

## CAADRIA2018

### Adaptable Design-Construction Method for Remote-Location

Experiment with Reverse-Engineering System to expand the possibilities of natural materials with Bamboo concrete shell as a case study

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### Abstract

In this paper, the aim is to develop a construction system that utilizes digital technology which measures the completed shape and checks its degree of safety. This is because in the case of conventional construction, it is assumed that drawing and structure are consistent by using advanced construction techniques. However, it cannot always be assumed that there are correct composition parts and advanced construction techniques in all geographical areas. Under such conditions, and through the use of digital technology, it can be easier to integrate the errors that occurred while the structure is being built as part of the construction process rather than to try to make the structure consistent with the original design.

### 1.Introduction

In this paper, the place where the infrastructure is not sufficient is defined as the 'Remote-Location'. In the case of on-site construction, there is usually a difficulty concerning delivery access and transportation. For example, overall costs do typically increase due to the high costs of transporting workers, materials and construction heavy machinery. On the other hand, the transport and dissemination of digital technology is easy. As such, when establishing this system, it is expected that construction capabilities will increase. In addition to this, in conventional construction work, the design is decided in advance, and it is difficult to change it during the course of construction. However, when this construction system is used, it becomes possible to perform construction by allowing errors that occur during construction to be part of the building up process. By using digital technologies, we expect to develop construction techniques that are easy and affordable, and additionally, certain accuracy is guaranteed in the outcome. Thus, this can enable the possibility of building various architectural forms even in remote areas that are characterized with the aforementioned constraints. In order to pursue these possibilities, research has been carried on following the paper of CAADRIA2017 (Naoki et al 2017).

### 2.Achievement of previous 'Bamboo Concrete Shells' (Naoki et al 2017)

The following points can be cited as the result of CAADRIA2017's paper. As a result the discovery of a form that is easy to elevate with the use of bamboo. Bamboo is easier to make than curved lines than straight lines. The realization of a geometric model adapted to the characteristics of bamboo. The geodesic direction is good. The shape of the structure can be finalized considering sunlight and surrounding environment on site. Because the created model was a parametric model. Although significance of the construction system could prove, it stayed at the stage of measuring the shape, and a feedback system between construction site and 3D model was not established between the "measuring" and the "checking with the model" parts. In conclusion, regarding the concept of 'Digital

Construction', one of the useful benefits of digital technology when used for onsite construction is increased adaptability. In another word, the adaptability of digital technology increases the possibility of digital construction. In response to the conclusion of last year, the research to make this feedback system more practical was conducted.

### 3. Practical thinking in construction system of 'Bamboo Concrete shells'

#### 3-1. Concept of construction methodology

One concept was drawn from the efforts of last year. That is 'Reverse-Engineering System'. This system is not conventional Reverse-Engineering. First, a 3D model, adaptable 3D model, that can integrate the construction situation is prepared. Next, the real shape to be built is measured with a laser range finder. The measured data is feed backed to the adaptable 3D model, and the current shape of the structure is generated. This flow of construction is defined as the 'Reverse-Engineering System'. By using the Reverse-Engineering system, natural materials will be easier to use. Even natural materials that have been avoided due to individual differences can ensure a certain resistance by checking the shape that was built. The next chapter is the content of the development of the Reverse-Engineering System.

#### 3-2. Technics and measurement of the shell form.

The following diagram(figure.1) is basic concept of Reverse-Engineering System.

