2026

A Modular Bamboo Wall System for Seismically Stable, Low-Income Housing in Assam, India

A4 REPORT Masterthesis TU Delft

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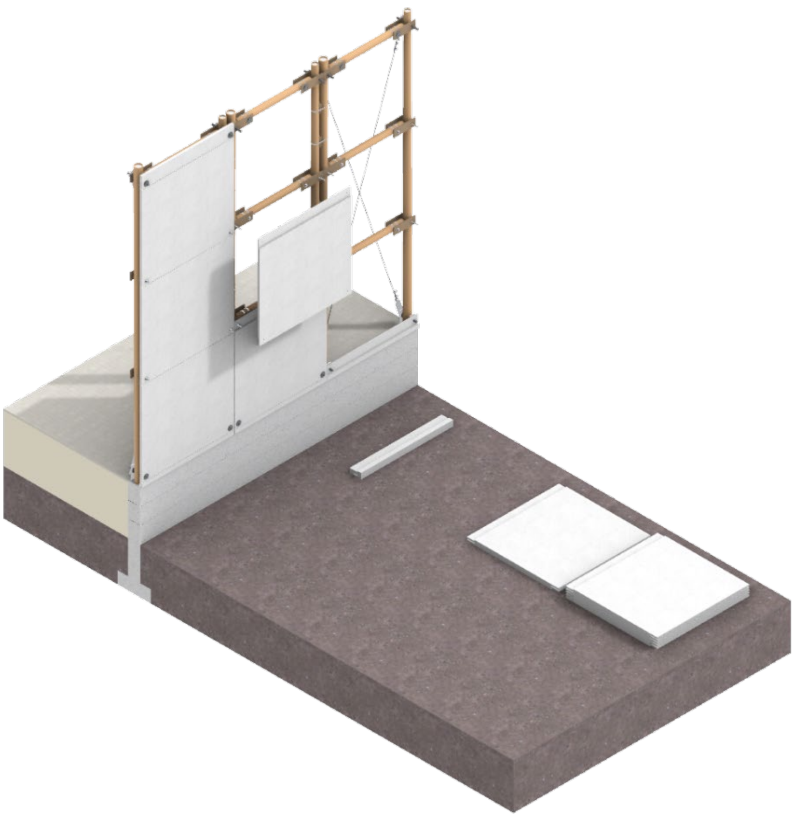

Acknowledgements:

would like to begin by expressing my sincere gratitude to my mentors, Stijn Brancart and Marcel Bilow, for their guidance throughout this thesis project. Your patience, encouragement, and willingness to share your knowledge helped me navigate subjects that were entirely unfamiliar to me. Your expertise and critical insights helped shape this thesis and I have learnt a lot about being a researcher.

I would also like to thank my fellow students who worked alongside me throughout this journey. Although each of us conducted our own research projects, sharing both our excitement and concerns have made the experience far more rewarding. Your support, discussions, and camaraderie provided motivation during challenging moments and helped make this demanding period an enjoyable one.

I would also like to thank my family for their unwavering support throughout my studies. Your encouragement, patience, and confidence in me have been a constant source of motivation. The late night calls have been invaluable for comforting me and getting me to sleep again.

Completing this thesis has been both a challenging and rewarding experience. It has provided me with the opportunity to explore a field far beyond my original expertise and has contributed greatly to my academic and personal development.

Abstract

Rural and low-income housing in Assam, India, is undergoing a quiet but dangerous transition. The traditional Assam-type house - a lightweight bamboo and timber-framed structure with a documented record of surviving major earthquakes - is being replaced by unreinforced masonry and concrete, materials that perform poorly under seismic load. Two pressures drive this shift: a cultural perception of concrete as modern, and the increasing scarcity of structural timber. The result is a significant increase in seismic risk for the communities that are most vulnerable.

This thesis asks whether the structural and vernacular logic of the Assam-type house can be carried forward in a modular form that competes with concrete and masonry. The proposed answer is a modular bamboo wall system, developed using the Modular Function Deployment Adapted (MFDA) method through two design iterations. The system uses Guadua bamboo as a structural proxy for native Assam species, IS 1893 for seismic loading, and a parametric Karamba3D model to compare bracing configurations against hard and soft criteria covering modularity, buildability, structural, and seismic performance.

The final system comprises three module types: a 1×3 structural culm module, a panel cladding module, and a corner steel-cable bracing module. It satisfies all hard criteria, achieves a modelled storey drift of 1.57% against an 8% benchmark, weighs 49 kg in its heaviest module, and is buildable on-site by two people using only hand tools. The cable bracing acts as a ductile fuse, dissipating seismic energy in tension yield before any bamboo element reaches its compressive limit.

The result is a viable design proposition: a modular bamboo wall system that, pending full-scale physical testing and material substitution with native Assam species, offers a structurally sound, locally buildable, and culturally continuous alternative to the masonry and concrete construction currently displacing the Assam-type house.

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1. Introduction

Disaster Prone Regions

Countries that are prone to natural hazards such as earthquakes, flooding and extreme weather events are constantly at risk of large infrastructural damages. In 2015 alone, globally, 68 million people were affected and US $66.5 billion dollars in damages were recorded (UNISDR Annual Report 2016, 2016). India is one of the most disaster prone countries in the world which hosts 1/6th of the world population, experiencing floods, drought, typhoons and earthquakes annually (Patel et al., 2024). Low-income and rural regions are especially vulnerable as inhabitants lack the capital to properly prepare for these hazardous environments and to adequately rebuild once they have been impacted.

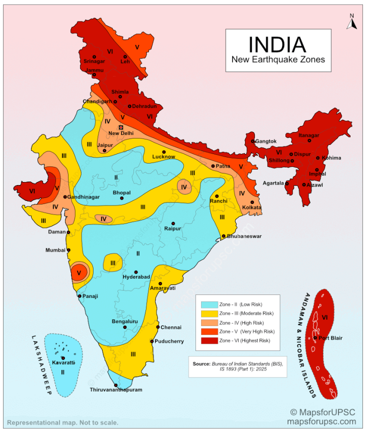


Figure 1 - Sharma S. (2025). Earthquake prone areas in India. Seismic Zones of India: Earthquake-Prone Areas with New Map

Figure 2 - Assam, India highlighted in red.

Assam, India – A Socio-Geographic Review

Assam is a region in India which is considered high-risk as it lives entirely in a high seismic Zone (classification V) and experiences seasonal flooding and hurricanes regularly. Disaster resilient housing programs in the region either don't reach rural populations effectively or focus on single hazard solutions which don't perform well when hazards combine (Das & Mukhopadhyay, 2018). Poverty is also a common issue in Assam, especially in rural areas, partly due to these extreme weather events and natural disasters which impact their housing and agricultural livelihood. About 42% of the population lives in a rural setting which is higher than the national average (Rahman & Mehnaz, 2024). In Assam, multidimensional poverty affects 33% of the total population, also making it one of the poorest states in the country (Paranan Konwar, 2020). Part of the reason for this poverty is due to rapid population growth, frequent natural disasters, geographical remoteness, and housing deprivation, the latter of which affects 69.3% of the population. Rahman & Mehnaz (2024) further mentions additional restraints to the state's economic development coming from a lack of skilled labour, underutilization of their natural resources and limited entrepreneurship.

The Extinction of Vernacular Architecture

Traditional vernacular architecture is also being abandoned for contemporary masonry and concrete structures for its perceived durability and improved status (Sharma, 2025). Assam is known for its bamboo/timber framed housing called Assam-type or Ikra-type which has proven to be effectively resistant to certain extreme conditions like earthquakes (Pathak et al., 2020). This is credited to the bamboo culm walls which are extremely ductile and lightweight. Bamboo is praised in international circles for its earthquake resilience, high strength to weight ratio and high production rate making it ideal for rural construction (Adier et al., 2023). Unfortunately, this valuable vernacular knowledge is being replaced for non-engineered masonry structures which are historically terrible and dangerous during earthquakes and cyclones. This cultural shift is taking place across the world despite the additional costs and increased risks. In India, 50% of the total housing consists of clay, adobe or stone walls, and another 35% of brick, which are very vulnerable constructions in seismic scenarios (Gutierrez, 2004). The destructive 1993 Latur earthquake claimed up to 11000 lives and left over a million homeless people. Some regions had lost 70% of their buildings (Gupta et al., 1998).

The Solution

The regional economic and geographic difficulties, alongside their cultural shift towards unsafe masonry construction, highlights the pressing need to rethink the construction practices of the region. An alternative method should be introduced which builds on the strengths of the local vernacular and combines it with modern techniques, while maintaining its accessibility to the local population both financially and practically, in terms of locally available materials, skills, maintenance and potentially even self-construction.

Modular building techniques could be used to offer a potential solution. Modular construction has proven to reduce construction time, lower cost and cut material waste (Zohourian et al., 2025). For rural populations that are subject to extreme weather conditions and earthquakes, a merging of low-tech construction with modularization offers the communities to create a standardized system which can easily be repeated, repaired and replaced after a disaster or natural deterioration. Not to mention, modular systems allow the isolation of failures to individual modules which can be replaced without impacting the rest of the system.

A modular approach also allows the structural behaviour of the bamboo composite walls to be properly studied and isolated. It allows for controlled experimental testing, repeatability, and a direct comparison with unreinforced earthen construction. Modularity and prefabrication also future proofs the product, allowing for different joining, layouts and reinforcement types to be designed for future alternatives.

1.1. Problem Statement

Low-income communities in seismically active regions of northeast India lack an affordable, locally buildable, and repairable structural wall system that draws on vernacular bamboo construction traditions while meeting basic seismic safety requirements. The displacement of the traditional Assam-type house by unreinforced brick and concrete construction has increased seismic vulnerability in the region, while offering no improvement in cost, buildability, or cultural continuity.

1.2. Sub Problems

- Conventional brick and concrete alternatives are energy-intensive, costly, supply-chain dependent, and require skilled labour.
- Unreinforced masonry is extremely dangerous in earthquake-prone areas and has been shown to perform significantly worse than traditional vernacular construction under seismic loading.
- Traditional vernacular bamboo construction is increasingly perceived as a low-status material and is being abandoned despite its demonstrated seismic performance.
- There is no established design methodology that combines modular construction principles, low-skill assembly, local natural materials, and seismic performance requirements.

1.3. Research Question

To what extent can a modular bamboo-based wall system provide adequate seismic performance and buildability for low-income housing in Assam, India?

1.4. Sub Research Questions

Modularity: How can modular construction principles be applied to create self-supporting, stable modules that enable efficient assembly without requiring complex connections or highly skilled labour?

Buildability and accessibility: To what extent can the module be fabricated and assembled using low-tech tools and minimal skill?

Structural system: Which combinations of bamboo and locally available materials are suitable for producing a modular building unit with sufficient cohesion and dimensional stability under gravity and lateral loading?

Seismic-relevant behaviour: How does the module and its interlocking system behave under simplified lateral loading representative of earthquake-relevant actions?

1.5. Innovation

This research addresses the gap between modular construction theory and the practical reality of low-tech seismic construction in developing regions. Modular construction is primarily developed for high-income, industrial contexts with access to materials and tools which allow for precise interfacing and tolerances. No existing design methodology combines standardisation, low-skill assembly, local natural materials, and seismic performance requirements. This research draws on the structural logic of the vernacular Assam-type house and attempts to translate it into a modular, prefabricated system that can be produced, assembled, and repaired by local communities using locally available materials and tools.

1.6. Projected Impact

The developed system has the potential to offer an affordable, locally buildable, and repairable alternative to both the declining vernacular and its seismically brittle concrete and masonry replacements. The modular prefabrication strategy reduces on-site labour and skill requirements, making construction accessible to communities with limited access to heavy machinery or expensive materials. The use of bamboo as the primary structural material reduces embodied energy relative to conventional alternatives and supports circular construction principles through replaceability and material reuse. The system aims to preserve the structural logic of vernacular building traditions while introducing the benefits of modular design: standardised elements, defined interfaces, and localised damage potential. Putting bamboo into a modern modular system changes the people's perception of it as a sign of poverty, to a real structural and environmental asset.

1.7. Objective

Design and analytically evaluate a modular bamboo wall system for low-income, single-storey housing in seismically active Assam, India. The system must be buildable using low-tech tools and locally available materials, meet basic seismic performance criteria through analytical and digital evaluation, and demonstrate modularity through standardised elements, defined interfaces, and the capacity for module-level repair and replacement without disturbing the surrounding structure.

1.8. Sub Objectives

a) Material system — identify which combinations of locally available materials satisfy the structural, buildability, and modularity criteria simultaneously, and assess the extent to which the system can reduce dependency on conventional energy-intensive materials.
b) Seismic-relevant behaviour — evaluate the lateral load performance of the wall system under monotonic loading using digital structural modelling and identify the governing failure mode and its location within the system.
c) Connection and interface development — develop a complete set of module interfaces that transfer loads effectively, accommodate bamboo's morphological variability, and allow module-level disassembly and replacement.
d) Buildability evaluation — assess the buildability of the system through scaled prototyping, digital modelling, and cross-referencing of tools and materials against local supply chains, documenting constraints, and informing design improvements.

1.9. Boundary Conditions

Scope

- Single-storey wall system for housing in Assam, India
- Bamboo as the primary structural material, supplemented by steel at critical connections where biobased alternatives are analytically insufficient.
- Modular prefabrication with on-site dry assembly

- Evaluation through analytical calculation, digital modelling, and scaled physical prototyping.

Materials

- Bamboo as the primary structural material.
- Locally available materials including cement mortar, steel threaded rod, steel cable, and timber as supplementary elements.
- Materials selected for local availability in Guwahati, verified against IndiaMART as a proxy for regional supply chains.

