

P. Janssen, P. Loh, A. Raonic, M. A. Schnabel (eds.), *Protocols, Flows and Glitches, Proceedings of the 22<sup>nd</sup> International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2017*, Paper 109 (Preprint). © 2017, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

## BAMBOO CONCRETE SHELLS

*An Adaptable Construction Method Using Onsite Materials in a Remote Location*

NAOKI IMANISHI<sup>1</sup>, SHINICHIRO HINOKI<sup>2</sup>,  
MIZUKI MURAOKA<sup>3</sup>, RAN TATEYAMA<sup>4</sup>, YUICHI ABE<sup>5</sup>,  
HOTTA KENSUKE<sup>6</sup> and YASUSHI IKEDA<sup>7</sup>

<sup>1,2,3,4,5,6,7</sup>Keio University, Japan

<sup>1,2,3,4,5,6,7</sup>{t13120ni|t12745sh|t13932mm|ran1005|kamex|kensuke|yasushi}@sfc.keio.ac.jp

**Abstract.** This paper proposes an on site construction support system with digital techniques, to solve the issue of logistical inconvenience on remote islands, where industrialized construction methods are absent. Transporting heavy machines are costly and difficult in the rural area isolated from cities. In addition, sourcing materials produced outside implies a heavy ecological footprint, so construction materials be better to be locally produced. The design has to consider the use of local materials as well as structural strength. As a case study, Kuchinoerabu island in Japan is chosen as the site. The shell is made by concrete reinforced by bamboo readily harvest-able in wild. Through the study, several technical issues are revealed: bamboo differs individually in material properties, unskilled labor frequently makes mistakes, the concrete placing in 3-dimensional surface is difficult to construct. The system proposes the following functions. 1) Synchronizing data between CAD and materialized part. 2) Checking errors between the target and produced part. 3) Inputting material characteristics on site. 4) To make structural analysis, and reflects its execution. These functions minimize the margin of error, and encourage unskilled labor to work accurately.

**Keywords.** Bamboo; natural material; digital construction.

### 1. Background and Social Problems

There are social issues when one attempts to construct buildings on isolated islands. The first problem is following; in remote places, especially rural area,

there are few advanced construction devices, as well as heavy machineries. Skilled labourers to operate general or specific devices for construction work are also missing. The second issue is the difficulty of transporting materials. Since the 20th century, factory made standardized/industrialized parts are used from design to construction. But on the other hand, in remote island there are few production bases, thus, the logistics becomes difficult. Shipping is expensive and would put a heavy burden on the site environment. Thirdly, an environmental adapting building is required ; Kuchinoerabu-island is set as the site, where there are extreme weather conditions such as fierce wind in typhoon seasons. The structure has to be structurally robust and utilizes local materials. In order to ensure the effectiveness of the proposed system, the building experiment was done in Kuchinoerabu-island. Located far away from Tokyo, reaching the site takes 1.5 hours on plane and twice transfers on ship. The place is known to have had extraordinary environmental conditions, including a volcanic eruption.

## 2. Bamboo Reinforced Concrete Shell by Digital Construction System

In this section, referring from existing research (Yamamoto et al. 2010), general idea of this building are explained.



*Figure 1. Bamboo reinforced concrete shell.*

### 2.1. WHY BAMBOO REINFORCED CONCRETE SHELL ?

The project of bamboo reinforced concrete shell (figure 1) explores the topic of shell structure and its construction method, while in ordinary constructions steel are used as reinforcements. This project is the answer for three social issues raised above. Solution 1) Effortless construction. This surfacing by steel trowel method is much more effortless than form construction method, because it is able to reduce time to make form by sandwiching wooden panels. The

required technique of this concrete placing method is relatively difficult for unskilled labors but can be reduced by using the proposed system. Solution 2) Low environmental impact. For the purpose of alleviating the environmental burden, the proposal attempts not to bring in external materials. So the wild bamboos that grow luxuriantly there are chosen for reinforcement for concrete. Fecundity of bamboo is very high, so that a wild bamboo forest can expand quickly. Appropriate consumption rate of the bamboo can bring positive effect for vegetation in there. Solution 3) High structural performance to respond to windy weather on the island, weight and strength of the material are required. The proposal employs concrete as the structure, instead of using only weaving bamboo straps. In addition, the unique character of bamboo straps of bending toughness in normal direction of annual ring because of fiber direction, has inspired the design to become a curved surface rather than a box-like form. In order to answer these requirement, a hypothetical design proposal is suggested and tested on that island (Inoue et al. 2009).

