The Environmental Performance Of Contemporary Bamboo Architecture In The Tropics

A case study of an educational building designed by Ibuku in the warm and humid climate of Bali, Indonesia

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ABSTRACT: This research critically examines the environmental performance of contemporary bamboo architecture in tropical regions, focusing on a case study of an educational building designed by Ibuku in Bali, Indonesia. Amidst the rapid development and modernization affecting tropical countries, traditional architectural practices often get overshadowed. This paper highlights the importance of local materials, craftsmanship, and innovative designs for sustainable living. It specifically explores bamboo's potential as a sustainable construction material in tropical climates – as the vegetal rod that comes out of the ground -, highlighting the significance of bamboo species selection, processing techniques, and the application of durable design principles in bamboo architecture. The paper presents an in-depth analysis of The Green School near the town of Ubud, a project that exemplifies the innovative use of bamboo in contemporary architecture. The study investigates various aspects of its environmental performance, including daylighting, natural ventilation, and thermal comfort. The school's thermal performance was rigorously evaluated through fieldwork employing data loggers and spot measurement tools, complemented by user interviews. The research provides both qualitative and quantitative insights into the efficacy of bamboo architecture in ensuring comfort with minimal energy consumption.

KEYWORDS: bamboo, vegetal rod, warm and humid climate, fieldwork, thermal performance

1. INTRODUCTION

The hasty development of emerging tropical countries has led to the proliferation of inappropriate architectural practices that replicate designs intended for very different cultures and environmental conditions. These uncontextualized practices, create built environments in the tropics which rely heavily on mechanical systems, consume non-renewable energy all year long and thus pose significant environmental threats. To counteract this trend, the use of local ecological materials, local craftmanship and innovative environmental designs is crucial for sustainable living. This paper delves into the case of Bali, Indonesia, a region, heavily impacted by tourism and rapid modernization, which holds rich examples of vernacular and contemporary bamboo architecture. For the past decades “ruthless” developers have focused on the southern part of the island, building fully airconditioned high rise resorts, encouraging foreigners to maintain their customs from abroad. Not only has this phenomenon gentrified the local Balinese population away, but also constitutes a real threat by gradually separating locals from their culture. A direct consequence is the decrease of tolerance from the Indonesians regarding their perception of comfort. However, further inland, lies the Balinese cultural capital town of Ubud where genuine traditions are perpetuated and relation to nature kept strong. Abundant around the tropics, bamboo has traditionally been used as a construction material for the warm and humid climate. Although varied uses and applications in building construction have established bamboo as an environment-friendly, energy efficient and cost-effective option, recent transformation techniques of the material have derived it from its natural state. Therefore, drawing attention of designers away from its initial potential as a vegetal rod. Reporting guidelines for bamboo selection, preservation and processing in Indonesia is necessary to set the conditions in which bamboo holds its best potential to generate sustainable architecture. A significant challenge that has slowed the development of bamboo architecture resides in its social perception. Bamboo remains widely misunderstood and attributed exclusively to extreme contexts, either for old traditional uses (vernacular architecture, scaffolding, etc) or temporary emergency sheltering. However, several noticeable examples of bamboo buildings have achieved to elevate the material to more contemporary and modern uses, at locations where the strongest bamboo species grow abundantly. The focus of this paper will be on Indonesia, as it detains a strong handcrafting heritage combined with a traditional know how regarding the use of bamboo. This set of conditions creates new possibilities to generate sustainable and environmental architecture using natural bamboo rods for contemporary lifestyles.

2. CONTEXT

2.1 The climate of Indonesia

Indonesia lies between latitudes of 11°S and 6°N and experiences a tropical warm and humid climate characterized by annually consistent temperatures around 27°C with little diurnal variations and high incident solar radiation reaching 1000 Wh/m². Humidity levels are high averaging around 84% and winds are moderate averaging at 2.5m/s, hence the majority of the population living in naturally ventilated houses to ensure thermal comfort. Winds are generally predictable, usually blowing in from the south-east during the dry season (May to September), and from the northwest during the rainy season (November to March).

