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Optimizing the Potential of Bamboo Structuresin the Context of Bangladesh: A Synthesis of Natural Materials and Forms, Traditional Techniques, and Digital Analysis

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ABSTRACT

Bamboo, commonly referred to as green gold is a renewable fast-growing, lightweight and strong natural resource giving substitute to traditional building materials. Although bamboo is widespread in Bangladesh and remarkable of its structural and visual beauty, to date it continues to be treated as an underrated material in the field of contemporary architecture, as a result of the lack of technical information and formal appreciation. This paper commences this as a research-based design project to bridge this gap by addressing the architectural possibilities of bamboo and other natural materials by integrating traditional building methods with parametric design tools. The study is undertaken with the following primary objectives, to identify and study traditional bamboo crafts and tool making technology, to explore the inspirational character of natural forms and their role in the development of structurally optimized bamboo architecture, to design digital, parametrically driven bamboo structure that emerges as an urban multi-programmed center adaptable to diverse climate and cultural contexts. The methodology will involve looking at theories and practices developed on bamboo architecture along with bamboo buildings and studying traditional tools and objects made by bamboo or similar natural material. Biomimicry and the generation of natural forms will also be overviewed as part of research towards the organic architecture. Digital tools will be employed to carry out parametric modeling and structural simulation, with testing and detailing development guaranteeing functional and aesthetic requirements. The result is supposed to be a parametric bamboo space frame prototype as an urban pavilion for multiple uses. This pioneer product will act as a solution for the impact of local ecology and environment, to inform people more knowing about the natural material application in the modern sustainable structure. The proposed system will be implemented by a physical scale model and demonstrate its feasibility. Finally, the project aims push the boundaries of what can be done both by hand and on machines and, in the process, reignite local traditional bamboo skills with their contemporary equivalent, harnessing the energy and enthusiasm of both the trade and the industry and encouraging widespread public and professional acceptance of bamboo as a material for use in responsible modern design.

INTRODUCTION

In recent years, bamboo has gained popularity as a building material due to its environmental and economic sustainability. It grows quickly and may be harvested in three to six years, renewable material that grows rapidly up to 1200 mm per day, offering a sustainable alternative to traditional wood, lightweight, and possesses high tensile strength and elasticity. These qualities make bamboo a renewable and cost-effective option for construction (Shinohara & Chan, 2023). Bamboo is frequently utilized as a load-bearing material in systems including props, framing, formwork supports, low-rise building structural elements, and even bridges. Its use in construction has several benefits, including as a high strength-to-weight ratio, reinforced nodal zones that promote efficient load transmission, internal diaphragms at nodes that assist avoid local buckling, and a handy size and form for simple handling (Follett & Jayanetti, 2008). Its high strength, light weight, and tubular structure provide excellent seismic resistance, as seen during the 1991 Costa Rica earthquake, where bamboo buildings remained largely intact. Bamboo also has low thermal conductivity (0.30–0.40 W/m·°C), making it a good insulator; a bamboo wall needs to be only 1/15th the thickness of concrete to provide similar insulation. Known as "vegetable steel" for its tensile strength, bamboo resists torsion and central compression well, though it has low shear resistance. It's cost-effective, and with proper treatment, bamboo structures can last over a century like the 3rd-century bamboo suspension bridge in An-Lan, China, still in use today (Lapina & Zakieva, 2021). Bamboo has been utilized extensively as a structural and non-structural construction material in many traditional homes throughout Asia and Indonesia. Bamboo is frequently thought of as an inexpensive, transient material (Nurdiah, 2016) despite its many uses. Due to a widespread prejudice against its use, many contemporary builders even call it "the poor man's timber" (Lobokivov *et al*., 2009). Bamboo's fibers are incredibly robust, making it an excellent choice for building. Its tensile strength is on par with steels, while its compressive strength is double that of concrete. Furthermore, bamboo fibers can span longer distances and have a higher shear strength than wood. Bamboo's ability to bend without breaking is one of its special qualities. Bamboo even outperforms steel, which has a tensile strength of around 23,000 N per square inch,

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with a tensile strength of over 28,000 N per square inch (Anagal *et al.*, 2010; Nurdiah, 2016). Bamboo used in construction requires preservation, as it is vulnerable to termites and fungi. It is commonly treated with a borax-boric acid solution through methods like soaking or injection, which effectively extend its lifespan (Purwito, 2015).

Frank Lloyd Wright used the phrase "organic architecture" in his essay "The Language of Organic Architecture." The shapes and patterns seen in nature serve as the inspiration for organic forms. Structures built on these designs frequently have distinctive, eye-catching aesthetics that defy accepted reasoning. According to Sarkisian *et al.* (2008) and Nurdiah (2016), irregular geometries are usually the result of such spontaneous inspirations. The use of bamboo as a construction material is being investigated more and more by academics, architects, and builders. Bamboo's structural qualities are being pushed to the maximum as architectural forms change to become more organic, fluid, and dynamic. Researchers are looking at what form's bamboo can sustain, how it can shape buildings, and which techniques work best for creating unique bamboo structures. Because of its inherent strength and flexibility, bamboo has shown a lot of promise for usage in naturally curved building. To attain their distinctive designs, these buildings frequently use form-active or semi-form-active structural systems (Nurdiah, 2016).

Bangladesh has a tropical monsoon climate and is situated in northeastern South Asia, roughly between 20°75'N and 25°75'N. With the exception of the mountainous parts in the northeast and southeast and a few raised sections in the north and west, the nation is primarily flat with fertile plains (Alam *et al.*, 2015; Banik, 1988). Bamboo grows all around the nation because to these ideal soil and temperature conditions. Across around half a million hectares of land, Bangladesh is home to 33 species and 9 genera of bamboo. While 26 distinct kinds of bamboo are grown on the remaining 300,000 hectares in village areas, the remaining 200,000 hectares are forest regions where seven species grow naturally (Chowdhury, 2022). Bamboo resources are abundant in Bangladesh and are essential to the ongoing growth of the national economy. Although bamboo is widely available in Bangladesh, we have not yet made full use of this valuable natural resource in extensive building projects. Bamboo has always been utilized extensively in rural regions, particularly for temporary construction, fencing, scaffolding, and basic shelters. But even in rural areas, its usage has been steadily decreasing, mostly as a result of inadequate preservation and treatment methods. Bamboo that has not been treated is extremely susceptible to pests, dampness, and rot, which shortens its lifespan and decreases its structural dependability. This has hampered its use in more formal or permanent architectural projects and added to a growing skepticism of its permanence. However, there have been few noteworthy outliers that demonstrate bamboo's potential in contemporary vernacular building. Examples of innovative projects include the Arcadia Education Centre in South Kanarchor - Anandaloy Building and the METI Handmade School in Rudrapur (Arcadia Education Project, South Kanarchor, 2016; ArchDaily, 2010; ArchDaily, 2021). These architecturally skilled structures combine bamboo with other regional materials and showcase creative, environmentally conscious, and sustainable design principles. Their accomplishment serves as an example of how bamboo can be used to construct effective, visually pleasing, and climate responsive architecture when the right methods and careful planning are applied. Bamboo, on the other hand, has become a popular building material in nations like Bali and Indonesia. They have created sophisticated engineering systems, preservation techniques, and even parametric design techniques to create incredibly intricate organic shapes out of bamboo. Large-scale bamboo buildings including residences, resorts, and schools have been created by renowned architectural firms like Ibuku in Bali, pushing the limits of bamboo construction both aesthetically and physically.

