CONSTRUCTION BASED ON MAN-MACHINE COLLABORATION - A CASE STUDY OF A BAMBOO PAVILION

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Abstract
With the development of advanced digital design approaches and mechanical facilities, architectural intelligence liberates conventional construction from conventional paradigms. Computational design and digital fabrication have achieved progress in space innovation, construction efficiency, and material effectiveness. However, those high-tech manufacturing techniques are not widely available in developing countries, where the locals used to carry construction experience from age to age in a nonacademic way. This study explored a collaborative workflow of complex structural design and machine-aided construction in Chinese rural areas. First, we designed a bamboo pavilion parametrically in an irregular site on a hill. Second, its primary structure was optimized based on determining critical load and earthquake resistance to meet local building codes. Then, before material processing, every bamboo component was numbered by algorithm, with its location and morphological data of length and radian calculated accurately on the construction drawings. In the transitional process from the conventional paradigm by experience towards man-machine collaboration, local workers' manual techniques helped minimize construction errors and improve details, which were not adequately predicted and considered beforehand. This study case suggested that respective advantages of both traditional and digital modes should be integrated and balanced based on collaboration between local construction workers and professional researchers, especially as a social role for future vernacular architecture practice.

Keywords
Parametric design; Machine-aided; Bamboo material; Collaborative construction.
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ABSTRACT
With the development of advanced digital design approaches and mechanical facilities, architectural intelligence liberates conventional construction from conventional paradigms. Computational design and digital fabrication have achieved progress in space innovation, construction efficiency, and material effectiveness. However, those high-tech manufacturing techniques are not widely available in developing countries, where the locals used to carry construction experience from age to age in a nonacademic way. This study explored a collaborative workflow of complex structural design and machine-aided construction in Chinese rural areas. First, we designed a bamboo pavilion parametrically in an irregular site on a hill. Second, its primary structure was optimized based on determining critical load and earthquake resistance to meet local building codes. Then, before material processing, every bamboo component was numbered by algorithm, with its location and morphological data of length and radius calculated accurately on the construction drawings. In the transitional process from the conventional paradigm by experience towards man-machine collaboration, local workers' manual techniques helped minimize construction errors and improve details, which were not adequately predicted and considered beforehand. This study case suggested that respective advantages of both traditional and digital modes should be integrated and balanced based on collaboration between local construction workers and professional researchers, especially as a social role for future vernacular architecture practice.

Keywords: Parametric design; Machine-aided; Bamboo material; Collaborative construction.
1. INTRODUCTION

In an age of the intelligent building industry (Ghaffarianhoseini, Berardi, AlWaer, et al., 2016), architects are increasingly focused on improving design and construction patterns to shape new living styles and relieve environmental burdens. However, compared with the development of advanced building industries and construction technologies applied in modern mega-cities, villages in rural areas in China face a decline in conventional construction (Vellinga, 2006). On the one hand, modern buildings widely use industrial materials like concrete, glass, and steel, which dominate the overwhelming majority of the local construction market. On the other hand, local craftsmen full of conventional techniques in wood, bamboo, and soil gradually lose their competition in terms of construction efficiency, durability, and ornamental. Those vernacular architecture styles are relatively less fashionable and delicate than modern approaches like digital design and robotic fabrication, which have been proved practically in advanced architecture laboratories worldwide.

This study discussed an exploratory practice of balancing conventional construction and machine-aided fabrication. Professional architects led the design and construction process with local workers' participation. The performance of such a collaboration mode was observed and evaluated through a hands-on project on a bamboo pavilion (Figure 1), whose design process first started in 2019 and is currently under regular use. The reasons why selecting bamboo as the primary material for the pavilion lie in three aspects: 1) as a natural and organic material, using bamboo aims to respond to rising worldwide topics of sustainability and environmental protection, significantly contributing to the goal of carbon neutrality (Xu, Xu, Zhu, et al., 2022); 2) A raw bamboo rod has excellent bending performance (Chen, 2016), whose deformation happens in proper pressure and shape reinstatement is automatic after removing the external forces. So it is considered suitable and competent in innovative structure design to achieve material potential; 3) there has been a long history of bamboo utilization in China, particularly in some rural areas where bamboo once supported the local economy and society in ancient times.

