Impacts of long-span bamboo structure towards architectural-spatial experience

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Abstract. Bamboo had recently been considered a significantly reliable material in constructing long-span structures due to its flexibility, durability, reduced dead weights, as well as its availability in most tropical regions. Contemporary architects favor its usage in constructing long-spanning structures as it allows freedom in designing spaces enclosed beneath it and creates a profound impact to the spatial experience of the building user. This research aims to provide an understanding regarding the impacts of bamboo structure to the spatial experience that the structure creates, through a description and comparison of several case studies. The research concludes that bamboos are mostly used in a planar truss system due to the feasibility in constructing its joints. Truss system made it so that bamboo members are placed within the structure in accordance to the forces that it needs to distribute and withstand, both vertically and laterally. The organization of multiple linear elements of a bamboo truss gave rise to a sense of orderly, organized complexity on the building which profoundly contributes to the spatial experience of its user.

1 The trend of bamboo architecture

Bamboo was a primary component of architecture in vast regions of South East Asia, Africa, and South America. The abundance of bamboo in that region on account of its tropical climate had given rise to a culture of architecture that revolves around the evergreen plant. Its usage had then significantly declined as technology developed. Bamboo buildings slowly changed to wooden constructions prior to colonization era. Industrial revolution introduced concrete and steel structures, which largely influenced the design of buildings in latter days.

However, bamboo had recently enjoyed a new era of global attention. The increasing level of concern towards climate change had forced architects and engineers to employ more sustainable building materials. Subsequently, a handful of them turned their attention to bamboo. Bamboo are known to have decent tensile and compressive strength but with significantly less economic and environmental drawbacks (carbon footprint). Further, bamboo grows to full size at a much faster rate than that of wood, making it much more renewable [1]. Such features are now driving architect to produce innovations revolving the integration of the traditional material to the contemporary style.

The bamboo trend grew exponentially faster in the Asian region, the place where it used to thrive in traditional era. Abundance of bamboo obviously contributed to the matter, just like it did in the past. However, another possible reason to the resilience of bamboo trend is the society's strong grasp on cultural heritage. That is to say that in spite of the rising

popularity of modern construction materials, the knowledge of indigenous bamboo engineering are still passed down through generations, albeit in rural areas and villages. Perhaps it was this local wisdom that made it easy for Asian-based architect to adopt bamboo engineering into their contemporary designs.

As bamboo architecture grew and expand, its design are no longer used solely for its economic-and-environmental-sustainability. Bamboo had been an attraction on its own merit. Bamboo may have an inherent, unconventional beauty unique to it. That trait drove architects to compete in the creation of grand designs using the almost-forgotten material.

This research aims to analyse the trait of bamboo and the impacts of a bamboo structure to the architectural quality of a building. The method by which this research is conducted is an analysis on three case studies. Each of these case studies will be assessed based on five primary aspects that is considered to signify architectural impacts, namely *building exterior*, *interior structure*, *building function*, *light*, and *symbolism*.

2 Understanding the role of structure in architecture

There was a time in which a building's structure was considered a purely a load-bearing element to be judged separately from the building's façade and interior; supposedly a better representation to the aesthetics element of a building. However, the last few decade of architectural growth have shown significant improvement in the way people perceive aesthetics. In

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light of that change, Bjorn Sandaker argued that a structure, being an object existing in space, will inevitably influence the space it exists in, consequently possessing a *spatial* role [2]. These spatial roles were then divided into several aspects which are, among others, *contextuality*, and *utility*.

1. *contextuality*; that a structural element interacts to the architecture of the building it supports
2. *utility*; that a structural element contributes the functionality of the space it exists in

That proposition can be compared with an earlier argument made by Andrew Charleson. His argument revolved around the role of structure as a part of architecture. He proposed, among others, five possible roles; namely *exterior*, *interior*, *light*, and *function* [3].

1. *Building exterior*; that a structural element can be an integral part of a building's façade by modulating, shading, or texturizing it.
2. *Interior Structure*; that a structural element can form compositions within a building's enclosure.
3. *Structure and Light*; that a structural element may contribute to lighting either by allowing light to enter the building, or by obstructing its entry to the building.
4. *Building Function*; that a structural element directly contributes to the building's intended function in accommodating activities by compartmentalizing spaces or articulating pathways.

On balance of both aforementioned arguments regarding the roles of structure, Charleson's proposition on architectural role can be considered as an elaboration to the specifics of Sandaker's proposition regarding spatial roles. The combination of the two arguments can be a basis of assessing the multiple variables of possible architectural-spatial impacts of a structural element, as explained in Table 1.

Table 1. Variables for Assessing Spatial-Architectural Impacts.