Construction and tools

- Buildable using simple hand tools — bolting, strapping, wedging, and lashing.
- No high-temperature processes or specialist machinery
- All precision work confined to factory prefabrication; on-site assembly requires no customisation or wet trades.

Testing limits

- Structural performance evaluated analytically using IS 1893:2016, IS 15912:2018, ISO 22156:2021, and EC3
- Digital structural modelling using Karamba3D under monotonic lateral loading.
- Physical prototyping at scale for connection and assembly evaluation
- No mechanical testing, cyclic load testing, wind, fire, or durability testing within scope

1.10. How to read this thesis

This thesis follows a three-step design methodology — *generate, evaluate, improve*.

Chapter 1 outlines the problem, research questions, and boundary conditions.

Chapter 2 reviews the four fields this research is based on: seismic design, the vernacular Assam-type house, bamboo as a structural material, and modularity. Section 2.4 introduces the MFDA framework which structures the rest of the thesis.

Chapter 3 defines the design basis and the hard and soft criteria against which every iteration is evaluated. It is useful to keep the hard and soft criteria alongside the paper so it can be referenced back to.

Chapter 4 describes the methodology and the two analytical tools developed for this work: the seismic calculation tool and the bamboo control tool.

Chapter 5 is the core of the thesis and is structured as two design iterations. The first section generates and evaluates a complete modular concept (5.1, 5.2); the second addresses its shortcomings and arrives at the final system (5.3).

The Conclusion answers the research question and sub questions. The Discussion reflects on the results and limitations of the analytical and digital methods used and suggest the next steps toward a built prototype.

2. Literature Review

This literature review will investigate the structural, material, and construction principles that will inform the development of a seismically strong and bio-based, modular wall system for low-income housing in Assam, India.

This review follows this structure:

1. The seismic design principles for resilient design
2. Vernacular construction in Assam and Northeast India, and why they have performed well in earthquakes, and why they are being replaced.
3. Bamboo as a structural material, focusing on mechanical behaviour, seismic performance, and the connection types.
4. Modular design theories and the relationship between modularity, seismic design, and bamboo construction.

This review will help identify the current practices, design principles, and general knowledge base, as well as the research gaps that support the direction of this research.

2.1. Seismic design principles

Background

Over 90% of earthquake deaths are due to the collapse of non-engineered, heavy buildings of stone, brick, and adobe. These materials all have high density, are weak in tension and in shear. Common construction characteristics leading to failure comes from a lack of ductile joints, weak mortar, unbonded joints, the absence of connections between the roof, walls and foundation, large wall openings and, most importantly, weight. Some of these issues stem from certain socio-economic reasons and some are a product of time. Large, damaging earthquakes occur infrequently and unpredictably. Populations have two ways of responding to earthquakes, either preventatively or consequently. These seismic behaviours are respectively coined as a seismic prevention culture or a seismic repair culture (Ortega et al., 2017). Unfortunately, due to the scarcity of large seismic events and rapid urbanisation, a seismic repair culture has become the norm in most developing countries, while traditional preventative techniques are being forgotten. Financial and geographical constraints prevent proper access to the modern preventative measures that are necessary for large and heavy concrete structures. All of these aspects compound and cumulatively lead to a society with weak infrastructure for seismic resilience (Arya et al., 2014).

In places such as Assam, which borders an actively growing mountain region – the Himalayas - the likelihood of a devastating earthquake is significantly higher. The Indian continental plate is currently crashing into the Eurasian plate at a rate of 47mm per year (Houseman & England, 1993) and slowly disappearing under it in an event called ‘subduction’. This results in daily earthquakes of varying magnitudes. North East India is predicted to annually have an earthquake of magnitude 6, with a magnitude of 8 or higher occurring every 50 years (Goswami & Sarmah, 1983). Properly applying seismic design principles to old and new buildings is essential to preventing fatal and costly damages.

Why buildings fail in earthquakes: inertial forces and brittle mechanisms

Earthquakes cause a multitude of primary and secondary effects. The primary cause of structural damage is ground acceleration (shaking) which translates the horizontal and vertical forces of the earthquake directly into the building, testing the structure's ductility and foundation. The shaking can adversely lead to ground failure, where the ground either splits or liquefies.

The UNESCO report (2014) identifies eight damage influencing factors of which four are relevant to this research; 4) stiffness distribution, 5) ductility, 6) strength and connection, and 8) workmanship.

The inertia forces of earthquakes are expressed in this formula:

$$F = m \times a = kW.$$

Force = mass x acceleration

This formula demonstrates that the heavier the structure is, the more force it experiences, hence, lightweight materials are preferred in seismic design. Other material factors such as ductility and energy dissipation are crucial to consider for proper seismic design. Non-engineered buildings, particularly masonry, adobe and stone are designed to only carry vertical loads. Earthquakes introduce lateral loads such as bending and shear which these brittle materials cannot handle. This leads to tensile failure, the first mode of failure, creating cracking and splitting. Once cracking occurs, there is no direct load transfer anymore and the structure begins to progressively collapse. A ductile structure has the ability to deform without losing its load carrying capacity and fail slowly and predictably. Solid, brittle masonry structures lack this ductility and fail suddenly. Ductility is almost always offered by steel elements which have a plastic deformation capacity, bending before fracturing. When steel bends, intermolecular bonds are being broken, which releases energy in the form of heat. In this way, the seismic energy that is being applied gets transformed and released as heat, preventing that energy from entering the rest of the system, protecting the building as a whole. This mechanism is called 'energy dissipation'. For proper seismic design, a ductile building is essential for avoiding sudden, brittle collapse.

There are a number of brittle mechanisms to look out for in low tech houses: out of plane wall collapse, shear cracking along mortar joints, sliding at the interface of mortar and masonry, and the loss of connection between walls, floors and roofs. These are all symptoms of a system which cannot absorb or distribute the reversible lateral loads of earthquakes. For seismic design it is important to avoid construction methods which allow for brittle collapse as much as possible. A flexible, ductile system will allow occupants the time to escape while minimizing damage to the structure, reducing reparation costs and speeding up down-time.

Lessons From Past Earthquakes

On January 25, 1999, a magnitude 6.2 earthquake struck the El Quindio Department in the bamboo region of Antiguo Caldas. The intense earthquake caused over 1000 deaths and 40000 homeless people. The worst damages occurred in multi-story reinforced concrete and masonry buildings which were built before 1984. The bahareque bamboo vernacular architecture performed remarkably well, withstanding the heavy shaking with little to no structural damage. Any damage to the bahareque architecture was due to

1. material deterioration,
2. heavy masonry façade renovations which overloaded the frame,
3. foundation failures

None of these damages were due to the inherent performance of the bamboo frame and cemented wall. This case study proves that a properly maintained bamboo construction can perform better than concrete and masonry in seismic events and highlights the value of a lightweight, flexible and low-tech construction (Gutierrez, 2004).

North-East India in 1897 and 1950 saw two of the most devastating earthquakes in recorded Indian history. The 1897 earthquake, nicknamed the Great Assam earthquake, was magnitude 8.1, while the 1950 Assam-Tibet earthquake reached an 8.6 magnitude, the largest ever recorded globally. A memoir about the Great Assam Earthquake mentioned that all of the stone and masonry buildings in the epicentre were completely levelled, while only half of the timber buildings were only damaged. In 1950 (Documentation on Past Disasters, Their Impact, Measures Taken, Vulnerable Areas in Assam., 2022). The recent 2011 Sikkim (M6.9) earthquake was better documented with comparable results showing that masonry and concrete structures were severely damaged, while there was only one reported case of damage to an Ikra house on the third story of a school where the plaster fell from the walls. These experiences reinforce the essentiality of traditional lightweight structures, while demonstrating that there is still improvement to be had.

Principles for future design

The evidence reviewed in this chapter points to four principles for the seismic design of low-tech housing systems in high seismic zones.

1) **Minimize mass** – The inertial force equation as well as the case study review establishes that the seismic force a building experiences scales directly with the weight of the building. Heavy materials such as stone, brick and concrete are therefore not suitable for high seismic zones unless rigorously engineered to withstand the lateral loads.
2) **Provide ductility** – Brittle failure is the mechanism that leads to most earthquake deaths. It occurs when the material has no capacity to deform when it reaches its strength limit. Steel can plastically deform, slowly yielding once it reaches specific limits. It is a predictable ductile behaviour that can be used and designed for to prevent sudden collapse.
3) **Distribute load paths** – the failure mechanisms outlined by UNESCO, such as out-of-plane wall collapse and shear racking, are caused because they do not have alternative load path once the primary connection fails. Multiple redundant load paths can redistribute forces when one element has yielded.
4) **Survivability over strength** – The case studies show that seismic design is not about preventing all damage but to prevent collapse. This allows occupants to escape on time, preventing casualties. If a system can visibly deform without collapsing, can have repairable damages and keeps its occupants alive.

2.2. Vernacular architecture in North-East India

Traditional vernacular housing in Assam and other parts of Northeast India is commonly called ‘Assam-type’ or ‘Ikra-type’ construction. It is mainly used in rural contexts and has been for many decades. In urban contexts it is not immensely popular as people prefer reinforced concrete structures. However, there are still assam-style buildings which are still in use (Chand et al., 2019).

Recent field-based research has framed Assam-type housing as part of a broader Local Seismic Culture developed across the Indian Himalayas, in which construction knowledge evolved empirically through repeated earthquake exposure rather than formal engineering design (Baldev et al., 2024).

Assam-type / Ikra house construction logic

Assam houses are usually built on shallow foundations, typically a concrete strip foundation. Generally, the structures are raised on short stilts or plinths against flood damage and moisture propagating up from the ground. These conditions are common for the region as it lies in a monsoon prone area.

The timber frame structure is arranged regularly and lacks intermediate joist and studs at sill level to prevent against moisture infiltration, extending the lifespan of the structure. The jointing of the timber frame is simple and has very few connections, which add to the flexibility of the joint. Posts are placed on a pedestal and connected to the foundation using bolts and a simple steel L clamp which is embedded into the concrete slab foundation. Beams are connected to the main post using a mortise-and-tenon joint which is nailed in place. The vertical studs all have a tooth at each end which are slotted into a continuous groove in the horizontal beams. This connection is then also nailed into place.

One of the characteristic features of the house is the infill that they use. The lower portion of the timber frame, up till sill level, is filled with brick masonry. Long nails join the timber frame to the masonry, acting as shear connectors. Above sill level the walls are filled with Ikra panels. The grooves that are cut into the beams are filled with a woven mesh of bamboo strips or river reeds. The bamboo studs in the weave are also inserted into holes made in the main posts to provide out-of-plane stability. The panels are then plastered using mud or cement on both sides making the total thickness around 45 mm. Windows and doors fit flush between the studs and are placed in the centre of the walls. Gabled roofs are important in this climate due to heavy rainfall and good ventilation. These roofs primarily consist of timber or bamboo trusses supporting clay tiles or galvanized iron sheets (Chand et al., 2019).

Figure 3 - Chand B., Kaushik H. B., Das S. (2019). Typical Assam House. Lateral Load Behavior of Traditional Assam-Type Wooden House

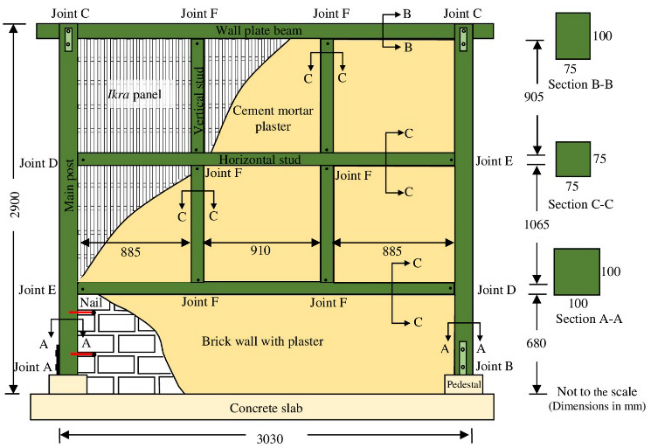


Figure 4 - Chand B., Kaushik H. B., Das S. (2019). Details of a typical frame of Assam-type houses. Lateral Load Behavior of Traditional Assam-Type Wooden House

Baldev et al. (2024) identified this construction logic of a lightweight enclosure with a flexible primary frame as a recurring style across the Himalayan vernacular systems. This suggests that the Assam-type house shares a regional logic for seismic design using local materials.

Seismic performance of the Assam-type house

The seismic strength of this construction type is owed to the light mass of the walls and roof, lack of diagonal timber members, good wall-to-wall connection, regular plan, small openings, the infill panels, and the lack of rigid joints (Chand et al., 2019). This structure is both flexible and ductile. Ductility is defined as the ability for a material to significantly deform plastically without fracturing, leading to slow predictable failure as well as energy dissipation. This ductility is performed by the steel elements in the connection which have a plastic deformation capacity (Chand et al., 2020). The steel elements include steel brackets and bolts in the main post and beam structure, while the studs use a mortise-and-tenon joint in combination with steel nails. In the cyclic testing of the Assam-type house joints, all of the connections in the main frame remained intact throughout the entire cyclic loading while having minimal damage, demonstrating their ductility. In addition to the steel elements, the development of gaps between the steel and timber, as well as the play between the bolts and holes adds to the total ductility of the system. A completely rigid joint would have to resist each load cycle entirely, while a slightly loose joint delays the moment the joint is activated and dissipates energy through friction. The lack of stiffness does, however, lead to significant lateral drift in the structure, up to 8.7%. This is not inherently bad and can act as a warning to occupants to get to safety, however, too much drift can lead to upturning of the structure and should be checked against.

