Ternary Shed: An Exemplar Design for Bamboo Construction

Harry F. Mills, Mateo Gutierrez Gonzalez, and Hamish Buchhorn

Abstract The Ternary Shed is an exemplar bamboo building design that demonstrates bamboo's mechanical and aesthetical characteristics in construction. The design draws on a triad of knowledge from Latin American low-cost construction techniques, Australian timber construction methods, and contemporary Chinese bamboo design. The Ternary Shed is a two-story pavilion made of round bamboo poles and engineered bamboo products, entirely designed for prefabrication to enable rapid, accessible on-site construction. The flexibility and adaptable layout results in a structure that can be deployed for many uses and typologies worldwide. The design was submitted for the International Bamboo Construction Competition 2019 and presented at the 2019 International Horticultural Exposition in Beijing, China, where it placed third overall. The experience of participating in the competition and the design process was an opportunity to raise public awareness about bamboo's potential use in construction and to demonstrate its versatility and strength as a renewable building material.

Keywords Round bamboo · Laminated bamboo · Renewable building products · Resource conscious design · Construction

1 Introduction

The Ternary Shed is a two-story bamboo pavilion designed to promote bamboo construction and address the needs and challenges presented in the International Bamboo Construction Competition 2019 (IBCC 2019). The project raises public awareness about bamboo's opportunity and potential for use in construction. The

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Ternary Shed has been designed to be an adaptable pavilion that can function as a temporary medical facility, warehouse, office building, community educational hub, campground shelter, tea house, bar, cafe, restaurant, and other uses. The design combines the traditional round bamboo design techniques from Latin-America [1], the contemporary concepts of timber design applied in Australia, and modern engineered bamboo materials created in China [2]. Most of the Shed's building components can be prefabricated offsite and transported for on-site construction. Doing so enables rapid construction, a small workforce, lower labour cost, and safe construction practices. After use, the building can be deconstructed and reused in other future applications.

The structure is designed to withstand extreme environmental events such as earthquakes, wind events, snow, rain, and typical gravitational dead and live loads. *Phyllostachys pubescens* (Moso bamboo) is the primary load-bearing material. Round bamboo poles provide vertical and lateral stability creating a 3D truss to enable the material to use its remarkable axial strength to withstand tensile and compressive axial forces. In contrast, engineered bamboo members on the second floor efficiently take the vertical loads' bending moments and shear forces. Furthermore, the laminated bamboo beams and flooring deliver a finished product of excellent visual appearance. The roof is a curved grid that transfers the loads to the prominent vertical members. The primary structural support for the roof is a central composite beam that cantilevers over the opening area of the pavilion. By designing the cantilever over the entrance, the roof creates a sense of welcoming to the space whilst highlighting the capabilities of bamboo, as demonstrated in Fig. 1.

2 Concept Design

The design of the Ternary Shed considers the need and opportunity to showcase bamboo's ability to be affordable and prefabricated in the short span of 24 h. The concept draws on the state-of-the-art residential, community, and temporary structures, with precedent projects listed in Table 1. The design highlights bamboo's structural capacity through a round and laminated system to support a two-story building with three anchoring supports on the ground plane. The structure is exposed to demonstrate the ability of round bamboo and bamboo veneers. The bamboo systems work in conjunction with engineered timber for the stairwell structure. Semi-transparent polycarbonate panels in two neutral pastel tones of green and white form the cladding of the roof. Areas typically requiring a balustrade are designed with a recycled textile fishnet, seen in the stairwell and second floor. The net allows for ventilation, natural light, continuity of eyesight and keeps the attention pinned to the bamboo structure. Different levels of bamboo construction technology inform the overall architectonic and structural design: (i) low-tech joins like lashing connections with steel wire, (ii) mid-tech links on the joints of round bamboo, (iii) using steel bolts, dowels and mortar refill, and (iv) high-tech connections using flexible and adaptable steel rods and plates. Several mixed construction techniques are utilised along the prefabrication

Fig. 1 Ternary Shed, perspective of campsite facility

and construction process. The structure enables the pavilion to remain full ventilated, capturing summer breezes while providing extensive shading to occupants.

For low-tech construction detailing, Latin-American construction methods such as round bamboo combined with bolted connections filled with mortar are used to connect round bamboo to round bamboo members [7]. The roof members also use composite bamboo beams joined by bolts and metal bands [8]. More sophisticated construction technologies such as laminated bamboo bearers and joists and laminated bamboo flooring are incorporated on the secondary level [9]. Other bamboo materials such as bamboo scrimber (Strand woven bamboo) and bamboo veneer [2] are proposed for non-structural wall partitions, cabinetry and furniture. These systems and preliminary sketches are displayed in Fig. 2.

