

DIGITAL CONSTRUCTION OF BAMBOO ARCHITECTURE BASED ON MULTI-TECHNOLOGY COOPERATION

Constructing a new parameterized digital construction workflow of bamboo architecture from traditional bamboo construction technology

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Abstract. Limited by the non-standard nature of bamboo, bamboo has always been regarded as a traditional, restrictive, and time-consuming building material. Therefore, there is an urgent need for an enhanced parametric design system and digital construction workflow to upgrade the traditional bamboo construction process. In this paper, through the analysis of the bamboo pavilion "Diecui Gallery" under the traditional construction method, five main factors restricting the development of bamboo architecture are obtained: difficult positioning of supporting structure, low efficiency of material selection and matching, the manual processing of materials, non-standard node and low utilization rate of non-standard waste materials. Then, through literature review, we proposed the technical means to improve these factors and put forward a multi-technology collaborative digital construction workflow. The workflow will comprise augmented reality, 3D scanning, robot-aided construction, 3D printing, and design rules. Moreover, by building parametric benches, we used augmented reality technology and new design rules to verify multi-technology collaborative fabrication workflow possibilities and effectiveness. This paper wants to explore a parametric design method based on bamboo material characteristics and multi-technology collaborative workflow, to improve the utilization rate of non-standard bamboo components in parametric design.

Keywords. Bamboo Material; Multi-technology Collaboration; Parametric Design System; Augmented Reality; Digital Construction Method; SDG 11.

1. Introduction

Compared with wood, bamboo has the advantages of a short growth cycle, easy to obtain, and low economic cost, so it is a better eco-sustainable building material.

Nowadays, designers have been widely studying bamboo as an eco-friendly building material. In ancient China, people used the excellent bending properties of bamboo to weave it and made many nonlinear living utensils. With the improvement of science and technology, modern architects explore nonlinear bamboo architecture or bamboo construction design. However, the specific growth and non-standard bamboo pose many parametric bamboo architectural design challenges. This paper will compare and analyze the traditional construction and multi-technology cooperative mode of Diecui Gallery bamboo pavilion and bamboo chair and discuss a new parameterized bamboo architecture design workflow. The design form of the bamboo gallery is nonlinear and parameterized (Fig. 1).



Figure. 1. The bamboo pavilion "Diecui Gallery"

2. Background

Chaozhou-Xidong Cooperative, which is located on the bank of Han River, has an ideal ecological environment. Bamboo is rich in local resources, with green, low-carbon, beautiful, fast growth, and excellent characteristics. Furthermore, a group of experienced and skilled bamboo craftsmen, the local traditional bamboo craft industry is developed.

There are flowerbeds, farmland, and riverside culture here, which attracts many tourists to sightseeing. However, the purely natural environment lacks rest space with humanistic flavor, and tourists lack a structure to protect themselves from the sun and rain and enjoy tea in the process of playing here. In order to be in harmony with the natural environment, we designed a bamboo pavilion called Diecui Gallery for the small town of Xidong in Chaozhou based on local materials.

Through parametric construction, a modern-style bamboo promenade was designed. Through careful material selection, cutting, forging, splicing, and joint efforts by local bamboo masters, we have worked together to solve many problems to successfully build a bamboo promenade and quickly put it into use. We explored the reasons for the decline of local bamboo architecture. Firstly, the local design works are too traditional and unattractive; the automation level of the construction process is low, and the production efficiency is low. Secondly, the material selection takes too long and wastes a lot of staffing and material resources; the utilization rate of non-standardized bamboo materials is low, resulting in much material waste. In order to

help the local bamboo industry revitalize and promote bamboo culture, we will discuss a new multi-technology fusion processing flow.

3. Traditional construction methods and limiting factors

To understand the traditional construction process (Fig. 2), designers used video recording equipment to record the whole process and count the time needed for each stage. The analysis found that it took the longest time in the material selection and design communication stage (Fig. 3). The reason is that the utilization rate of bamboo is low, always looking for suitable bamboo but wasting bamboo at hand.

