International Journal on Advanced Science Engineering Information Technology

Vol.7 (2017) No. 3
ISSN: 2088-5334

Bamboo Architectonic: Experimental Studies using Bundled-Bamboo-Split (BBS)

Anastasia Maurina[#], Budianastas Prastyatama[*]

[#]*Architecture Department, Universitas Katolik Parahyangan, Jl. Ciumbuleuit no.94, Bandung, 40141, Indonesia*
E-mail: anastasia.maurina@gmail.com

[*]*Architecture Department, Universitas Katolik Parahyangan, Jl. Ciumbuleuit no.94, Bandung, 40141, Indonesia*
E-mail: mikail.budi@unpar.ac.id

***Abstract*— Urban areas have a great role in the climate change. The sector of building construction engages with that issue through environmentally friendly design. Building material is one of the important roles on that issue. Bamboo can be regarded as a sustainable construction material. Whilst, bamboo is considered as low-class material, even called as "the poor man timber" by many modern builders. Applying bamboo in contemporary design architecture effectively revamp the bamboo's image. Nowadays, contemporary bamboo architects are exploring the organic building form, which requires curved structural elements. Sometimes, the natural bamboo's curvature cannot fulfill the architects' demands. Therefore, it's required a technique to curve the element, one of which is using bundled bamboo split (BBS). The research issues are the effect of using BBS to formal-spatial function and mechanical function; and the effect of bamboo species and bundle's interval to BBS's compression strength. This experimental research was held in two kinds of experiments. Firstly, design and build experiments: implementing BBS into three types of curve structural elements. Secondly, laboratory-test experiments: comparing BBS's compression strength based on bamboo species and bundle's interval. This research could be concluded that (1) considering from formal function, using BBS as the structural element is very beneficial for a building with organic form; (2) considering from spatial function, Using BBS is appropriate to its function as dynamic spatial elements which contribute in creating atmosphere through its texture and color; and (3) considering from mechanical function, the selection of bamboo species and the bundle's interval will affect the BBS' compression strength. To get a higher compression strength, BBS can use bambu gombong with smaller bundle's interval. Due to its compression strength, BBS is not recommended to be structural elements that distribute the pure compression load.**

***Keywords*— bundled-bamboo-split (BBS); curved structural element; compression strength**

I. INTRODUCTION

Urban areas have a great role in the climate change. Attention to the climate changes represents our best chance to improve the quality of life for the greatest number of people across the world [1]. Environmentalists exploiting fears over global warming have thrust building standards aimed at "environmentally friendly" design and construction into the limelight [2]. Building material extremely has the important role on that issue. Bamboo can be regarded as a renewable construction material. It can be harvested and replenished sustainably with virtually no impact on the environment. Compared with other construction materials – e.g. concrete, steel, and plastic – it has lower embodied energy. In addition to helping local climates through photosynthesis, bamboos also help to control erosion and flooding. Bamboos can also be regarded as a recyclable material since their products can be incinerated or digested in sewage [3]. Because of its sustainability, bamboo as a building material became more popular today. Whilst, bamboo is considered as low-class material, even called as "the poor man timber" by many modern builders [4]. Applying bamboo in contemporary design architecture effectively revamp the bamboo's image [5].

Latter-day, the contemporary bamboo architects, are exploring the organic building form. This statement is aligned with reference [6] in Nurdiah paper "The Potential of Bamboo as Building Material in Organic Shaped Buildings". Her thought is the evolution of modern bamboo architecture has become more dynamic, moving and flowing [6]. The organic form has been generated or created inspired by natural forms in nature. Organically inspired structural systems typically exhibit interesting aesthetic qualities, which are not necessarily intuitive [7].

Some of the Indonesian architects that develop the bamboo organic architecture are Ketut Arthana (i.e. Fivelement, Puri Ahimsa, Bali – Fig. 1a), Andry Widyowijatnoko (i.e. Main Hall OBI Eco Campus, Jatiluhur – Fig. 1b) and Effan Adhiwira (i.e. Dodoha Mosituwu, Poso – Fig. 1c).

Fig. 1 Bamboo organic architecture: a.five element, puri ahimsa [8]; b. main hall OBI eco campus [9]; c. dodoha mosituwu [10]

Those organic bamboo buildings will require curved structural elements. Bamboo's modulus of elasticity (23.775—89.225 kg/cm2) [11] is lower than wood's modulus of elasticity (60.000-125.000 kg/cm2) [12]. This proves that bamboo is more flexible than wood, so bamboo is potential to be used as curved elements. Even bamboo has an elastic and flexible characteristic, but sometimes, the natural bamboo's curvature (1/20) [13] cannot fulfil the curved shapes with a certain angle, especially at bamboo's nodes [14] and does not bend symmetrically all the time [15]. Therefore, it has required a technique to curve the element. According to reference [16], there are two methods: hot bending method and cold bending method. In my last research [17], the selection of bamboo's bending method will affect the appearance of the building and affect to the curved elements' strength.