## 2.2. PROBLEMS WHEN CONSTRUCTING THE SHELL

When executing three solutions revealed that ‘errors’ would be the serious issue. The problem of solution 1; the human hand work may cause various errors, when bamboo felling and timber-rizing it, when worker making foundations, when a worker weaving it by handcrafting errors, when plastering with hand trowel. The problem of solution 2; because of using local material, it can not be guarantee uniform materials. So each bamboo strip slightly differ from others, that induct errors inevitably. The problem of solution 3; there are no parts division based on architectural idea, such as wall, ceiling in shell structure. So that this smooth surface does not have singular point, it may able to says structurally better. However, to materialize three dimensional surface into reality without guidance is hard for human. Thus, deviation between desired shell and realized shell would occur. As above, three solutions surely makes ‘errors’. In order to solve this problems, the design and build system is proposed here. That system has divided into two parts supplementally ; first is pre-construction method to make a CAD model which has allowance range, second is during-construction method checking data with digital devices.

## 2.3. HOW TO SUPPORT WITH DIGITAL CONSTRUCTION SYSTEM

The concrete system is explained below. The aim of this system is to design a construction system that guarantees a building’s construction quality even the subject (worker/machine, or those hybrid system) creates a discrepancy between the finished outcome and the original design, but that gap still lays within the possible allowance. The construction is considered “complete” when the worker corrects this misalignment created by unexpected site circumstances and decisions through adjustment informed by the system, whereas in conventional constructions, completion is defined as almost perfect material realization of building as designed in drawings, which often led to inferior quality as a result of this unrealistic management methodology (figure 2). As a method-

ology of this, 1) pre-adaptability and 2) post-adaptability, and 3) those hybrid adaptability are assumed. The first method is referring to the design process that is before conduct materialize (construction). The idea that the objective data (geometry) originally contains the approvable range. The second method is mainly work on construction steps. That is have been taking difference during construction steps, then operate somehow to recover towards original object (can be geometry) next part, following way; one may have to break and rebuild the previous part, or other is modify next part for recovering to original with admitting existing part. Thirdly, those hybrid method that are take difference then make new target(can be a geometry, can be an objective function) based on those conditions. In this method, materialized part is going to give up, then re-calculate in next step, which allows multiple possibility.

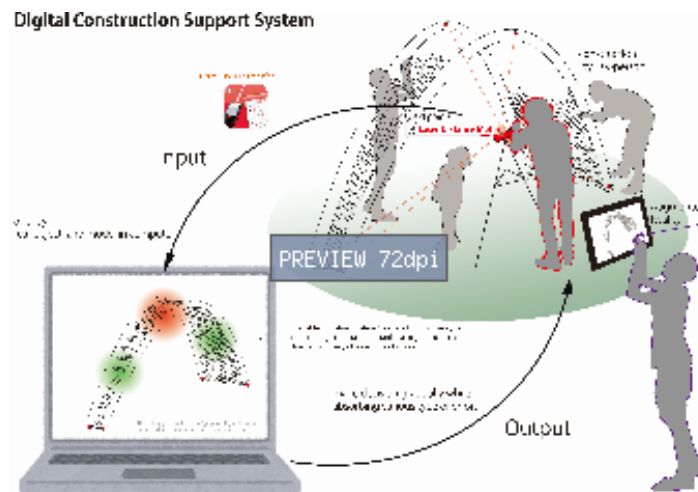


Figure 2. Digital construction support system.

### 3. Digital Construction Technology

In this section, concrete methods for digital design and construction are introduced. These includes how to make building construction with using data, but also relates to digital design too.