The infill Ikra panels also demonstrated to be essential to the overall stability of the structure. Its ability to slip along the grooves added friction to the system and continued to provide in-plane lateral stability to the wall despite the beams having been dislodged from the main post. Due to the panel's lightweight nature and flexible connection to the timber frame, it did not damage the surrounding timber. (Chand et al., 2019).

Chand et al. (2019) illustrated the wall system and its seismic elements in two analytical models, in order to compare the results of the analytical model with the results from the experimental model (**FIGURE X)**. Analytical model (a) and (b) are identical in every way, except for the Ikra panel infill, which is replaced by an equivalent diagonal strut. It shows that there are many points of plastic hinging in the system at the interfaces between the beams and posts, and that Ikra panel has a plastic hinge mechanism. The rest of the connections are pinned and moment releasing, allowing for racking. Stability is provided by the Ikra panels/struts. These two analytical models will be used in the concept development process to translate the seismic design principles to the modular structure.

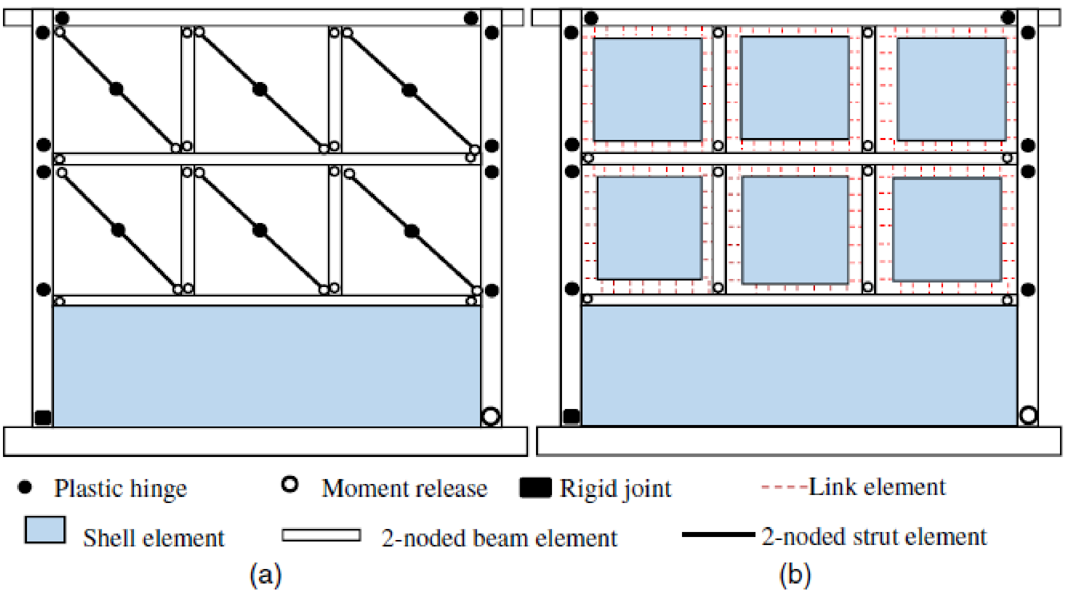


Figure 5 - Analytical models of (a) equivalent diagonal struct for Ikra panels; and (b) using link and shell elements to represent Ikra infill (Chand et al., 2019).

The seismic performance of Assam-type houses aligns with field observations of other vernacular architecture across the Indian Himalayas. Surveys of over 300 vernacular buildings identified that low seismic mass, high ductility, flexible connections and clear load paths are the most influential factors for earthquake resilience (Baldev et al., 2024).

Based on this research a few principles can be taken for the design of a ductile bamboo structure:

1. Have a regular framing system
2. Use lightweight-infill walls
3. Use ductile steel connections for energy dissipation
4. Create friction dissipation between elements through controlled slip
5. Leave a small gap between the bolt and bolt holes
6. Bolt the frame to the foundation using steel L brackets to allow for in plane rotation of the posts
7. Do not insert the frame into the foundation

The extinction of the Assam-type house

Cultural shifts and natural resource scarcity around the world are causing vernacular architecture to be replaced by brick and concrete (Gutierrez, 2004), and this also extends to Assam. Northeast India is experiencing an “unscientific shift” from the traditional vernacular architecture to unconfined/partially confined masonry and reinforced concrete (Pathak et al., 2020).

In villages Assam-type is still common but their numbers have been decreasing over the last two decades. This is especially the case in urban areas where they are demolished for unconfined masonry and reinforced concrete. This is due to a number of push and pull factors. Increasing costs, lack of availability of timber, vulnerability to pests and fire are all pushing local people towards the transition. While socio-economic aspirations, rapid urbanisation and the perception that modern materials provide better safety than the traditional alternative (Baldev et al., 2024; P. Kaushik & Kaja, 2016; Pathak et al., 2020). Baldev et al. (2024) adds that North-East India is experiencing a degradation in local seismic culture. Historically, the locals understood the importance of seismic prevention, with the Assam-type house being as a result of their experience with devastating earthquakes. However, with the current transition this knowledge is slowly being lost, with fatal consequences.

It is paradoxical that North-East India has an abundance of natural resources, yet its poor infrastructure and strong seasonal fluctuations make transportation expensive and unreliable. A lot of modern materials required for their modern housing, such as brick, steel and concrete must be processed and imported from outside the region, making the long distance between material sources and construction sites amplify the cost of construction (Barbhuiya et al., 2025). Unfortunately, locally available bamboo is being underutilised as a result. Table X by Barbhuiya et al. (2025) provides an overview of the availability and transportation of materials essential for Assam-type houses.

Table 1 - Assessment of material availability and transportation for Assam-type houses, Barbhuiya et al. (2025)

Material	**Availability**	**Source locations**	**Transportation considerations**
Bamboo	Widely available, especially in rural areas	Local forests, bamboo farms	Lightweight, easy to transport; may require special vehicles for bulk transport.
Thatch	Commonly found, particularly in flood-prone areas	Local vendors, agricultural areas	Easy to transport; often sold in bundles, but care is needed for preservation.
Timber (Sal, Teak)	Moderately available; dependent on regulations	Forest reserves, local sawmills	Heavy; requires flatbed trucks; availability may vary due to environmental regulations.
Brick	Readily available in many regions	Local brick kilns	Bulk transport can be costly; stacking needs to be done carefully to prevent damage.
Stone	Available but location-dependent	Quarry sites in hilly regions	Heavy and requires specialized equipment for transport; may have limited access in remote areas.
Cement	Available through various suppliers	Cement factories in Assam	Heavy; transported via trucks; ensure proper storage to prevent moisture damage.
Sand	Generally available, often from riverbeds	Local riverbanks, quarries	Easily transported but can be subject to environmental regulations on sourcing.
Steel	Available from regional distributors	Steel manufacturing units	Heavy; requires special handling equipment; bulk purchases can reduce costs.
Clay	Readily available for brick making	Local clay pits	Easy to transport in bulk but requires care during wet conditions to avoid damage.
Paint/Finish	Available at hardware stores	Urban centres, local suppliers	Lightweight; standard transportation methods are adequate; needs careful handling to avoid spillage.

The future

The findings of Baldev et al. (2024), Pathak et al. (2020) and Kaushik & Kaja (2016) indicate that the current trend towards masonry and concrete systems are significantly more harmful than good, both seismically and culturally. Instead, Barbhuiya et al. (2025) recommends a multi-lateral approach for reducing costs and increasing accessibility. Local sourcing should be prioritized where possible by identifying sources of regionally available materials to reduce transport costs and delays. In the case of essential non-local materials, using strategic supply chain partnerships with regional suppliers can drive down costs by buying elements in bulk and streamlining distribution. Improving road conditions would be useful, however, utilizing local waterways is an efficient and established mode of transport that could be better taken advantage of.

Barbhuiya et al. (2025) further stress that modular prefabrication of building components in nearby hubs has a lot of potential, by minimising on-site material requirements and logistical constraints of bulk transport needs. These prefabrication hubs should incorporate a community based work-force, training up local artisan in sustainable construction techniques to ensure adoption of the system and a longer building lifespan as they are more likely to maintain their housing (Kaminski et al., 2016). Adapting the seismic logic of the vernacular to modular prefabrication is an essential factor to consider for long-term feasibility.

Both Kaushik & Kaja (2016), and Barbhuiya et al. (2025) highlight the benefits for the use of bamboo as a construction material due to its abundance in Assam, reduced seismic weight, insulative properties and as a symbol of local identity. Bamboo has the ability to enhance aesthetic appeal while preserving local craftmanship. Developing a bamboo-based wall system embodies these principles by adopting vernacular materials and seismic techniques to address present day challenges. The reintroduction of a systemised form of construction with bamboo has also been proven to revitalize the people's understanding of bamboo, counteracting the perception of it being a 'poor man's' material (Kaminski et al., 2016).

2.3. Bamboo

Raw bamboo has been used in architecture for millennia and has embedded itself into cultural practices throughout the world - in Asia, Africa and Latin America. Its abundance, cheap price and desirable mechanical properties have always made it an attractive material. With the invent of modern materials such as concrete and steel which are stronger, more durable and behave more predictably, bamboo has seen a decline in prevalence. Bamboo is limited in making as large a structure as is possible with steel and cement, and with the rapid urbanisation of the built environment, bamboo became restricted solely to low-rise domestic housing. Today, however, it is experiencing a type of renaissance. Bamboo has been rediscovered for its inherent mechanical strengths and sustainable advantage over contemporary structural materials. It can now be reengineered to minimise its flaws and maximise its potential, allowing for standardisation and large-scale structural uses. How and when bamboo is used for construction depends on the context; traditional dwellings made of bamboo are due to convenience and economy of materials. Contrarily, modern bamboo buildings come from the desire for natural texture and a reduced carbon footprint (Hong et al., 2019).

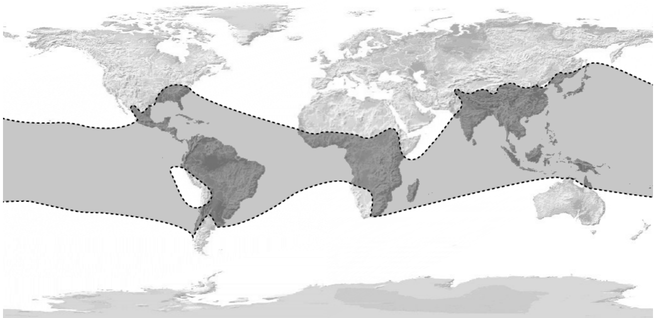


Figure 6 - Bamboo growing regions world map

Bamboo as a plant

Bamboo is increasingly becoming more popular as an alternative to timber, and in some cases to steel and concrete (Adier et al., 2023). This is because bamboo is not a timber species, it is instead a woody grass with a hollow culm and distributed nodes that help prevent local buckling (Madhushan et al., 2023). The bamboo culm is tapered along its height with increasing node spacing. The anatomy of the culm can be categorised into nodes and internodes. The internode is the hollow section of the tube with axially oriented fibres. The diaphragm has cells oriented perpendicular to the culm. A cross-section of a bamboo wall shows a collection of vascular bundles which increase in density and decrease in size towards the exterior. Towards the top, the wall tapers and the number of vascular bundles decrease and increase in density. It has naturally evolved to withstand its own self-weight and lateral wind forces.

Bamboo grows as a system of roots from which grow a collection of culms. It reaches its mature height within months and is harvestable within 3 – 6 years, significantly faster than structural timber which can take anywhere from 25 – 60 years. Some culms can reach a height of up to 20 meters in just three months. Regular harvesting of culms has no effect on the health of the root network, allowing them to continually produce new culms. Their fast growth rates allow them to act as highly effective carbon sinks making it a very sustainable alternative to timber. Moso bamboo can sequester up to 5 tonnes of carbon per hectare per year (Trujillo & López, 2016).

Mechanical behaviour of bamboo

Despite bamboo being used globally for millennia, research into the structural properties are relatively recent and still in its infancy (Trujillo & López, 2016). There are 1250 of species of bamboo, with fewer than a hundred of which can be used structurally (Trujillo & López, 2016). Mechanical properties vary widely between species, harvesting age, moisture content, geographical location and morphological location. As an organic material with natural irregularities in the structure, its properties cannot always be accurately predicted for each culm making it hard to create a standardised code of practice. As a result, large safety factors and conservative values are used in the grading and calculating of bamboo structures to ensure a reliable performance across the board. Due to limited local availability, this report will use Guadua Angustifolia as a proxy for the structural bamboo species available in Assam. Guadua has been measure to have the following mechanical strengths parallel-to-grain (Correal D & Arbeláez C, 2010):

Table 2 - Mechanical Properties of G. Angustifolia (Correal D & Arbeláez C, 2010)

	Value			Unit
	High	Low	Avg	
ρ	828.60	705.50	772.05	kg/m3
E	18.00	16.80	17.33	GPa
σ	42.60	41.50	42.08	MPa
τ	8.20	7.60	7.98	MPa
MOE	19.40	15.80	17.63	GPa
MOR	103.80	86.90	99.23	MPa

Many of these bamboo species have parallel-to-grain strengths comparable to high-quality hard woods, and a tensile strength approaching mild steel while remaining significantly less dense. Their strengths peak at 3-4 years of aging, after which there is a slow decline. Their strength increases further once the bamboo has been dried and treated. It is important to note that these strengths have been achieved when the bamboo has been loaded parallel to the grain – axially along the member. Bamboo is famously weak perpendicular to the grain.