2.2 The local climate of Ubud, Bali

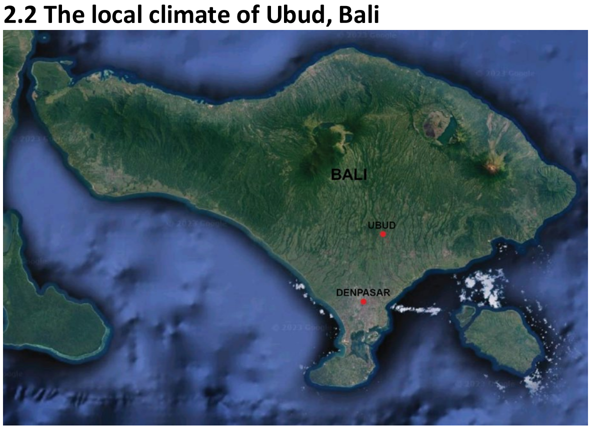

Figure 1: Location of Ubud on the island of Bali (source: Google Maps)

Ubud is centrally located on the island of Bali at 220 meters in altitude, with the nearest coast at more than 10 km (figure 1). Annual temperatures (figure 2) are slightly cooler than in the coastal areas, ranging from 20 to 30°C with a narrow diurnal temperature range of +/- 7°C. Relative humidity levels remain above 80% and natural ventilation is permanently needed to relieve from heat stress. Sky illuminance is high with frequent overcast sky conditions which can easily cause disturbing glare [1]. Rainfall is substantial with an annual average of 2244mm mostly occurring during the wet season facilitating a dense vegetation. The dry season has fewer rainy days, lower humidity levels and clearer skies.

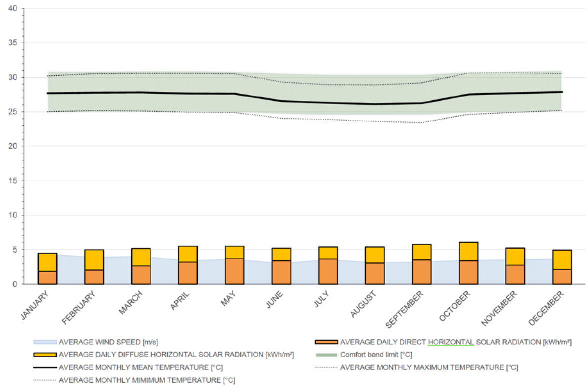

Figure 2: Climate analysis of Bali

Indonesians reckon witnessing climate change as conditions have now become less predictable. Historically, an annual sudden change of wind direction occurred during a week in April and another in September, these events were traditionally the object of social gatherings in the rice fields and a celebration for the kite festivals. Although wind patterns are now more scattered, prevailing winds can still be considered to be south-eastern and north-western, respectively during the dry and wet season.

3. BAMBOO A VIABLE RESOURCE IN BALI

3.1 Overview on bamboo

This study highlights the potential of bamboo as a traditional construction material well-suited for warm and humid tropical climates. Despite its historical significance, bamboo has been overlooked due to modern material preferences. A shift towards bamboo architecture in the tropics offers benefits such as being affordable and widely available. It is a lightweight material with the tensile strength of steel and compression resistance of concrete which can be used to build structural cores, columns, beams, staircases, slabs, roofs, facades, partitions, frames and furniture [2].

3.2 Bamboo a locally abundant natural resource

Over 1000 bamboo species flourish between the latitudes of 50° North to 20° South, with Asia accounting for 67% of the global distribution. This rapid-growing grass demands meticulous harvesting to ensure optimal construction performance. Culms attain their full height within an eight-month period, exhibiting their maximum diameter upon emergence. A two-year maturation period is essential for the outer layer to shed and branches to develop. The prime harvesting window for a bamboo culm is post three years, coinciding with peak internal density, verifiable via sonic testing. Post-harvest, the culms undergo a two-week solar drying phase, during which they experience shrinkage. Minimizing shrinkage is crucial to avert cracking. Subsequently, the culms are immersed in a heated boron solution for a full day, a step imperative for eliminating natural sugars and deterring insect infestation. The final stage involves exposing the green poles to sunlight until they achieve a yellow hue, indicating the depletion of chlorophyll. Selecting species that are highly adaptable to the local climatic, soil, and topographic conditions is essential to meet the expectations of rapid growth, superior quality, and robustness. Traditional practices, now substantiated by contemporary research [6], recommend three specific species for construction in Indonesia (figure 3), capitalizing on their wide availability, proven adaptability and structural integrity.