#### 3.1. PARAMETRIC MODELING

The margins for construction of the bamboo-reinforced concrete shell are considered and parametric parts are determined. This parametric model offers pre-adaptability for the precision of the construction process. The actual parameters (figure 3) are: 1;Diameter of the base circle 2;Location and diameter of the inner circle 3;Range of an inflation of the base torus geometry 4;The used portion of the base torus (angle) 5.Locations and shapes of the holes.

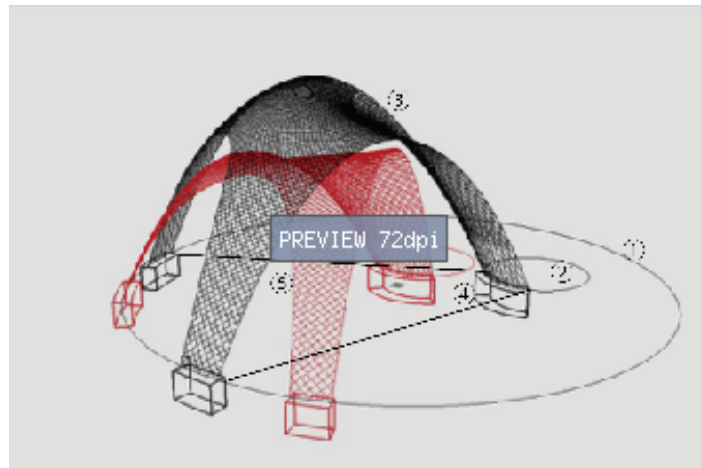


Figure 3. Parametric 3d model

The surface of shell is surrounded by curved edges, which is called edge arches here. Each edge arch is made from two bamboo timber, start from the ground. The construction process starts from installing these edge arches. The length between point A and point B (figure 4) is calculated automatically. Thus the required material length can be seen immediately, then able to search from bunch of different material mountain.

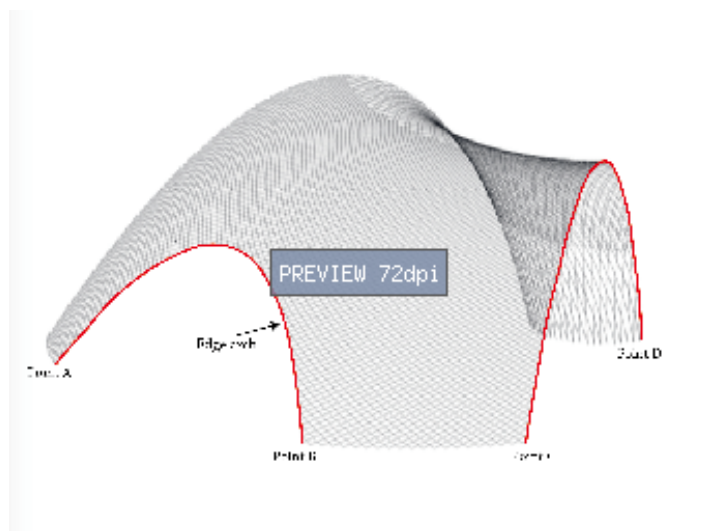


Figure 4. Automated calculations for the length of the edge arches.

On the torus structure, appropriate distribution of the bamboo (figure 5) is radial as in the (a). In order to verify this, (b) was made with the split bam-

boo whose width is same for the actual construction. From this experiment, it turned out that the concentrically twisted geometry is not suitable for bamboo. However, the radial geometry was successfully constructed. In the case of (c) bamboo breaks when the angle between the bamboo and the shell is too big, whereas in the case of (d) the bamboo's elasticity is utilized as the bamboo is more in parallel direction with the shell (Yamamoto et al. 2010). However, in order to create a stable shell, the bamboos have to be crossed. When creating a concentric geometry, the bamboo became perpendicular the surface of the shell on the upper part. Hence, this distribution of the bamboo is problematic. The curvature of geometry was calculated (e) on the 3d model and determined 60 degrees that is one of optimal angle(f) (Brink et al. 1996).

