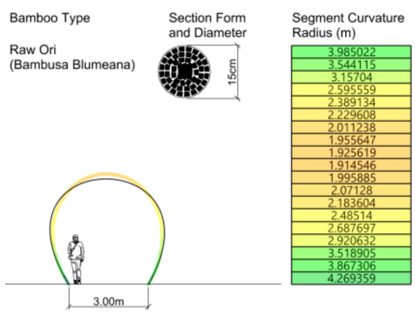
Setup:
Target Form: Articulated two-rod arch
External Load Type: Absent
External Load Position: Absent
External Load Value: Absent
Span: 9.00m
Culm Length: 11.66m
Bamboo Type: Raw Ampel (Bambusa Vulgaris)
Section Form: Natural hollowed culm
Section Diameter: 12cm
Minimum Allowable Bending Radius: 2.74m
Minimum Bending Radius in the System: 3.73m

Iteration 2



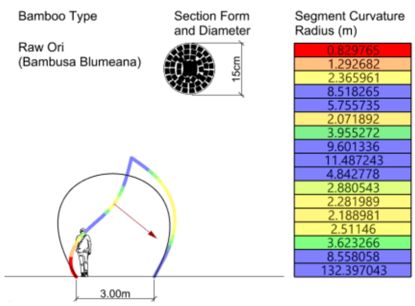
Setup:
Target Form: Articulated two-rod arch
External Load Type: Absent
External Load Position: Absent
External Load Value: Absent
Span: 3.00m (changed)
Culm Length: 12.32m (changed)
Bamboo Type: Raw Ampel (Bambusa Vulgaris)
Section Form: Natural hollowed culm
Section Diameter: 12cm
Minimum Allowable Bending Radius: 2.74m
Minimum Bending Radius in the System: 1.88m (changed)

Iteration 3



Setup:
Target Form: Articulated two-rod arch
External Load Type: Absent
External Load Position: Absent
External Load Value: Absent
Span: 3.00m
Culm Length: 12.32m
Bamboo Type: Raw Ori (Bambusa Blumeana) (changed)
Section Form: Split bundle (changed)
Section Diameter: 15cm (changed)
Minimum Allowable Bending Radius: 1.23m (changed)
Minimum Bending Radius in the System: 1.88m (changed)

Iteration 4



Setup:
Target Form: Restrained pointed arch (changed)
External Load Type: Point Load (changed)
External Load Position: 0.31 (changed)
External Load Value: 100kN (changed)
Span: 3.00m
Culm Length: 12.32m
Bamboo Type: Raw Ori (Bambusa Blumeana)
Section Form: Split bundle
Section Diameter: 15cm
Minimum Allowable Bending Radius: 1.23m
Minimum Bending Radius in the System: 1.01m (changed)

Source: Author

Conclusion

This paper explores the potential usage of BambuFlex, a digital tool for the early form-finding stage of bending-active arch bamboo structures. The algorithm has demonstrated the ability to integrate form creation with Indonesia's unique local context of bending approaches and bamboo materials. With the current computational power, digital form-finding of bending bamboo can be done with direct material feedback almost as instantly and accurately as a physical-based approach. The digital tool also permits designers to incorporate real-world scenarios within the system, such as external load cases in a more controlled manner, which are often missing in scaled physical models. With its parametric nature, form modification can be rapidly done with minimum time and cost expense. Ultimately, the architect could spend more energy to explore more design alternatives within the early design stage.

However, digital tools also have some limitations. The validation has only been done with small scale samples, increasing its inaccuracy potential. Bamboo is still represented as a homogenous material, while in the real world, it is quite the opposite. Moreover, the algorithm has not yet been able to simulate the rich information present in the physical model, such as culm direction or crack behavior, which significantly affect the creation of form. In reality, the arch structure could also be combined with other types, adding more complexity, which the algorithm has not yet been

Source: Author

able to replicate. Consequently, the digital simulation result still does not fully indicate the actual structural behavior of physical bamboo. The program's accuracy depends on the user's correct input and presumption. False input would also mean an invalid result, unlike a physical model that always corrects to a certain degree. Calculation using digital form-finding also demands high computational power.

Based on the reflection above, The Author positions the tool not as a complete replacement for the conventional scaled physical model but rather as its complement. The digital tool could be used in the first stage to allow rapid design exploration, while a scaled physical model comes later for further validation. Citing Addis (2014) and Crolla (2018), digital form-finding can be used to absorb the laborious process of physical form-finding, while the physical model could be positioned as an independent check for the outcome of digital tools. In the future, more study is needed to improve the algorithm to incorporate larger tests and more features in the form-finding process of bending active bamboo structures.

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