In principle, BBS' technique is splitting bamboo into several strips that unidirectional fibres. The bamboo split can be used more easily to make a curve form than bamboo poles [18]. Afterwards, these bamboo splits were bundled with knots and/or glue. With this technique, the curvature's dimension and form can be very diverse in accordance with the architectural design.

There are few researches about bamboo as curved structural elements, especially in BBS. Due to this reason, architects often relied solely on intuition and logic of structure in determining the BBS structure. Therefore, this research aimed to create a deeper examination of BBS' technique. The research issues are the effect of using BBS to formal-spatial function and mechanical function; and the effect of bamboo species and bundle's interval to BBS's compression strength.

II. Material and Method

This experimental research was held in two kinds of experiments.

A. *Qualitative Experimental Method by Design and Build Experiments.*

In this experiment, the research implemented curve structural elements (arch, curve column, and curve beam) using BBS on architectural design and experimenting BBS's construction. The results of this experiment will be qualitatively analysed based on Sandaker's theory [19]: The architectural analysis of structural form should, therefore, take into consideration the two main aspects of structure-that structures have both a mechanical as well as a spatial function.

B. *Quantitative Experimental Method by Laboratory-Test Experiments.*

The goal of this experiment is comparing BBS's compression strength based on bamboo species and bundle's interval. The bamboo species that will be tested are bambu apus (Gigantochloa Apus) and bambu gombong (Gigantochloa Pseudoarundinacea), while the bundle's intervals that will be tested are 25 cm and 50 cm. The sample was limited by diameter (8-10 cm), moisture (12-14%) and the age of bamboo (> 3 years).

III. Result and Discussion

A. *Bamboo Curved Line-Forming Elements*

According to reference [20], the structural forms classified either as line-forming elements or as surface-forming elements. Using bamboo as structural elements, the structural forms derived from line-forming elements. Line-forming elements further distinguished as straight or curved. The structural system has curved – lines forming element is arch structure.

If singular bamboo pole used as arch structure, the arch became asymmetrical. The asymmetrical arch happened because the bamboo's radius of curvature decreases continuously from the thick to the thin one [13].

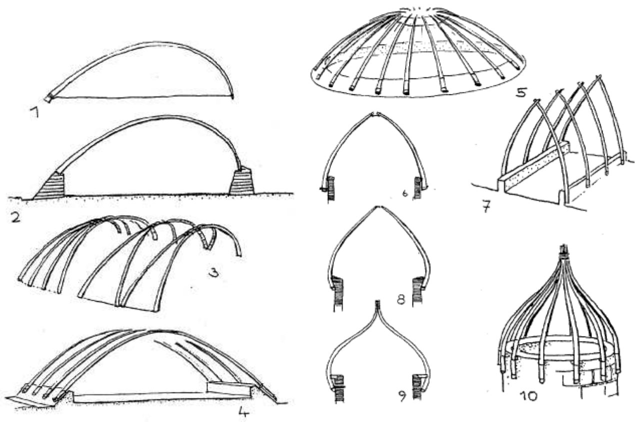


Fig. 2 Bamboo arch structure [16]

The arch elements can be arranged in centralized (Fig. 3) or linear configuration (Fig. 4) [13].

Fig. 3 Centralized configuration of bamboo curved elements [16]

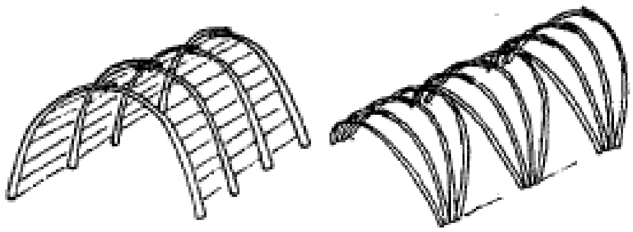


Fig. 4 Linear configuration of bamboo curved elements [16]

The arch structure will distribute the compression axial load [21]. Depend on the joinery; the arch structure classified as (Fig. 5):

- fixed arch,
- hinged arch (2 hinged arch, 3 hinged arch, and 4 hinged arch)
- fixed and 1 hinged arch