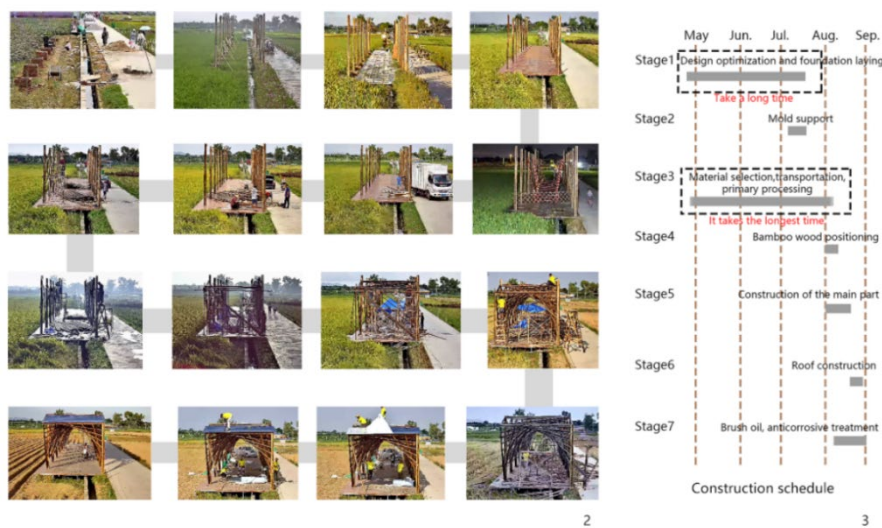


Figure. 2&3. Construction process and schedule

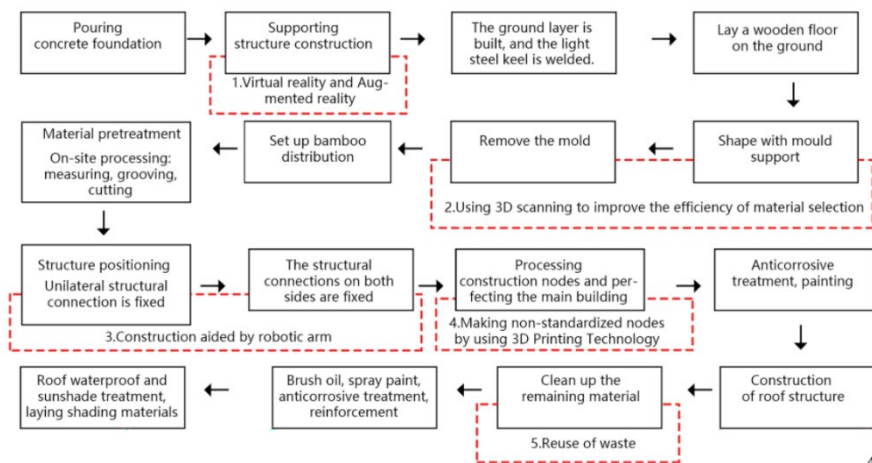


Figure. 4. Five restrictive factors in the process of construction and the digital technologies to solve them

Five factors restrict the construction speed of parametric bamboo buildings in the whole construction process. We have found five digital technologies to optimize these problems (Fig. 4).

3.1. DIFFICULT POSITIONING OF SUPPORTING STRUCTURE

When building a more complex building shape, it is usually necessary to determine the location of the main structure or the main force-bearing structure. Significantly, there is broad variation in the material properties of bamboo, and reducing errors when using unskilled labor is difficult (Imanishi. N. et al., 2017). Once the main load-bearing structure is mislocated, it may lead to the failure of the whole construction. However, due to the irregular and non-standardized form of parametric design, the location of the main stress structure is a complex problem to solve. When the curve's shape is found in space, the positioning will be much more difficult. In this regard, some scholars try to use augmented reality technology and mixed reality technology to locate the parameterized shape in space. ARgan is a geometrically complex bamboo sculpture that relied on Mixed Reality (MR) for its joint creation by multiple sculptors and used the latest Augmented Reality (AR) technology to guide manual fabrication actions (Goepel & Crolla, 2020).

