INSPIRING THE NEXT GENERATION

CONFERENCE PROCEEDINGS

The 7th International Conference on Spatial Structures and the Annual Symposium of the IASS

Edited by: Alireza Behnejad, Gerard Parke and Omidali Samavati

IASS 2020/21
SURREY 7
International Conference on Spatial Structures 2020/21

UNIVERSITY OF SURREY

Table of Contents

Foreword:

The present proceedings contain a collection of 330 papers on various aspects of analysis, design and construction of spatial structures such as gridshells, barrel vaults, domes, towers, retractable systems and tension structures. These papers were written by 763 authors, representing a total of 44 countries for presentation at the seventh International Conference on Spatial Structures.

The International Conference on Spatial Structures has been organised and held on five previous occasions by the Spatial Structures Research Centre of the University of Surrey in 1966, 1975, 1984, 1993 and 2002, and in 2011 in collaboration with the International Association for Bridge and Structural Engineering (IABSE) and International Association for Shell and Spatial Structures (IASS).

The seventh conference was hosted by the University of Surrey from the UK during 23rd – 27th August 2021; it was combined with the 2020 annual symposium of the IASS. The conference was named IASS 2020/21 – Surrey 7 and its strapline was "Inspiring the next generation".

The planning and delivery of the conference had a long history: beginning in January 2016, and latterly very heavily affected by the worldwide Covid 19 pandemic emerging during late 2019/early 2020. The original planned dates were 24th – 28th August 2020, but as the impact of the pandemic became more profound, the mode of delivery evolved from fully in-person, through hybrid in-person/virtual to eventually becoming fully virtual throughout the revised dates during 23rd – 27th August 2021.

The Scientific Committee was formed in May 2018 and had a membership of a hundred and twenty one leading International Engineers and Architects, from both industry and academia; representing over thirty countries. After a worldwide call for abstracts, the Scientific Committee received 468 submissions involving 1061 authors and subsequently each abstract was reviewed at least twice by members of the Committee. Feedback on the abstracts was presented to almost all of the authors and afterwards, three hundred and thirty nine full papers were received. The full papers were, in turn, reviewed by members of the Scientific Committee, who generously gave their time to provide feedback to the corresponding authors. This proceedings include contributions submitted directly by the authors and the editors cannot accept responsibility for any inaccuracies, comments and opinions contained in the text.

The editors would like to take the opportunity to thank all authors for submitting their contributions, the Scientific Committee for reviewing the abstracts and full papers and the Organising Committee for their countless effort in making the conference a success.

Alireza Behnejad, Gerard Parke and Omidali Samavati

University of Surrey, Guildford, UK, August 2021

Acknowledgements:

The conference organisers gratefully acknowledge the support of the following sponsors:

Summary of Sessions (alphabetical order):

Contents:

21st century fabrication and construction of shells (IASS WG 5)

Active bending

Formian in the design activity of architects and engineers

Graphic statics

Proceedings of the IASS Annual Symposium 2020/21 and the 7th International Conference on Spatial Structures
Inspiring the Next Generation
23-27 August 2021, Guilford, UK
S.A. Behnejad, G.A.R. Parke and O.A. Samavati (eds.)

Design and Construction of Reciprocal Frames Made of Bamboo with Connections by Means of PVC Pipe and Rope

Koichiro ISHIKAWA*, Sovannara SRUN[a], Sokol PHON[b]

*School of Architecture and Civil Engineering, University of Fukui
Bunkyo 3-9-1, Fukui-shi, Fukui-ken, Japan
ishikawa@u-fukui.ac.jp

[a, b] Department of Safety and Social Infrastructure Engineering, University of Fukui

Abstract

The purpose of this paper is to propose a low-technology connection of reciprocal frames made of Moso bamboos and confirm the construction workability and the low costs. The geometrical shape of the reciprocal frame is generated by configuration processing of Formian. The length and the external diameter of the bamboo member are around 1.5m and 60mm, respectively. The height and the span length of the frame structure are 2.41m and 5.72m, respectively. The structure is composed of three-member assemblies of the bamboo. Estimation method of predicting a Young's modulus, bending strength and a thickness based on the external diameter is proposed to carry out the structural analysis for the evaluation of structural performance. The estimation method is based on data of the measurement and the bending experiment of the bamboo. The bamboo reciprocal frame designer can prepare the data such as a Young's modulus, bending strength and a thickness for the structural analysis and carry out the analysis. In conclusion, the reciprocal frames would provide temporary evacuation accommodations in low cost and excellent workability. Timber reciprocal Frame designers is also able to carry out the structural analysis by means of the configuration processing of Formian and the estimation method of the characteristics of the bamboo member and the connection composed of the pipe and the rope.