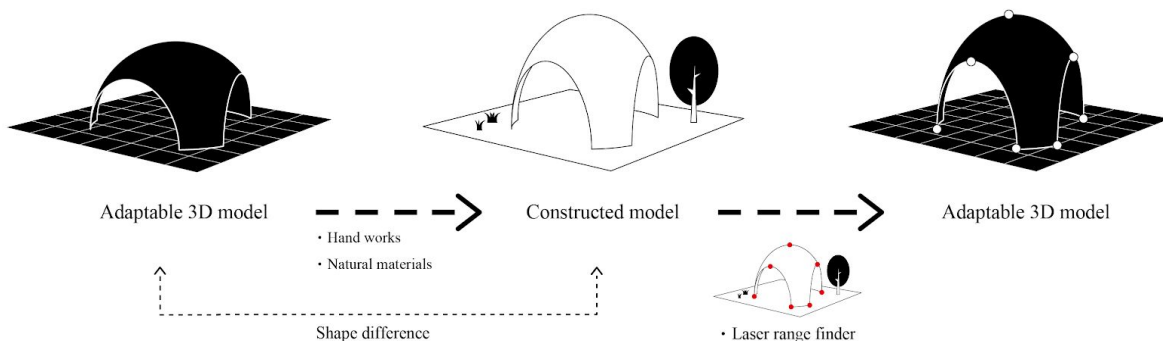


figure1:Reverse-Engineering system diagram

This system uses the laser range finder and Excel to measure the target point coordinate data. Next, using rhinoceros and grasshopper, the measurement data is recreated on the adaptable 3D model and analyzed. The point coordinate data measured by the laser range finder can be connected by interpolating the curve. In this way, the bamboo shape is recreated on the adaptable 3D model. That is, if there are many points to be measured, it will be accurate as the reproduction of the shape.

However, if the number of measurement points is excessive, it will make construction rather difficult. It is necessary to clarify the following two points.

- 1) In order to grasp the general shape of the shell, what part of the bamboo should be measured?
- 2) How many points must be measured for the bamboo shape selected in 1) to be reproduced on the 3D model? Regarding 1), this geometry is a structure, ridge arch, that forms a shell which is radially divided

from the shell top. Next, the shape is roughly determined by the arch, edge arch, which becomes the opening of the shell. Furthermore, a rhombus grid is constructed so as to draw the geodesic direction between the arches (figure 2). In addition, the edge arch has a rib arch to increase the overall strength and prevent rainwater from flowing into the shell. In other words, the ridge arch and the edge arch create the general shape of the shell (figure 2).

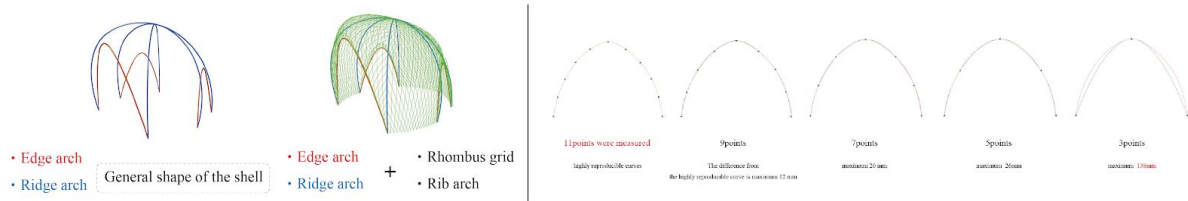


Figure 2: Bamboo Concrete Shell geometry, Ridge arch, Edge arch and Measurement study result of bamboo arch

(2), it was verified whether the reproducibility would be high by measuring at least the number of points. The arch was divided into 3 points, 5 points, 7 points, 9 points, 11 points. Then the measurement of the bamboo arch was performed in each different case (figure 2).

When connecting 11 points, highly reproducible curves are reproduced. The curve was compared with 9, 7, 5, 3 points respectively reproduced curves. A difference of maximum 12mm at 9 points, a difference of maximum 20 mm at 7 points, a difference of 26mm at maximum at 5 points, a difference of 138 mm at maximum at 3 points. From this result, it was found that the difference is increased by 3 points. Since it was found that there was no difference to 9 or 7 or 5 points, it was decided as the number of points to measure 5 points that are not troublesome. (Figure 3). However, this result is considered to change the length of each arch depending on the size of the structure.

### 3-3. Link adaptable 3D model and construction process.

The construction process consists of the positioning of the foundation, the edge arch, the installation of the ridge arch, the creation of a rhombus grid, the setting of a rib arch and the concrete casting. The adaptable 3D model created by grasshopper is also created by the same on-site construction process. Therefore, making measurement and confirmation easier. By linking it with construction, the adaptable 3D model incorporating the construction information shows the shape that can be finally formed. Therefore, measurement with a laser range finder is also performed for each construction step. By making the adaptable 3D model like it was shown above, implementing the Reverse-Engineering System will be easy. Next, advantages and disadvantages of the 'geometry that facilitates Reverse-Engineering' which can be confirmed are listed at this stage (Seturo et al 2009).