Seismic design relevance

Bamboo has a high strength-to-weight ratio, meaning that it can be sized smaller than equivalent timber or steel sections. The result is a structure which is strong enough to resist seismic forces and light enough to have low inertial forces. In seismic design, mass is the primary driver of inertial force, therefore, the lighter the structure, the lower the force it experiences. This makes bamboo highly advantageous for earthquake-prone regions, where heavy systems such as brick and concrete attract much more seismic forces.

Its inherent flexibility also means that bamboo can deflect significantly before reaching its strength limit. This gives the structure longer natural period of vibration, shifting it away from the resonance frequency that is produced by the ground. Based on its lightweight yet strong characteristics it is a suitable material for seismic design as it reduces the total weight of the structure, reducing the resultant inertial forces which are experienced more extremely by heavy rigid systems like brick and concrete (Bredenoord, 2024).

Variability and durability limitations

However, the actual properties of bamboo can vary strongly with species, age, culm height, wall thickness, moisture and natural defects, so bamboo culms have to be selected careful and graded properly (Mali et al., 2024). Selection and grading criteria can be found in international and national standards documents such as ISO 22156 and the Indian Standard 15912 where criteria such as maximum tapering, minimum diameter and thickness can be determined. These documents also include all relevant calculations for determining structural acceptability. Even after the selection procedure, they are still susceptible to moisture, fungi and insects which can cause the culm to degrade within 5-10 years (Yadav & Mathur, 2021) and therefore have to be treated to reduce the starch content. A properly treated bamboo culm can extend its lifespan up to 50 years or more (Bredenoord, 2024). Plastering bamboo with cement or clay has also shown to improve the moisture resistance of a bamboo culm. Proper maintenance is stressed by a number of papers in order to extend the lifespan and to ensure a functional system for the likely event of an earthquake or storm.

Bamboo Connections

In bamboo structures, connections are usually the weakest and most complex part. Its hollow structure and thin walls, variability along length and anisotropic properties make it hard to standardise and ensure a strong/safe connection. Joints usually govern the safety, ductility and durability of a structure, especially in wind and earthquake conditions.

Despite the bamboo culm being able to withstand large axial forces, it is the joints which have to transfer loads between structural elements through parallel-to-grain shear, bending or axial loading.

Widyowijatnoko (2020) explores most of the traditional and innovative bamboo joints, building on the works of Janssen (2000) who categorized and grouped how force is transferred through bamboo culms as illustrated in figure 7, (Widyowijatnoko & Harries, 2020). Eight groups were established based on the principles of: the way force is transferred, and the position of the connector.

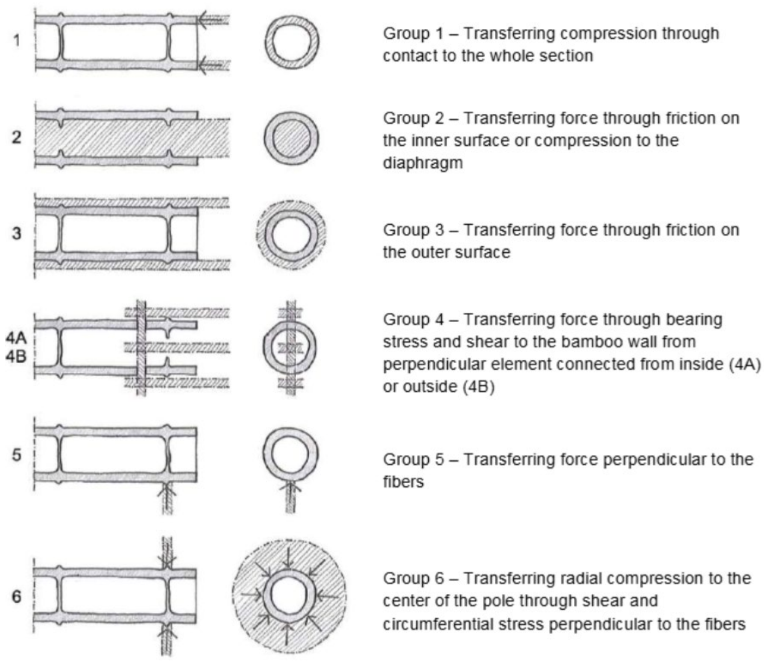


Figure 7 - Widyowijatnoko (2020). Main categories of bamboo joint classification.

Most traditional methods for connecting bamboo involve groups 1,4,5, and 6 and use biological materials as connectors such as bamboo/wooden dowels or lashing with natural fibres. Some of these connections are made using expert craftmanship and utilise the natural morphology of the bamboo to their advantage, while others are easy enough to be performed by unskilled workers. Unfortunately, the use of natural materials generally leads to unpredictable and brittle failure which is unpreferable when building structures which have to adhere to national standards and sustain lateral seismic loads. Modern bamboo connections are dominated by bolts and other steel elements such as gusset plates, steel plates, hose-clamps, and rope/wire. Nowadays, these connectors are preferred as they are relatively cheap, easily accessible and have predictable limits. There are a few engineered connections which use more advanced techniques and technologies to create stronger joints; however, these are generally inaccessible to low-income communities and will not be explored in this literature review.

The review of bamboo connections indicates that many modern jointing techniques are incompatible with rural low-skilled construction as they rely on carbon-intensive and costly materials. This highlights the need for more traditional connection methods or new connection strategies for single storey housing in seismic regions. Simple connection techniques with bolts and fasteners which are more accessible can also be considered to ensure safety and strong connectivity.

Bamboo Construction Types

Li et al. (2022) gives a comprehensive overview of the *Use of Bamboo in Constructions***.** The paper describes four types of bamboo construction types:

1. Round Culm (raw bamboo)

This is harvested bamboo that has not been worked except for preservation. It is used for full structural frames, posts, beams, bracing, trusses and arches. It usually comes with a lightweight infill or cladding. Traditional systems exist globally, examples include the Assam-type house, bahareque and quincha.

2. Engineered Bamboo Panels

This is a type of industrial bamboo which has been processed into laminates, panels or scrimber products. It involves a considerable number of adhesives and preliminary working to flatten (and strip) the curved members and align them for lamination. The products range from shear walls to beams.

3. Cross-laminated bamboo / hybrid panel

Bamboo and timber are cross laminated to create panels with strength in two directions. The orientation of the elements can be predetermined for specific needs. These panels usually act as shear walls.

4. Hybrid systems

Bamboo can be combined with concrete, steel and timber for structural optimisation. Bamboo is selected for its axial strength and is used in those areas of the system. Examples include bamboo reinforced concrete and bamboo-steel space trusses.

For the scope of this research any form of engineered bamboo is considered infeasible as it requires highly technical industrial processes and materials as well as skilled labour which are generally unavailable in rural Assam. Therefore, round/half culms will be the preferred form of bamboo going forward.

In summary, bamboo offers a unique combination of low weight, high tensile capacity, and flexible behaviour that is effective for seismic applications in low-income contexts. However, due to its variability, durability and connection challenges the structural performance is not governed by the material but by how it is detailed and integrated into a system. It suggests that the bamboo should be used as continuous framing with only axial loading, or as a reinforcement element.

2.4. Modularity as a design strategy for low-tech seismic construction

Modular design is defined as “designing products by organizing sub-assemblies and components as distinct building blocks (i.e. modules) that can be integrated through configuration to fulfil various customer and engineering requirements” (Tseng et al., 2018). It was first introduced in 1965 by Martin K. Starr as a third evolution of industrial production to make mass production with genuine variety possible. This variety stems from the production process where a relatively small number of standardised modules are manufactured, each of which can combined with others in many different configurations. He identifies the distinction between interchangeable parts and interchangeable modules as the difference between identical parts playing one function in one system, while modules are interchangeable between different product configurations – one module can be used in multiple various products. Essentially it is about combining a finite set of standardised components into the maximum useful configurations. In this research, this translates to a small of set of modules which combine to produce a wide range of housing configurations.

This chapter aims to review methodologies for synthesising new modules as well as design principles for modular design, especially in the context of low-tech, seismic design.

Establishing modular architecture

Architecture is defined here as the way that functional elements are assigned to physical components and how they interact with one another. There is a proposed four step process for establishing modular architecture, (Tseng et al., 2018):

.1. Map components to functions through a conceptual model
.2. Cluster elements into modules based on modularity criteria
.3. Create a geometric layout to identify interfaces spatially
.4. Identify important interactions in the conceptual model

This is the foundational framework for designing a modular system which forms the basis of more formal interpretations, methods and tools used to design a modular system.

The FBS framework (Functional – Behavioral – Structural)

Sonego et al. (2016) propose that modular design should be viewed from three different perspectives simultaneously.

Functional View: This is what the product does from the customer's perspective. This means grouping functions together that are relevant to the same customer group.

Behavioural View: This view looks at how technology and solution principles can be used to group the functional requirements of each element; elements that satisfy a shared functional requirement and technical parameter should be grouped together.

Structural View: This part looks at the physical parts and how they are manufactured and assembled. Modularity in this view is about the physical interactions between elements and the manufacturability. This is perhaps the most relevant perspective for this research.

Modular design tools

The Encyclopaedia of Production Engineering lists a number of tools and methods that are useful for decomposing a system to help define elements, functions and potential modules. It is organized based on the type of modular design taking place, namely functional, technical or physical modularity (Tseng et al., 2018). This research is focused on physical modularity as it involves the production of physical modules, the tolerances, spatial relationships, and assembly sequence, mainly manufacturability. This modular type yields tools such as the MFD method, the Interaction Matrix Analysis (IMA) and the Module Identification Matrix (MIM). The interfacing between the physical modules must be worked out precisely because it determines whether or not it works in practice and that there is no hidden coupling between modules that were supposed to be independent.

Modular Function Deployment (MFD)

Modular Function Deployment method (MFD), was first coined by Gunnar Erixon in 1998 for structuring products using the concept of 'module drivers' to aid designers in creating a good product structure based on a set of criteria (Erixon, 1998). He elaborates on 5 steps in this design method:

1. Clarify product specifications
2. Analyse functions and select technical solutions
3. Identify possible modules
4. Evaluate concepts
5. Improve each module

This five step process was later adapted into the MFDA by Sonego et al. (2016) to take into account the different levels of complexity and novelty of a modularisation project, hereby allowing the ability to choose between a collection of stages and tools that are best adapted to each specific product development project (Sonego et al., 2016).

Module Indication Matrix (MIM)

MIM has a comprehensive approach to modularity and supports as many modular drivers as is desired and necessary. This tool is used to identify which modular drivers would influence different elements in a product's system. The table is set up with modular drivers listed in rows, while the relevant elements are listed in the columns. It uses a skewed weighting scale 9 (high importance), 3 (medium importance), and 1 (some importance). Using the skewed valuing system, it makes it easier to identify different module 'nucleuses' around which the most relevant elements are combined to form a module (Wee et al., 2017).

There are two approaches to the MIM based on complexity. The first, most simple approach is to assign a value to each box based on the modular driver's influence weighting (R) and to then sum the values of each row. The ideal number of modules to be selected is calculated through the square root of the number of elements in a system (Sonego et al., 2016). This corresponds with the number of rows to be selected. The rows with the highest sum values become the nucleus of the modules. The remaining elements are clustered around the nucleus based on engineering judgement and rationale. The second, more complicated method is to assign each module driver an importance value (I) using the same skewed value system as before. The modular driver's influence weighting (R) is then assigned to each element, just as before. The importance value (I) is then multiplied against the module driver influence weighting (R) in a calculation called the modular driver satisfaction grades (MSG). This is highlighted in the following equation:

$$MSG_x = \sum_{i=1}^{n} I_i \times R_i$$

The values are then summed for each row and the rows with the largest values become the module nucleus. The additional multiplication adds an extra level of skewing based on how important the driver is to the stakeholder and its goals; different products have different requirements for modularity, making certain drivers more important than others (Wee et al., 2017). An example of the MIM matrix is shown in figure 8.

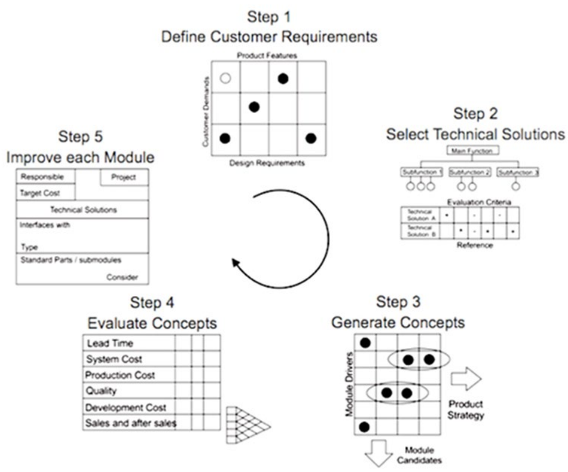


Figure 8 - MFDA operational steps (Sonego et al., 2016)

Interaction Matrix Analysis (IMA)

The Interaction matrix analysis is a table that shows the interactions between components of an analysed engineering system. It is part of analysing the functions of elements in a system. This step is necessary for functional modelling and further analysis.

To create this matrix, all of the components are arranged along the header rows and columns of the table in identical order. The components should be organized in a specific order: 1) the target component(s) of the system, 2) the system components, 3) the supersystem components. System components act upon each other to drive the mechanism, while system components act on the target component to achieve the desired results.