The purpose of this project is to investigate how bamboo and other natural materials are used in Bangladesh, with an emphasis on how they are used in small-scale architectural forms that are influenced by organic design ideas with structural strength. In order to improve bamboo's sustainability, durability, and appropriateness for contemporary building, it will look into its structural and material qualities. Along with evaluating public structure and the viability of implementing such buildings in practical settings, the study may open the door for a wider incorporation of bamboo architecture into modern practice. This study aims to support a more sustainable and contextually sensitive architectural approach in Bangladesh by fusing traditional materials with organic design and structurally practical construction techniques.

MATERIALS AND METHODS

The methodology of this study will be primarily driven by primary data collection, complemented by extensive secondary data analysis. The research will commence with case studies of parametric bamboo structures from around the world to gain insight into global practices, design strategies, and innovative applications. For the development of the project, the study will also examine traditional and natural construction techniques practices often rooted in everyday life and passed down through generations, whether consciously or unconsciously and assess how they can be effectively integrated into modern construction systems. Emphasis will be placed on evaluating the relevance and adaptability of these techniques within contemporary architectural contexts. Further exploration will involve material studies focusing on natural resources for both structural and surface components. The design process will include the simultaneous development of physical prototypes and computational models, allowing for a cohesive integration of form, structure, and surface. Later stages will involve the selection and performance testing of materials, particularly in terms of weather resistance and waterproofing. The final deliverables will consist of detailed architectural drawings, material specifications, and scaled physical models that demonstrate the practical feasibility and design potential of the proposed bamboo based structural system.

Case Study Analysis

The Swirling Cloud Pavilion, located in a grove on the university campus, was created for the 2018 "Bamboo Garden Festival" on commission from Beijing Forestry University academics. The pavilion, which is 120 square meters in size, was used as an information booth during the festival and is still used as a versatile area for socializing, resting, and meeting people. The design emphasized flexibility and structural freedom, making use of the site's wide and unfettered surroundings. The design process began by leveraging bamboo's natural strengths—its superior bending and tensile resistance compared to wood. Using modern processing and digital technologies, bamboo components were precisely shaped and bent in factories, then assembled on-site. Digital tools ensured that the curved forms aligned with structural stresses and construction practices, allowing accurate realization of the conceptual design. Bamboo was chosen as the main building material because of its remarkable tensile strength, resistance to bending, and sustainability. Whether handled on-site or in sophisticated manufacturing settings, raw bamboo is much more malleable and simpler to shape than wood. The bamboo maintains its shape and doesn't distort when left outside after being dried and treated. These characteristics made it possible to create an organic, flowing shape that went well with the festival's natural concept and the campus setting. The roof tiles were constructed using bamboo slits and PMMA (polymethyl methacrylate) panels, which are held up by a waterproof membrane and reed mats underneath, creates a pleasing harmony between practical functionality and visual appeal (Han, 2019).

Figure 1: The pavilion, featuring spiral bamboo structures and elegant curves, harmoniously integrates with the natural environment (Han, 2019).

The TOROO Pavilion is an eye-catching piece of public art that investigates the architectural possibilities of using split bamboo as a main building material. TOROO, a bending-active grid shell structure, is a prime example of how traditional craftsmanship, digital design, and ecological building can work together harmoniously. Being the fastest-growing, carbon-sequestering natural resource available to builders, bamboo was purposefully chosen for its sustainability and versatility. It is also far more sustainable than traditional lumber. Its usage in contemporary building is further supported by its historical significance in vernacular architecture and its accessibility in quickly growing areas. Thin bamboo splits are used throughout the pavilion to emphasize the material's remarkable bendability, which is welcomed here as a crucial architectural feature rather than a drawback. Completely hand-tied, the construction adheres to exact specifications taken from a computer design environment. The pavilion's final shape was produced by a digital approach that accurately mirrored the behavior of real materials under stress using sophisticated physics simulation engines and computer-coded parameters. This computer procedure guaranteed a balance between visual lightness and structural stability. This projects effectively illustrates bamboo's structural strength and suppleness (Myers, 2019).

Figure 2: A digitally fabricated bamboo structure featuring spiraling forms and smooth curves that blend seamlessly with the surrounding landscape (Myers, 2019).

A mid-tech architecture system called Colihue Nest investigates the aesthetic, structural, and constructive possibilities of the natural bamboo species colihue. The project illustrates the material's mechanical strength and flexibility through a mix of computer modeling and actual testing, allowing for its use at architectural sizes. A logic of material aggregation forms the basis of the system, creating immersive and living worlds. Its structure consists of a paraboloidal grid shell surface enclosed by a stiff border of catenary arches. Laminated colihue canes are weaved into this three-dimensional structure in an apparently asymmetrical yet structurally sound way. By providing different degrees of density, opacity, and shade and spreading wind and environmental pressures with little resistance, the final shape resembles the dynamic characteristics of a bird's nest. Because of this characteristic, the structure is flexible, lightweight, porous, and able to bend in response to changing pressures (PA Editorial Team, 2023).

Figure 3: A mid-tech bamboo structure exploring Colihue's structural and aesthetic potential, functioning simultaneously as both envelope and framework through its flexible, versatile form (PA Editorial Team, 2023).