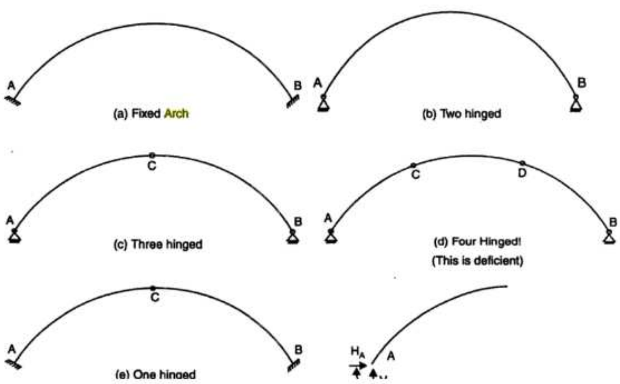


Fig. 5 Arch's joinery [21]

Based on IL 31 [13], critical loads increase proportionally to the flexural rigidity of the arch and are inversely proportional to the third power of the span. The system of joinery between arch and foundation will determine the buckling-resistance. If the arch is used fixed joint on both sides, it withstands loads, which are 2 to 3 times greater than an arch with pin joint on both sides (Fig. 6). The risk of lateral slip (arch tilt) increases more or less proportionally to the arch rise 'f'. The effect of deformation because of creep and behaviour of connection and fastening means must.

Only the funicular arch structure will distribute load compression-axially. The others arch structure (hyperbola, parabola, ellipse, and circle) will distribute load transversally; this is cause deflection of the arch, which is resulting bending [22].

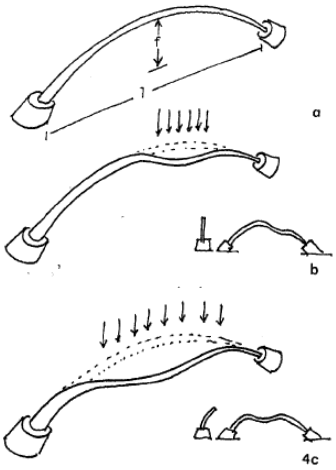


Fig. 6 Arch deformation [16]

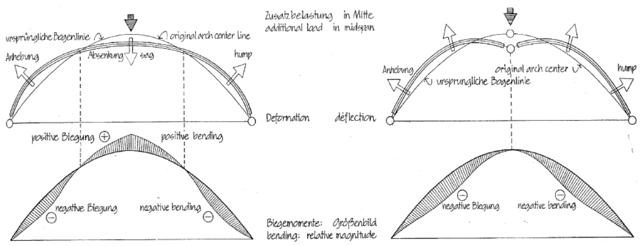


Fig. 7 Arch deflection and bending moment diagram [22]

B. *Design and Build Experiment*

Experiments using BBS as the curved line forming element was applied to the Bamboo Surau at Cibodas Village, West Java (Fig. 8) [23].

Fig. 8 BBS at bamboo surau at cibodas village [23]

The building shape is formed from the result of transformation between square shape in it's floor-plan and a circular shape of the roof, resulting in two opposite-directions curved roof forms (hyperbolic-parabolic). The curved structural elements that are using BBS are shown in Table 1 and Fig. 9.

TABLE I
CURVED LINE-FORMING STRUCTURAL ELEMENTS

Curved Structural Elements	Properties	
	Curvature	Radius
1. The Main Arch	Single	Small
2. The Secondary Arch (Sloping)	Single	Small
3. The Main Curved-Column	Singe	Large
4. The Secondary Curved-Column	Double	Multi
5. The Middle Curved-Beam (Ring)	Single	Small
6. The Bottom Curved-Beam (Ring)	Single	Large

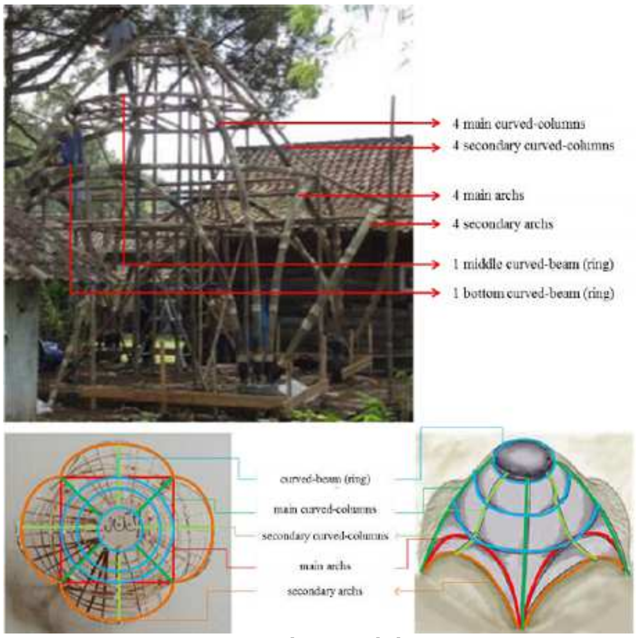


Fig. 9 Curved structural elements

In order to find the optimal BBS's construction, experiments were carried out using variant belt materials (clamps, rope fibres, hemp rope, wire, and reinforcing steel) and with/without adhesive material (glue), the configuration of bamboo splits and bundling techniques. The result of belt material experiment is shown in Table 2.