Sandaker	Charleson	Parameter
Contextuality	Building Exterior	The structure interacts with the the architecture of the building by being an integral part of the facade
	Interior Structure	The structure communicates with the users of the building by displaying compositions within the enclosure
Utility	Building Function	The structure contributes to the functionality of the building by accommodating its activities
	Structure and Light	The structure contributes to the functionality of the building by providing its users with natural lights

3 Characteristic of bamboo as long-span structure element

Bamboo's stem are hollow in the middle, making it fairly light in weight. Consequently, its stability is derived from the ring-shaped culm instead of the entire section. This fact proves to make bamboo a much more stable structure in comparison to wood as it has weaker outer-parts and firmer inner-parts instead of the other way around [4]

Fig. 1. Culm Section
 (source: bamboobotanical.ca)

Fig. 2. Cross Section
 (source: flaviodeslandes..com)

Hundreds of bamboo species are available as option for construction. There are 1012 species of Bamboo available in Asia-Pacific region alone [5]. The height of each species ranges between 2 meters to an astonishing 35 meters. Diameters of the trunks also ranges between 5 centimeters to 30 centimeters. It needs to be noted that the trunk are larger at the base and much smaller at the peak.

Given the limitation of its form in nature, multiple members of bamboo should be joined to allow freedom of form and span. The results of conjoining bamboo members would be bamboo monobeams or trusses. Standard joints employ bolts and knuckles in order to lock two, crossing bamboo members forming a fixed joint. However, other methods were also invented such as tying the members together to avoid breaking the bamboo due to the stress carried by bolts [6].

4 Long-span bamboo structures

4.1 The great hall, OBI eco campus, Jatiluhur

The Great Hall of OBI Eco Campus is an assembly hall of Outward Bound Indonesia facility. The structure spanned 20 meters across in the form of portal frame with straight elements [6].

Fig. 3. Interior
 (source: outwardboundsindo.org)

Fig. 4. Exterior
 (source: outwardboundsindo.org)

The portals are formed of joined bamboo members, forming a planar truss in which each members transfers compressive and tensile loads axially. The members were joined together using bolt-knuckle joints, strengthened by palm ropes knots. In addition to the trusses, bracings were positioned between each portals to increase lateral stability [6].

Fig. 5. Trussed Portal System
 (source: Maurina et al, 2014)

Fig. 6. Truss Isometrics
 (source: Maurina et al, 2014)

Fig. 7. Bracings
 (source: Maurina et al, 2014)

Fig. 8. Joineries
 (source: Maurina et al, 2014)

4.2 Mandala Agung, Puri Ahimsa, Bali

Mandala Agung¹ is a meditational facility located in the Puri Ahimsa Resort compound. Its span is derived from a ribbed-shell structure system, formed by seven vertical arches bound by horizontal hoops [6].

Fig. 9. Interior
 (source: rooang.com)

Fig. 10. Exterior
 (source: rooang.com)

Each of the arches were made of a truss. The trusses were configured in radial order, with a crown at the apex of the structure which unites all of the trusses. Singular bamboo hoops provided the shell with its lateral stability. Knuckle and bolts were used to join bamboo members together [6].

Fig. 11. Trussed Arch
 (source: Maurina, Enggarsari, Krisanti, & Adhisaksana, 2014)

Fig. 12. Crown
 (source: Maurina, Enggarsari, Krisanti, & Adhisaksana, 2014)

Fig. 13. Hoops
 (source: Maurina, Enggarsari, Krisanti, & Adhisaksana, 2014)

Fig. 14. Joineries
 (source: Maurina, Enggarsari, Krisanti, & Adhisaksana, 2014)

4.3 Wind & water bar, Binh Duong

Wind & Water Bar is a thatched dome structure built in the middle of a lake in Binh Duong Province of Vietnam. Similar to Mandala Agung, this building employs a ribbed-shell structure system, formed by vertical arches bound by horizontal hoops which forms its 15 meters-spanning dome.

Fig. 15. Interior
 (source: inhabitat.com)

Fig. 16. Exterior
 (source: votronghia.com)

Each of the arches were also made of a truss. The trusses were configured in radial order, with a compression ring uniting all of the trusses while serving as a skylight. Singular bamboo hoops provided the shell with its lateral stability with the help of bracings. Palm ropes were used to join bamboo members together.

Fig. 17. Trussed Rib
 (source: dezeen.com)

Fig. 18. Trusses
 (sumber: floornature.com)

Fig. 19. Bracings
 (sumber: 10plus1.jp)

Fig. 20. Joineries
 (source: inhabitat.com)

4.5 Comparing the structures

The comparison provided above shows that most of the building employs trusses as their local structural form, most likely in account of making the most of bamboo's limited length and form. In forming these structural

elements, joineries were generally employed by the buildings in order to allow a large, stable structural span.

Table 2. Structural Comparison

Building	Local Structure	
	Elements	Joineries
The Great Hall	Planar Trusses, supported by v-shaped bracings	Bolt & knuckle, palm rope joints
Mandala Agung	Trussed Arches, Trussed Ribs, supported by hoops	Bolt & knuckles
Wind & Water	Ribbed shell, Trussed Ribs, supported by hoops and bracings	Palm ropes joint

The decision to employ trusses also coincides with bamboo's natural ability to carry axial-loads. That is to say that a trussed structure would allow bamboo to transfer loads axially even when forces were globally perpendicular to the structure. Hence, the bamboo structure is capable of spanning impressive distances while carrying huge amounts of load.