Traditional Technique and Natural Built Form Analysis

Traditional techniques and instruments passed on from generation to generation of indigenous knowledge and craftsmanship provide a window into the reasoning of their structures and material efficiency. One of the examples is polo, which is a dome shaped fish trap made with bamboo and in high use in shallow water areas. The polo is usually hand-made, with a short opening about 6 inches in diameter, 2-4 feet in diameter at the base, and 2-3 feet in height. It is made with thin strips of bamboo, woven and tied with flexible slips of cane. Topologically, the game is built on a good compacting of components whereby some vertical laid pieces of interwoven bamboo generate a lattice framework to provide equal division of pressure throughout the pole and avoid stress pockets for increased stability. These verticals are sheathed in horizontals, and then layered by binds, tied in places around the structure, to hold the form together and stop it "buckling" under strain. There is added value to the material of BAMBOO itself - it is flexible, strong, can bend easily, and can also withstand various environmental conditions without losing shape. Furthermore, the dome geometry has an inherent dissipation effect for applied external loads, ensuring stability and preventing overturn of the structure. The combination of traditional knowledge, material efficiency and inherent logic of structure in the polo design provides an interesting point of reference for potential models for sustainable, low-tech construction technologies (Figure 4) (Fishing Gear, 2021). On the other hand, nests built by weaverbirds are an amazing example of natural engineering, and highlight ways to achieve both strength and resilience. Birds weave their work overlapping, wherein grasses, twigs, and leaves of a pliant nature are woven together in the form of a network with each layer stronger than that which it encloses. This results in locking fibers that make one tight-knit fortress to withstand the elements and the opposition. Flexible material also makes the nest flexible, that can bend and respond to environmental stress, as well as hold eggs and neonates (Koll, 2016).

Figure 4: Natural form and structure and traditional gear used in daily life.

Design Concept

In order to combine design and improve construction feasibility, the idea is designed to take advantage of the existing form and stability of fishing gear polo. Inspired by natural solutions or forms, and in particular by concepts and applications of grid shells, the design combines roofing surfaces with selective perforation and openings to ensure shade and rain protection and to provide natural ventilation. Both traditional and biological structures are examined and it is found that among the structures which consider in this paper, overlapping or intersecting structures are most stable because they have more joints connected and load distributes more evenly which in turn requires less deformation. These woven lattices also make it possible to design with free form shapes, segmented spaces, and opens, and control of the openings without worrying about the overall form. Overlapping and crossing fibrous webwork the design of course holds the surface skin, but it also simultaneously constitutes the primary/secondary structural system. And a spherical or dome form, famous for being stable can be obtained and is Sustainable for making lightweight stimulative parametric structures through bamboo.

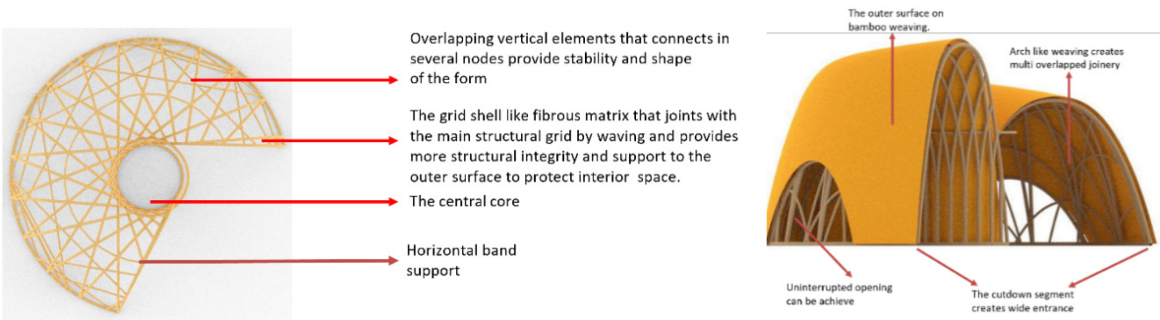

Figure 5: Concept and massing form development
Source: Author

Material Selection

For the design, mitinga bamboo (Bambusa tulda) was specifically selected due to its availability and structural suitability for the project's needs. This species is not only abundant in the region but also known for its strength, flexibility, and lightweight nature ideal qualities for modular and sustainable construction. The bamboo was carefully harvested from its natural environment, then stored and prepared with attention to maintaining its integrity (Figure 6). To ensure durability and resistance to pests and decay, basic bamboo treatment was carried out. This included soaking the culms in a borax-boric acid solution a common, low-cost, and eco-friendly method. This simple treatment significantly extends the bamboo's lifespan, making it more resilient for architectural applications while remaining accessible for small-scale or urban construction projects.

Figure 6: (From left to right) The source of the bamboo Culm; storage of the bamboo; Mitinga shows mature strong node at 700-900mm distance; Relatively straight, large internodal distance
Source: Author

In bamboo construction, adherence to building codes and technical guidelines is vital for ensuring safe, sustainable, and efficient project outcomes. In Bangladesh, the Bangladesh National Building Code (BNBC) provides comprehensive standards for bamboo construction, including detailed classifications and mechanical data for various species. Mitinga bamboo (Bambusa tulda) is listed under Group B, Special Grade for its excellent structural performance and suitability in load-bearing roles. The BNBC documents the variation of mechanical properties along the culm height: the modulus of elasticity (MOE) ranges from 114 kg/cm² at the bottom, 140 kg/cm² at the middle, to 166 kg/cm² at the top; the modulus of rupture (MOR) decreases from 883 kg/cm² (bottom) to 745 kg/cm² (middle) and 671 kg/cm² (top); while the compressive strength increases from 529 kg/cm² at the bottom to 596 kg/cm² (middle) and 620 kg/cm² (top). These values are critical for accurate input into structural analysis software like Karamba3D, enabling precise digital simulations and optimized bamboo-based designs that align with sustainable architectural practices.

For the roofing material, various natural options were investigated to identify a suitable solution capable of providing effective shading and protection from rain. Initially (Figure 8), hogla leaves were considered for direct weaving onto a grid structure. However, this approach proved unsuitable due to the large scale of the structure and the inability of the leaves to remain securely attached to the grid without additional binding or support. Subsequently, alternatives such as mat tiles made from hogla leaves and bamboo mats (chatai) were explored as potential roofing materials. These options demonstrated promise in delivering adequate shading and rain protection, while aligning with the project's emphasis on sustainability and the utilization of locally available resources. Compared to hogla leaf mats, bamboo mats are preferred due to their denser weaving pattern and greater structural strength. Nonetheless, challenges were encountered in effectively sealing the perforations using binding materials, which risked producing a rigid and less flexible surface. This necessitates further refinement to optimize bamboo mats for rain protection applications. Mats made from shital pati or cane presented more favorable outcomes, owing to their intricate weaving patterns and inherently flexible material properties. Despite having fewer perforations, these mats can be filled with binding agents without compromising their flexibility or creating a hard surface. Consequently, shital pati emerges as an ideal roofing material, offering a balance of functionality, durability, and suitability for rain protection.