Fig. 10 BBS construction experiments

Considering the properties, it was decided that hemp fibres will be used as belt material, with the support from clamps or wire before being tied (which will then be revoked after the cord is attached). Usage of white glue (wood adhesive) is also helpful to optimize the durability of hemp fibres.

TABLE II
BELT MATERIAL COMPARISON

Belt Material	Properties			
	Strength Factor	Colour (Atmosphere)	Ease of Construction	Durability
1. Clamps	++	Silver (*modern*)	Very easy	Corroded
2. Rope fibers	+	Black (*dark*)	Easy	Pest
3. Hemp fibers	+	Light brown (*natural*)	Easy	Pest
4. Wire	++	Dark Silver (*industrial*)	Very easy	Corroded
5. Reinforcing steel	+++	Dark Silver (*industrial*)	Difficult	Corroded

To produce +/- 10 cm diameter elements, BBS needs +/- 64 bamboo splits (average dimension: 1x2 cm) with 80 cm bundled interval (to gain element's stiffness). The following is the steps of making BBS:

- Making stakes on the ground that adjusted with the designed radius. (Fig. 11a)
- Placing the bamboo-stripes layer by layer (Fig. 11b)
- Fastening with clamp or wire to obtain a maximum density/ firmness.
- Embodying the area to be tied using white glue
- Binding with hemp rope that has been moistened in advance to obtain the optimal firmness. To produce +/- 10 cm long bundled is required 1.5-meter long hemp rope.
- Re-embodying the rope using white glue (Fig. 11c)


Fig. 11. BBS Construction Phase

In order to gain optimum strength and durability, bamboo strips should be preserved in advance (bamboo strips are more easily attacked by termite/flea in comparison to bamboo poles) and optimally dried-moisture content must 12% (to minimize shrinkage) [5]. The bundling technique is used common flute knots.

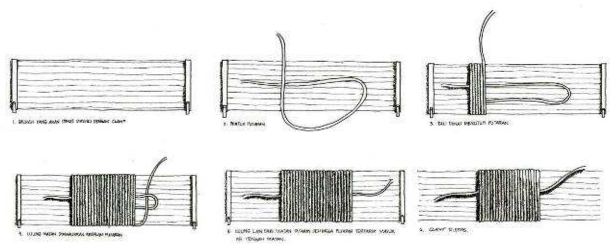


Fig. 12. Flute Knots [23]

1) The Mechanical Function

The building form, which is similar to a dome, will distribute the gravitational load in two-way-span of two forces, namely: meridional force and hoop force [1] (Fig. 13). The meridional force will be distributed axially though compression by curved-columns and arch [12]. The position of the secondary arc, which has a 60^0 slope, is a response to the tension force (parallel with the elements) on the bottom of secondary curved-column. The hoop force will be distributed axially through compression force (perpendicular to the elements) by middle curved-beam, and tension force (perpendicular to the elements) by bottom curved-beam.