The structure can be assembled rapidly due to the prefabrication of beams and round bamboo members. The roof and facades are designed to be prefabricated offsite with Computer Numerical Control (CNC) routers. The laminated bamboo veneer wall, partition, and stair elements are modularised for accessible construction and deconstruction. With the modularity of the design, the Ternary Shed layout can be altered to multiple variations depending on the context and occupier needs. For example, four layouts were proposed for the IBCC without impacting the structural system and load-bearing elements. Layout changes occur with the shifting of cabinetry, partition walls and other non-structural members. The following section highlights the different layout options of the Ternary Shed.

Table 1 Precedent projects

Project image				
Project title	Pachacamac [3]	RAUM pavilion [4]	Tower house [5]	Comedor uumbal [6]
Designer	Studio Tom Emerson ETH Zurich, Taller 5 PC University of Peru	Overtreders W	Austin Maynard architects	Lucila Aguilar Arquitectos
Construction	2019	2019	2014	2016
Features	Woven white polyester textile, timber & frames bamboo	Polycarbonate and wooden frames with exposed structure	Multifunctional uses. Vertical space connected/protected with a net	Cantilever roof on round bamboo, round bamboo grid shell

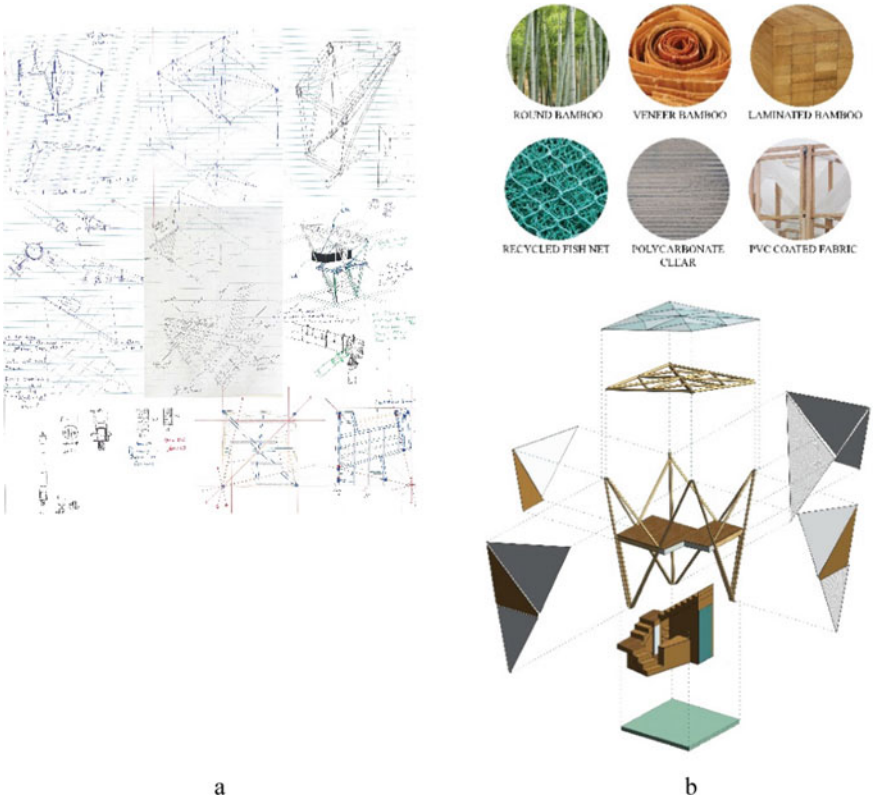

Fig. 2 Process sketches **a**; and materiality and exploded isometric view **b**

2.1 Office

The office layout presented in Fig. 3 is a semi-enclosed space that provides a well-ventilated, natural light-filled area with ample privacy and security. Exposed bamboo and timber panels give comfort and enhance work productivity. The upper level is