1- Petung (Dendrocalamus Asper):

Height of culm: 18-25 m
Diameters: 10-20 cm
Thickness: < 2 cm
Timber bamboo used for structural elements and furniture.

2- Tali (Gigantochloa Apus):

Height of culm: 10-20 m
Diameters: 10 cm
Thickness: < 2 cm
Straight bamboo used for roof structures, furniture and scaffolding.

3- Duri (Bambusa blumeana):

Height of culm: 10-15 m
Diameters: 6-12 cm
Thickness: < 2 cm
Curvy bamboo used for flooring, railings and furniture.

Figure 3: Species used for construction in Indonesia.

3.4 Durable bamboo design principles

Bamboo is acknowledged as a sustainable construction resource within tropical regions. Nonetheless, the inherent variability of bamboo culms precludes standardization, making the quality of craftsmanship a determinant of structural integrity. The irregularity of bamboo's anatomical structure complicates the development of uniform mechanical joints for assembling construction components. However, this challenge is mitigated in countries like Indonesia, where a rich heritage of handcrafting tradition empowers designers with the ability to devise efficient, bespoke solutions. Adherence to fundamental principles is essential for optimizing the longevity of bamboo construction elements. Joinery, being a critical aspect of bamboo construction, demands meticulous attention. Joints are the most susceptible to damage and cracking if not properly executed. A prevalent method involves sculpting the end of the receiving pole into a 'fish mouth' shape to snugly accommodate the adjoining pole and facilitate effective load distribution [3]. While traditional construction utilized bamboo pegs and rope to secure joints, contemporary methods employ threading and bolting for enhanced stability. For principal structural components, infilling with concrete is an additional measure that is taken to augment their strength.

Figure 4: Picture of fish mouth joint with bamboo pin (source: courtesy of Pt. Bamboo Pure)

Bamboo's porous nature allows it to absorb and release moisture, and significant changes in moisture levels can negatively impact its durability [3]. Hence, implementing protective measures against precipitation and direct, intense solar radiation becomes imperative, particularly on the building's windward side where water penetration is more profound. These protective strategies can be realized through various approaches. One effective method is to design the roof overhang to extend sufficiently such that the extremity forms a 45° angle to the ground when viewed in relation to the base of the bamboo structural component. Should achieving this angle be impractical, an alternative is to elevate the base of the bamboo culms. This can be done by creating a concrete foundation or placing a stone beneath the base, thereby diminishing the exposure relative to the roof's overhang.

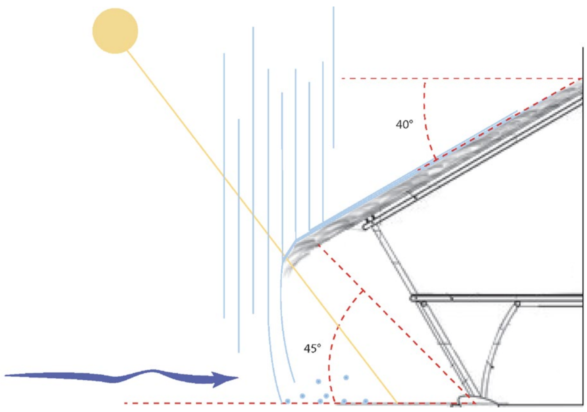

Figure 5: Typology to protect structural elements from weathering effects.

4. CASE STUDY: THE GREEN SCHOOL BY IBUKU

Situated near Ubud in Bali, The Green School, constructed in 2007 and designed by Ibuku, stands as a contemporary example of bamboo architecture in the tropics. It serves approximately 500 students, ranging from kindergarten through high school, drawn from both international and local backgrounds. This institution fosters a unique educational milieu, immersing students within an architecture entirely made of a natural material.