Advantages: 1) Makes it easier to feed back the laser measurements and the information obtained thereby onto the adaptable 3D model. 2) The construction process is easy and accessible. 3) The method of filling with the rhombus grid between the ridge arch reduces the risk of encountering problems because the bamboo is arranged in the geodesic direction.

Disadvantage: Comparatively, it was easier to change last year's 3D model's shape (Naoki et al 2017) according to the on-site conditions. However, this year's adaptable 3D model has no relation between

edge arch and ridge arch, not on the same curved surface. Therefore, parameters such as the size of the edge arch and the ridge arch and the inclination position must be arbitrarily adjusted.

#### 4.Verification experiment in 2017



Figure3:Bamboo Concrete Shell 2017 and Construction process

Last year, it was a construction method that could cope with the site's environment, but this year an experiment was conducted to decide what kind of construction process is best for dealing with natural materials used for construction. In August 2017 the construction of a dome-shaped bamboo concrete shell with a height of 2 meter was performed (Figure 3). The site was the same as last year, at Kuchierabu-Island, which is located in the south of Japan.

The construction period was about 2 weeks, the work was done with a minimum of 2 people, and a maximum of 10 people cooperating at once. For the outline of the shell, the required number of round bamboo is 125, preliminary is 20, and cast concrete is 0.9m<sup>3</sup> (Figure 3).

This experiment was aimed at comparing the two methods.

- How to bring the constructed model closer to the 3D model ? (Conventional way in general public) (Bui Trong et al 2010)
- How to bring the 3D model closer to constructed model ?(This concept is Reverse-Engineering System)

##### 4-1.How to bring constructed model closer to 3Dmodel ?

The length of the bamboo for arch and the position of the installation point, the start point and the end point of the bamboo, on the ground are fixed, and the curvature of the bamboo is controlled by the support. Position the support and cut the supporting bamboo to a predetermined length. Fix the arch bamboo at the top of the supports bamboo. In this way, bending of the bamboo is realized as shown in the design.

##### 4-2.How to bring the 3D model closer to constructed model ?

The length of the bamboo for arch, the installation point on the ground, the start point to the end point of the bamboo, shall be fixed. The shape of the arch is left to the natural curvature of the bamboo. The measure with a laser range finder is done at the same time as the construction process. In order to improve the accuracy, it is done multiple times, not only once. Details are described in the following flowchart (Figure 4).