If an interaction exists between two components, then it should be marked. The resulting table must be symmetrical along the diagonal axis as the interaction between two elements is mutual both ways. If there is uncertainty in the existence of an interaction, then it is recommended to mark it, to ensure that all interactions are identified (Interaction Matrix – TRIZ Knowledge Base, 2025)

	Component 1	**Component 2**	**Component 3**	**Component 4**	**Component 5**	**Component 6**
Component 1		+	+	-	+	+
Component 2	+		-	-	-	+
Component 3	+	-		-	+	+
Component 4	-	-	-		+	+
Component 5	+	-	+	+		-
Component 6	+	+	+	+	-	

Figure 9 - IMA Matrix example

Modular Seismic Design

Traditional seismic design does not directly translate to modular architecture due to the unique structural qualities compared to conventional structures, i.e. the discrete inter-module connections and the discontinuous floor diaphragms. There is currently no seismic design method proposed for modular buildings and how they respond under lateral loading, presenting a gap the current body of literature (Wang & Chan, 2023). Furthermore, the little modular seismic design research available is focused mainly on steel structures, indicating an incomplete field of literature in this area. This is in part due to how new modular structures are as a field. However, there are certain principles that can be synthesized from the small body of literature focused on the relationship between seismic design and modularity.

1. **Controlled failure hierarchy:** research has shown that modular structures tend to fail in the columns, which are critical members which lead to global collapse. Failure should therefore be focused away from the columns into the inter-module connections.(Sendanayake et al., 2019)
2. **Ductile deformation of inter-module connections:** These connections should be allowed ductile deformation to dissipate energy. (Sendanayake et al., 2019)
3. **Distribute plastic drift concentration**: this method is proposed by Wang & Chan (2023) for steel frame modular architecture. They propose distributing lateral loads over each inter-module connection in the inelastic range so as to reduce plastic drift concentration in any one point, thereby improving collapse prevention performance.

These three main principles can be reimagined and applied to low-tech, modular design.

Types of modular products in architecture

Peltokorpi et al. (2018) attempts to categorise different modularization strategies according to its suitability for different objectives. There are different levels of modular construction which exist; component (1D), panels (2D), volumetric modules (3D), hybrid systems, and whole-buildings (Peltokorpi et al., 2018; Zohourian et al., 2025).

The 1D component refers to an element which fits in a larger building framework like a beam, post, connector, etc., and they provide a specific function.

2D panels are planar units that have multiple functions bundled together into one unit. This unit is repeatable and usually work as walls, floors or roof panels. The complexity of the system is concentrated in the panel which makes on-site construction easier.

A 3D volumetric module is often referred to as a ‘pod’ or ‘box’ module. It is a unit which encloses a space and have everything from structural stability to finishes and services integrated fully.

Hybrid systems combine various levels of modularity. For example, a structural frame is constructed, and modular pods are inserted into the frame.

Whole-building modularity is considered to have a modular system in which the building can grow and contract. This is often done in combination with standardised modules for scalability and repeatability.

Modularity is relative

Across the disciplines of architecture and product design modularity has multiple different definitions. In architecture it usually refers to “the construction of a building from many instances of standardized components” while in the design of complex systems like a space station it refers to the use of independent units (Ulrich, 1994). In essence, they refer to the same thing; it is the way a product, which being a building or a space station, is divided into components. These components can be repeated, connected, and replaced without redesigning the whole product.

Ulrich (1994) therefore, argues that modularity is relative. Mikkola (2006) builds on this knowledge by introducing the concept of ‘the degree of modularity’. This is based on the idea that modularity can be measured by how clearly a product can be divided into distinct components and how the interaction between components is concentrated at the interfaces; the more clear the boundaries are between components, the more modular it is (Mikkola, 2006). It also means that in a highly modular system, components can be modified or replaced with minimal impact on others.

When this is applied to construction it suggests that a building can also have this degree of modularity, that not all of the building elements have to be modular. Instead, modularity can be selected based on the need for modularity. In the case of seismic design, elements that tend to get damaged can be selected for modularisation so that the damage can be localised and easily replaced without having to impact the rest of the building.

Modularity for low-tech, bamboo systems

There is a limited body of literature focused on modularity in the context of low-skill, vernacular architecture. Major barriers to modular architecture in developing countries includes the absence of skills and knowledge, a lack of accepted standards, and difficult site characteristics (Akinradewo et al., 2021). There is currently no infrastructure that exists in developing countries that use a modular method of construction. There is also no design methodology which combines standardization, low-skilled assembly, local materials and structural performance. Together these present a significant gap to be addressed. This research aims to further this field by combining information on modular design strategies, standardized component logic, and vernacular structural knowledge.

Tolerances and interface management of bamboo structures

Managing tolerances is essential for the global accuracy of modular structures, allowing for standardized and predictable interfacing (Qi et al., 2021). Bamboo culms have a natural variability in diameter and curvature which is almost impossible to standardize. The issue with using such materials is that the inherent variability leads to error accumulation, making global accuracy almost impossible. Most vernacular bamboo structures rely on manual correction to reach relative, local accuracy, instead of global precision. There are multiple historical methods that are employed to absorb the irregularities of natural materials, such as preassembly, lashing, wedging and infill.

Preassembly is the preliminary technique for managing variability, where a set of elements are graded and organized so that they can be selectively placed in a system. This is traditionally done with stone stacking, where rocks are organized based on their size and shape so that each stone can be used to their maximum benefit. This translates to bamboo construction where bamboo culms are selected based on national standard criteria for desirable length, curvature, diameter and tapering. This is the first step in minimizing the extremes of variability within a selected range (Bhavan & Marg, 2018).

Adaptable jointing, which can conform to varying shapes and sizes, is the secondary step to the standardization of irregular structures. An example of this would be the use of lashing in traditional bamboo construction; a wrap-around technique, which can adjust to whichever geometry it encounters. This avoids the requirement of precision where it cannot be guaranteed. Wedging is another example of adaptable jointing, and is one of the six classical simple machines (Fortunado, 2023). A wedge has a tapered structure, which when forced in one direction, applies a perpendicular force, prestressing the gap. The taper geometry uses shimming to become a variable gap filler, requiring no precision and only simple tools. In more advanced bamboo connections, it used to make a friction fit connection on the inside of the culm (Widyowijatnoko & Harries, 2020).

Infilling is a very traditional method used in wattle-and-daub systems like Ikra and Bahareque construction, which apply mud, plaster, or mortar to an irregular frame system to equalize the surface and protect the bamboo from moisture (Soares et al., 2025). The infill is used not as a precision connection but as a conforming joint. This manages any tolerances using the infill materials mouldable properties.

Truly standardizing bamboo connections and creating precision fits is impossible. Therefore, irregularities should be minimized wherever possible, and tolerances should be managed using adaptable, conforming connections such as the ones discussed above.

Standardized bamboo connections

One of the largest challenges to designing a modular system using bamboo is the standardization required for prefabrication and assembly. Bamboo has a highly variable morphology, with vertical tapering, varying culm wall thickness and non-isotropic material characteristics. This makes forming predictable, standard connections extremely difficult. There are a few connections that have been designed which attempt to standardize the interface between culms using adjustable ring clamps in different configurations (Shan et al., 2023):

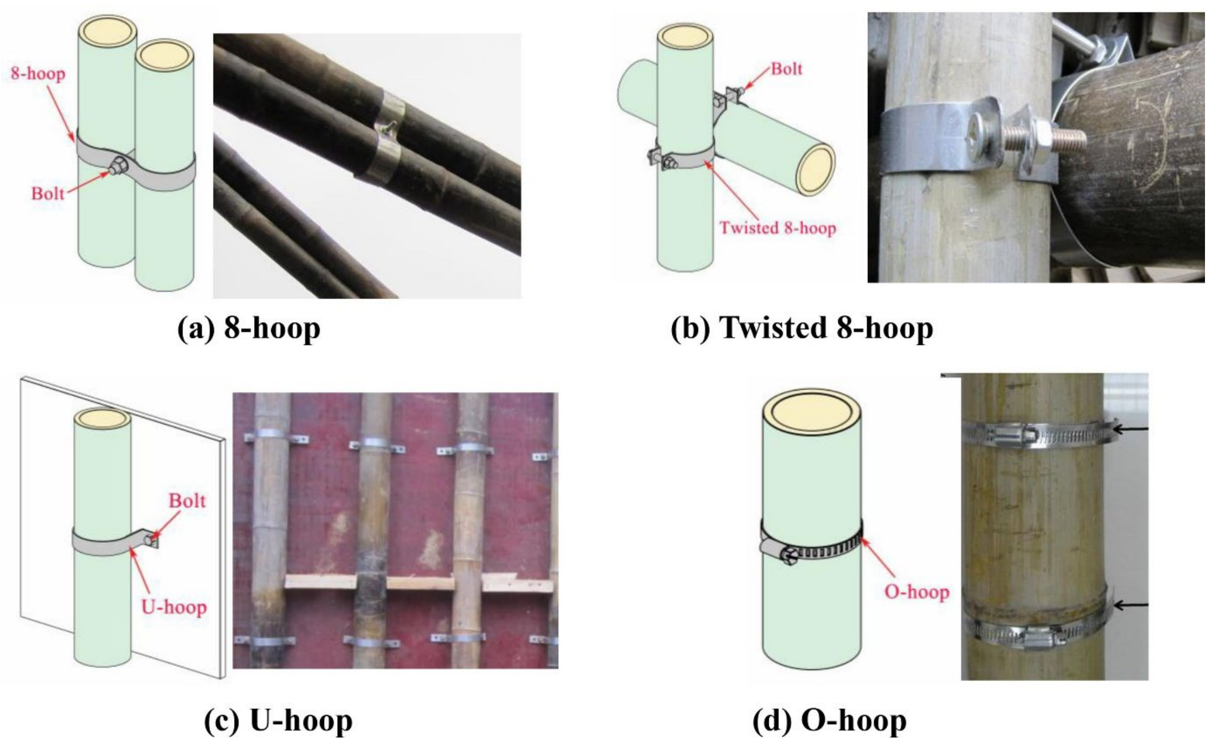


Figure 10 - Shan et al., 2023. Standardised bamboo connection details.

The most relevant connections for this paper are (a) the 8-hoop and (d) O-hoop. The O-hoop is perhaps the most suitable standardised connection type as it is cheap, adjustable, and available off-the-shelf almost anywhere (Shan et al., 2023). Furthermore, it is traditionally used to reinforce the culm and prevent longitudinal splitting. The adjustability of the O-hoop allows it to also adapt to the differential tolerances that exist between two adjacent culms. The 8-hoop connection is not adjustable and more expensive to realise as it has to be prefabricated for the intended culms.

2.5. Conclusion

Modular design theory is currently well-developed after roughly 60 years of evolution. It offers solid frameworks and tools for system decomposition, interface identification, and module identification. However, these tools assume industrial production conditions and have not yet been adapted to low-tech, rural contexts where such conditions are not realistic. Despite the maturity of modular design theory and its use in structural design, the relationship between modularity and seismic design is still developing. Research is limited to steel structures and expensive prefabricated elements. There are a few core principles which can be derived from this research; however, a step is required to adapt it to low-skilled, rural contexts. Furthermore, there is a complete lack of research regarding modular design for the context. There are many barriers to the development of such a modular system including the morphological variability of elements such as bamboo culms, however, some promising research has been conducted to attempt the standardization of bamboo connections for prefabrication. Together, these gaps identify the need for a design approach which applies the modular design framework and modular principles to low-skill assembly, natural material variability, and seismic performance requirements. This combination does not yet exist in literature.

3. Design Basis

This section is dedicated to the research done, and tools set-up, to further the design process and develop a suitable hard and soft criteria. This section traces the system through the five stages of its lifecycle, from raw bamboo to long-term reparation, in order to extract the contextual constraints that govern the design

3.1. Contextual constraints

Harvesting and Treatment

To achieve the most durable form of bamboo there are a few principles outlined in the *Design Guide for Engineered Bahareque Houses (2016)*. Firstly, the bamboo must be treated. This can be done through a number of methods: water soaking, smoking, painting, boron, and copper treatment. Smoking, painting, and water soaking are the most traditional form; however, it only marginally improves the lifespan of the bamboo. Therefore, boron or copper treatment is required which can extend the lifespan of the bamboo by 30+ years, given that it is an internalised element. Exposed bamboo has a life expectancy of 2-15 years for boron, and 30+ years for copper. Boron is a common and cheap chemical which comes in the form of salt for fertilizing. Boron treatment can be achieved through a number of methods: modified boucherie, bath soaking, dip diffusion, and vertical soak diffusion. Only the modified boucherie method does not require breaking through the internal nodes which are important for maintaining lateral strength, however, the only limitation is that it must be done 24 hours within harvesting. All the other methods are also still viable. Copper based treatment is more effective than the boron treatment for preserving the bamboo, however, it is significantly more expensive and difficult to acquire. This would not be suitable to low-income communities; therefore, a boron treatment is the best option. As an additional precaution, to have the bamboo last up to 50 years, the bamboo must be covered and protected from moisture. If it does have exterior exposure its lifespan will be significantly reduced.

A few methods of boron treatment require to be soaked which can be done in tanks or baths and takes 7-14 days for the solution to fully permeate the culm. Once soaked it must stand vertical for another 30 days to dry out completely. The modified boucherie method takes a fraction of the time as it uses pressure to force the solution through the body of the culm using a compression tank and compressor. The startup cost for this system is around 500 USD (Village Bamboo Preservation Unit | Science, Technology and Innovation (STI) Portal, n.d.). Each bamboo culm takes only 4-5 hours to be treated, significantly cutting the time needed by the more passive methods. According to the United Nations' Science, Technology and Innovation (STI) Portal, this technology is aimed at low-income and low-skilled settings, promoting the development of timber alternative materials and therefore suits perfectly for this scenario. An additional benefit is that the culm diaphragms do not need to be punctured, preserving its structural quality.