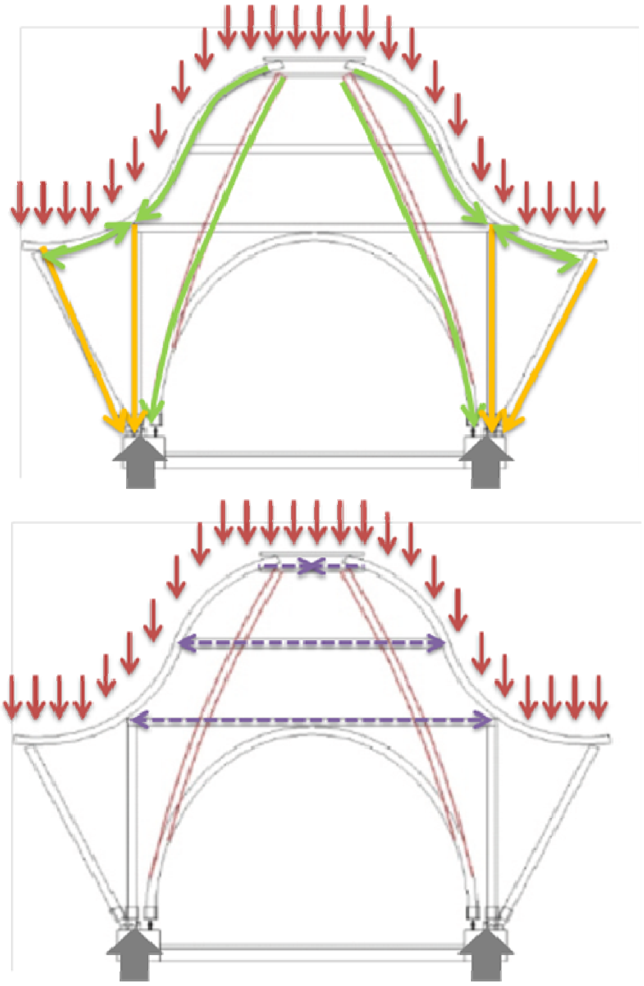


Fig. 13 Gravitational load distribution. meridional force (top) and hoop force (bottom).

TABLE III
THE ELEMENTS' FAILURE

Curved Structural Elements	Failure				Load Effect
	Normal Failure	Bending Failure	Shear Failure	Torsion Failure	
1. The Main Arch	0	+	+	0	Direct
2. The Secondary Arch (Sloping)	0	+	+	0	Direct
3. The Main Curved-Column	+	0	0	+	Direct
4. The Secondary Curved-Column	+	0	0	+	Direct
5. The Middle Curved-Beam (Ring)	0	0	+	0	Indirect
6. The Bottom Curved-Beam (Ring)	0	0	+	0	Indirect

+ : evidence of failure
0 : no evidence of failure

The building has been regularly observed and qualitatively analysed. The structural elements deformed that can be visual observed. Thus, the cause of failure can be seen. Table 3 shows the analysis of the elements' failure.

All elements deformed, but the main curved-column had the most severe buckling (beyond the limits). This caused the shear failure of curved-beam

Table 4 is the analysis of the type of structural elements, the ways of load distribution, and the internal force that occurs in structural elements.

TABLE IV
INTERNAL FORCE

Curved Structural Elements	Type of structural elements	Way of load distribution	Internal force
1. The Main Arch	Form active	Axial	Normal – C
2. The Secondary Arch (Sloping)	Form active	Axial and transversal	Normal - C Bending
3. The Main Curved-Column	Column	Axial	Normal – C
4. The Secondary Curved-Column	Column	Axial	Top of elements: Normal C Bottom of elements: Normal T
5. The Middle Curved-Beam (Ring)	Ring Beam	Axial	Normal – C
6. The Bottom Curved-Beam (Ring)	Ring Beam	Axial	Normal T

Normal C: Normal Compression Force
Normal T: Normal Tension Force

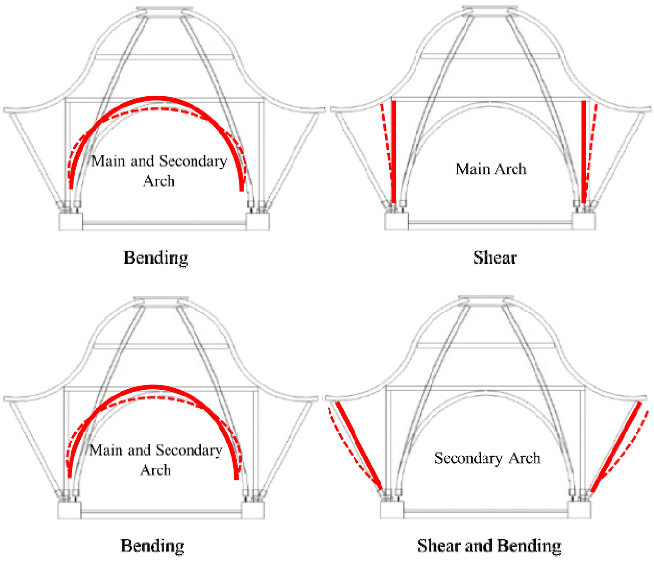


Fig. 14 Bending and shear failure at BBS' Arch

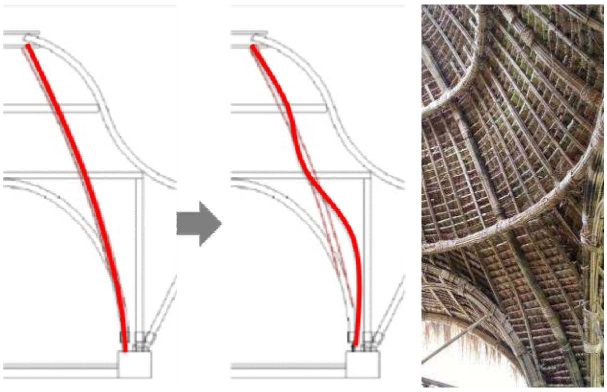


Fig. 15 Buckling at main curved column

Assessing from the structural elements' failure and internal force, it can be concluded that the BBS has less compressive strength.