Fig. 1: Bamboo Pavilion (Anji, China, 2021)
2. METHODOLOGY

Typically, local bamboo craftsmen inherit manual techniques and specific prototypes of raw bamboo construction from the older generations without any modern professional training in academic institutions. They are full of practical experience in building small-scale and simple structures through living practices and activities for several decades. However, such non-standard practices have gradually failed to compete with modern machine-aided construction based on bamboo composites (Sun, He, and Li, 2020), produced and commercialized in construction factories. Compared with conventional construction, the latter shows superior and stable performance in design complexity, fabrication automation, and even architectural intelligence. The differences between the two approaches are listed in Table 1, according to the actual conditions of this project.

Table 1: Comparison between two ways of design-construction workflow.

<table>
<thead>
<tr>
<th></th>
<th>Conventional Construction</th>
<th>Machine-aided Construction</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Practitioner</strong></td>
<td>Local people</td>
<td>Professional staff</td>
</tr>
<tr>
<td><strong>Material</strong></td>
<td>Raw bamboo</td>
<td>Bamboo composite</td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>·specific prototypes</td>
<td>·Computer-aided parametric design</td>
</tr>
<tr>
<td><strong>Design Process</strong></td>
<td>·Simple shape</td>
<td>·Complex shape</td>
</tr>
<tr>
<td></td>
<td>·Small scale</td>
<td>·Large scale</td>
</tr>
<tr>
<td><strong>Construction process</strong></td>
<td>·Situated construction</td>
<td>·Pre-fabrication</td>
</tr>
<tr>
<td></td>
<td>·Manual techniques</td>
<td>·Mechanical assembly</td>
</tr>
<tr>
<td><strong>Advantages</strong></td>
<td>·Experienced</td>
<td>·Automatical calculation, record, and adjustment</td>
</tr>
<tr>
<td></td>
<td>·Real-time adjustment and compensation</td>
<td>·Accuracy control through visual sensors</td>
</tr>
<tr>
<td><strong>Disadvantages</strong></td>
<td>·Lack of scientific summary and data</td>
<td>·Lack of sufficient experience</td>
</tr>
<tr>
<td></td>
<td>·High error rate</td>
<td>·Machine availability</td>
</tr>
</tbody>
</table>

We took the challenge of making a joint effort with the engagement of bamboo craftsmen. Though there were unpredictable barriers throughout the design and construction process when both sides had no similar collaboration experience, it was reasonable to take advantage and optimize the entire workflow in the notion of nonlinear thinking (Knyazeva, 1999) to deal with the uncertain and dynamic factors. It did not mean to invite local people to help build a bamboo pavilion under our commands but to invite them to devote their previous experience to semi-automatic construction using raw bamboo.

3. PROJECT IMPLEMENTATION

3.1. Study Area

This program was in Anji County, Zhejiang Province, China (Figure 2). Anji has a manual tradition of bamboo production and tectonic, which supports the backbone industry and primary source of social finance income. Due to limited plasticity, raw bamboo is seldom favored in the local construction market compared with industrialized materials. We were entrusted with supervising the whole design and construction program on a small hill full of bamboo and tea trees, where a pavilion was planned to provide visitors with an outdoor space for entertaining activities like tea breaks.
3.2. Parametric Design

The design was intended to create a flowing curve shape in response to the natural and free-form surroundings (Figure 3). The vertical facade was open without envelopes to show an affinity with nature. Besides, the space for activity was sheltered by a gently slanted crescent-shaped roof, complying with the site's sloping terrain. In addition, we tested the structural unit of bending bamboo to explore the flexural capacity of raw bamboo with its loading action. As a result, almost each component form was various in radian and length, increasing difficulties for later fabrication.