Immediately once the culms have been treated, they should be dried. The modules require predictable bamboo culms that are as straight as possible, therefore any culms that have more than a few degrees of curvature must be straightened. This is crucial for later steps which the standardization of elements and modules is reliant upon. The straightening of curved bamboo is done best while the culm is still green, and its cellular structure has not become too rigid. Attempting to straighten dried bamboo could lead to large internal molecular stresses, which cause splitting and cracking and is best avoided. There are two methods to achieve a straightened culm: heat straightening and mechanical straightening. Heat straightening is the quickest method, involving a heat source, such as an open fire or heat gun, and a straightening jig. The culm is heated till the outer culm seems slightly soft and waxy, then it is held in a straight position using the jig till the lignin rehardens and realigns. Care should be taken for not overheating the culm with the consequence of blistering or cracking the inter-node. Mechanical straightening only requires the straightening jig. However, the culm must be held in place for a few weeks while it is left to dry. The downside to mechanical straightening is that it would require a separate jig for each culm in continuous use for multiple weeks. The most economical option would be heat-straightening as the process can be systematised to manage multiple culms at a time and quickly treat all incoming raw culms in an assembly line. For example, multiple culms could be heated at the same time by the same heat source and then placed into a matrix of jigs for half-an-hour cooling, after which they can be stored for drying. Arihant Engineering on IndiaMART also provides steel bamboo straightening machines which can manage whole bundles at a time.

Design implication: Bamboo culms must be boron-treated within 24 hours of harvest and shielded from moisture in service, which co-locates the manufacturing facility with the bamboo source and rules out exposed load-bearing culms.

Fabrication

Ideally the manufacturing facility of the modules is as close to the bamboo farm as possible to minimise the transport costs and the logistics of manoeuvring such large culms. An alternate possibility is to cut the culms down on-site for easier transport to the facility. This requires on-site grading and working.

The grading of culms follows the criteria set out in IS 15912:2018 (clause 5.4), which grades bamboo for structural purposes. Guadua bamboo will be used as a proxy for bamboo species native to India. Guadua has mechanical properties which fall within the range of a Group A bamboo, in accordance with IS 15912. Grading for Group A is based on the following criteria:

- Wall thickness ≥ 8 mm for load-bearing members
- Taper ≤ 5 mm/m
- Curvature ≤ 75 mm over 6 m
- No defects: bore holes, collapse, cracks >3 mm depth, or signs of decay

The bamboo is then segregated in steps of 10 mm based on mean outer diameter into Grades:

- Special grade : Diameter > 70 mm
- Grade I : 50 mm < Diameter ≤ 70mm
- Grade II : 30 mm < Diameter ≤ 50mm
- Grade III : Diameter ≤ 30mm

Once the appropriate culms have been graded and selected, they can be cut down to the size of the members used in the modules. A trained individual from the facility can be allocated to conducting/supervising this process at the farm.

This facility has a host of local workers manufacturing the different modules. All the resources and tools necessary for production gets sent to this location. It is a covered facility which provides a stable place of work where resources are centralised, and production can continue year-round, uninhibited by daily and seasonal changes. In doing so, more precision-based work can be achieved which is essential for modular systems which require consistent joint geometry and interface dimensioning. At this location new modules can designed, built, and evaluated for future product diversification. The economic model is fundamentally local: low-skilled and semi-skilled workers from the region are recruited here, providing more jobs, a source of income and the opportunity to be trained in this field. Investments in this business will be reinvested back into the community. This reflects the recommendation by Kaminski et al. (2016) that beneficiary communities be involved throughout the construction process.

Design implication: Culms must meet IS 15912:2018 Group A, Special grade (Ø > 70 mm), so the system must accommodate culm-to-culm diameter variation. Precision operations are confined to the factory; on-site work must remain simple with only hand tools.

Transportation:

Once the modules are prepared, they are loaded flat or standing onto the transport vehicle. Rural populations have bad road infrastructure and limited space to traverse. Assam presents multiple logistical constraints: most of the rural roads are single lane and only 3.0-3.75m wide as specified under PMGSY, rural road standards governed by IRC-SP:20. This limits the type of vehicles available for transportation. Anything with a load bed larger than 3m in width would have trouble manoeuvring and making turns. Long vehicles would become stuck in turns which further limits the load bed dimensions. Canopy clearing heights and other raised infrastructure might further impede vehicles. There are multiple modes of transport available to rural populations which are listed in the hierarchy below:

Table 3 - Transport vehicle hierarchy

Transport Type	Load Bed (L X W)	Payload	Road type required
Walking	-	50 kg (two people)	Any path
Bullock carts	2.5-3.0m x 1.2m	300-500 kg	Earthen road
Tractor trolley	3.0-3.5m x 1.8m	4 tonnes	Earthen road
Mini truck (Tata Ace)	2.2m x 1.5m	850 kg	Paved village road
Medium Truck	4.0-6.0m x 2.1m	3-5 tonnes	District road

For the average rural location, the tractor trolley is identified as the most accessible and viable mode of transportation as it is already culturally established and is capable of managing the variable terrain it is likely to come across. Historically it is also the dominant freight mode in rural India, handling the majority of agricultural and construction material transportation across poor road surfaces (Ramanayya & Anantharamaiah, 1993). Their load bed dimensions are approximately 3.5m x 1.8m, which sets the upper geometric bound for each module. From this transportation hierarchy a principle can be established: the more remote the location, the smaller the payload and module geometry. The modules are targeted towards rural communities who are transitioning from a vernacular assam-type house to concrete and masonry structures. It is therefore safe to assume that these communities have modes of transport which can accommodate the hauling of necessary material. In cases where communities provide their own form of transportation, the tractor trolley is the most available and economical option. In the case of the transportation being provided by the manufacturing factory then a larger, slightly more industrialised vehicle would be available such as a mini truck such as the Tata Ace. As recommended by Kaminski et al. (2016) it is important to involve the beneficiary in as many parts of the construction process to improve their sense of ownership on the process and the house which in turn leads to better maintenance and a longer lifespan. Therefore, the tractor trolley will be taken as the design baseline.

Design implication: The tractor trolley and ISO 11228 set the design baseline, bounding modules to 3.5 m × 1.8 m and to 50 kg.

Construction:

On-site assembly is the final stage and the one which is most involved with the limitations of the user group. The design must assume that construction takes place in a rural setting with low-skilled labour, and access only to hand tools and basic portable equipment. Specialised trades cannot be assumed available, and any operation that requires them must be relocated to the fabrication facility where more complex and intensive processes are organised.

The user group is also a key design driver. Construction is intended to be conducted by the inhabitants themselves, in line with the recommendation by Kaminski et al. (2016) that beneficiary communities be actively involved throughout the construction process. This introduces the design problem of *buildability*: connections must be intuitive, and accessible for low-skilled workers. Errors must be visible and reversible rather than hidden and permanent.

Design implication: Construction is constrained to dry, hand-tool, two-person assembly with the foundation as the only wet trade, so all precision work is relocated to the factory, and the on-site sequence must remain simple and reversible.

Reparations - General

As outlined by Kaminski et al. (2016), the structure is aimed to last 50 years with general maintenance and reparation work such as painting, refilling of cracks and reparation of minor structural elements. In the event of module degradation or distortion, the module should be maintained or replaced entirely, depending on the severity of the damage. The replacement of the module should not impact the surrounding structure so that damage can be locally addressed without invasive intervention. For proper maintenance, the interfaces should be accessible for inspection and repair.

Design implication: The system must support a 50-year service life with low-skill maintenance, so connections and finishes must be inspectable, individually replaceable, and reachable with simple tools.

3.2. Hard and soft criteria

Based on the literature review and the contextual constraints, a set of hard and soft criteria have been set up. They are divided into three sections: modularity, buildability, and seismic design, each with their own hard and soft criteria. This is because they work in parallel, where one section is not more important than the other.

Table 4 - Hard and soft criteria

	Modularity	Buildability	Structural design	Seismic Design
Hard Criteria	Each module must be able to scale linearly across the grid	Modules can be no larger than 3.5m x 1.8m	All bamboo connections must be pinned	System must incorporate plastic deformation for ductility
	All interfaces must be accessible for inspection, repair, and disassembly	Max module weight < 50 kg for carrying by two people	Masonry restricted to foundation	Drift cannot exceed 8% drift from Assam-type house
	All external module connections must be universally connectable	All connections must be demountable	Failure must be measurable and predictable	The design load must fall within the plastic range of the ductile elements
			The bamboo structure must be protected from moisture contact	
			Each wall plane must be stable in both lateral directions	
			Bamboo compressive stress cannot exceed 15.5 MPa	
Soft Criteria	All modules and interfaces must be aligned relative to the grid	Damaged elements can be replaced without dismantling the horizontally adjacent structure	Loads carried by the culm should travel axially along culm	Incorporate at least one principle from the Assam-type house
	Minimise and concentrate the number of interfaces	Construction steps can be understood by someone with little to no building experience		
	Minimal customization	Use tools and materials available in Guwahati		
	Minimise the degree of tolerance as much as possible	Connections require minimal on-site alterations		
		Prioritize materials that can be transported in bulk		

4. Methods

4.1. Methodology

This research aims to modularise the vernacular system of the Assam-type house. Therefore, the Modular Function Deployment Adapted (MFDA) method, as proposed by Sonego et al. (2016), will be adopted to ensure a systematic deconstruction and modular development of a new wall-based system using bamboo as the primary structural material. The system being developed has been identified as low complexity and low novelty regarding it being an adaptation of a low-skilled, vernacular system. As a result, steps one and two of the MFDA can be ignored, and steps three to five will be used going forward. This is a three-step process, with additional sub-steps relevant to this research:

Table 5 - Methodology structure

1. Generate concepts:	2. Evaluate concept:	3. Improve modules:
a) Deconstruct the Assam-type house	a) Evaluate against hard and soft criteria	a) Organise problems
b) Identify modules	b) Modularity	b) Systematically solve problems
c) Generate analytical model	c) Buildability	c) Re-evaluate the concepts
d) Identify interfaces	d) Structural design	
e) Select options for first iteration	e) Seismic performance	
f) Generate first iteration model	f) Synthesize problem list	

[FIGURE X – METHODOLOGY]

Each step has multiple sub steps and tools to organize the process. In step one, in order to generate ideas, the current assam-type house system will be deconstructed and analysed using the Interaction Matrix Analysis (IMA). This will help organise the system in target components, system components, and supersystem components and identify where the interactions lie between them. The following step is to identify which elements are most suitable to act as the module nucleus, around which the other elements are clustered, using the Module Indication Matrix. Once the modules concepts have been formed, an analytical structural model will be developed in order to simplify the complexity of the system and identify the connection typologies that have to be addressed. For each typology, different relevant options will be identified and compared, after which, one of each option will be selected going forward. These will be combined to form a complete system configuration.

The second step is to evaluate the concepts through the hard and soft criteria, scaled prototyping and connection detailing. Once the concept has been evaluated, any shortcomings will be carried over in the third step where they are individually are addressed. Once all of the issues have been analysed and solved, the second iteration will be constructed and reevaluated. Any further shortcomings will be deferred to future research and research limitations in the discussion section.

4.2. Research Design

The MFDA methodology outlined above is carried out using four research tools, each applied at a specific step. Table 6 summarises which instrument supports which step of the process.

Table 6 - Research design

MFDA step	Sub-step	Research instrument
Generate concepts	Deconstruct Assam-type house	Interaction Matrix Analysis (IMA)
	Identify modules	Module Indication Matrix (MIM)
	Synthesise module concepts	Conceptual design + 3D digital modelling (Rhino)
Evaluate concept	Hard and soft criteria	Criteria scoring (Chapter 3)
	Seismic performance	Seismic Calculation Tool + Karamba3D model
	Structural design	Bamboo Control Tool + analytical hand calculations
	Buildability and modularity	Scaled prototyping
Improve modules	Resolve shortcomings	Iteration on the same four instruments

The IMA and MIM are described in detail in Section 2.4 and are not repeated here. Full-scale physical testing of bamboo connections were not conducted. It is the most representative method of assessing mechanical performance, but it requires cyclic-load equipment and a large number of iterations that are beyond the scope of this master's thesis. The research is instead focused on preliminary design development through an analytical and design-research study.

4.3. Research Methods

The four research tools are described below in the order in which they have been used.

Seismic Calculation Tool

The Seismic Calculation Tool is an Excel-based implementation of the equivalent static method specified in IS 1893 (Part 1):2016 for low-rise buildings. It calculates the design base shear, V_b:

$$V_b = A_h \times W$$

V_b = Seismic design base shear

A_h = Design horizontal seismic coefficient

W = Seismic weight of the structure (dead load + live load)

Inputs are filled into parameter cells, grouped into four blocks: building geometry, dead and live loads (per IS 875 Parts 1 and 2), site seismic parameters (zone factor, importance factor, response reduction factor, structural time period), and the load combination factors specified in IS 1893 cl. 7.4.2. Outputs include the seismic weight, and the design base shear which form the basis of the calculations conducted in chapter 5.4. By parameterising the inputs, the tool also allows the consequences of changes in building geometry or load assumptions to be tested without recomputation.

Bamboo Control Tool

The Bamboo Control Tool is an Excel-based tool that calculates the design load limits based on the bamboo structural design standards of IS 15912 and ISO 12256. The tool utilises input parameters of bamboo morphological and mechanical properties to check for the structural limits of the system. These limits primarily include beam checks (bending moment, bending stress, deflection) and column checks (Euler buckling and compressive stress). By changing the input parameters for bamboo, alterations to length, diameter and wall thickness can be tested without recomputation.