2) The Formal-Spatial Function

The building form is the geometric forms which are symmetry and concentric. The roof form was comprised of 4 hyperbolic-parabolic which has regular double curvature. This form causes all the structural elements have regularity in dimensions both length and radius.

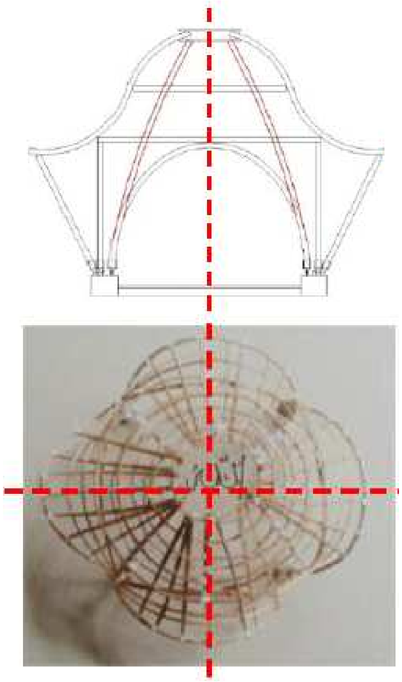


Fig. 16 The symmetry and centralized geometric form [23]

Because of the symmetrical-concentric building form and the regularity in the dimensions, the deformation of the structural elements will affect the building form.

All the structural elements are exposed, i.e. arches, curved-columns, curved-beam, rafters and thatched roof. Those elements contribute to the creation of the building's atmosphere. The rough texture of BBS will render an informal-natural atmosphere. Furthermore, the BBS' colour (brown-yellow) creates psychological effects of warmth and comfort, which supports the building's function.

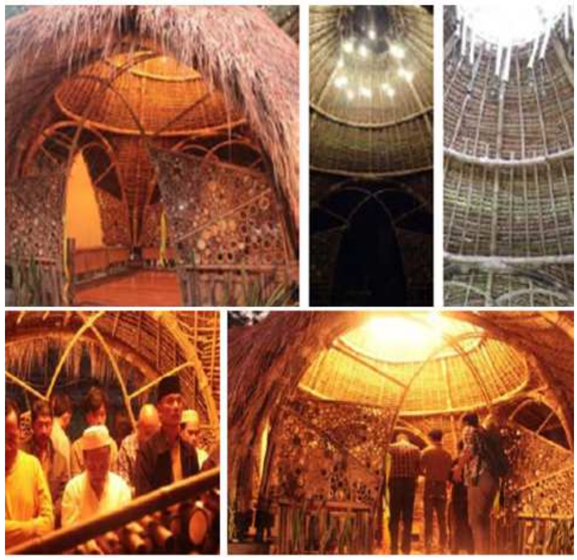


Fig. 17 Building's atmosphere [23]

In formal-spatial function, the flexible characteristic of BBS generates a curved form and space. However, this flexibility can cause an excessive element's deformation that may transform the shape of the building from regular to irregular. Colour and texture of BBS also contribute in creating informal–natural–warm and cosy atmosphere.

C. BBS' Compression Strength

The laboratory test had compared BBS's compression strength based on bamboo species and bundle interval. The bamboo species that were tested are bambu apus (Gigantochloa Apus) and bambu gombong (Gigantochloa Pseudoarundinacea), while the bundle intervals that will be tested are 25 cm and 50 cm.

1) Ultimate Compression Load

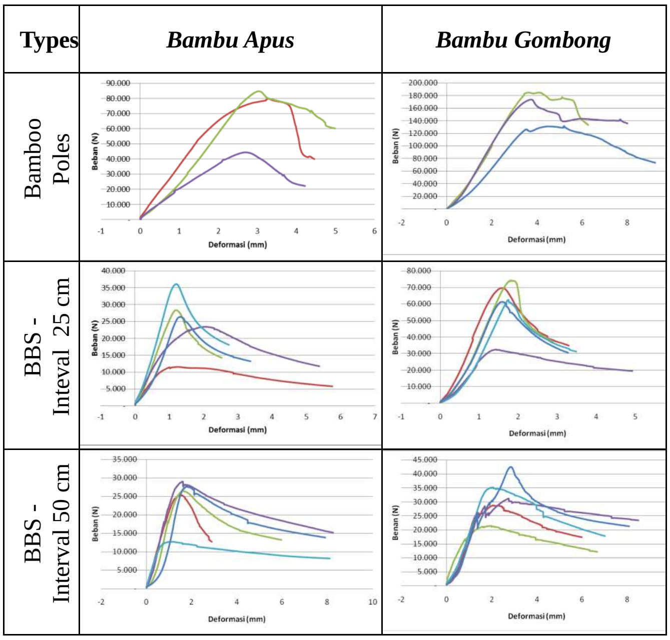
Table 5 shows the comparison of ultimate compression load based on bamboo species and bundle's interval.