Initially, unmanned aerial vehicles collected geographic information beforehand with image data converted into virtual landforms. The primary design ideas were virtually expressed in a digital model through architectural software Rhinoceros, and physical force was roughly simulated in the Grasshopper plug-in. Through a digital model, the geometric pattern of every bamboo component was supposed to be calculated and diagrammed precisely in an ideal case. However, the raw bamboo material behavior could not be simulated and evaluated accurately either in the existing software applications or tested as a scale-down physical prototype in real time. Such a dilemma was explained in several aspects (Crolla and Goepel, 2020): 1) the flexural capacity depended on a series of raw bamboo properties of specie, age, height, diameter, and internode length et al., while both single effect and composite quality of those bamboo properties on the flexural capacity had not experimented sufficiently beforehand in the laboratory; 2) bamboo behaviors were further influenced by the bending machining of processing equipment, environment (air temperature, humidity) and techniques (drying temperature, applied bending-force et al.), whose potential performance under bending moment were sometimes uncontrollable; 3) there were realistic limitation of the construction period and budget so that a cost-efficient approach was preferred. Thus, increasing uncertainty might have stopped the project midway if decision-makers had kept thinking about strictly automatic machine-aided construction. Finally, we decided to give up the attempt of complex bamboo material testing work in the laboratory and then searched for help from the local bamboo craftsmen on site.
In the design generation stage, several alternatives were generated by controlling spatial parameters (Grobman, 2010), which realized continuous and delicate adjustment according to the functional, aesthetic, and visual criteria. The craftsmen's role in the design process was their evaluation after completing the primary generative design stage. They screened the embryonic form of every bamboo component on the drawing for potential material suggestions on structural stability. Their verbal instructions were indirectly coded as empirical parameters to assist design evaluation and virtual simulation. The critical point was to control bending bamboo components' curvature to ensure their material behaviors. In case a bamboo rod was bent beyond its capacity, unpredictable cracks began to appear in the weak part of the rod where the external force was concentrated (Askarinejad, Kotowski, Youssefian and Rahbar, 2016). It was suggested that once the weakness of cracks happened in the bending process, the bamboo rod should be deserted; otherwise, it would lose its resistance to bending, and the crack might grow broader and larger under loads of roof, snow, and other environmental factors. This optimization advice drove the designers to adjust the previous scheme to ensure structural stability before fabrication.

3.3. Fabrication and Assembly

As for the selection of bamboo material specification, local bamboo on the left side of Figure 4 was around 6 cm in diameter, with 8 cm on the right side. As is shown in Figure 4, the natural form of bamboo varies with internode, thickness, and diameter, which determines the high probability of machining error. Though bamboo of 8 cm in diameter has been more commonly used in the local area of Anji, we finally chose the thinner bamboo of 6 centimeters under the guidance of the craftsmen after the pre-production attempt. The reasons were considered in the following aspects: First, bamboo is commonly wide at the base and tapered at the top, so it cannot be standardized like error-free building components fabricated in the factory. The morphological character of 6 cm in diameter is relatively more consistent than the 8 cm in diameter bamboo, which has its own advantages of accuracy control. Secondly, the thinner bamboo is, the more flexibly it performs under pressure. As a result, bamboo of 6 cm was tested to not only meet the requirements of C-shaped bending but also preserve a strong bearing capacity than thicker bamboo. This experience of selecting the appropriate bamboo type was well gained by the craftsmen and applied before on-site fabrication.
Human-machine collaboration (Liang, Wang, Kamat and Menassa, 2021) improves productivity, efficiency, precision, and safety in construction factories. Thus, we decided to pre-fabricate bamboo components in the factory by thermal bending facilities and then transported them to the construction site. The factory provided a stable environment for bamboo processing, replacing conventional in-situ fabrication. We found that such a primary machine-aided processing mode had grown maturely in the local industry, but there was still a significant gap from pre-programming to adaptive manipulation. Especially in the assembly stage, manual assembly played an irreplaceable role in dealing with complex deformation problems.