Keywords: bamboo spatial structures, reciprocal frame, bamboo, PVC (polyvinyl chloride) pipe, rope, low-technology, low costs, construction workability, estimation method of bamboo characteristics, configuration, formian.

1. Introduction

Bamboo plants are widely growing in many countries like Japan and tropical countries such as Cambodia, and are now attracting attention as new resources of construction material in the 21st century, as timber resources are decreasing. Bamboo grows to be usable in only 3 to 5 years, unlike wood and other biological materials. For this reason, surplus of bamboo and damage to forests due to proliferation of bamboo are becoming a problem. However, since this rapid periodic logging can be performed, its effective use is thought to contribute to the reduction of atmospheric CO_2. In addition, bamboo in the architectural field is limitedly used as a non-structural material such as a finishing material, and is rarely used as a structural material. Therefore, if bamboo materials can be actively utilized in the construction field, it is possible to reduce the manufacturing cost of buildings and as a result, lead to the possibility of making the most of the bamboo resources on the international level.

In particular, bamboo is light and can be efficiently processed by hand, so it is considered to be an effective means for residents to construct pavilions or temporary buildings in areas affected by large earthquake, tsunami and so on.

This study deals with temporary spatial structures such as reciprocal structures by using bamboos because of the above background to achieve the SDGs (Sustainable Development Goals). The realizing of the structures also contribute to resources and costs with regard to the destruction of bamboo forests and the reduction of CO_2.

2. Research Objectives and Methodology

The purpose of this paper is to propose a low-technology connection of reciprocal frames made of Moso bamboos and confirm the construction workability and the low costs. The geometrical shape of the reciprocal frame is generated by configuration processing of Formian. The length and the external diameter of the bamboo member are around 1.5m and 60mm, respectively. The height and the span length of the frame structure are 2.41m and 5.72m, respectively.

Bamboo reciprocal structures are suitable for temporary buildings. The bamboo member is subjected to bending stresses due to applied loads, while bamboos have enough resistant capacity with regard to the bending moments. It is also easy for bamboos to obtain at low cost and stabilizes this structure by means of PVC pipes and ropes. This is a reason why bamboos are used in the structures.

In this study, the possibility aimed at expanding the use of bamboo materials and the application of reciprocal structures to temporary structures would be confirmed by carrying out its bending strength experiments. The structural analysis is also carried out to investigate the load carrying capacity.

3. Strength Measurement of Bamboo due to Bending Moment

It is necessary for the proposed reciprocal structure to evaluate the structural performance and confirm the habitability in safety, even though its use is a temporary structure. This is a reason why structural analyses are required for the realization.

In this study, experiments are carried out to propose formulas for relationship between the external diameter and the internal diameter with regard to Moso bamboos. It is also shown that relationships of the bending stiffness and the maximum bending moment are obtained by using the external diameter easily. Moso bamboo culms used in experiments are harvested at the bamboo forest in Echizen town, Fukui prefecture, Japan. The validity of the empirical formulas for estimating the properties such as the internal diameter, the maximum bending moment, and the bending stiffness in term of the external diameter is also shown in comparison with the previous studies [1] and [2].

3.1. Measurement of Cross-section of Moso Bamboo Culms

3.1.1. Specimen

The test specimens are 4 Moso bamboo culms (green) of more than 3 years old, harvested on July 27, 2019.

3.1.2. Measurement method

The cross section was measured according to the following procedure.

(1) Label the central sections of each internode from the butt end to the top end, with the node near the stem base regarded as the first node.
(2) Measure all internode lengths,
(3) Saw the central sections of the internode and take a specimen piece.
(4) Measure the cross-sectional dimension at the base opening side of the specimen piece using a 1/100 mm caliper and through the method shown in figure 1 below.

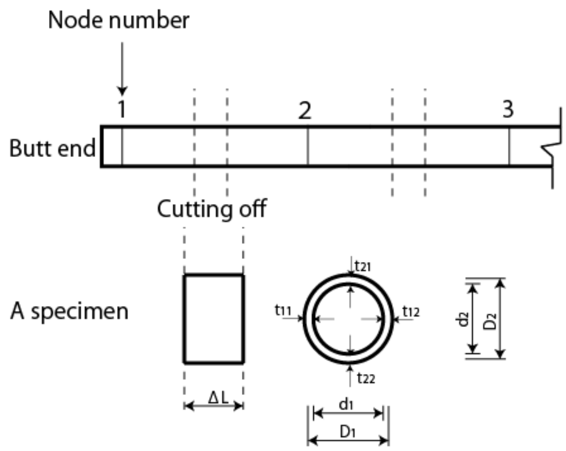


Figure 1: Experiment Specimens Preparation

3.1.3. Results and discussion

Fig. 2 combines data from this study and the previous study [1] (14 Moso bamboo culms).