Figure 8: (From left to right) Hogla leaves single weaving and hogla mat weaving, bamboo mats (chatai), shital pati or cane sheet
Source: Author

Material Preparation

To enhance the surface waterproofing and improve rain protection, the material was coated with a mixture of resin (in a 2:1 ratio) and Arabic gum as a binder. While the Arabic gum alone did not significantly contribute to waterproofing, the resin-coated surface effectively prevented water leakage. Multiple applications of the resin coating yielded increasingly satisfactory results. The resin imparted hydrophobic properties to the surface, causing water to run off rather than penetrate or drip through the material. Applying a layer of epoxy resin to a 4 square foot shital pati, a traditional woven mat, can improve its water resistance. Because of its excellent bonding and moisture-resistant qualities, epoxy resin is frequently used to waterproof natural textiles. When applied thinly, epoxy resin typically covers 12 to 16 square feet per 100 milliliters. Applying at least two coats is advised for sufficient water resistance. According to this calculation, a 4 square foot area would require 50 to 70 milliliters of resin in total, with 25 to 35 milliliters needed for each application. The shital pati's surface should be carefully cleansed and dried before application to provide good adherence. According to the manufacturer's recommendations, a brush or roller can be used to apply the resin for even coverage, and enough curing time must be given in between applications. This process adapts the material for long-term and practical usage while enhancing its durability and preserving its classic appearance. This behavior was confirmed through a 24-hour exposure test conducted under natural open-sky conditions, during which no water leakage occurred; instead, water merely shifted position on the surface (Figure 9).

For weatherproofing, additional protective coatings such as clear varnish and linseed oil were applied. However, it was observed that the clear varnish, being a chemical treatment, altered the material's natural appearance by imparting a glossy finish. Therefore, a preference was established for natural, non-toxic solvents in combination with linseed oil for the treatment of bamboo. This method provided effective weather resistance while preserving the bamboo's natural aesthetic and promoting environmental sustainability. Both the linseed oil and resin-coated surfaces demonstrated valuable performance after two days of experimental observation (Figure 9).

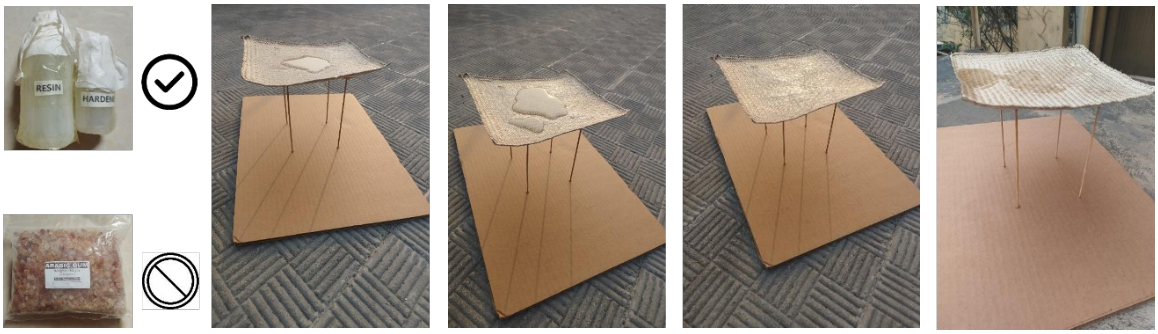

Figure 9: (From left to right) testing of resin and linseed oil coated shital pati weaving mat for understanding its durability, strength
Source: Author

Joinery Analysis

Traditional joinery techniques for bamboo encompass a variety of methods to securely connect bamboo poles without relying on nails, screws, or adhesives. These vernacular joinery practices are deeply rooted in the inherent characteristics of bamboo and are governed by unwritten rules, established standards, and cultural norms. The advantages of traditional bamboo joinery include its sustainability, as it avoids the use of metal fasteners and synthetic adhesives; its adaptability, allowing for flexible and resilient structural connections that accommodate bamboo's natural movement; and its ease of assembly and disassembly, which facilitates repair, reuse, and recycling of materials also the development of handcrafted connections using moorings made from polyester and polypropylene ropes enable the assembly of bamboo structures even in remote locations around the world. Additionally, these methods enhance the aesthetic value by preserving the natural appearance of bamboo and promote local craftsmanship and cultural heritage. Such time-honored techniques can be seamlessly integrated into modern bamboo construction, either in their original form or with appropriate enhancements to meet contemporary performance requirements (Seixas *et al.*, 2016).

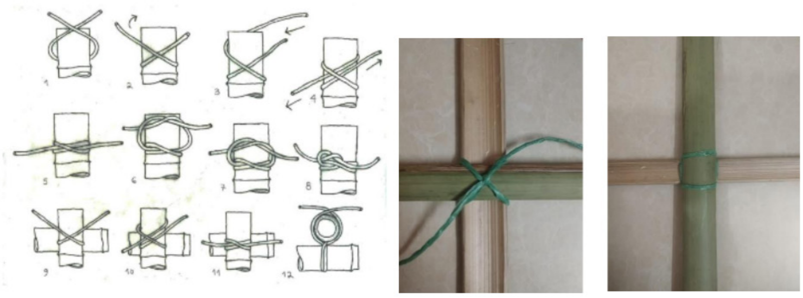

Figure 10: Joineries
Source: Author

Modeling In Karamba

For the structural analysis of the parametric organic structure, Rhinoceros 3D with Grasshopper and the Karamba3D plugin were utilized. Grasshopper enabled efficient and flexible generation of complex, organic parametric forms, while Karamba3D facilitated real-time structural feedback, allowing for informed design decisions during the iterative development process. During the final massing development phase, multiple design iterations were conducted to refine the structural logic and spatial configuration. The primary structural system consists of a layered bamboo framework, inspired by both traditional joinery techniques and natural structural principles. The system incorporates two distinct cross-sectional dimensions of bamboo strips, selected based on their specific structural roles. Primary Structural Elements The main load-bearing elements are bamboo members with a cross-section of 40mm × 15mm (I-profile), which function as the primary ring supports. These elements were modeled in Karamba3D as line elements, with custom material properties defined manually in the material editor. Bamboo, being a naturally anisotropic material, was modeled as an orthotropic material, accounting for directional mechanical behavior. The following values were input based on literature and empirical data- Young's Modulus (Dir 1 & Dir 2), In-plane Shear Modulus, Tensile Strength (Dir 1 & Dir 2), Shear Strength (in kN/cm²). Secondary structural grid shell complementing the primary ring, a network of 20mm × 10mm bamboo strips forms a lightweight grid shell, resembling a bird's nest structure. These elements interlock and overlap to create a continuous shell, distributing loads efficiently. Similar orthotropic material properties were defined for these members in Karamba3D. Support conditions were defined using point supports in Karamba3D, strategically placed to simulate realistic boundary conditions. For load analysis, both self-weight (gravity loads) and variable point loads were considered to evaluate structural performance under diverse environmental conditions such as wind pressure, rainfall accumulation, or human interaction loads. Overall, this integrated method of structural modeling combining parametric generation, real-time analysis, and material-specific simulation allowed for a design that is contextually rooted, structurally sound, and materially expressive.