4.1 Overview of the Heart Of School

Figure 6: Aerial and west & elevation view of HOS (source: courtesy of Ibuku)

Figure 7: Ground floor view & offices of HOS

The master plan's spacious design facilitates wind flow, and the eastward descending slope of the terrain helps prevent wind blockage between structures. At the core of the HOS's design is the hyperbolic shape that supports the roof's load. This principle is central to the building's structure, as detailed in the study. Constructed from three bamboo species identified in this research, the building utilizes bamboo for floors, ceilings, stairs, railings, furniture, and versatile blinds, all handcrafted from bamboo culms, resulting in a notably lightweight construction. Roof pitches and extended overhangs are specifically designed for efficient water runoff and to shield the bamboo's foundation. Additional adaptive features, such as the bamboo blinds (figure 6), address rain, sunlight, and glare. The building is confined only by its roof as there are no walls, allowing the building to be opened to more than 80 % of its elevation. With floors and partition made extremely permeable to maximise air movement (figure 7), and considering acoustic limitations of the material, the program is distributed to prioritise privacy of classrooms and avoid disturbance by adjacent users. A practical remedy for the squeaking caused by footsteps on multiple stories bamboo structures is the use of repurposed rubber from old tires as dampers. The school operates from 8:30 am to 3:30 pm, Monday through Friday. Break times are scheduled for a 15-minute snack at 10 am and an hour-long lunch at noon, during which significant activity is permitted on the ground floor. Throughout the day, classrooms and offices are in continuous use, with study areas experiencing higher occupancy in the afternoons.

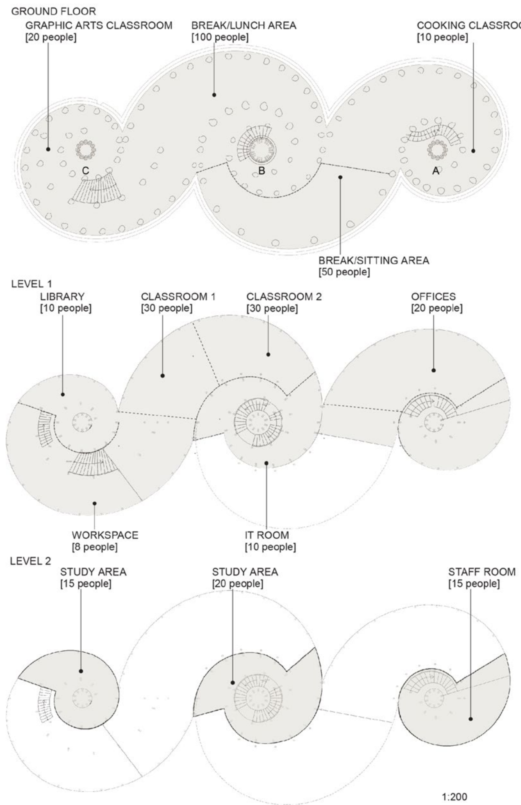

Figure 8: Floor plans, program and occupancy of HOS (courtesy of Ibuku)

The HOS has its longer facades set perpendicular to the prevailing North-West and South-East winds, prioritizing natural ventilation potential over easier solar control. Extensive openings facilitate effective cross ventilation, enhancing comfort regardless of wind direction. Positioned atop a hill and adjacent to a river to the East, the HOS benefits from the cooling effect of the South-Eastern wind, which accelerates as it moves up the hill, delivering a cooling breeze at its peak [7]. The North-western side opens onto a grass-covered sports field, where wind can develop over cooler surfaces prior to entering the school.

Figure 11: Aerial views comparing vegetation growth

Furthermore, rapid and dense vegetation growth means the landscape conditions at the design stage likely differed considerably from the current ones. This temporal discrepancy is illustrated by comparing aerial photos from 2012 and 2016 (figure 11).

Vegetation, including bushes, mid-sized plants, and tall palm trees, now encircles parts B and C of the Heart of the School (HOS), significantly impeding breezes at the level of the openings and reducing comfort during peak temperatures. This observation is corroborated by interviews with two teachers who report a lack of air circulation in these areas. Conversely, another teacher on the ground floor of part A experiences frequent cool breezes.