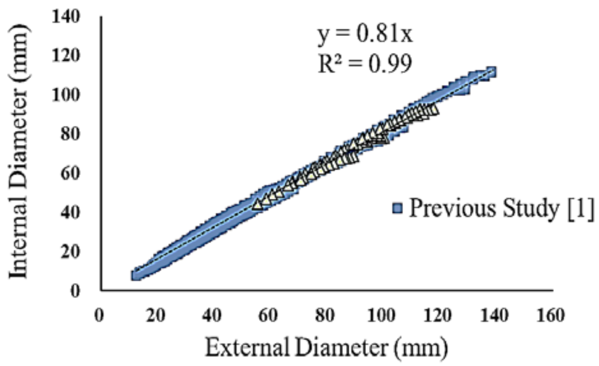


Figure 2: Relationship between internal and external diameter

The proportional relationship between the internal diameter and the external diameter is recognized in Fig.2. Therefore, the regression line is obtained by the following equation.

$$d = 0.81 \cdot D \tag{1}$$

Where d is the internal diameter and D is the external diameter.

It is confirmed from the regression linear equation that, the internal diameter d (mm) at any culm length position of Moso bamboo culm, can be estimated with high accuracy in term of the external diameter D (mm) at the position. As a result, the cross-sectional performance such as cross-sectional area, cross-sectional modulus and so on can be estimated by using the external diameter.

3.2. Experiment on Bending Strength of Moso Bamboo Culms

3.2.1. Specimens

The test specimens are 9 Moso bamboo culms (green) of more than 3 years old which were harvested on October 08, 2019.

3.2.2. Measurement method

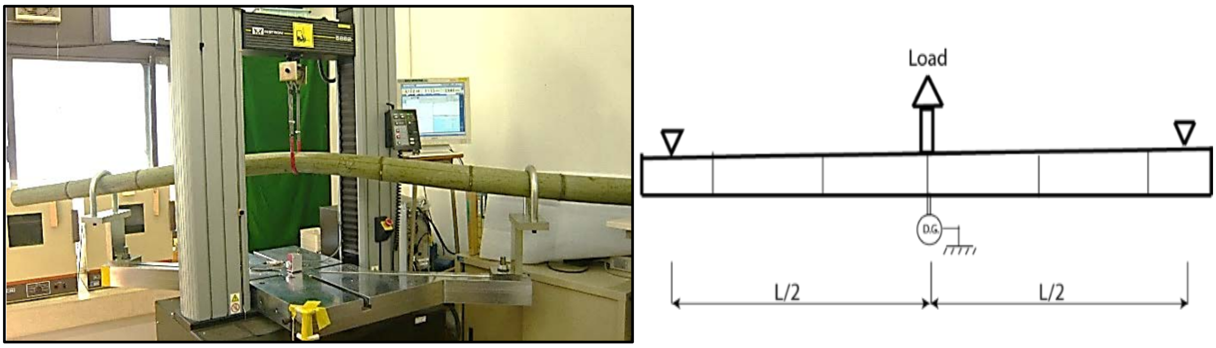


Figure 3: Three-point Bending Experiment

The bending test was performed by a three-point bending method using a centrally concentrated load (load applied to the node by a wire) at a load speed of 20 mm / min with a span of 2000 mm. The bending deflection was measured by a winding displacement meter attached to the load point.

3.2.3. Results and discussion

The internal diameter of the specimens can be estimated in term of the measurable external diameter, which is based on the empirical formula (1). The hollow circular section beam, the secondary moment of section (I) can be calculated by using a material mechanics. In addition, the bending stiffness EI (E: bending Young's modulus) and the maximum bending moment M_{max} can also be calculated by using the above mentioned values. The following figures are plotted by using the experimental data and the previous study [2] (14 Moso bamboo culms).