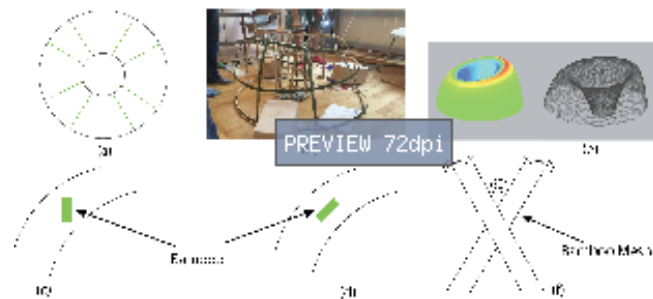


Figure 5. Design of donut-shaped bamboo geometry.

### 3.2. LASER RANGE FINDER

In order to check the errors, a laser rangefinder is deployed to conduct measurement accurately throughout construction and feedback is given to the parametric model. The measured data is stored in an Excel file which would be loaded to the 3d modeling software. As the geometry is a curved surface, a laser rangefinder is chosen among other options for measuring the shape. If the geometry is a cube, for example, the more points have to be measured. Plus, some points are unmeasurable from a certain spot. On the other hand, a curved surface requires fewer points to be measured. Besides, in this concrete shell, no points is hidden by itself. Thus, using laser rangefinder is reasonable.

### 3.3. AUGMENTED REALITY

AR technology is used for guiding the mesh geometry when the bamboos are woven. Unity and Vuforia are used. AR marker is made with Vuforia. In Unity, the marker and 3d models are related and checked through Android tablet during the construction process. AR played a role as a balancer of the mesh direction. Even if the actual shape deviates from the originally designed model, it can guide the direction of the mesh.

#### 4. Experiments

In this section, two experiments are shown below. One is done without proposed system, other is done with proposed system.

##### 4.1. EXPERIMENT1

The construction period is 6 days. The total number of construction workers is 4 people. The location is within the premises of Keio university, Kanagawa, Japan, not on the island (figure 6). There was also a secondary purpose to determine the construction procedure of the concrete shell to be built for Experiment 2. First, the position of foundations of building was determined with a laser rangefinder fitting to the digital 3D model. After that, the building was built not using digital technology but just by hand manually. The bamboo weaving phase was completed as scheduled. However, there was a problem with the number of supports and the height of edge arch. The number of supports was not considered in the construction process of Experiment 1. Moreover, a serious problem arose as an error on the edge of the arch was found. The edge arch was about 10cm lower than the 3D model. As the shell became lower by 10 cm, it seems that the shell approached a planer shape from the curved shape, and the weight of the concrete was directly applied in the vertical direction and buckled (figure 7). (Terai et al. 2010)



Figure 6. Construction process & Buckling

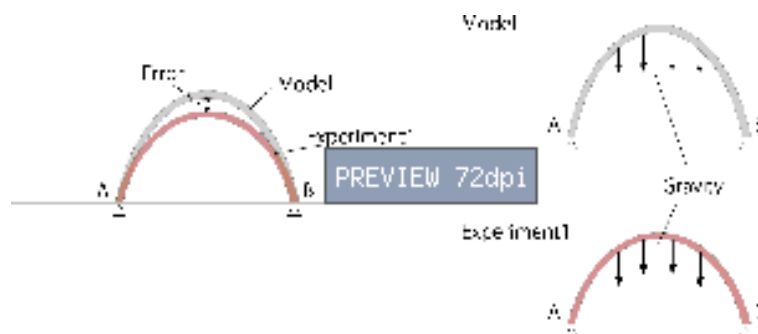


Figure 7. Error of edge arch

## 4.2. EXPERIMENT2

In experiment 2, a post-adaptability system was adopted in addition to the pre-adaptability 3D model of Experiment 1. The system has the ability to check up building information during construction. The Construction period was from 8/4 to 8/14, for a total of 12 days, the location was Kuchinoerabu island. The construction process was divided into two terms. The number of construction workers was three for the first term, four for the second term and eight for casting concrete. The size of the bamboo reinforced concrete shell was designed to be twice as large as Experiment 1.