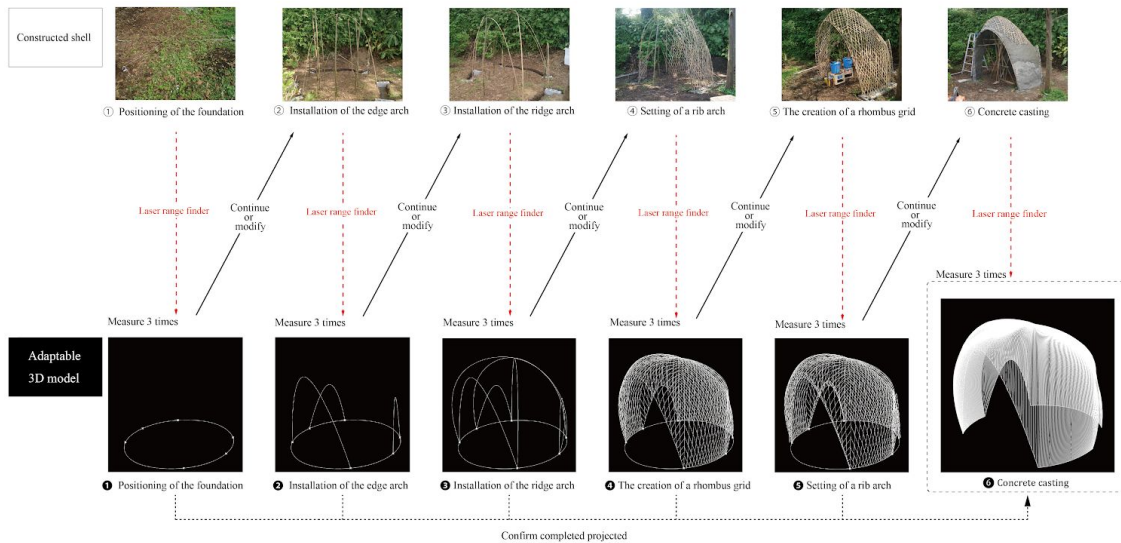


Figure 4: Measurement flowchart

In the above order, it is possible to grasp the shape of what was constructed. And the size and position of the bamboo to be used in the next process are predicted.

## 5. Experiment result / Assessment

### 5-1. Result and Assessment of 4-1

In the method of bringing the constructed model closer to the 3D model, bamboo breakage and twisting has occurred. When construction is done ignoring those characteristics of bamboo, the curve required on the 3D model is not reproduced. Because the curvature which can not be reproduced with bamboo and the direction the bamboo wants to bend naturally influence (figure 5).



Figure 5: Forced the bamboo closer to the model.

In order to reproduce the curve more than now, it is necessary to select each bamboo. Increase the curvature indication by support or indicate the curvature in another way. The indication of bamboo



curvature by the support carried out in this experiment had a lot of time loss, which is a laborious work. In the method of bringing the model closer to constructed model, this process can be omitted and the flow of construction is made smooth.

## 5-2. Result and Assessment of 4-2

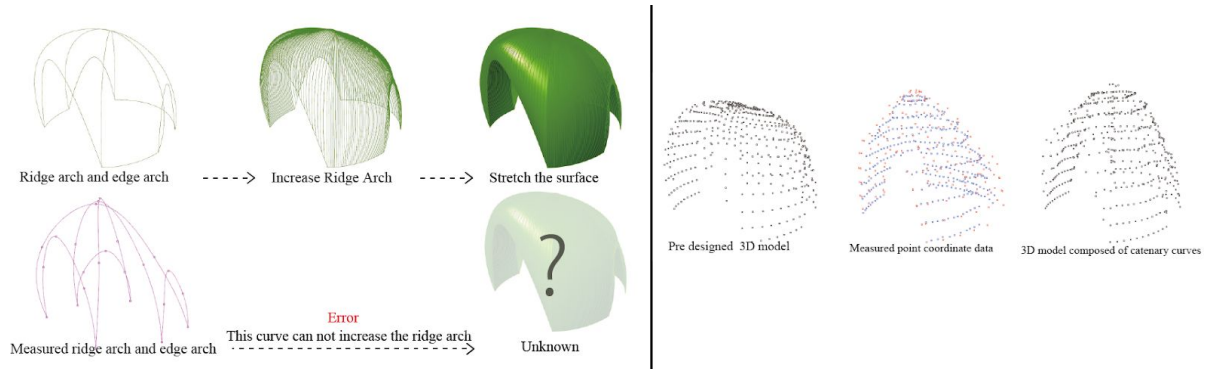


Figure 6: Surface creation process and Comparison of three models

In the method of bringing the 3D model closer to the constructed model, measurement could be done smoothly because the measurement point was fixed. Since it was linked with construction, the timing of measurement was easy to understand. On the other hand, there are two problems to be considered. The first problem is that it is not possible to create a rhombus grid between each arch. In detail, from the information of the measured ridge arch and edge arch, it is not possible to predict the completed rhombus grid in the process of creating the next mesh. The configuration of the geometry linked with the construction process has led to easier measurement. However, there is also a problem in feeding back the measurement results to the 3D model. From the information of the ridge arch and the edge arch, there is a problem with the method of reproducing the curved surface between the arches. At the time of this experiment, the ridge arch division line was increased, and the surface was created (Figure 6).

However, connecting the point coordinate data of the measured ridge arch resulted in a twisted curve. When practicing how to paste the surface as described above, such curve data caused an error on the 3D model. When connecting the measured point coordinate data, the following two points are considered as causes of the twisted curve. 1) It is a material with a structure that bamboo itself twists. 2) Manual error in measuring bamboo will occur. Therefore, the 3D model that can tolerate such twist and error is necessary.