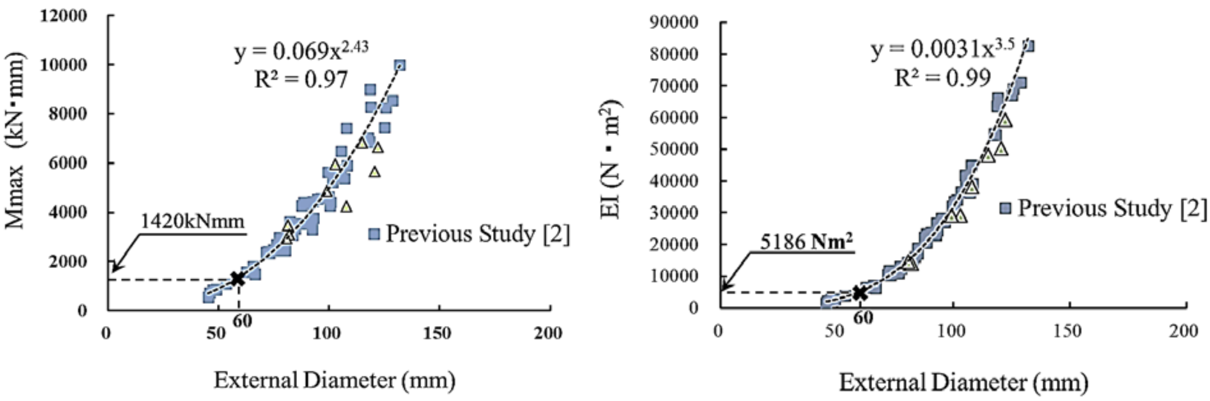


Figure 4: Relationship between M_{max} , EI and the external diameter, respectively.

A strong correlation exists between the external diameter and the maximum bending moment M_{max} and also the bending stiffness EI, as shown in the above figures. In other words, the rigidity and strength, which are a necessary input data for the structural analysis, could be estimated with relatively acceptable accuracy in term of the external diameter. This shows a real possibility of bamboo temporary structures for the design in safety against external loads such as a wind load, a snow load and so on.

4. Overview on Reciprocal Structure

The reciprocal structure is a self-supporting three-dimensional structure, having a large span and is formed by overlapping short members. Such structures may be considered to be invented by humans, but in fact small inter-organisms called cocolithophore [3] also show that interwoven or interlocking systems exist in nature. The problem with the reciprocal structure is that bending stress is generated in each member.

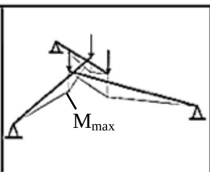
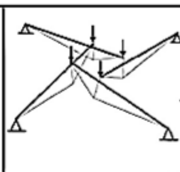
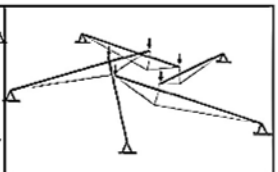
5. Outline of The Dome

In this study, the dome was constructed by using practical joints composed of PVC pipes and ropes. First, the configuration of this dome is generated for achieving this purpose. Second, it is necessary to analyze and examine the possibility of using bamboo and expanding the mutual structure to a temporary space structure.

The reciprocal structure is composed of three or more inclined members forming a unit. Large-scale such structures, constructed as a complex frame of one or several similar units, have an intrinsic beauty derived from their inherent self-similarity and symmetric patterns.

In order to determine the unit to be used for the dome, the units shown in Table 1 are structurally analyzed. Then, the following result is obtained.

Table 1: Maximum bending moment of frame unit of three or more members

L=1.5m e=6cm a=0.3 P_{total}=3kN			
Load	1kN	0.75kN	0.6kN
Mmax	38.7kNcm	43.0kNcm	41.2kNcm

It can be confirmed that the maximum bending moment M_{max} of each unit is almost the same from Table 1. Thus, a three-member unit is relatively more efficient in terms of materials used than four or more units. In this research, the dome is proposed using a unit of three members in consideration of cost and workability.

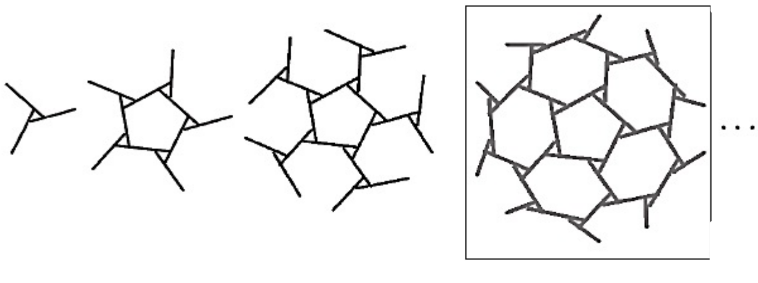


Figure 5: Structures, composed of members with the increase in units 3, 10, 20, 35 …