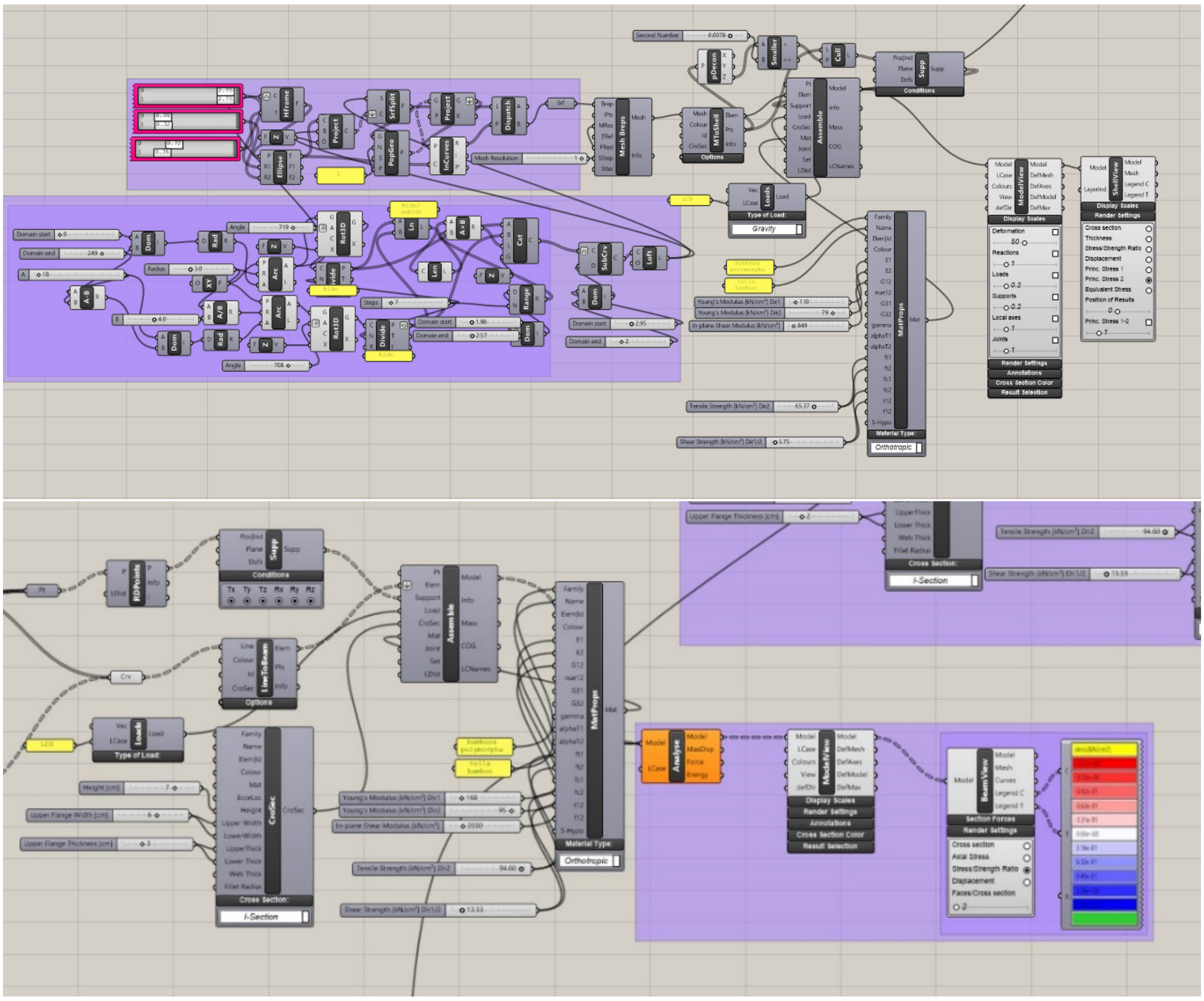

Figure 11: Grasshopper definition showcasing parametric bamboo grid shell geometry with real-time structural analysis using Karamba3D
Source: Author

The Karamba3D "BeamView" analysis results for a parametric bamboo grid shell structure, visualizing displacement (top) and axial stress (bottom) across its components. The displacement legend (in cm) ranges from a minimum of 1.16e+01 to a maximum of 1.16e+02, with the average around +3.47e+01. While some secondary supporting arches exhibit relatively higher displacement due to their slenderness and flexibility, the main structural ring shows significantly lower movement, indicating its effective performance in stabilizing the system. The horizontal elements also participate in the load redistribution and show manageable bending behavior, which is expected given bamboo's orthotropic nature responding differently along and across its grain under load. Importantly, the overall displacement remains within a tolerable range for lightweight natural structures, and with further refinement such as optimizing cross-section dimensions, adding intermediate supports, or enhancing joint stiffness—this performance can be improved for real-world application. The axial stress results (in kN/cm²) reveal a balanced pattern of tension (blue) and compression (red), with maximum values at +1.26e+00 (tension) and –1.32e+00 (compression), and average stress levels near ±3.3e–01. The stress distribution highlights structural efficiency, as the supporting arches bear dynamic compression-tension behavior while the

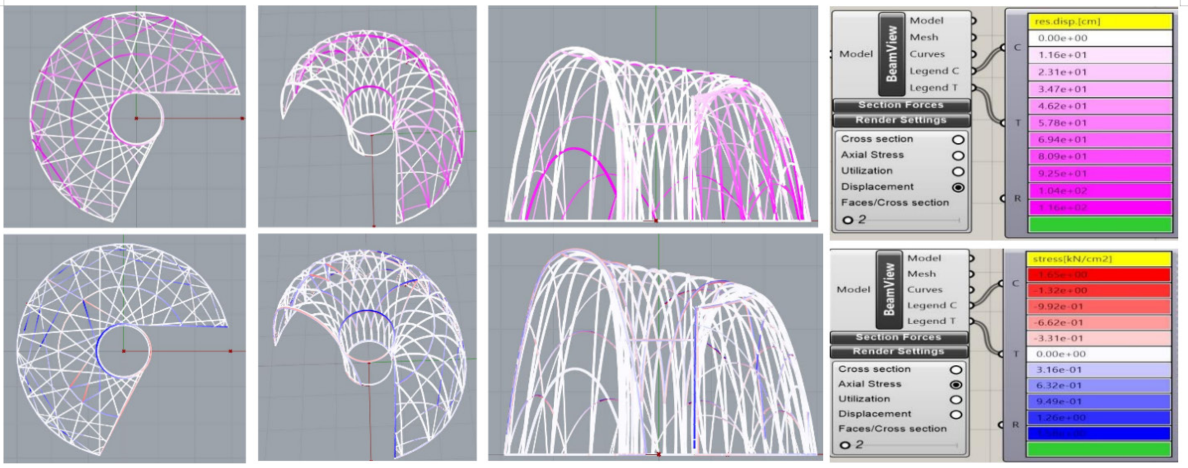

Figure 12: The structures displacement and stress measurement
Source: Author

main ring remains largely neutral, efficiently distributing loads. These outcomes affirm the accuracy of the orthotropic bamboo model and its potential in flexible parametric construction, especially when paired with careful calibration of material properties and section geometries to ensure displacement control and structural integrity under loads.