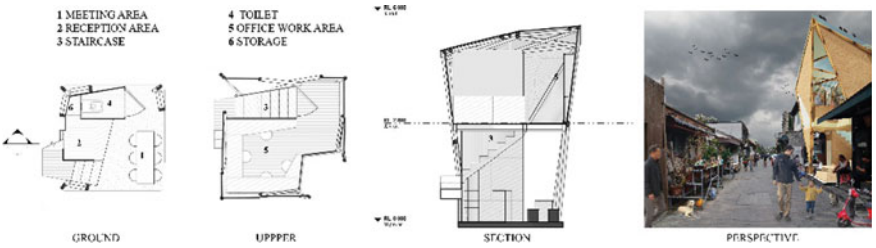

Fig. 3 Ternary Shed, drawings and perspective of office layout

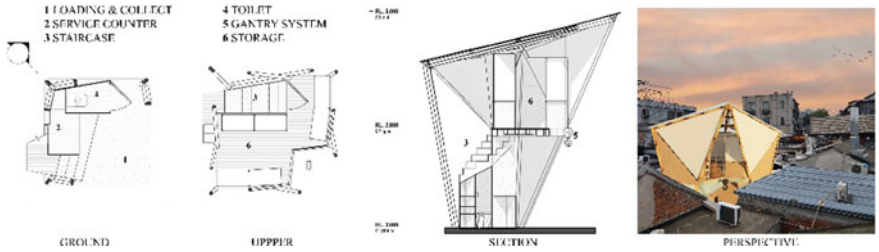

Fig. 4 Ternary Shed, drawings and perspective of warehouse layout

the primary working zone with a capacity for up to six people. The lower level hosts a meeting and lunch area, reception, and toilet. The polycarbonate hybrid roof allows for natural dappled light to filter throughout the structure.

2.2 Warehouse

The warehouse layout has closed spaces designed to store goods either in the lower or upper level, as shown in Fig. 4. A gantry crane is located on the main supporting beam of the roof to bring goods up or down. A staircase to the rear of the building wraps around and through the structure, providing alternate access upstairs. A door secures the upstairs area, and the kiosk area on the ground is secured by a pull-down shutter system, providing a fully enclosed and secure warehouse for all occupants.

2.3 Community and Educational Hub

The community and educational hub displayed in Fig. 5 is a multifunctional space that hosts several social activities. The lower level contains an informal gathering zone with an interactive screen adjacent to a service counter and storage station. An

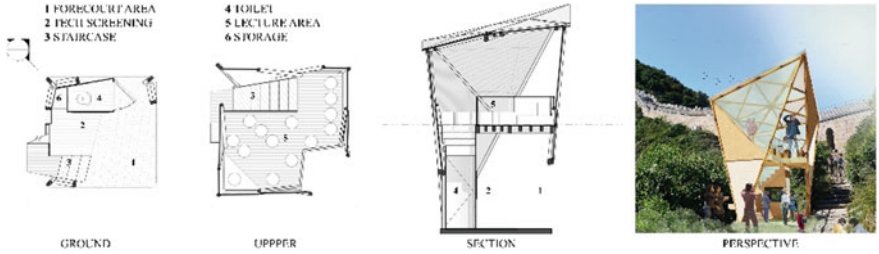

Fig. 5 Ternary Shed, drawings and perspective of community & educational hub layout

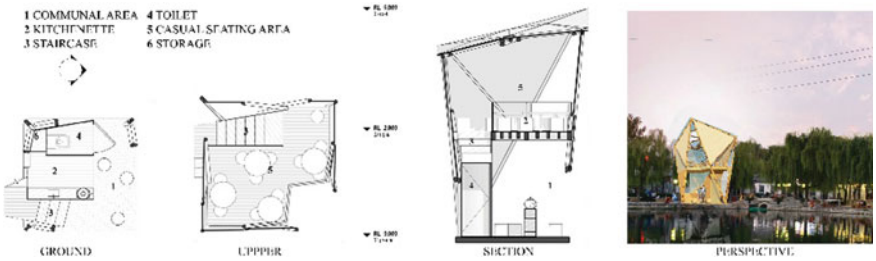

Fig. 6 Ternary Shed, drawings and perspective of and relaxation house layout

enclosed private pod is positioned at the perimeter of the gathering zone and storage area. The private pod can be used as a self-contained toilet and shower or a temporary sleeping shelter. The upper level has a gathering zone with a raised platform for presentations and speaker events. The area is equipped with mobile furniture that can be assembled in various layouts for lectures, talks, seminars, workshops and other community or educational activities.

2.4 Tea and Relaxation House

The tea and relaxation house presented in Fig. 6 is an open layout for social spaces such as a bar, cafe, restaurant, or communal kitchen. A small kitchenette and prep area with a few seats are located at the lower level. The upper level contains multiple tables that can seat up to twelve people. The room is well lit and open to attract natural ventilation while also providing shelter for occupants on both levels. The area is designed to be accessed 24/7 and provides sanitary and cooking facilities.

3 Design Development

3.1 Structural Background

Bamboo is the primary load-bearing material for both the floor slabs and supporting columns of the Ternary Shed. Round bamboo members are used when subjected to axial forces parallel to the fibres. Bamboo columns and bracings act as a 3D truss to provide lateral stability. The 3D truss has been designed to withstand wind and seismic forces, transmitting all gravitational loads from the secondary level and roof to the ground plane. Laminated bamboo beams work in conjunction to provide the secondary level's required shear and bending capacity and restrain lateral buckling of the round bamboo elements under compression to increase the compressive capacity.