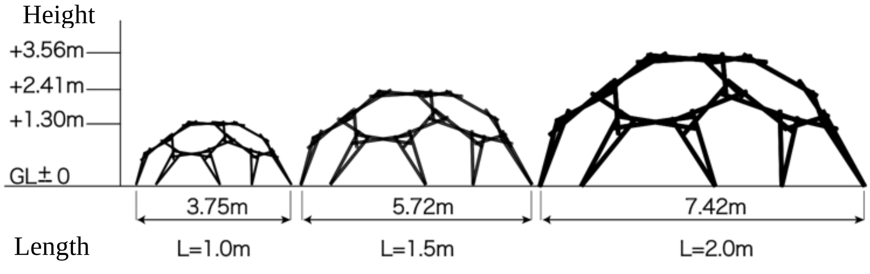


Figure 6: Relationship between member length and dome height

It would be appropriate space with the 5.72m span with a 1.5m member length and the 2.41m height for temporary structures, as shown in Figure 6.

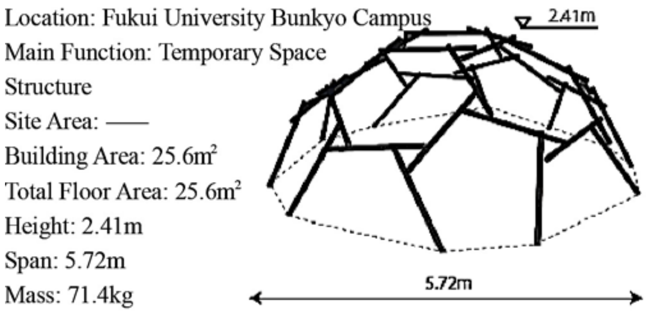


Figure 7: Determination of the shape of the dome

6. Comparison of coordinates

In this study, first, the shape of the dome was generated by morphological analysis [4] using a genetic algorithm [3] (hereinafter abbreviated as morphological analysis). Here, the validity of this shape is compared and examined with a model and a full-scale dome described in Chapter 4. The model used a styrene cylinder. Based on this model, the three-dimensional coordinates are compared and examined below. Second, the structural performance is investigated by the structural analysis.

It was found that the three-dimensional coordinates were almost the same, but it was confirmed that the difference became smaller as the nodes became higher in Figure 8. Although the position of the fulcrum was relatively large, it was confirmed that the other nodes almost coincided in Figure 9.

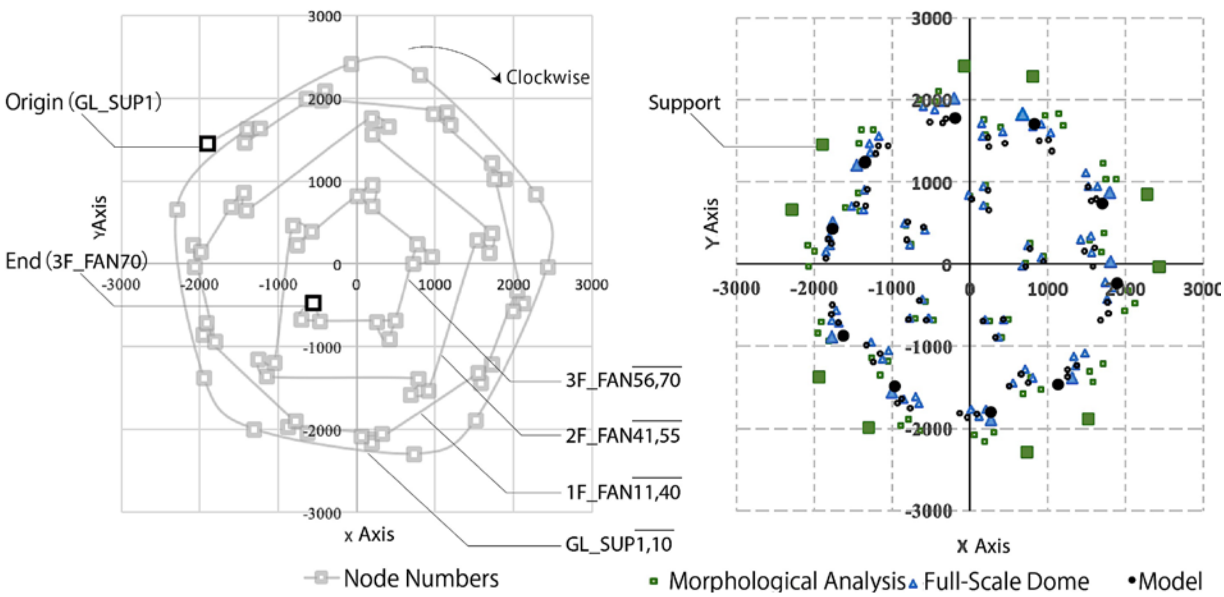
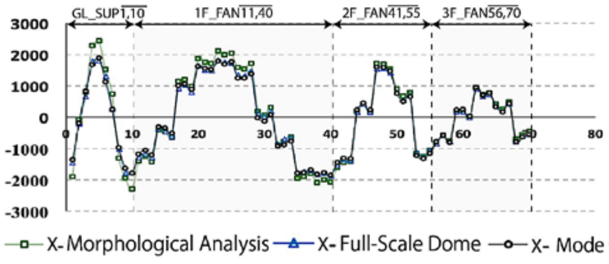
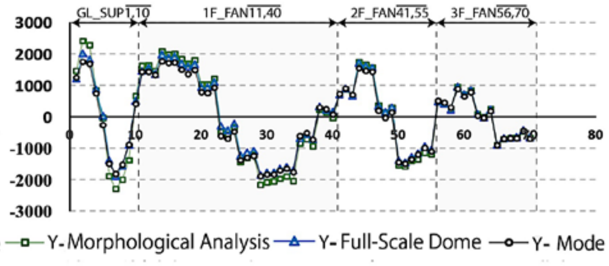