Next problem is that the difference between pre-designed shape and result is so huge. By giving priority to the bending of natural bamboo, measurements were made on how much error it has with the 3D model. Experiment: How much is the difference between the 3D model and the actual structure? Result: The shell after the concrete casting was measured by 502 points with the back side and the front side by laser range finder. Using that data, a highly reproducible "measurement result model" was created (Figure 6). It was thought that a deviation of 350mm occurred before casting the concrete and then deviated further by 49mm due to creep reduction, resulting in a total deviation of 399 mm.

Even with the concept of Reverse-Engineering, it is a problem that there is a 'huge' difference in prediction and result. As for the reason, it seems that it is because there is no information such as the

direction in which bamboo naturally bends when creating a curve in pre-designed 3D model. A curve is an arbitrary curve connecting points with each other by an interpolate curve. Because of catenary curve similar to actual bamboo curve. If this curve was supposed to be a catenary curve, the overall shape approached the actual bamboo curve (Figure 9). In other words, by clarifying the tendency of the bending direction of bamboo and by providing this information in the pre-designed 3D model, it becomes possible to make the prediction closer to the result. Furthermore, even when predicting the shape to be created in the next construction process, by providing the bamboo characteristics in the pre-designed 3D model, it becomes a shape close to the actual structure.

## 6. Conclusion

In conclusion, there are still two problems to be dealt with. 1) Information of bamboo characteristics are essential to the adaptable 3D model. 2) The model that can tolerate with bamboo twist and error is necessary. However, in a construction that uses natural materials with physical properties that cannot be changed, a Reverse-Engineering System that allows what is already made is less labor-intensive when compared to conventional construction methods, thus leading to facilitation in the process of construction.

## 7. Consideration

In order to bring constructed model to the adaptable 3D model, it is necessary to grasp the characteristics of natural materials and to add information of it to the adaptable 3D model. However, it must grasp the characteristics of bamboo which bamboo not only draws naturally, but also difficult to measure with a laser range finder. One of them is 'tensile strength'. Bamboo concrete shell such as reinforced concrete, expects bamboo to have tensile strength. Therefore, it is necessary to test, digitize, and evaluate how much tensile strength can be expected for bamboo, Ryukyu bamboo, to use (Francis et al 1966, Masakazu et al 2010).

Therefore, bamboo strength test is being conducted. Divide four pieces of bamboos, pull it from both ends, and prepare a device to check the broken load. Currently, the test is continued and the results are collected. From the results, it is beginning to turn out that the strength of bamboo is very fluctuating. In other words, through an experiment that brings the 3D model closer to the constructed model, the result that was obtained is that 'the shape to be built can be grasped for the first time at the site'--1). At the same time, because there are individual differences in bamboo, it is necessary to assume that 'it is possible to grasp physical properties for the first time at the stage of collecting bamboo'--2).