Furthermore, the input parameters are used to translate the variability of bamboo culms into the geometric and structural limits that a modular system must accommodate. The tool quantifies both outer diameter between culms, tapering, wall thickness and culm spacing, which is used to produce three categories of output: tolerances (the worst-case gap between adjacent culms at any height), grid parameters (the nominal diameter, centre-to-centre spacing, and bolt spacing required for linear scaling), and module weights. The tool organises all of the dimensional assumptions about bamboo in one place, so that changing one assumption updates every value that depends on it.

Karamba3D Structural model

The structural behaviour of the wall under lateral load is comparatively assessed using a linear-elastic finite-element model built in Rhino and Grasshopper with the Karamba3D plugin. Karamba allows alternative structural layouts to be continuously computed and analysed with varying parameters without the limitations of statical determinacy.

The model is used comparatively rather than predictively. Linear-elastic analysis under monotonic load cannot represent cyclic seismic response, friction slip, or post-yield behaviour, and the model therefore makes a number of simplifications that limit the accurateness of the output values. Used comparatively, design variants can be chosen based on favourable relative responses.

Scaled prototyping

Scaled physical prototyping of connections and structural models is used as a qualitative research instrument. Its purpose is to understand the physical construction implications and structural logic of the system.

5. Results

5.1. Generate Concepts – First Iteration

Using the adapted Modular Function Deployment framework proposed by Sonego et al. (2016), the system was concluded to be of low complexity and low novelty. This is in contrast to complex systems such as rocket engines which have many individual elements and interfaces in one system. As a result, the first two steps of the five-step process can be skipped, instead beginning at step 3, concept development.

Generating concepts is the first step, in the three-step methodology of the MFDA, in which a system is deconstructed into its individual components, analysed using the IMA and MIM, after which module concepts are constructed and analysed.

5.1.1. Deconstruction of Assam-type House

To begin the development of a modular system it is essential to analyse the current system. Chanda et al. (2019) have set-up a generalized representation of the Assam-type timber house which creates the perfect framework from which to begin the analysis.

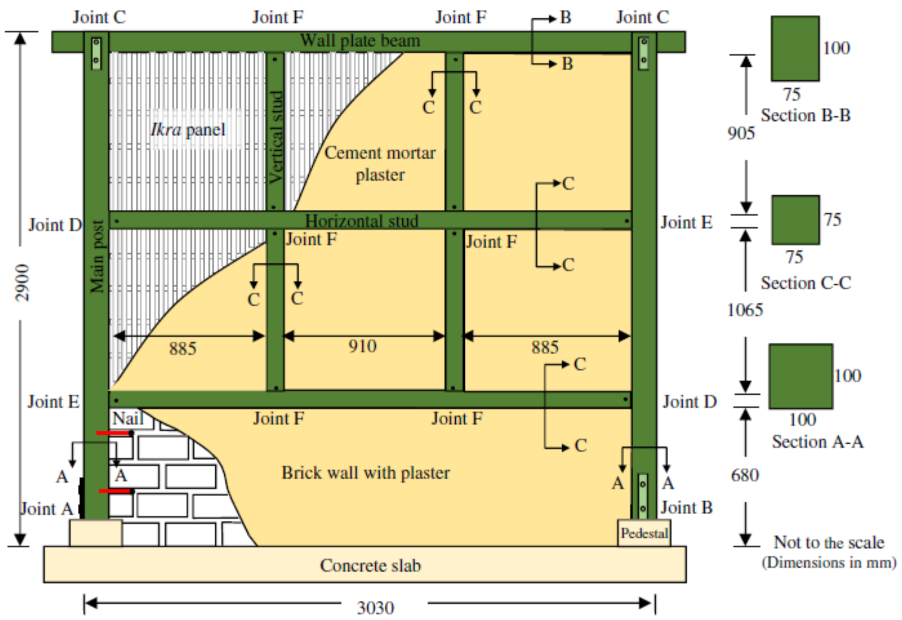


Figure 11 - Details of a typical frame of an Assam-type house. (Chand et al., 2019)

The first step to deconstructing the system to be modularized is to separate all of the components and arrange them in the Interaction Matrix Analysis (IMA) as shown in figure 11. This will help determine all of the interactions between the components which will be used for further analysis in the next step. It is important to determine the system boundaries so that all of the components can be organized in target components, system components and supersystem components. This research is developing a modular wall system from the current Assam-type wall. This identifies the wall of the house as the system boundary. Any components outside of this boundary, including the roof and foundation, that directly influence the system, makes up the supersystem components. The target component of the wall is the rest of the building, as the function of the wall is to carry the horizontal and vertical loads to the foundation, ensuring stability and enclosure. The system components are any elements that are within the wall and are sampled from the illustration from Chand et al. (2019). This deconstruction is illustrated in figure 12**.**

When constructing the IMA, the components are arranged left-to-right/top-to-bottom in order of target component(s), system components, and supersystem components. Any direct interaction between two components is marked with a '+'. while the others are left blank. If the interaction between two components is bad, then the cell is highlighted red.

The IMA shows that the timber posts and beams interact with almost all other components in the system, distinguishing them as the structural centre of the system through which all interactions travel through. The Ikra panel, and infill only interact with each other and the frame, as well as the seismic ground motion. This due to Chand et al. (2019) discovering the seismic strength attributed to the panels, and how they help maintain the stability of the frame. Moisture has a negative influence of the structure as it leads to the long-term degradation of the structure's performance, therefore, all of its interactions have been highlighted as red. As a result, moisture interaction with the system must be avoided as much as possible.

		Target	System								Supersystem			
		the building	timper posts	timber beams	ikra infill panel	plaster material	paint	brick plinth	fasteners	door + window frames	Seismic ground motion	roof structure	foundation	moisture
		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
the building	C1		+	+	+	+		+	+	+	+	+	+	+
timber posts	C2	+		+	+	+		+	+	+	+	+	+	+
timber beams	C3	+	+		+	+		+	+	+	+	+		+
ikra infill panel	C4	+	+	+		+					+			+
plaster material	C5	+	+	+	+		+	+			+			+
paint	C6	+				+								+
brick plinth	C7	+	+	+		+			+	+	+		+	+
fasteners	C8	+	+	+				+		+	+	+	+	
door + window frames	C9	+	+	+				+	+		+	+	+	+
Seismic ground motion	C10	+	+	+	+	+		+	+	+		+	+	
roof structure	C11	+	+	+					+	+	+		+	+
foundation	C12	+	+					+	+	+	+	+		+
moisture	C13	+	+	+	+	+		+		+		+	+	

Figure 12 - IMA Analysis

5.1.2. Module Indication

To begin concept development, the system components from the IMA were used in the Module Indication Matrix (MIM) which uses a set of scored criteria to help identify the elements function in a modular system (figure 13). The scores are numbered as 1 (low driver), 3 (medium driver), 9 (high driver). The reason for these jumps is to help distinguish the strong relationships between components, helping them stand out from the other components in the system. The components with the highest scores are candidates for modularization and any additional components with a similar weighting in the same category, and shared interactions in the IMA, are grouped into that module. It is proposed by Erixon (1998) that the ideal number of modules in a system is equal to the square root of the number of components. In the typical Assam-type wall there are six elements which equate to an ideal number of 2.2 modules. This was then rounded up to 3.

In preparation for the MIM, a few alterations were made to the component list as a result of certain design criteria and modularization logic. Firstly, the brick plinth (C7) was excluded as it is not a candidate for modularization because the design criteria restrict it to a non-modular foundation element. The fasteners (C8) were also excluded as it is too small and variable to be considered for modularization. For the purpose of modularization, the beam and post components (C2 + 3) were combined as they form a single structural frame element which cannot be meaningfully separated into independent modules.

			Structural frame	Ikra panel	Plaster material	Paint	Window/door frame
		"I"	C2+3	C4	C5	C6	C9
Development and Design	Carry-over	1	3	1			1
	Technical evolution	3	9	9	1	3	3
	Planned design changes	9	3	9	1		3
Variance	Scaling	9	9	3	1		3
	Styling	1		3	3	1	3
Production	Common unit	9	9	9	9	3	9
	Manufacturing Variety	3	9	9			9
After Sales	Service & Maintenance	9	3	3	9	3	3
	Upgrading	9	9	9	3	9	9
	Recycling	9	9	9	1	9	9
9 = Strong Driver 3 = Medium Driver 1 = Some Driver	Sum Weight of Driver		435	436	222	226	364
	Module Candidates		x	x			x

Figure 13 - Module Indication Matrix (MIM)

As a result of the MIM, three modules were identified: a structural frame module, an Ikra panel module and a window/door frame module. The plaster component is grouped with the bamboo panel module as they share high drivers for upgrading. The paint component is joined in this module as the IMA analysis indicated that its only interaction is with the plaster material. The window and door frame became a module as it had high values for common unit, upgrading and recycling, which are all important drivers in this system. The module had medium values for the other important drivers, contributing to a total driver weight of 364.

Now that the three main modules are identified, the next step is to establish the spatial layout of the system. The structural frame module will form the main load bearing system on which the other modules are connected. To protect the bamboo from moisture, the Ikra panel module will become a cladding module instead of an infill and will sit on the face of the structural frame. This will slightly change the structural performance of the panel as the lateral load will now be transferred through the fasteners into the panel, instead of the frame directly bearing on it. The window and door modules exist in-plane of the wall and, therefore, have a structural function as they share the responsibility to transfer forces to the foundation. To help organize the system a grid is set-up, derived from the Assam-type house.

The wall system was reconstructed in Rhino to find general measurements and to set up a preliminary ordering system for module design. From this system, different variations of the grid were constructed (figure 14, 15). The original grid had a visibly regular structure, however at closer look had slight variations in distances between each grid line, perhaps taking into account the thickness of the timber member along that line of the grid. Based on the representative wall section from Chand et al. (2019), the average grid spacing (Grid 0) was 0.98 x 0.95m. Different variations were explored that were similar to Grid 0. Grid 1 was the most similar, adjusting the grid to the closest rounded value of 0.95 x 0.95m. Grid 2 simplifies this further into a grid of 1 x 1m, while Grid 3 takes a separate approach by subdividing the grid into four rows and columns to emulate the height of the plinth row from Grid 0. In the end, Grid 2 was selected as the basis for preliminary system development due to its simplicity. Final grid dimensions will be confirmed once connection details and tolerances have been resolved.

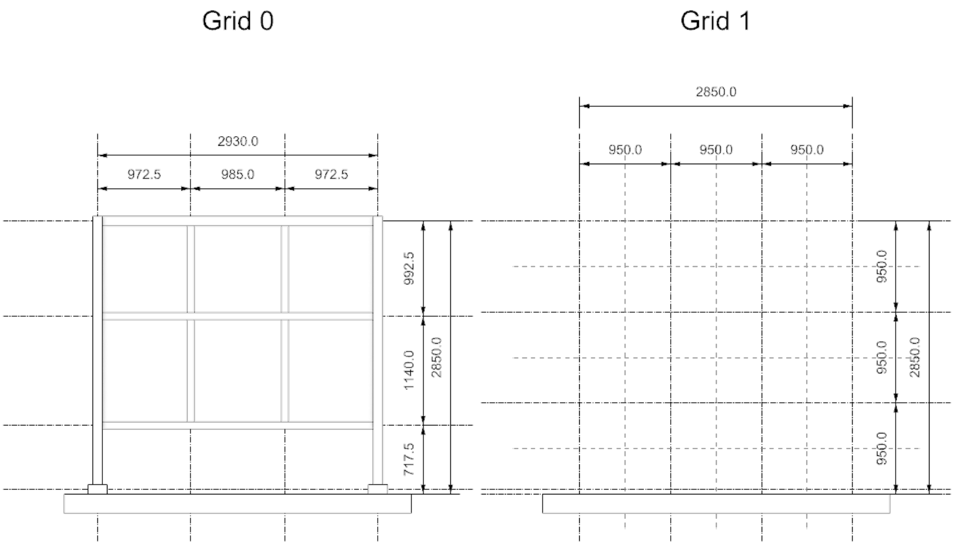


Figure 14 - Grid 0 and Grid 1

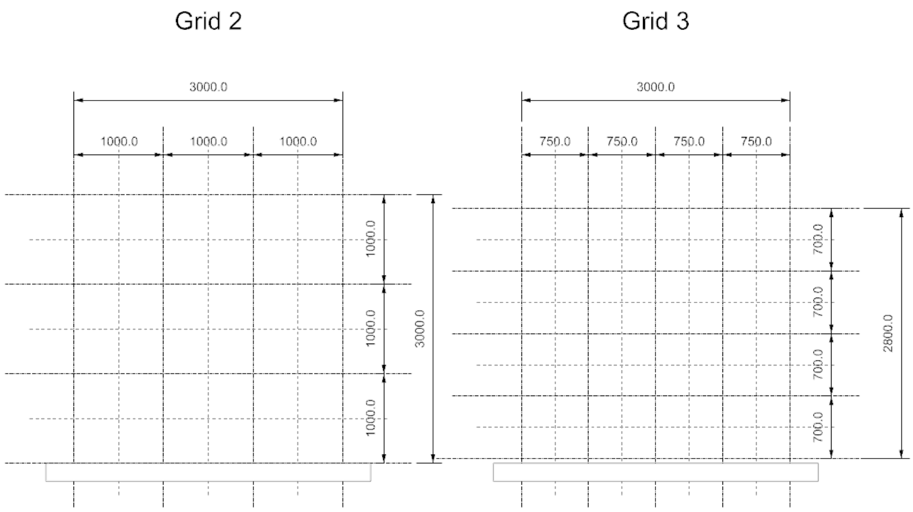


Figure 15 - Grid 2 and 3

5.1.3. Module Selection

Based on Grid 2, four types of module sizes were considered for linear scaling: A) a small 1x1 stackable module, B) a 1x3 module, and C) a 3x3 module. The smallest Assam type house has a minimum width of 3 meters (H. B. Kaushik & Babu, 2009), therefore, modules larger than 3x3 were not considered. A 1x2 and 2x2 module were also not considered as it would not lead to proper linear scaling. Module C was immediately discarded based on the hard criteria that the module cannot be larger than 3m x 1.8m. This is based on the constraints provided by the maximum load bed area for a tractor trolley. Both module 2 and 3 satisfy these preliminary constraints and therefore will be explored going forward.