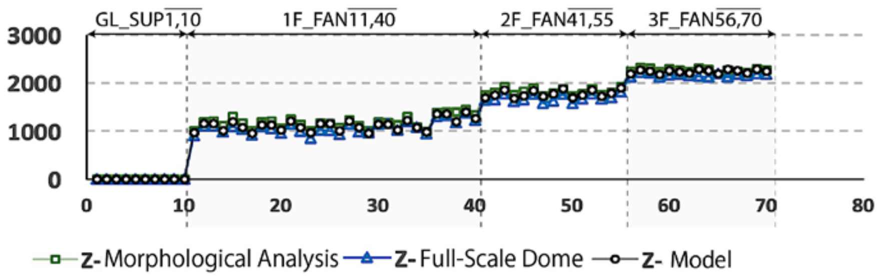
Figure 8: Comparison of Coordinates from the Top view



(a)



(b)



(c)

Figure 9: Comparison of XYZ Coordinates

7. Trial assembly

7.1 Development of joints with efficient workability

The proposed joint uses PVC pipes and ropes as shown in Figure 10. Further, the position of the main joint can be adjusted by ropes. Therefore, it is possible to easily assemble the dome by overlapping the members.

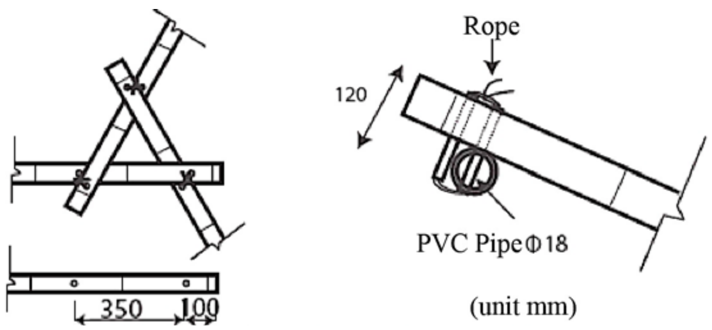


Figure 10: Detailed view of the joint used for this dome

The feature of this joint is that the direction of the hole or the PVC pipe can be adjusted at the time of assembly as shown in Figure 10. Also, by connecting the members with ropes, the eccentricity can be kept in Figure 11.

Figure 11: Joint using PVC pipes and ropes

7.2 On-Site Construction

Trial construction was conducted for the purpose of easy construction and grasp of problems during construction. In this dome, the member length was 1.5 m, but the member length was changed to 1.7 m as shown in Figure 12, so that the members could be properly overlapped. The member is preliminarily drilled at four places and penetrated through a PVC pipe. 35 members were manufactured by two persons in about 45 minutes.

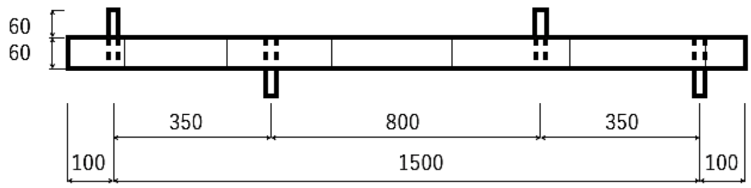


Figure 12: Module of members

The assembly at the site was performed as a unit consisting of three members connected by ropes as follows. In four steps, two people worked in about 1.5 hours without using special tools.