Following the basic shape's research into structural stability and validation, the design then advanced into material specification and considerations for its real-world application. The geometrical information was sent from the parametric model in Grasshopper to AutoCAD and SketchUp to be able to be documented and built with a high level of precision. This allowed to accurately pull and analyze joinery configurations and structural dimensions. Number of bamboo strips, identification and counting location of the joinery components and examination of their individual lengths and profiles were all carried out as part of a comprehensive inspection of the bamboo members. The research also plotted the numbers of rods that need merge at each joint, and the locations of all critical junction positions. Support points were also evaluated with regard to number and spacing in order to ensure structural stability and load distribution. This part of the project achieved a linking between digital design phase and the production based on the material as well, all necessary data was generated for the structural detail drawing production. The module data and illustrations are used to produce the physical proto-type and final construction of the modular bamboo

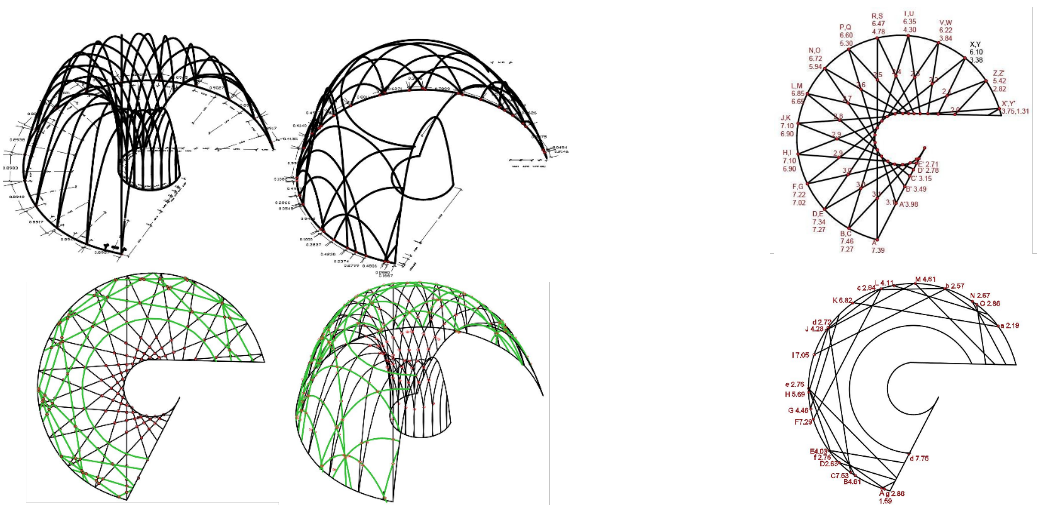

Figure 13: Construction, joinery counts, junction positions, support point distribution, and bamboo strip lengths are all shown in the structural development design for the bamboo framework
Source: Author

Shital Pati tiles, a traditional woven mat material made from Murta (Schumannianthus dichotomus), are used as the main cladding element on the roof surface of the bamboo shell construction (Figure 14). Traditionally crafted by hand, this natural material has been transformed into a modern parametric framework. The bamboo grid shell underneath supports the hand bonded tiles with wire. Through the promotion of regional handicraft and renewable resources, this integration not only increases the structure's sustainability but also guarantees cultural and material contextual significance. The following sequential workflow was used in Rhinoceros 3D to complete the digital modeling and surface penalization process. Step 01 Surface generation, the initial design was defined by generating a lofted geometry, derived from a network of guide curves. This lofted geometry was then converted into a NURBS surface to serve as the base for penalization. Step 02 Surface Discretization, the NURBS surface was divided into a mesh grid, optimized for both visual uniformity and fabrication feasibility. The grid resolution was carefully chosen to ensure a balance between structural support, material flexibility, and tile handling ease. Step 03 Mesh Topology, the mesh subdivision resulted in a total of 2,002 quadrilateral and 1,297 triangular polygons, allowing for maximum surface coverage with minimal material waste. This mixed tiling strategy supports the surface curvature more effectively than pure quads or triangles alone. Step 04 Surface Unrolling for Fabrication, the subdivided surface segments were unrolled to create 2D templates for fabrication. A total of 239 mesh panels were unrolled, and the area deviation between the 3D and 2D surfaces remained within acceptable tolerance levels, ensuring geometric fidelity and precision in the physical prototyping stage. Step 05 Module Organization, each split section of the roof consists of five parts of varying sizes, scaled appropriately for efficient installation and ease of handling. These modules are intended to be assembled manually, maintaining the material's flexibility while accommodating the complex curvature of the roof form. This methodological workflow enables the translation of traditional material culture into a contemporary architectural expression, fostering a synergy between parametric design tools and vernacular construction techniques. The approach also supports modular prefabrication, reduction of construction waste, and ease of transportation and on-site assembly.

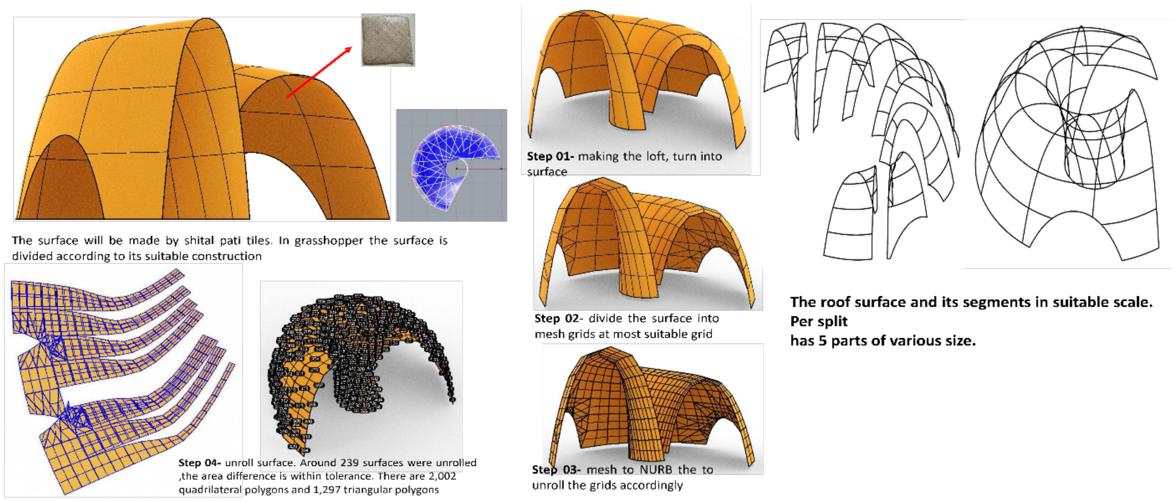

Figure 14: The surface development and construction details
Source: Author

In order to reduce the complexity of installation, Figure 15 provides a step-by-step illustration of the entire construction process. To guarantee clarity, boost productivity, and make it easier for both skilled and unskilled workers to understand, each step has been meticulously ordered. The system's modular design, which permits simple assembly, disassembly, and possible component reuse, is also highlighted by this visual breakdown and figure 16 shows the final outcome visualization of the project.