4.2 Methodology

The potential for natural ventilation is investigated through wind speed spot measurements. The thermal performance is investigated through temperature spot measurements and recordings from four temperature and humidity dataloggers placed on site. The daylight performance is investigated through lux spot measurements. The application of the durable bamboo design principles is analysed based on photographs of the construction elements.

4.3 Results: HOS environmental performance

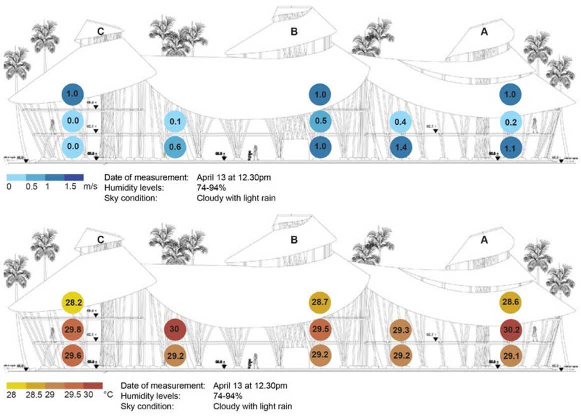

Figure 12: Wind speed & air temperature measurements (after: elevation by Ibuku)

Spot measurements across the HOS showed low to moderate wind speeds ranging from near 0 to 1.4 m/s and temperatures from 28.2°C to 30.2°C (figure 12), pinpointing that higher temperatures occur in zones with calmer wind conditions and conversely. Airflow does improve at higher floors, but lengthy windward roof spans could deflect breezes unless openings are strategically placed. Surrounding vegetation hinders airflow on both the ground and first floors of part C. There's a slight increase in air movement near part A, where vegetation is less dense. The first floor across all three parts of the HOS experiences more stagnant air compared to other levels due to the roof overhangs extending to the first floor's height, which, while shielding against sun and rain and reducing glare, also impede the desired direct airflow. To monitor further these conditions, four data loggers were placed, one on each of the three floors of part B - the central and most occupied section - and one outdoors. Air temperatures were recorded over a school week in April 2016, from Monday to Friday (figure 13). The analysis focuses on the last three recorded days which show diverse climatic conditions: (i) Wednesday 13/04, precipitation between 11:30 am and 1 pm, (ii) Thursday 14/04, intermittent cloud cover during the day's warmest hours, (iii) Friday 15/04, clear skies and consistent solar radiation.

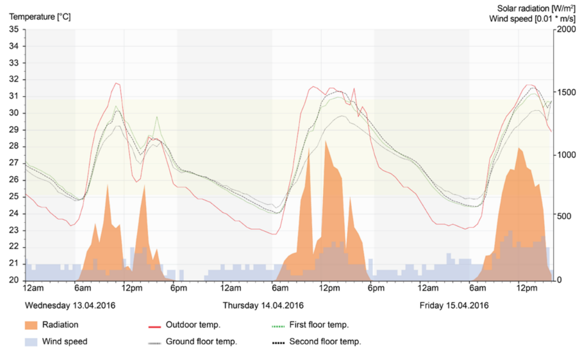

Figure 13: Wind speed & air temperature measurements (after: elevation by Ibuku)

These observations highlight the building's responsive lightweight structure, as evidenced by the semi-internal temperatures mirroring outdoor temperature fluctuations without delay. Daytime temperature differentials were observed as follows: a 1° difference between the ground floor and the first floor, and an additional 0.5° increase from the first to the second floor. This gradual temperature rise confirms the presence of a stack and buoyancy effect, facilitated by the high permeability of most vertical elements. Furthermore, the building's structural hyperbolic core functions as a conduit (figure 14), allowing warm air to ascend to higher openings. Consequently, warm air accumulates at upper levels, potentially causing discomfort in low wind conditions.