3.2. LOW EFFICIENCY OF MATERIAL SELECTION AND MATCHING

The second problem lies in the selection of materials. In the process of building parametric buildings with bamboo as the primary material, because the length, coarseness, and curvature of each bamboo are different, operators often spend several times to find a large number of bamboo and select the right size of bamboo. As the selection of materials takes much time, it takes a long time to wait for the next step of construction after the foundation construction, which seriously reduces the speed of construction. In order to improve the selection efficiency and model matching degree of non-standard bamboo materials, Katie MacDonald uses sensing, scanning, and other feedback techniques to explore new opportunities that may arise in the field of non-standard materials. To better understand the natural changes in diameter, straightness, and cross-sectional area, they created a catalogue of pole attributes, which were then calibrated using a 3D scanning system (Katie. M. 2019).

3.3. SLOW PROCESSING SPEED OF MATERIALS

The third factor that restricts the speed of construction is material processing. The parameterized design contains mathematical rules and has strong logic. Therefore, the material processing process has a lot of repetitive work, such as slotting, drilling, bending, grinding, etc. However, the local bamboo master still uses the traditional manual operation without any mechanical automation means, which will bring some problems: firstly, the pure manual operation often depends on the work experience of the constructors, and different builders have different experiences, which leads to errors in the processing of materials. The building must be overturned and redone when the error is too large to be resolved. It will waste builders' time and energy. Secondly, designers will make a series of parameter adjustments when carrying out parametric design, which leads to different sizes of each groove or curvature of each bamboo, and the builders are unable to accurately measure the curvature or the size of the notch,

which makes it difficult to build buildings. Based on these problems, studies are done towards the auxiliary construction of the manipulator, through the algorithm to control the manipulator can accurately cut or bend and other operations. These methods will significantly increase the possibility of parametric design landing. Pradeep Devadass elaborated a method of robot positioning and machining non-standard wood components in the Wood Chip Barn project by the students of design + Make at the Architectural Association's Hooke Park campus (Pradeep. D. 2016).

3.4. NON-STANDARDIZED JOINT CONNECTION

The fourth problem belongs to the problem of joint connection. At present, the main joints used in bamboo construction are binding connection + mortise connection, bolt connection, sleeve connection, groove connection, metal belt or U-shaped iron plate connection, prefabricated metal connection, and cast-in-place cement connection. The joints of parametric design are usually not uniform and non-standardized. The binding connection will lead to poor structural stability, and the joints need to be regularly overhauled and replaced. The use of bolt connection is easy to cause the bamboo to crack along the grain direction, and it is easy to cause construction error when opening holes. Sleeve connection requires high unity and standardization of bamboo diameter, which is contrary to parametric design and material properties. Connecting with metal belts will reduce the structural stability. The use of prefabricated metal parts can effectively reduce the difficulty of construction. However, the loosening of metal components can quickly reduce structural strength, and non-standard metal components will increase the construction cost. The method of pouring cement connection is not easy to control the amount of cement, and the joint can not be adjusted after fixed. It is not suitable for flexible parametric design. We can understand the limitations of applying these joint processing methods to parametric design through the above analysis. Therefore, ETH's design team developed a new bamboo connection system based on 3D printing technology (Kladefira, M. et al., 2021). The generation of the connections was automated thanks to a digital process and developed to fulfil mechanical requirements.

3.5. LOW UTILIZATION RATE OF NON-STANDARD WASTE MATERIALS

The fifth problem is the reduction of waste materials and waste utilization. Parameterized bamboo buildings consume much bamboo of different sizes. Due to the unique properties of parametric design and the material characteristics of bamboo itself, there will be a surplus of bamboo of different sizes in the processing process. On the one hand, to reduce the waste of materials, we need to rethink the logic of parametric design. At the beginning of construction, we should consider a series of waste problems and seek effective design methods to improve material utilization.

On the other hand, it is necessary to balance design innovation and material characteristics. The characteristics of parametric design should not be sacrificed to pursue the efficient use of materials. This requires us to consider the reuse of non-standardized components in the construction stage, redefine the allowable range of errors in the material processing stage and try to eliminate and balance the errors in the processing and construction stages by design means. The TOROO project effectively

absorbs accidental errors in the construction process and challenges the construction environment under highly unpredictable conditions (Crolla & Goepel, 2020).