The BBS' capability to resist compression load is much smaller than that of bamboo poles. The smaller bundle interval of BBS can resist a greater compression load. BBS's with the highest ultimate compression load is *bambu gombong* with 25 cm interval (6.125 kg = 36.7% from ultimate load of bamboo poles ~ similar to *bambu apus*' ultimate load).

TABLE V
ULTIMATE COMPRESSION LOAD

Bamboo Species and Type		**Ultimate Load (kg)**		
		min	**Max**	**Avg**
Bambu apus	Bamboo poles	4.534	8.648	7.108
	BBS – interval 25 cm	1.178	3.686	2.569
	BBS – interval 50 cm	1.297	2.962	2.477
Bambu gombong	Bamboo poles	13.438	18.852	16.684
	BBS – interval 25 cm	3.309	7.582	**6.125**
	BBS – interval 50 cm	1.899	3.669	2.895

TABLE VI
LOAD TO DEFORMATION GRAPH



1) *Deformation and Failure*

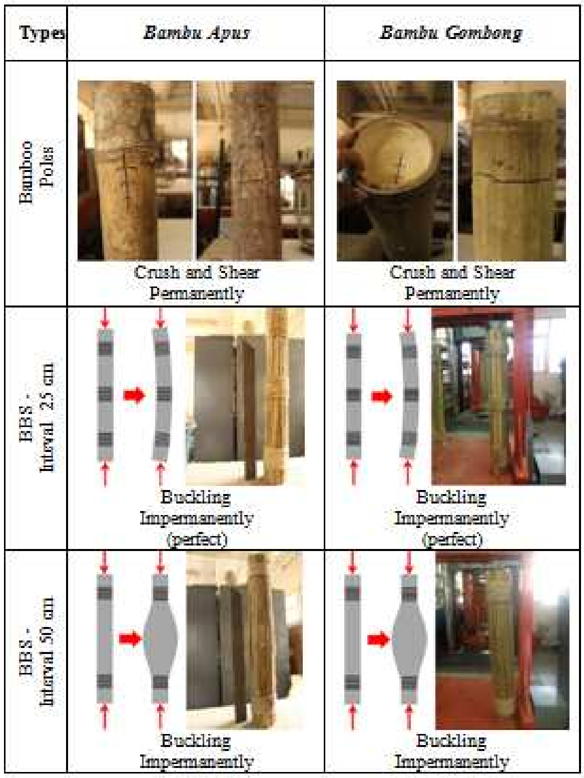
The following table will show the comparison of deflection and failure based on bamboo species and bundle's interval.

TABLE VII
DEFLECTION

Bamboo Type	Deflection	Failure	
		Type	Tendency
Bambu Apus			
Bamboo poles	4.65%	Crushing and Shearing	permanent
BBS – interval 25 cm	2.17 %	Buckling at the same direction	impermanent perfectly
BBS – interval 50 cm	2.35%	Buckling at the different direction and torsion at bamboo split	impermanent
Bambu Gombong			
Bamboo poles	5.75%	Crushing and Shearing	permanent
BBS – interval 25 cm	2.52%	Buckling at the same direction	Impermanent perfectly
BBS – interval 50 cm	3.05%	Buckling at the different direction and torsion at bamboo split	impermanent

BBS's deflection (2-3%) is smaller than a bamboo pole's deflection (4-5%). The whole of BBS type will buckle upon receiving a load, but only BBS with 25 cm interval will perfectly return back to its original form after it no longer receives the load. That is starkly different from bamboo poles that will have a permanent failure: crush and shear.

TABLE VIII
FAILURE



IV. CONCLUSION

This research concludes that: Considering from its formal function, using BBS as the structural element is very beneficial to construct a building with organic form. However, due to the flexible characteristic of BBS, the elements can deform excessively that will transform the shape from regular to irregular.

Considering from its spatial function, using BBS as the structural element is appropriate to function as dynamic spatial elements which contribute in creating informal–natural–warm and comfortable atmosphere through its texture and color.

Considering from its mechanical function, the selection of bamboo species and the bundle interval will affect the BBS' compression strength. To get a higher compression strength, using *bambu gombong* as BBS is better than using *bambu apus*. In addition, the compressive strength of the BBS can be improved by using the smaller bundle interval. Due to its compressive strength, BBS is not recommended to be used as structural elements that carry purely compressive load. These findings in the quantitative research done through comparison of BBS and regular Bamboo poles confirm the earlier conclusion done through qualitative analysis of the experimental design of the Bamboo Surau.