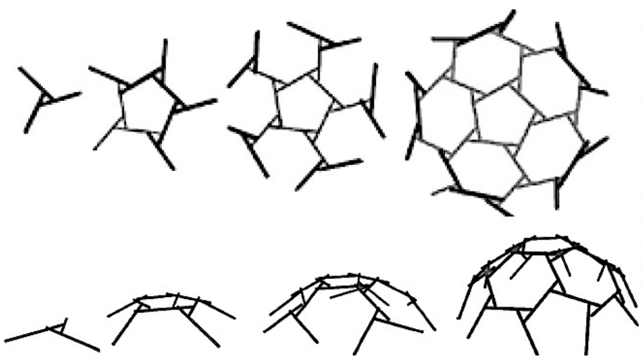


Figure 13: Determining the shape of this dome, which creates a space by overlapping members

Figure 14: Assembled dome

7.3 Results and Discussion

The assembled dome has a maximum height of 2.32m and a span of 5.50m. When the members are unitized, it is necessary to pay attention to the splitting of the bamboo material ends and the displacement of the joints due to the variation in the diameter of the bamboo culms depending on the degree of drying and the size of the drill mouth.

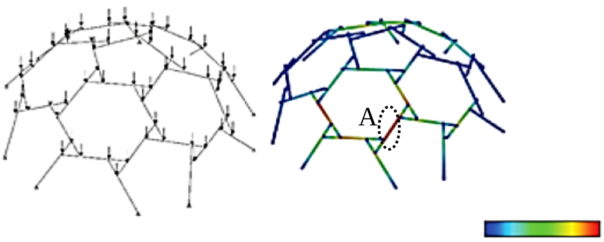
8. Structural analysis of this dome

To study the structural behavior of the dome subjected to vertical force, the elastic structure analysis of the model of the dome using the shape obtained from the morphological generation was performed as follows.

Table 2: Analysis conditions

Node	Pin
Support	Pin
Diameter	60mm
Eccentricity	60mm
Length	1500mm
Engagement Length	350mm
Young's Modulus	1500kN/cm2
Maximum Bending Moment	1420kN·mm

By using the empirical formula for the relationship between the external diameter and the maximum bending moment M_{max}, the maximum bending moment M_{max} of 1420 kN·mm was calculated for the average external diameter of a 60 mm member. And, by using the empirical formula for the relationship between the external diameter and the bending stiffness EI, the Bending Young's modulus E of 1500 kN / cm^2 was determined from the average external diameter of the member.



Total Load P_{total}=7.88kN   Maximum bending moment M_{max}=1420kN·mm

Figure 15: Analysis results

It is considered that the maximum bending moment (1420 kN·mm) was reached at the joint of the member A shown in Figure 15 due to the asymmetry caused by the coordinates studied in Chapter 6. However, in this structural analysis, the boundary condition and the joint are modeled as pins. Therefore, it is necessary to clarify the structural performance and proof stress of this dome in the future by evaluating the rigidity and proof stress of the proposed joint.

9. Conclusion

The bending strength performance of Moso bamboo culm was investigated by the experiments of the bamboo members. The results showed significant correlations between the internal diameter, the maximum bending moment (M_{max}), and the bending stiffness (EI) of the bamboo culm with respect to the external diameter. Therefore, the maximum bending moment and the bending rigidity for structural analysis can be estimated with relatively good accuracy in term of external diameter of the bamboo culm. It is also confirmed that, the validity of the empirical formulas of the material in this study for estimating the properties, such as the internal diameter, maximum bending moment, and bending stiffness in term of the external diameter is also confirmed in comparison with the previous studies [1] and [2].

It was shown that this joint is excellent in terms of practicality with cost reduction and efficient workability. It was also shown that the structural characteristics such as the bending stiffness and Young's modulus of the dome can be obtained by using the proposed experimental formula in this study and the coordinates obtained by the morphological analysis. Therefore, it is expected that the use of bamboo can be expanded and the reciprocal structure can be applied to temporary space structures.

Acknowledgements

This work was supported by JSPS KAKENHI Grant Number 18K04427. The authors would also like to thank Emeritus prof. Hideo HORIE of Toyama University for giving us guidance along the process of the experiments. Furthermore, we also extend our thanks to Mr. Takashi AKAZAWA for kindly providing us with Moso bamboo culms as the specimens in this research.

References

[1] Hideo HORIE: Estimation of Cross-sectional Dimension of Bamboo Culms, Journal of The Japan Wood Science Society Vol. 66, No.2, p.100-105, 2020.