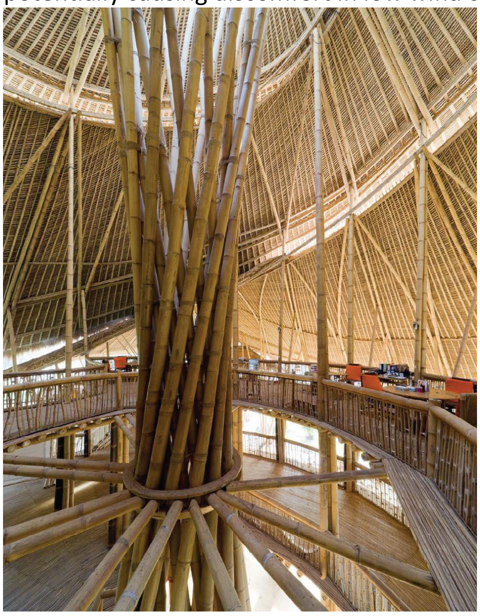

Figure 14: Permeable hyperbolic structural core

While temperatures generally fall within a comfortable range, during peak daylight hours, intense solar radiation significantly warms the surrounding ground and the surfaces of the building's roof. This results in overheating on the first and second floors. Although thatched roofs typically do not retain much heat, a portion of the heat is captured by the winds on the windward side and channelled into the interior spaces. This issue can be mitigated to some extent using existing retractable blinds. Solar radiation heats the soil, creating significant air movement and influencing wind speed. It peaks shortly after noon and diminishes by 6 pm, leaving the warm air trapped under the roof to cool down gradually overnight. During this time, there is a consistent 1 to 2°C difference between the ground floor and outdoor temperatures, persisting until morning. This phenomenon highlights the ground's thermal storage capacity, which releases heat via conduction and convection as the outdoor temperature decreases. The building's temperatures are significantly affected due to the extensive surface area of the roof covering the ground, enhanced further by extended overhangs. These overhangs channel the heat indoors, demonstrating the thermal dynamics in play [8].

4.4 Daylight analysis

The yellow bamboo's light reflectance is nearly 50%, enhancing the building's interior with a unique roughness that scatters daylight effectively. A key design feature is the circular top opening above each spiral's structural core, with a diameter of 2 to 3 meters, allowing ample sunlight to penetrate the interior. In regions with high sun paths and humidity, glare can become overwhelming, but due to its elevated position, rarely within users' direct line of sight, this opening minimizes glare issues. To preserve the bamboo's durability and mitigate direct sunlight exposure, a white translucent canvas covers the top opening, ensuring diffused daylight. Additionally, the core structure's reflective coating prevents the bamboo poles from cracking.

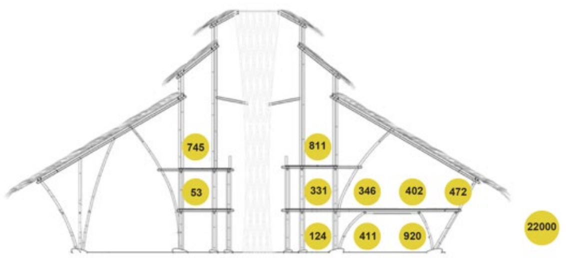

Figure 15: Lux spot measurements (after: section by Ibuku)

During a sunny day, spot measurements indicated that most areas achieve the necessary 300 lux for educational buildings (figure 15). The building's extended overhangs, essential for the HOS design, restrict sky visibility, further reducing ground reflections. This results in most daylight being indirect, leading to the necessity of artificial lighting in deeper areas of the plan, even on sunny days.

4. CONCLUSION

Bamboo, in its natural form, presents a wealth of sustainable options for creating contemporary environmental architecture that is not only cost-effective and functional but also fosters a connection between users and nature. This is exemplified by the Green School in Bali, which is constructed entirely from bamboo and demonstrates exceptional thermal performance. The school consistently maintains internal temperatures that are lower than the outdoor temperature during the day's warmest hours. Future enhancements, such as wind-driven modifications to the roof and strategic arrangement of nearby vegetation, are poised to further improve internal airflow, thereby elevating the comfort level for occupants. It's crucial to comprehensively educate users on these adaptive strategies to empower them with greater control over their environment. Bamboo's potential as a primary material for tropical architecture is readily achievable in regions where it has naturally thrived. In these areas, cultural practices and knowledge have evolved in tandem with the growth of bamboo, making it a fitting and accessible choice for sustainable building.

ACKNOWLEDGEMENTS

I would like to thank Ibuku for granting me access to the Green School and to the archives. I would also like to thank Jorg Stamm for sharing generously his knowledge and expertise in Bamboo construction.

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