5 Spatial experience in a bamboo structure

The research concludes that bamboo structures, as seen in the aforementioned buildings, have adverse impact to the architectural experience of those perceiving it. These impacts can be seen in the following aspects.

5.1 Building exterior

Repetition of vertical structural element can be seen in the discussed bamboo buildings, with some having significantly vast numbers of columns standing very close to each other.

This trait can be attributed to bamboo's lesser capability in handling compressive load in comparison to other material. The buildings should compensate for this deficit by increasing the number of elements supporting the building. Hence, the increased number of structural elements standing close to each other in bamboo buildings.

The presence of repeated elements in rhythm, according to Francis D.K. Ching, is one of the method to establish order in a composition [8]. Had this rhythmic array of structural element been exposed in the building's facade, it may serve as an impactful element to the building's exterior.

However in practice, two of the three buildings of discussion was designed not to expose its structural elements. This decision may be attributed the need to protect bamboo from the effects of weather (i.e. rainwater).

Fig. 21. Facade of The Great Hall
(source: outwardboundindo.org)

Fig. 22. Facade of Mandala Agung
(source: rooang.com)

Fig. 23. Facade of Wind & Water Bar
(source: arquitecuraviva.com)

In conclusion, buildings with bamboo structure does not have as much freedom in exposing its structure to the exterior as buildings with other, more weather-resistant materials for structure such as concrete.

5.2 Interior structure

While repetition of structures were rarely made visible from the outside, the array of structures were usually a dominant aspect in the interior of bamboo buildings, as seen in the interior of the three buildings in discussion.

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The most noticeable pattern, however, is the vaulted shapes of the three buildings. A vaulted or arched shape carries with it the capability to convert tensile stresses into purely-compressive loads [9]. This unique trait was the reason why arched structures, also called 'form

active' by Angus Macdonald [10], were often employed to form long-spanning buildings. Bamboo, being efficient in carrying loads axially, benefits from having form-active or semi-form-active shapes.

The point of apex is often the orientation to which other structural elements (e.g. rafters, girders, hoops, bracings) refer to in their positioning. Thus, the apex sets order to the structure, the way a datum that establishes order in a composition as argued by Francis D.K. Ching [8].

In conclusion, buildings with bamboo structure has the capability to form rhythmic composition in its interior, often oriented by the apex of the long-spanning building.

5.3 Structure and light

The apex of the spanning structures played another significant role in the spatial experience of the perceiver of the building ; the integration of natural lighting. Both Mandala Agung and the Wind & Water Bar sports a crown ring at the apex of their dome-like forms, above the center of the concentric configuration of the building.

Fig. 24. Skylighting in Mandala Agung
(source: fiveelement.org)

Fig. 25. Skylighting in Wind and Water
(source: votronghia.com)

The integration of skylighting comes naturally for both of those buildings. As both building has a dome-shaped form, the building will most likely experience compressive hoop stresses at its crown [11]. In account of that stress, the buildings would require the presence of

a compression ring to carry the hoop stresses. Therefore the skylight serves multiple purposes in both buildings.

The shape of skylighting is different in The Great Hall; it is linear in form and primarily made of the positioning of the thatch roof as opposed to the bamboo structures. The skylighting crevice was positioned on the point in the bamboo truss which carries the lowest amount of moment force [7].

Fig. 26. Skylighting in The Great Hall
(source: outwardboundsindo.org)

The skylights accentuate the apex of the building, highlighting it as more than just a datum in the composition of structures, but also as hierarchically higher point in the composition of the structure. The establishment of hierarchy is also argued by Francis D.K. Ching as a key principle in establishing order amidst a composition [8].

As importantly, skylighting obviously contributes to the atmosphere felt within the space that the building encloses. Natural light offers higher degree of visual comfort to building users in comparison to artificial lighting.

In conclusion, bamboo structure offers vast possibilities of integration with skylighting. Such integration would improve the composition of structural elements as much as it increases the visual comfort in a particular building.

5.4 Building function

The spanning structure allows for a higher degree of freedom for activities. Both The Great Hall and Mandala Agung serves as an all-purpose meeting room, which requires the room to be free of obstructions often caused by vertical structures. The Wind and Water Bar serves as a restaurant, which also requires as little obstruction as possible in order to accommodate the circulation of customers and waiters alike.

Integration of bamboo structure with the building's function is especially significant in The Great Hall. Each of the portal frames were more than two-stories in height. The portals were used to house a second floor that serves as balconies to the meeting hall. The portals further accentuates the linear balcony by framing them.

Fig. 27. The Linear Balcony Framed by the Portals
(source: votronghia.com)

6 Conclusion

In summary, the role of structure is to contribute to the architecture of the building it serves. At some specific aspects, bamboo might not be able to do that role. For instance, with the currently available technology, bamboo might not be an appropriate material to contribute to the building's exterior due to the material's need to be protected from weather effects.

That being said, a structure made of bamboo still has the potential to bring unique impact to its perceivers. They have, among others, the capability to establish order in the composition of structure as seen from within the enclosure, allow skylighting to be integrated to the building's design, as well as allowing the building to better accommodate various functions and activities.

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