## 8. Prospect

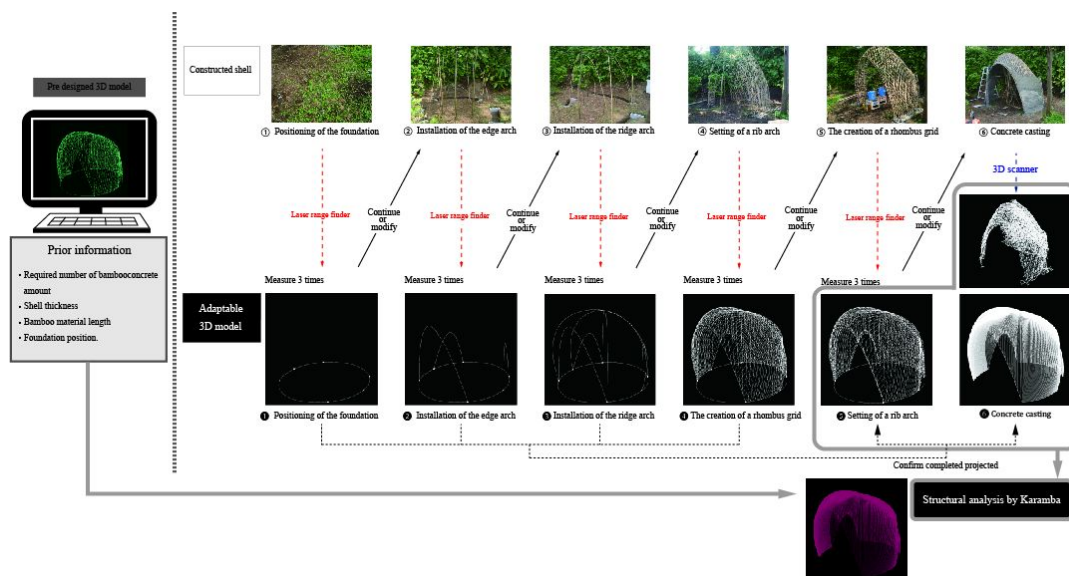


Figure 7: New Measurement flowchart

By considering both 1) and 2) that were described above, it is possible to calculate the structure in real time. The result of the structural calculation can be expected not only to grasp the current structure but also to assist in the correction of the structure. The creation of 'Bamboo Building Information Modeling' - making it possible to handle information on physical properties and the shape of bamboo as a model is also a goal in the future. Therefore, a new reverse engineering system is proposed.(Figure 7)

### 1. Increase accuracy of Predesigned 3D model

It is necessary to increase the accuracy of the prediction of the predesigned 3D model (5-2. Result and Assessment of 4-2). However, it is difficult to predict a complete form. There are two kinds of information (1) that must be grasped from the design stage and information (2) that can not be grasped in advance.

(1) The required number of bamboo, the amount of concrete, the shell thickness, the bamboo material length, the foundation position.

(2) Errors caused by the variation of the original bamboo during construction.

Although it is desirable to create a model that can predict accurately, variations due to natural properties of the materials (variations in the bending of bamboo) will certainly come out. By making simple measurements of the error at each construction stage and grasping the construction situation, it is possible to proceed with safe and accurate construction while correcting the trajectory iteratively. Therefore, in order to improve the accuracy of the prediction, it is thought that it is necessary to understand the degree of variation of bamboo and narrow the range of prediction on the Pre designed 3D model in order to improve the accuracy. Actually dividing the cases into different lengths of 1 m, 2 m, 3 m, changing the widths of both ends to create curves, and collecting data of variations using a laser rangefinder (Figure 8).



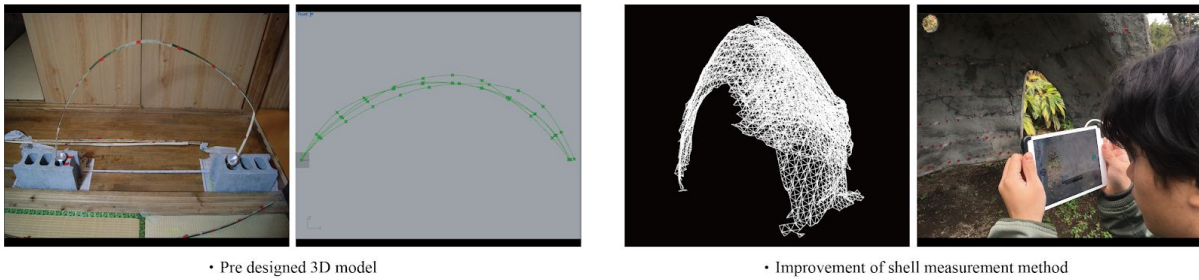


Figure 8: Bamboo bending test and 3D scan test

## 2.Improvement of shell measurement method

It is also necessary to improve the shell measurement method. Although the shape after concrete casting was measured by the laser rangefinder, the number of measurement points was 502, which was very troublesome. Therefore, a measuring method using a laser rangefinder and 3D scanning (iSense, Canvas, Roomcapture) was proposed. The 3D scan makes it possible to measure the shape of the actually constructed shell, which is necessary for structural analysis, faster and easier than the laser rangefinder.