A finite element model in SAP 2000 software [10] calculates the internal forces for load-bearing members analysing gravitational and lateral loads, as shown in Fig. 7.

One of the unique structural features of this building is the roof support. The roof is supported at three corner points to enable opening and cantilever of the roof above the entrance. The roof grid provides vertical stability and transfers the loads to the main round bamboo truss elements. Other traditional techniques like double bamboo beams and bamboo pole connections using metal dowels and mortar refill can be seen in the roof details shown in Fig. 8.

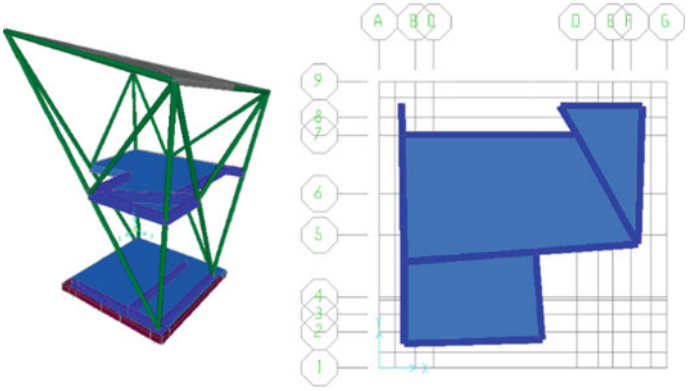

Fig. 7 3D model of the structure and plan view from the upper-level slab

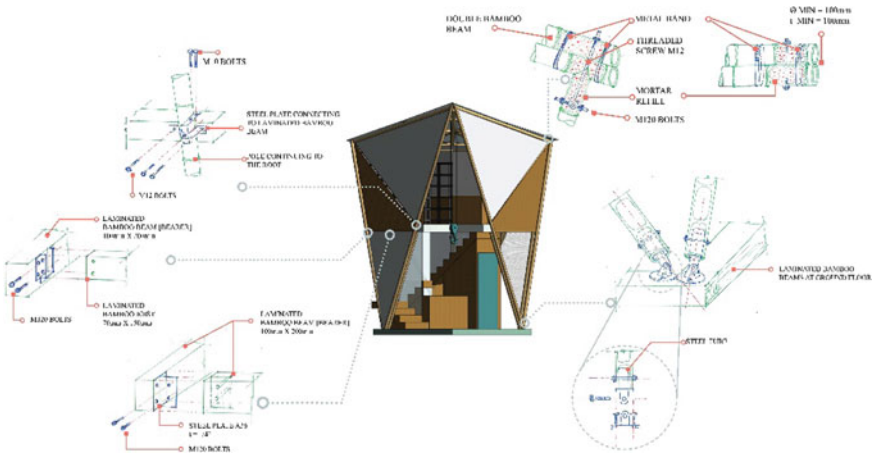

Fig. 8 3D model with construction details

3.2 Design Actions

Permanent and imposed loads: Permanent and imposed loads were considered following the requirements of Australian Standard AS 1170 [11]. Lower and upper-level slabs were designed to support an imposed load of 3 kN/m^2, recommended for offices, workrooms, and public areas. The roof was also designed to support vertical loads required to conduct repairs or provide access to that area, considering an imposed load of 1.5 kN/m^2. A detailed gravitational dead load assessment can be seen in Table 2.

Seismic and wind loads: According to the Chinese code of seismic design of buildings [12], Beijing has been classified with an earthquake-resistant fortification intensity of 7, and the basic design acceleration is 0.20 g. To account for the worst-case scenario, a basic design acceleration of 0.90 g was assumed. A standard value of wind load pressure of 0.45 kN/m^2 was considered for the wind actions to design the roof and the façade.

Load combinations suggested in the Australian Standard were considered for the design of the structure. Drifts were checked for seismic and wind actions, allowing for the structure not to deform more than 1% of the story height. Due to the high stability provided by the 3D truss, lateral displacements in the structure are considerably low. The structure is very stiff in all directions. Figure 9 shows the assigned permanent gravitational loads and the deformed structure under seismic load in the Y direction.