Material Selection And Estimation Strategy

A thorough material estimation chart that enumerates the major and secondary materials utilized in the construction of the Shital Pati roof system and parametric bamboo grid shell has been created in order to guarantee structural sustainability and efficiency. Split bamboo, complete bamboo culms, and traditional woven cane mats (Shital Pati) for the surface finish are among the natural, locally obtained materials used in the selection. While surface and binding materials like resin, linseed oil, nylon rope, and wire have been assigned based on functional requirements like waterproofing, flexibility, and joint reinforcement, each material type has been assigned based on its structural role, ranging from load-bearing rings to grid shell members and supporting columns. A combination of drawing-based measurement and parametric modeling has been used to estimate quantities, guaranteeing accuracy in execution while accounting for variations in the dimensions of natural materials. Informed choices for building design, sustainability evaluations, and procurement are also supported by the estimation in the Table 1.

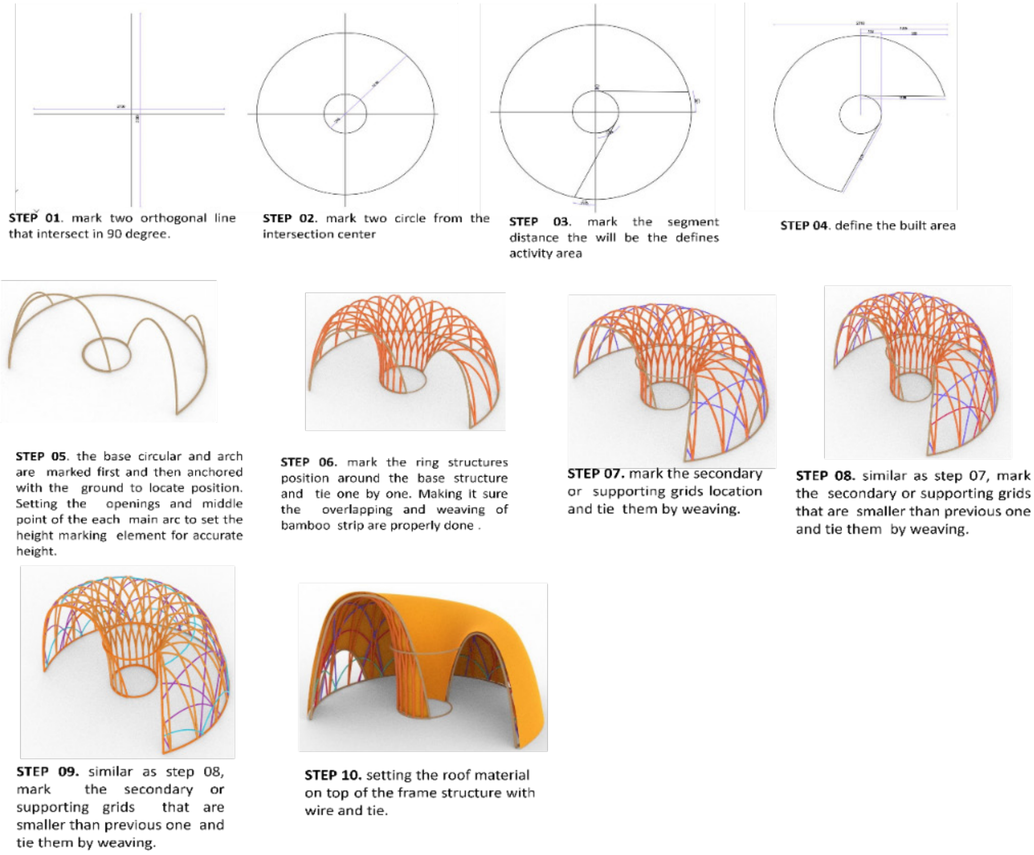

Figure 15: The construction and development phase of the bamboo structure
Source: Author

Figure 16: The construction and development phase of the bamboo structure
Source: Author

Table 1: Estimation of materials

Type	Material	Measurement mm	Amount	Length/ amount
Main structural elements	Bamboo split	40/15	33	Various, Max-7.39m Min-2.71m
Grid shell	Bamboo split	20/10	25	Various Max-7.53m Min-1.59m
Base binder	Bamboo split	20/10	3	various
Roof surface	Cane weaving shital pati	Various (measurement from drawings)	35	Various (Measurement from drawings)
Height determining support	Bamboo culm		15	Various Max-3.1 m, Min- 2.0m
Binding material	Nylon rope, wire		Depends on nodes (230)	
Roof binder	Resin (2:1)		Number of Coatings 2 coatings (optional 3rd UV top coat), Total Resin Mixture Approximately 25 liters	
Weather protective material	Linseed oil		Number of Coatings 2–3 coats recommended Linseed Oil (per coat); ~150–200 ml per sqm Total for 2 coats; 5–6.5 liters	

Source: Author

RESULTS AND DISCUSSOIN

This project primarily focuses on using bamboo, a naturally occurring material that is widely accessible in our context, and promoting parametric and organic structures in public settings to demonstrate and explore bamboo's physical capabilities to construct an organic structure with the least amount of expense and trouble. Figure 17 shows how the built prototype successfully demonstrates the interplay between digital tools, traditional building techniques, and natural forms. In accordance with the results, a 1:5 m scaled model was constructed, using Table 01 to scale the bamboo splits of the main structural ring and grid shell and the construction process followed to Figure 15's detailed instructions.