3.6. MULTI-TECHNOLOGY FUSION WORKFLOW

We have summarised five related digital construction technologies through a critical analysis of traditional construction workflows and literature review. The multi-technology convergence construction workflow is a free combination and optimization of these five digital technologies. The multi-technology fusion workflow has many irreplaceable advantages: firstly, we can freely combine different digital technologies according to the constraints of a specific project, increasing the flexibility and diversity of the workflow; secondly, the combination of two or more different digital technologies can significantly improve construction efficiency and reduce construction costs; thirdly, the synergy of multiple digital technologies opens up the possibility of industrial production of parametric bamboo buildings. Thirdly, the synergy of multiple digital technologies opens up tremendous possibilities for the industrial production of parametric bamboo buildings (Fig. 5).

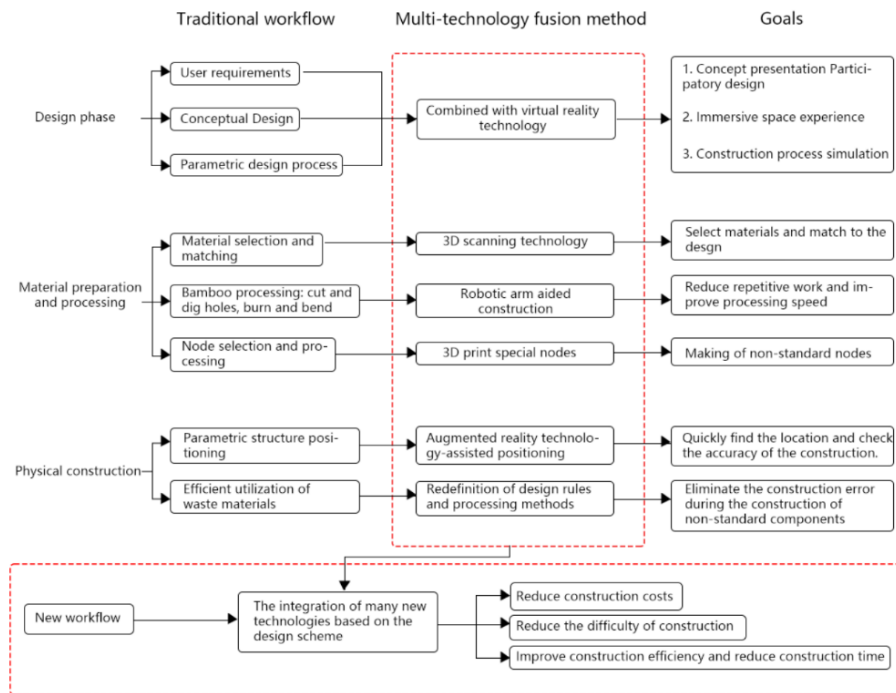


Figure 5. Traditional construction methods and multi-technology fusion workflow.

4. Exploration of Multi-Technology Fusion Workflow

For the Diecui gallery, to provide people with rest facilities. We designed a parameterized bamboo chair throughout the experience of building the Diecui gallery.

We designed a bamboo chair unit under each bamboo pavilion, the length of each bamboo chair unit is 5m, and the whole chair is composed of seven bamboo chair units. For designers, the logic of form generation can be clearly expressed in grasshopper. However, it is not easy to convey the whole form generation logic and construction model accurately to the bamboo master.

At first, we showed the expected construction effect to the workers in drawings and 3D models. Nevertheless, the chairs built are far from satisfactory (Fig. 10 stage1). Because of the limited cultural level of the builders, they can not accurately understand the generative logic of the designers. They can not consider the parametric design with multiple variables when machining chairs. Therefore, we have to rethink how to convey the designer's intention accurately and clearly express the construction logic to the builders. Finally, we use augmented reality technology to assist the construction and eliminate the size error through the new design method.

4.1. DESIGNER'S INTENTION: UNIT-HANDOVER-POSITIONING-CONSTRUCTION

4.1.1. Unit and handover combination

On the one hand, there is a size limitation for the bamboo material used as structural support, and each bamboo can be used as a load-bearing member for a portion of about five meters. On the other hand, for the sake of easy construction and transportation, we divide the chair nearly 40 meters long into seven units for construction; each unit is 5.6 m (Fig. 6). The back part of each unit is natural bamboo, which is tied and inserted between the backs of the chairs by twine (Fig. 7). The back part of the chair can use the leftover material after processing.