Structural design for critical members: The allowable stresses method and the characteristic values provided by the Colombian Bamboo Construction Code [13] were considered in the design of the laminated and round bamboo members, respectively. Other design frameworks such as ISO 22156 [14] were cited for all the critical members. The structural analysis indicated that the columns must be composed of at least two bamboo poles of a minimum diameter of 100 mm, and a minimum wall thickness of 10 mm due to the magnitude of compressive and tensile axial forces in the lower level. The main load-bearing beam in the roof should be made of a minimum of two poles of the same size. The bending stresses govern the

Table 2 Dead loads assessment

Permanent load: secondary level slab		
Bamboo flooring (Laminated bamboo)	0.24	kN/m^2
Services and fittings	0.15	kN/m^2
Joists and steel connectors	0.32	kN/m^2
Subtotal permanent load	**0.71**	**kN/m^2**
Permanent load: roof		
Bamboo mat	0.29	kN/m^2
Polycarbonate or transparent	0.20	kN/m^2
Services and fittings	0.15	kN/m^2
Battens and steel connectors	0.15	kN/m^2
Subtotal permanent load	**0.79**	**kN/m^2**

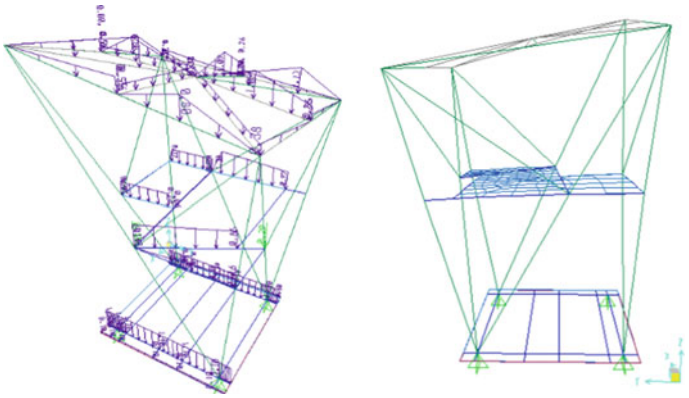

Fig. 9. 3D model with assigned gravitational loads (left) and the deformed structure under seismic load in Y direction (right)

final dimension of the laminated bamboo beams, resulting in rectangular loading bearers of 100 mm × 200 mm, and joists of 70 mm × 150 mm, separated maximum by 500 mm. The connections between the joists and bearers should be made by steel bolts and plates, as shown in the details presented in Fig. 8.

3.3 Construction Process

As represented in the scale 1:200 physical model in Fig. 10, the Ternary Shed explores multiple structural details to highlight the possibilities of bamboo as a renewable building material. The design reveals unique forms, shapes, and spaces across all levels, providing shelter, access to natural light, and ventilation. All design elements, including the laminated bamboo bearers, joists, floor, beams, wall partitions, round bamboo poles, steel connection tubes and plates, and triangular roof structure, are fabricated offsite. The elements can be assembled with low-tech methods on-site with a small number of people. With scaffolding or a scissor lift, the second level and roof elements can be installed quickly.

Fig. 10 Physical model

The round bamboo pole structure is assembled and attached to the ground plane, followed by the lifting and fitting of the second level bearers, joists and floorboards. The roof beams and round Bamboo bracing are attached to the perimeter structure and prepared for the roof elements. The lower-level wall partitions, cabinetry and other non-structural members can be set up internally. The triangular bamboo framed polycarbonate panels can finally be lifted onto and attached to the roof supports. The connections between the roof beams, round bamboo bracings and columns require scaffolding or scissor lifts to reach the apex.

4 Experience at INBAR IBCC 2019 Competition

The Ternary Shed proposal for the IBCC 2019 Competition was a rewarding and enjoyable experience. Visiting and presenting the proposal at the Bamboo INBAR Pavilion at the 2019 International Horticultural Expo was a unique opportunity that the team thoroughly appreciates. We are immensely pleased to have represented Australia in front of an expert panel of industry and academic leaders and be awarded third overall. The transdisciplinary nature of our team brought new collaborative experiences for undergraduate and postgraduate students from Architecture, Engineering and Design.

5 Conclusive Remarks

Bamboo is a low-embodied carbon material, and in comparison to other high-embodied carbon alternatives like concrete and steel, is natural and renewable. Its versatility and robustness mean bamboo can provide enthralling and economical infrastructure solutions when correctly used. With its fast growth rate and high rotation ability, bamboo's use in construction can increase to become an essential building material that can be deployed for uses and typologies worldwide.

The Ternary Shed proposal demonstrates several bamboo construction solutions for creating an adaptable and resource conscious design. The products and systems incorporate traditional low-cost and low-tech methods and contemporary digital fabrication techniques to enable rapid, accessible construction and deconstruction. Our transdisciplinary team presents an exemplar for bamboo construction by drawing on a triad of knowledge from Latin America, Australia, and China.

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