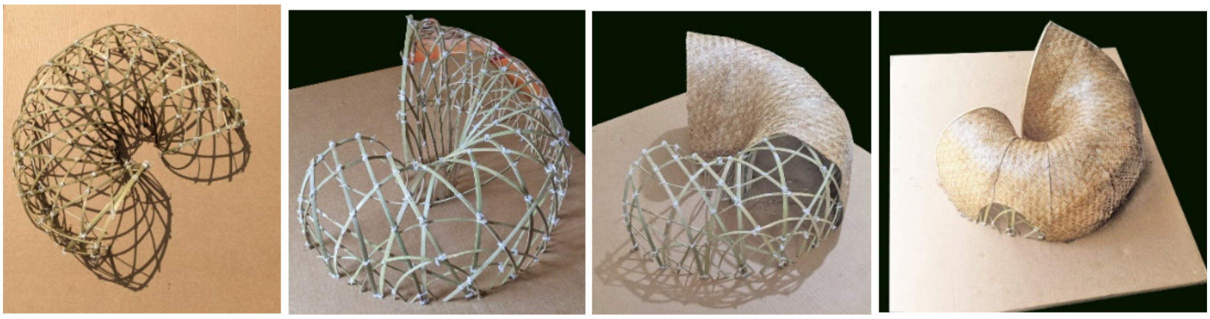

Figure 17: (From left to right) The main bamboo structure; the surface installation and final scaled model
Source: Author

The digital interpretation of natural patterns such as polo traps, weaver bird nests, and fishbone structures guided the development of forms that are both spatially expressive and structurally efficient. Traditional joinery techniques like lashing, notching, and splitting were employed in place of metallic fasteners, reducing dependency on foreign materials and enhancing the structure's flexibility. This approach not only honored indigenous construction knowledge but also aligned with sustainability goals. Moreover, avoiding metal fasteners mitigates common issues like corrosion and rust, which can compromise the structural integrity of bamboo. Advanced computational tools such as Grasshopper, Rhinoceros 3D, and Karamba were used to translate these biologically inspired geometries into adaptable, scalable digital models. By manipulating curvature and internal tension within structural members, the digital design process enabled precise control over both aesthetic form and structural behavior. The parametric design system enhanced design efficiency by allowing rapid testing of various configurations with minimal code adjustments. Simulation and analysis revealed strong resistance to both vertical dead loads and lateral wind forces, attributed to the triangulated geometry and the natural flexibility of bamboo joinery. Additionally, the integration of curved elements promoted a more uniform distribution of tension and compression forces, effectively reducing bending stress and improving overall structural stability and performance. The overall outcome of this project demonstrates that with the integration of proper structural and computational analysis, it is indeed feasible to construct diverse organic forms using bamboo as the primary material. combining digital tools with inspiration from natural geometries and traditional joinery techniques, the research successfully developed a structurally viable and aesthetically expressive bamboo structure. The study highlights that natural forms when digitally interpreted and structurally rationalized can guide the creation of lightweight, flexible, and sustainable architectures.

If this structure had been built using wood or other conventional materials, the cost would have been significantly higher, and the flexibility needed for organic form generation would have been compromised. Similarly, constructing such a fluid, parametric form using rigid materials like brick or concrete would have presented major technical and financial challenges. Bamboo's natural elasticity, lightweight nature, and ease of manipulation make it uniquely suited for these types of forms, offering both design freedom and structural resilience.

Though the project may face some limitations while constructing in real scale such as issues with material preservation and a general lack of skilled labor in bamboo construction, these challenges can be overcome through community involvement, local craftsmanship training, and shared learning. Most importantly, the outcome of the project will directly align with its initial objectives, to combine traditional bamboo techniques with digital design tools in order to produce a structurally sound, sustainable, and culturally grounded architectural solution.

The project's outcomes show how using locally available and renewable resources, like bamboo, can greatly lessen reliance on imported or high-carbon materials, like steel and concrete. In addition to being more economical and labor-efficient, the construction system supports sustainable building techniques. The structure is especially well-suited for use in areas of Bangladesh that are prone to earthquakes or flooding because of its lightweight and flexible nature. Its versatility also makes it perfect for temporary installations, public gathering places, and community centers, providing a robust, affordable architectural solution rooted in both innovation and tradition.

Discussion

This project will enabled further research into structural innovation, creative form generation, and integrating traditional craft skills of bamboo with modern approaches to design. The project demonstrates the potential of context responsive architectural resolutions in Bangladesh using locally available materials such as bamboo and Shital Pati and organic and parametric structural concepts. This work inspired reconsideration of the underrealized potential of bamboo, as imaginative structural systems and material investigations are still virtually undeveloped in this sector. Given the full-scale work and assembly, the research contributes with a basis for more effective methods concerning, for example, joinery, facade treatment and modular houses compatible with local practices and climate. It would be interesting in the future to investigate the incorporation of other natural or bio-based materials as jute composites, hempcrete, and clay-based coatings for further thermal performance, mechanical strength, and sustainability. Further studies in life time durability, environmental behavior and weather resistance of natural materials for instance bamboo and Shital Pati can further enhance the potential of this type of construction in rural as well as urban context. The assessment of the insulation of the thermal and waterproof features would be meaningful for their wider utilization. Finally, in the construction process, community participation and playing of skills are encouraged; all these lead the local artisans and the public to a better understanding of the architectural possibility of bamboo. This not only reinforces the cultural connection to the traditional craft, but also prepares the way for participative, sustainable and locally oriented architectural practices.

CONCLUSION

This project demonstrates how bamboo a natural, renewable material deeply rooted in traditional construction practices can be effectively used in contemporary architectural applications that are not only structurally stable but also visually expressive. By merging indigenous craftsmanship with digital design tools, the study presents a sustainable and contextually relevant design strategy that repositions bamboo as a material of architectural innovation rather than one associated with poverty or low-cost shelter. The prototype successfully showcases the potential of using parametric design and natural form inspirations to create multipurpose public structures suited to urban contexts in Bangladesh and similar environments. It also emphasizes the value of traditional joinery methods, such as lashing and splitting, in enhancing flexibility and eliminating the need for metal fasteners promoting both sustainability and local self-reliance. However, the research acknowledges certain methodological limitations, including the challenges of material preservation, the variability in bamboo properties, and the limited availability of skilled labor familiar with bamboo-based construction. The simulation tools used also had constraints in replicating real-world weathering and joint behavior, which should be addressed in future investigations. This study meets its initial objectives by successfully developing a parametric bamboo prototype that is low-cost, modular, and context-sensitive. It also establishes a new direction for integrating traditional techniques with digital processes in architecture. For practical application, this approach can be adopted for community centers, disaster-relief shelters, temporary installations, or educational spaces particularly in flood-prone or earthquake-sensitive regions where lightweight, flexible structures are beneficial. Community training initiatives and local workshops can help scale this system affordably and efficiently. Future research should focus on real-scale construction testing, long-term durability and maintenance strategies, fireproofing and treatment methods for bamboo, and expanding this system to hybrid typologies using other local materials. Integrating passive environmental simulations such as ventilation, solar gain, and thermal comfort would further enhance the architectural performance of such structures. By offering a replicable and adaptable solution rooted in both tradition and technology, this project lays the groundwork for future-ready, eco-conscious architecture in Bangladesh and beyond.

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