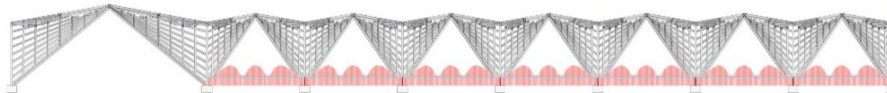


Figure 6. Unit

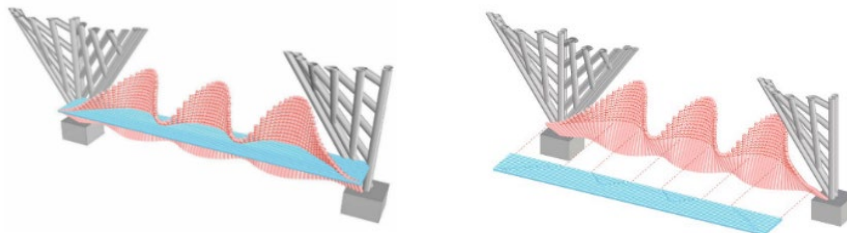


Figure 7. Handover combination

4.1.2. Eliminate dimensional error

In addition, the back of each unit is made of 92 bamboos, each with a diameter of about 6 cm. Since bamboo is a non-standard material, we had to consider the possible dimensional errors of non-standard materials in the design phase. Therefore, we chose to leave a redundant space between two units to dissipate dimensional and construction errors (Fig. 8).

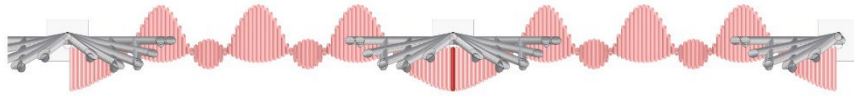


Figure 8. Eliminate dimensional error

4.1.3. Positioning and construction in the traditional way

In order to locate the bamboos, we numbered each unit's bamboos from left to right sequentially as 1-92 (Fig. 9). In addition, the bottom center of the first bamboo on the left (near the inner measurement of the pavilion) was used as the origin to determine the relative position of the bottom centers of the remaining bamboos. As shown in Figure 12, (0.060, 0.006) represents: the position of the bottom center of this bamboo is shifted 0.060 m to the right and 0.006 m upward (near the inner side of the pavilion) relative to the first one. The logic of the cell morphology generation is the same for each. In addition to the variable of relative position, the length of the bamboo and the angle of inclination are the other two variables of the chair. Again, we numbered each bamboo in order from left to right as 1-92. As shown on the right side of Figure 12, within the chart (0.838; 76.1°) stands for: this bamboo has an angle of 76.1° with the ground and a length of 0.838m.

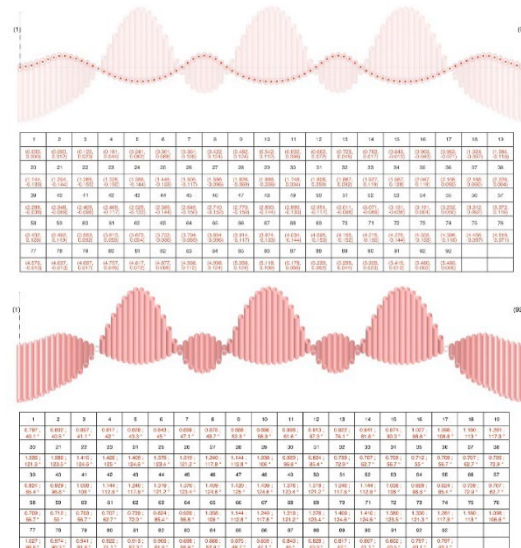


Figure 9. Positioning and construction in the traditional way

4.2. MULTI-TECHNOLOGY FUSION CONSTRUCTION METHOD

Building builders based on traditional experience is a standard form, and even if they have drawings and text descriptions to help them understand, they will still build the wrong form (Fig. 10 stage 1). Using HoloLens can help people understand the shape or position of the target intuitively and interactively (Fig. 10 stage 2 & 3). It helps achieve the visual effect of parametric design without drawings or is challenging to understand. AR provides an intuitive visual display for the builders accustomed to the traditional technology, such as the bamboo master in Chaoshan.