### 4.2.1. First Term

AR shows the position of each part in the target premise. The number of bamboo calculated in 3d model analysis was 113, with diameters from 4.0 to 5.0 cm. Each bamboo was cut into four in order to make use of the characteristics of bamboo. It also approached the streak width (2.0 - 3.0 cm) of the geometry of the shell set on the 3D model. The position of the foundation was done by using a laser rangefinder. Bamboos were sorted out matching with the edge arch. Round bamboos were adopted in Experiment 1, sometimes there was no well-matched bamboo. On the 3D model the bamboo's thickness of the edge was set to 5 ~ 6 cm. Therefore, in Experiment 2, The divided bamboos were overlapped to make their thickness closer to the 3D model edge arch. Concrete of the foundation part was cast. The degree of Z axis direction (height direction) deviation of the constructed edge arch from that on the digital model was measured with a laser rangefinder (figure 8). As a result, the edge actually constructed was about 5 cm lower. It was  $\frac{1}{2}$  degree of the error at Experiment 1, and the error can be amended by increasing the number of supports to support the shell at construction, we considered it within the allowable range.



Figure 8. First term construction process.



#### 4.2.2. Second Term

When building bamboo strings, AR was used as mesh guidance. The position of the edge support was measured with a laser range finder. Wire mesh fastened concrete to prevent concrete falling when casting concrete. Wire mesh was kept open with a gap of about 2 cm. Supports building was divided into two stages so as not to interfere with the work of assembling bamboo and the work of fastening the wire mesh. The support of the first step (until finishing and attaching the wire mesh to the bamboo shell) would be simple. Increase support in the second step (when bamboo shell concrete is cast). Cast concrete and dry it. The composition of concrete was 1 portion of cement, 2 portions of sand, and 0.3 portion of water. In addition, the amount of concrete was calculated based on the 3D model analysis and optimized to reduced weight on the shell. The thickness of shell on the digital model was 50mm, the actual constructed one varies from 50mm 70mm in different areas. Its curvature shape error was reduced. It passed the load vector test. One month after casting concrete, the load vector test 150 kg weight on the top of shell have tested again the intensity of shell structure was checked (figure 9). Now the structure is exposed as permanence experiment.



Figure 9. Second term construction process.

## 5. Conclusion and Prospect

In conclusion, towards the idea of 'Digital Construction', one of the useful benefits of digital technology in onsite construction is increased adaptability. Under this hypothesis, the result of Experiment 1 clearly demonstrates failure in the collapse caused by 'buckling'. Here, the proposed system was not used, so the assumed reasons of failure can be seen as the hypothesis of this system. That is the many site circumstances were not reflected in the design. On the other hand, in Experiment 2, the information (here the materialized geometry) is continuously taken from the site and updated to the digital model by using the proposed system. Manual, low-skill requiring shell structure construction is made possible by the system. (structural strength to be examined). While, as byproduct of this method, the allowance would be other key of parametric modeling when designer/constructor work together using this system. In another word, the allowance implies a number of possibilities within a tolerable range. Precisely speaking, if the margin of error is properly set, the model (ge-

ometry in this case) can move. The implication of this project is that there are two sets of keywords for digital construction in remote locations (figure 10). One is about parts quality, unique parts instead of standardized-product aspect in. The other is about the use of a guiding system, from primitive usage like answering predetermined quests such as Jigsaw Puzzle, to much more advanced usage like reacting to ad-hoc conditional change, car navigation system is an example.



Figure 10. The adaptability of digital technology increases the possibility of digital construction

Currently, the research is being conducted to attempt making those shell structure suitable for human habitation. Hence, the required architectural performance (structural strength for practice, environmental performance etc.), and architectural functions (toilet, kitchen, bedroom, living room etc) has to be pre-determined as objectives. Especially in architectural scale, the mean to divide inner space and outdoor space is yet to be studied, the notion of a semi-outdoor space is also attractive, as called Engawa in traditional Japanese intermediate space. On the other hand, on an urban scale, this proposal may have novel potential. That is how multiple shells can make grouping on site and it must be reviewed from the social aspect perspective, because this project is ongoing at the volcanic island.

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