However, 3D scanning also has problems. The Shell was measured using three kinds of scan applications: iSense, Canvas, Roomcapture. The rough shape and the thickness of the shell were much easier to measure than the laser rangefinder, but since the 3D model is formed by mesh data, it is difficult to grasp the detailed surface irregularities and the shape of the curve . In order to improve the measurement precision, it is primordial to research scan sensors and measurement devices for scanning methods (Figure 8).

### • Structural analysis by Karamba

In this part we will describe the structural analysis methodology for the shell (Figure 9). We measure the current physical conditions by enumerating the load conditions assumed for this shell, such as net-weight, wind load, lateral load, etc. After setting up the previously mentioned load conditions, we proceed by performing the structural analysis by using Karamba, FEM analysis, etc. for each load condition (Shigeru et al 1980, Hiroshi et al 1995). Based on the result, the weak part of the shell becomes known to us. By taking into account these informations, it is then necessary to consider whether reinforcement by a rib and a method to open a hole can be applied to the weak part of the shell in order to disperse the force.

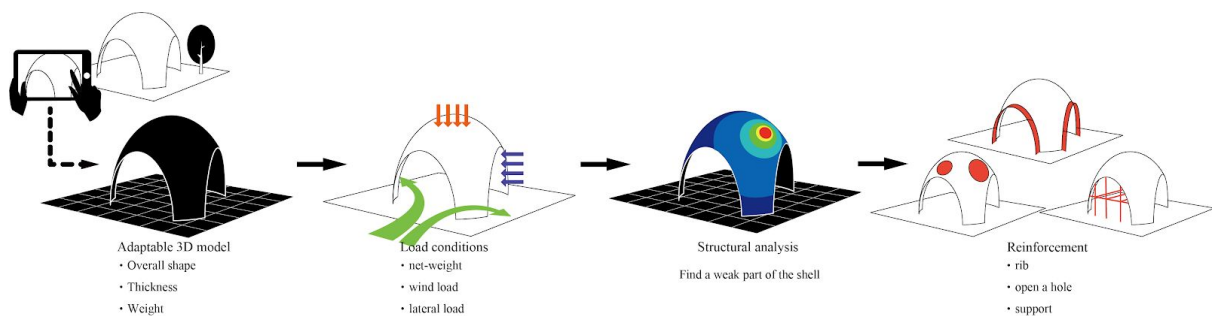


Figure 9: Structural analysis methodology for the shell

Finally, when establishing a method to grasp the current shape of the structure and grasping the physical properties of bamboo used as building material, the possibility of the idea of site-oriented construction instead of conventional design-oriented construction is expected to widen.

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## Reference

Francis, E. and Paul, J.: 1966, BAMBOO REINFORCED CONCRETE CONSTRUCTION., *California:U. S. NAVAL CIVIL ENGINEERING LABORATORY.*

Masakazu, T. and Koichi, M.: 2010, A basic research of adherability and flexibility of concrete that reinforced by bamboo, *Proceedings of the Japan Concrete Institute vol. 32, No. 2, 2010*, Page 1188.

Naoki, I.: 2017, Bamboo Concrete Shells An Adaptable Construction Method Using Onsite Materials in a Remote Location, *Proceedings of CAADRIA2017, XJTLU SUZHOU CHINA*, 445-455.

Seturo, I.: 2009, A Study on the Mechanical Properties of Bamboo, *Kobe: Otemae University Publicity.*

Bui Trong, C.A.U., Kazumasa, O.Z.A.W.A. and Masahiko, K.U.N.I.S.H.I.M.A.: 2010, A DECISION-MAHING METHOD ON DESIGN ALTERNATIVES FOR CONSTRUC- TION PROJECTS., *Journal of Construction Management, JSCE*, Volume 8 (2000) , Pages 11-23.

Shigeru.A: 1980,Present state and outlook of concrete shell structure,Jstage Concrete journal,Volume 18 (1980) Issue 11 Pages 61-65

Hiroshi.O,Youji.O, Yusuke.N:1995,SHAPE FINDING ANALYSIS OF HANGING MEMBRANE, *Journal of Structural and Construction Engineering (Transactions of AIJ)*,No.486, Pages 109-118.