In a parameterized bamboo structure, the builders use the AR model to assist the positioning and installation of the bamboo structure, which avoids the missing and wrong installation of the bamboo structure members and ensures the integrity of the bamboo structure installation. For bamboo buildings with a high degree of parameterization and special-shaped bamboo structures, AR-aided construction is precise at a glance, which dramatically improves construction efficiency from a visual point of view. There is no need to flip through the drawings. By integrating improved design methods and augmented reality technology, the accuracy and speed of construction are effectively improved (Fig. 10 stage 4).

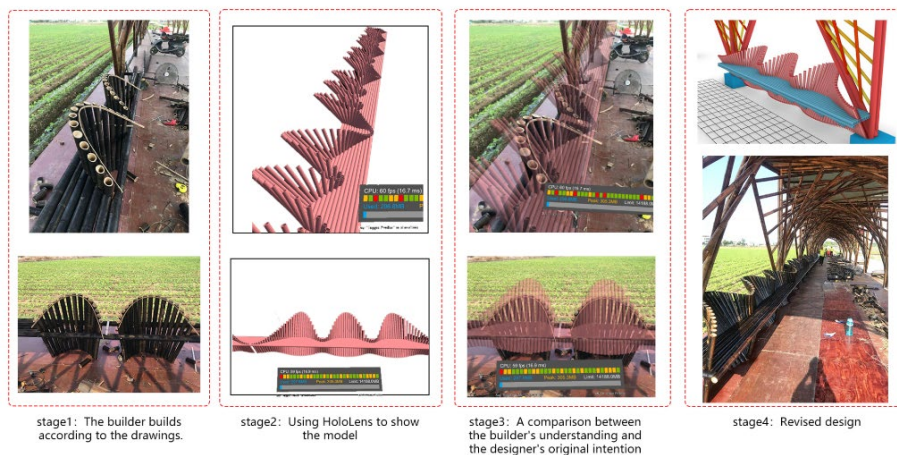


Figure. 10. Exploration of Auxiliary Construction of augmented reality

5. Conclusion

The geometric shape of the parameterized bamboo building is complex, and each bamboo pole's shape, size, and structural properties are unique. The traditional construction methods use professional intuition and construction experience for material selection and processing. It is not easy to ensure the applicability and coordination of materials in this process. There are many contradictions between nonlinear parametric design and irregular non-standardized bamboo from design to material selection and processing and construction. For example, in material selection, the master has to spend much time selecting the appropriate scale and similar structural properties of bamboo for processing, which wastes a lot of time and energy. In the construction process, bamboo components of different scales dazzle the bamboo

master, and it takes a long time to find matching components.

After analysis and summary, five limiting factors limit the industrial construction of bamboo buildings, but each limiting factor should have relevant solutions. The workflow of multi-technology collaboration is to be combined by adaptive technical means according to different projects. These technologies include augmented reality technology, 3D scanning, 3D printing of non-standard components, robot-aided construction, and non-standard material design systems. Because these technologies have their limitations, it is necessary to integrate them and work together to improve the production efficiency of bamboo buildings and reduce their processing costs. Last but not least, we will build a series of bamboo buildings for Chaozhou. We will constantly improve the collaboration of multi-technology integration workflows to build different parameterized bamboo buildings. We will also contribute to the industrial production of bamboo buildings.

Acknowledgements

This research was supported by the following funds: Later Funded Projects of National Philosophy and Social Science Foundation of China (No. 19FXWB026); Youth Project of National Natural Science Foundation of China (No. 51908158); Higher Education Research and Reform Project of Guangdong Province (No. HITSZERP19001); General Project of Stabilization Support Program of Shenzhen Universities (No. GXWD20201230155427003-20200822174038001); Shenzhen Excellent Science and Technology Innovation Talent Training Project (No. ZX20210096).

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