[2] Hideo HORIE: Strength Performance of Green Bamboo Culm as A Temporary Structural Member, 63rd Annual Meeting of the Japan Wood Research Society (Morioka) CD Version, D27-08-1515.

[3] Baverel O. L. S.: Nexorades: A Family of Interwoven Space Structures, A thesis for the PhD, Space Structures Research Centre, University of Surrey, p.22 & p.238-241, 2000.

[4] Nooshin H., Disney P., Yamamoto C.: Formian, Multi-Science Publishing Co. Ltd., 1993.

[5] Tim MICHELS, Lu LU, Russell ARCHER, Sigrid ADRIAENSSENS and Greta, TRESSERRA : DESIGN OF THREE HYPAR ROOFS MADE OF GUADUA BAMBOO, 2017

[6] Garavaglia E., Pizzigoni A., Sgambi L. and Basso N.: Collapse behavior in reciprocal frame structures, 2013.

[7] Godthhelp T.S., Roelfs R., Habraken A.P.H.W. and Jorrisen A.J.M.: The Timber Reciprocal Frame Designer: The Timber Reciprocal Frame Designer: Free Form Design to Production, 2019

[8] Garavaglia E., Pizzigoni A., Sgambi L. andBasso N., “Collapse behaviour in reciprocal frame structures”, *Structural Engineering and Mechanics,* Vol. 46, No. 4 pp. 533-547, 2013.

[9] Godthhelp T. S., Roelofs R., Habraken A. P.H.W. and Jorissen A. J. M.: “The Timber Reciprocal Frame Designer: Free Form Design to Production” *Structural Membranes 2019 Form and Force Proceedings of IASS Annual Symposium 2019*, Barcelona, Spain 7-10 October 2019.

差出人： iass2020surrey7@easychair.org が IASS2020-SURREY7 の代理で送りました
宛先： Koichiro Ishikawa
件名： IASS2020/21-SURREY7 notification for paper 809
日付： 2021年6月2日 13:50:46
添付ファイル： Brief Instructions for full paper submission and author checklist.pdf

---

IASS2020/21-SURREY7: (Full paper ID: 809)- Contribution accepted
Dear Koichiro Ishikawa,

Thank you very much for submitting your full paper entitled "Design and construction of reciprocal frames made of bamboo with connections by means of PVC pipe and rope" for the forthcoming IASS2020/21 Surrey 7 Conference, to be held virtually on the 23-27 August 2021.
We are very pleased to inform you that your full paper has been accepted.

1- You missed uploading or filling in some of the below items. Please follow up the attached brief instructions for full paper submission, carefully and upload the required info:
- Headshot
- Figure
- A single paragraph short abstract
- Publication agreement: license to publish.
- Publication agreement: declaration of third party copyright.

2- Please also revise the formatting of your full paper based on the provided guidelines. A simple checklist to make sure that your full paper follows the appropriate formatting is attached.

3- Below you may find the reviewer(s) comments to revise and improve your full paper.
Please log in with your Easychair account and follow the attached guideline to complete your submission at your earliest convenience between 7 to 14 June. Also, please upload the word file of your full paper to be included in the proceedings, as well as the revised pdf file.
Also, you can find the template of the full paper at https://www.surrey.ac.uk/sites/default/files/2021-01/IASS2021-full-paper-guidance.docx

The program for the conference is in preparation and we will send you the detailed program as soon as it is ready.

With very best regards,
Gerard Parke & Omidali Samavati
Chair & Vice-Chair of Scientific Committee IASS 2020/21 – Surrey 7
iass2020@surrey.ac.uk

SUBMISSION: 809
TITLE: Design and construction of reciprocal frames made of bamboo with connections by means of PVC pipe and rope

----------------------- REVIEW 1 ---------------------
SUBMISSION: 809
TITLE: Design and construction of reciprocal frames made of bamboo with connections by means of PVC pipe and rope
AUTHORS: Koichiro Ishikawa, Srun Sovannara and Phon Sokol

----------- Overall evaluation -----------
The paper is of very good scientific quality. In general manuscript of the paper fulfils most of the requirements spoken in the full-paper-guidance regarding the paper's format. It seems that a figure placed in the bottom of page No 6 is a part of Figure 8 presented on page No 7. I suggest to divide Figure 8 into two independent parts, which should be suitably shaped and have appropriate captions. Besides on pages No 7 and No 8 one can notice some empty spaces, what should be eliminated. Please arrange these pages according to the indications written in the guidance for preparation of the conference paper. All items of references should also be given according

this guidance.