ACKNOWLEDGMENT

This research was supported by Research and Community Service Institute of Universitas Katolik Parahyangan, Bandung, Indonesia. We thank our colleagues from Architecture Department and also from Sustainable Building Material and Technology Research Center

(SuBMiT), who provided insight and expertise that greatly assisted the research.

REFERENCES

[1] Nazanin Nafici, M. F. M. Zain., "The Effect of Landscape Architecture on Climate Change.", International Journal on Advanced Science Engineering Information Technology Vol. 2 (2), 2012, pp.70-72.

[2] Lippke, Bruce, "The Unseen Connection: Building Materials and Climate Change." California Forest, 2006, pp.12-13.

[3] Asif, M.,"Sustainability of Timber, Wood, and Bamboo in Construction.", Sustainability of Construction Materials, Boca Raton, FL: CRC Press LLC, 2009, pp.31-54

[4] Lobokivov, M., Lou, Y., Schoene, D., Widenoja, R., The Poor Man's Carbon Sink: Bamboo in Climate Change and Poverty Alleviation, Rome: FAO, 2009.

[5] Maurina, Anastasia and Henatta, Bpbby, "Promoting Sustainable Living though Contemporary Bamboo Architecture", in Proc. International Conferences on 15th SENVAR (Sustainable Environmental Architecture) and 2nd AVAN (Asian Vernacular Architecture Network), 2013

[6] Nurdiah, Esti Asih. "The Potential of Bamboo as Building Material in Organic Shaped Buildings", Procedia – Social and Behavioral Science, 2016, vol.216, pp. 30-38.

[7] M. Sarkisian, P. Lee, E. Long, and D. Shook, "Organic and Natural Forms in Building Design", CTBUH Technical Paper, 2008

[8] Fivelements Website. [Online]. Available: http://www.fivelements.org

[9] Outword Bound Indonesia Website. [Online]. Available: http://www.outwardboundindo.org

[10] Eff Studio Architecture. [Online]. Available: https://www.facebook.com/effstudioarchitecture

[11] Krisdianto, G.Sumarni, and A. Ismanto, Bamboo Research Overview: Compilation of Bamboo and Rattan Research Overview, Center of Forestry and Plantation, 2000.

[12] Peraturan Konstruksi Kayu Indonesia, Departemen Pekerjaan Umum, Direktorat Jenderal Ciptakarya, and Direktorat Penyelidikan Masalah Bangunan, 1961.

[13] Heinz, Frick, Ilmu Konstruksi Bangunan Bambu, Yogyakarta: Kanisius, 2004.

[14] Irwan, Yusril and Arif, W. Mohammad, "Eksperimentasi Metoda Laminasi dan Metoda Pengujian Kekuatan Pelapisan pada Bambu Laminasi untuk Dijadikan Konstruksi Furnitur", in Proc. Seminar Nasional XII Rekayasa dan Aplikasi Teknik Mesin di Industri Teknik, 2013.

[15] Chen, I Chih and Hou, June-Hou, "Design with Bamboo Bend: Bridging Natural Material and Computational Design", in Proc. of the 21st International Conference of the Association for Computer-Aided Architectural Design Research in Asia CAADRIA, 2016, pp. 125–133.

[16] Dulkenberg, Klaus, "Bamboo as a Building Material", IL 31: Bambus Bamboo, Institute for Lightweight Structure, Stuttgart, 1985.

[17] Maurina, A., "Curved Bamboo Structural Element", in Proc. of International Construction Workshop and Conference Parahyangan Bamboo Nation 2, 2015, pp.81-92.

[18] Widyowijatnoko, Andry and Trautz, Martin, "Conventional vs. Substitutive Bamboo Construction: The Classification of Bamboo Construction", in Proc. World Bamboo Congress Vol 10: Architecture and Engineering, 2012, p.17

[19] Sandaker, Bjorn N, On Span and Space: Exploring Structure in Architecture, New York: Routledge, 2008.

[20] Schodek, Daniel and Bechthold, Martin, Structure, 7th Ed. America: Pearson, 2014.

[21] Vaidyanathan, R., & Perumal, P. Structural Analysis, Vol. 2. New Delhi: Laxmi Publications. 2004.

[22] Engle, Heino. Tragsysteme; Structure Systems 4th Ed. Stuttgart: Deutsche Verlags-Anstalt GmbH, 1977.

[23] Maurina, Anastasia., Pujianto, Franseno and Gunawan, Yenny (Ed.), Surau Bamboo: Design, Construction and Appreciation, Bandung: UNPAR Press, 2015.