In Figure 5, a number rule was created in the cross-section of the bamboo pavilion. The entire structure consisted of 8 units of different sizes, each composed of 36 bamboo rods. Except for those total of 8*36 (288) main bamboo rods, there were sub-rods functioning as the connection between the two units. The petitionary work of numbering and locating hundreds of bamboo rods was executed through computer actuation, releasing the burden of workers to visually identify a particular bamboo rod.
Since bamboo building construction is characterized by a structural frame approach similar to traditional Chinese timber frame design and construction (Sanjeev, Amit and Aninash, 2017), the structure system organized different components from pillars, main beams, secondary beams, skew beams, and purlines as a whole (Figure 6). Among them, pillars and main beams were assembled as the first level of the pavilion skeleton, then strengthened by the secondary and skew beams to bear the roof load partially. In addition, purlines linked the first and secondary level structure together, with tiny bamboo branches covered at the top. The flexural property of bamboo led to potential shifts in location during each level assembly, whose second deformation was monitored by laser scanners in real-time. Since there were quantities of bamboo rods, it was impractical to sense (Vasey, Maxwell and Pigram, 2014) the location and dynamic form of every component once it had been fixed, which might have requested more time and data calculation. Therefore, an error-tolerant but flexible solution was proposed to examine the construction precision by sensing every structure unit of 36 bamboo rods as a cluster. The errors of clusters were compensated by the later part correspondingly.

Fig. 6: Bamboo structure system.

Overall, the optimized workflow and division of hybrid labor of workers and architects were illustrated through seven steps in Figure 7. Craftsmen’s evaluation and manual assembly were preserved as the base of workflow, but multiple devices of sensing and computer algorithms were equipped to help standardize the assembly work more precisely and efficiently. Smart devices played a role in specific conditions to assist visual inspection and calculation during in-situ assembly. For example, the location information of the two ends of a bamboo rod was generated in three dimensions in the digital model so that workers could assemble the rod by merely finding two destinations. In addition, since one end of a bamboo rod was fixed on the ground as a structural foundation, potential shifts of the other end were considered the primary source of errors. Therefore, the compensation process was simplified to adjust the structure by comparing finite details with their presupposed location.

However, it was tough to conduct the entire process of balancing the virtual model with the actual construction situation, similarly to autonomy and digital twins in the manufacturing industry (Rosen, Von Wichert, Lo and Bettenhausen, 2015). The main difficulty lies in the ability of system adaption. First, bamboo behaviors during construction had to be supervised to ensure their practical capabilities and precise location. Though the computer vision system helped a lot, we still found that manual fabrication was more adaptive to bamboo’s natural and original properties. Workers were good at predicting material performance through their experience and hand feelings, while few current artificial neural networks have been trained to gain such an ability to simulate bamboo behaviors. Second, conventional construction of low technology has a relatively high tolerance to structure distortion, which acts as resilience to dynamic changes. Such a significant departure from standard was hard to process in the computer and generate instructions automatically. As a result, the construction data recorded and saved in a unique project may not be applied in the other models fittingly.
4. DISCUSSION AND CONCLUSION

This case study pointed out that advanced machine and robotic intelligence improved the engagement of both architects and locals in the design and construction process, where we could generate design alternatives and manage the entire process through the executive control system. During the project, making an optimal decision meant thinking from multiple perspectives, including material performance, precision management, and budget control under time and financial restrictions. These factors put different weight on the rural areas where real-world conditions were usually worse than expected. Therefore, construction precision was not the final goal in intelligent fabrication, while there should also leaving space for workers to reach their potential.

We appreciated the efforts multiple groups have made in such a transition in the construction process. Involving the participatory and collaborative aspects of the workflow seems like a compromise to conventional construction, which is considered time-consuming and coarse. In the digital augmented design and construction trend, traditional craftsmen still have much wisdom that should not be neglected and replaced. Imitating their tectonic behavior (Brugnaro and Hanna, 2018) and learning their thinking model of evaluation, prediction and decision-making seem challenging but reasonable for more intelligent adaptive robotic fabrication and construction. Different from industrial manufacturing, it is proven that conventional wisdom should not be ignored in intelligent construction.

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