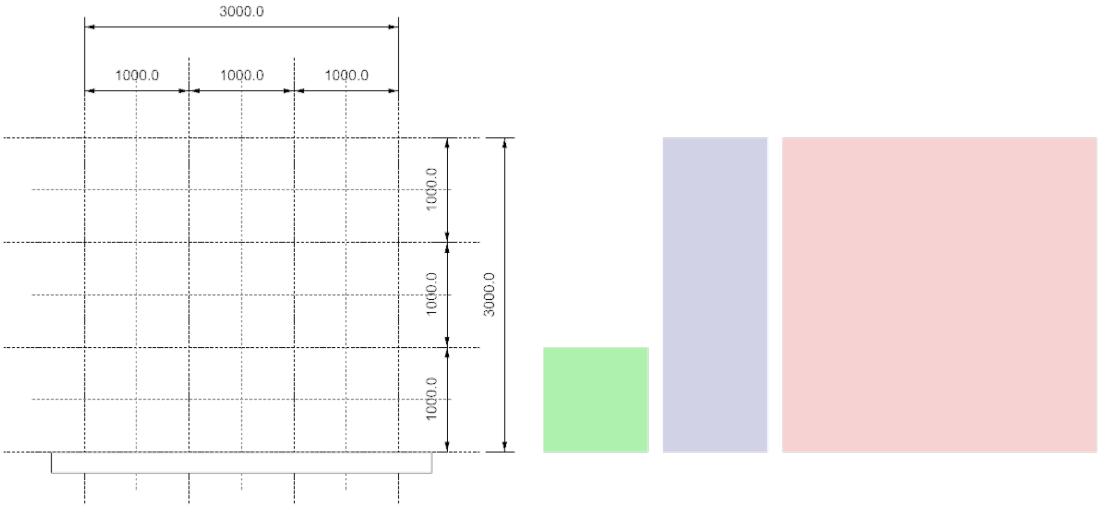


Figure 16 - Module Size Variation

Smaller modules do unfortunately invite the limitation of increased interfacing which introduces more points in the system where forces are transferred and potential failure can occur. This limitation will be considered in future stages of the design through proper jointing design.

When broadly analysing the implications of a stackable module system, three types of connections were identified, as shown in figure 16, which differed slightly from each other in terms of implications: 1) Intra-module, 2) Inter-module, 3) Module-foundation. There is also a fourth connection, the module-roof connection, however that is currently out of scope of the research therefore will not be explored at the moment. These connection typologies exist in both the 1x1 module and the 1x3 module.

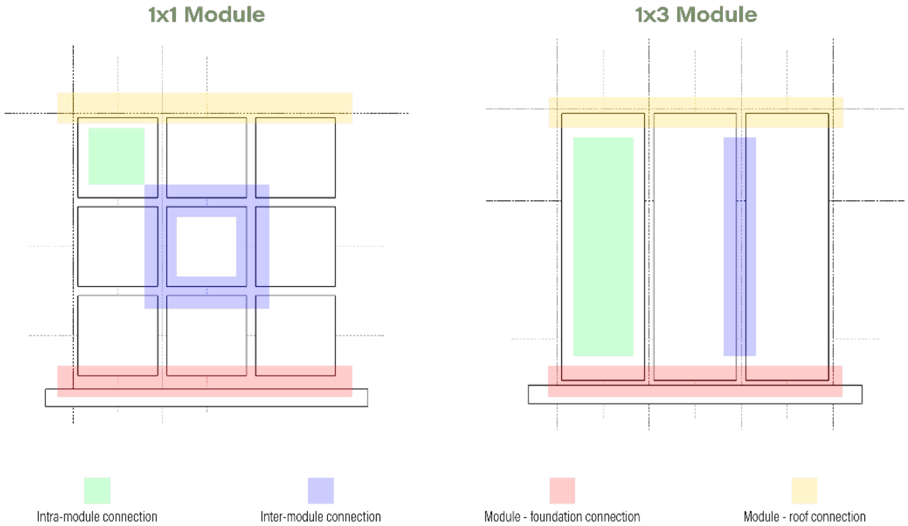


Figure 17 - Connection Typologies

Table 7 - Connection typologies and implications

Intra-module	Inter-module	Module - Foundation
• Will be constructed in a factory setting • Access to more machinery than on site • Connections are allowed to be slightly more complicated • Capable of higher precision work • Medium-skilled labour • Prioritize prefabrication efficiency • Design for disassembly?	• Will be assembled on site • Will be constructed by consumer – must be low skilled connection • Must be easy to repair • Connections must be consistent and intuitive across modules	• Must avoid ground contact and moisture exposure • Low-moderate skilled labour required • Must be visible for inspection and reparation • must be easy to repair – simple but strong connection • Most expensive connection

These connection typologies are considered in further exploration of the module types. In table 7 the implications of each connection are laid out. The information in this table was identified in the contextual constraints research which can be found. The key findings are that the intra-module connections can be more complicated as they are made in controlled environments, with access to better machinery and moderately skilled labour. The modules should be able to be placed and connected on-site by the future inhabitants, who are unskilled and untrained, therefore the connection must be intuitive and easily made. The same goes for the module-foundation connection, however, the joint will most likely involve different connectors and will be inherently more expensive, therefore it is considered as a different connection typology.

The structural frame module, being the central module around which the other modules are oriented, is the first to be developed. Instead of timber, it will be composed of bamboo culms. The culms can be arranged in four different categorical ways to form a frame based on the connection location between each other. These module variants can be oriented to form a total of eight variants. Orientation is important to consider because it determines how loads are transferred to the foundation and how the modules connect to each other. Each one is displayed in figure 18 as an analytical model. As bamboo cannot handle moment rigid connections due to the possibility of splitting, each inter-bamboo connection must be a pinned connection. A pinned connection is displayed as an open circle between two linear elements.

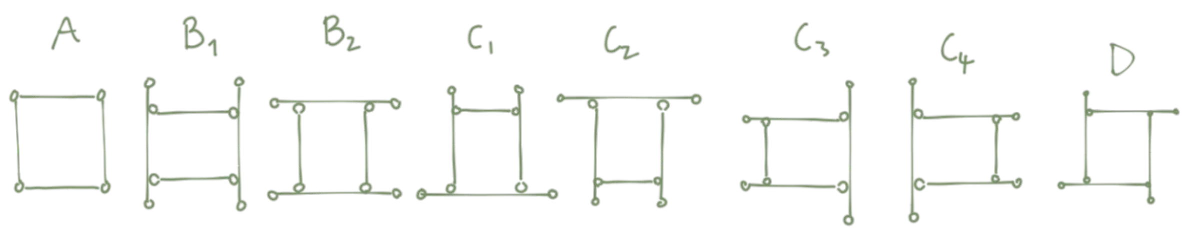


Figure 18 - Analytical configuration variants

Arrangement A assumes a connection at the ends of each culm. Arrangement B assumes two short culms which are connected to the wall of the two longer culms, which extend outwards. Arrangement C has three longer culms, two of which are vertically oriented and connected to the horizontally oriented member. Arrangement D is composed as a hashtag where each culm is connected to the wall of the other A shorter horizontal culm connects between the two vertical culms. Arrangement A would require an additional component to bridge the end-to-end connection and would require custom fitted manufacturing for each culm. This is not realistic for the context; therefore, this variant was immediately scrapped. The other variants were sketched in both the 1x1 and 1x3 module to properly analyse the implications of module assembly and to compare between the two modules to make an informed choice for which module variant to go forward with.

This exploration yielded two potential module variants for both the 1x1 and 1x3 module. The rest were all discarded for multiple reasons; 1) they relied on spliced end connections which are not pinned, cannot transfer loads reliably, and are difficult to standardize, 2) there was no direct load path to the foundation, relying on moments and shear which bamboo cannot handle.

$B_{1,2}$ (figure 19) was the most promising for the 1x1 module as the combination of the two orientations led to good inter-module connections that did not rely on end-to-end spliced connections, as well as a clear vertical load path and good linear scaling.

B_1 (figure 19) was the most promising variant for the 1x3 module as it also had a direct vertical load path to the foundation, and good pinned connections.

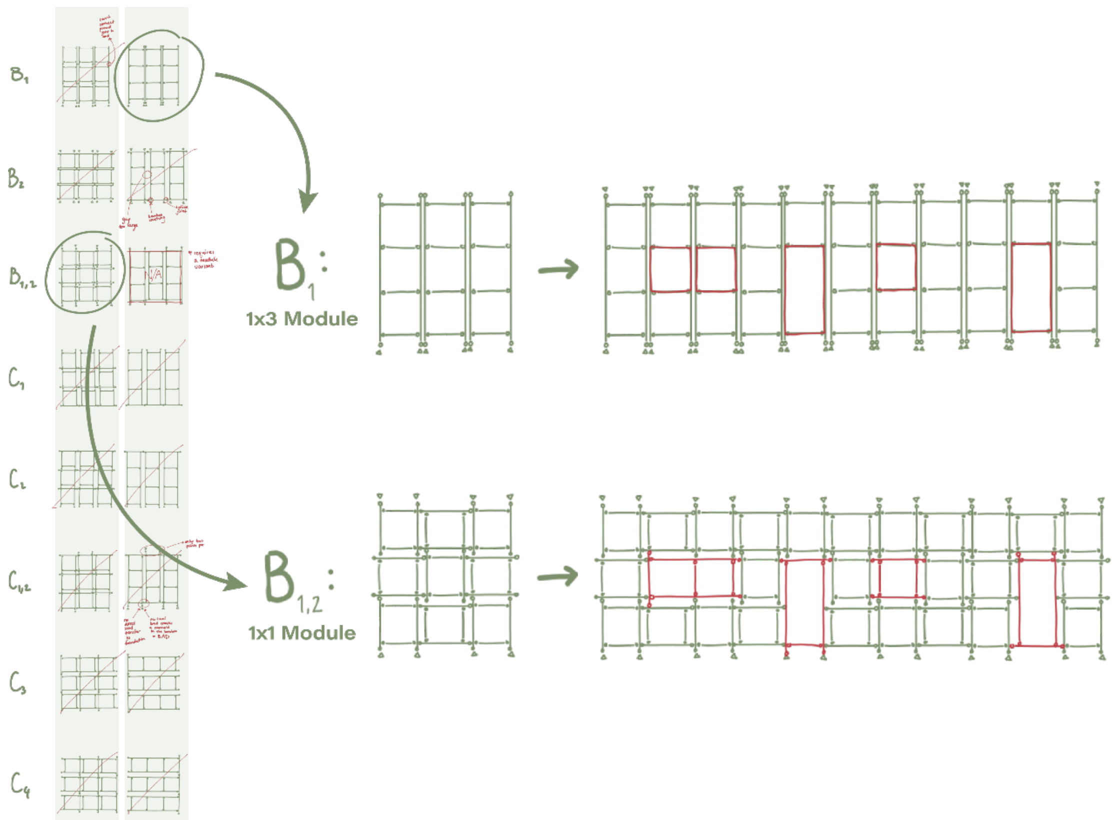


Figure 19 - Side by side comparison of scaling of module B_1,2 (1x1) and B_1 (1x3)

These two variants were then explored in more detail by scaling the modules across a wall to see how window and door modules could fit into the system. A comparison table was then set-up to list the advantages and disadvantages of both systems from the criteria lenses of modularity, buildability, and structural design. Seismic design is not relevant yet as the modules do not have any seismic performance without lateral bracing.

Table 8 - Advantages and disadvantages of the 1x1 module and 1x3 module

	Modularity	**Buildability**	**Structural design**
1x1 Module ($B_{1,2}$)	+ Scales horizontally and vertically + Can accommodate window + door modules + offers more design flexibility with windows and doors + clear inter-module connection points - has significantly more interfaces	+ easy to handle + easy to transport - more time consuming to construct - requires precision work	+ has clear vertical load paths - load travels perpendicular through culm = crushing - intermediate column hangs on adjacent columns
1x3 Module (B_1)	+ scales horizontally + less interfaces than $B_{1,2}$ - no clear inter-module interfacing - window and door module integrated into structural frame module	+ transportable + quicker to construct and assemble + more efficient use of culm length - larger to transport	+ has direct vertical load transfer to foundation - lack of clear horizontal load transfer

Both modules have their advantages and disadvantages for each lens. The 1x1 module, although easier to handle, with good linear scaling and clear connection points, had significantly more interfaces than the 1x3 module, which, makes it more time consuming to construct. However, the 1x3 module required the window/door module to be integrated in the structural frame module which meant that it lost its autonomy as a module.

The 1x1 module was initially explored for the reason that it had clear inter-module connections, two-dimensional linear scaling, is easier to handle, and could theoretically accommodate window and door modules. In addition, it is the most complicated of the two options due to the many interfaces to be solved making it ideal for a ‘critical-case’ design research strategy; by addressing the design challenges in the more demanding configuration, the solutions there would develop and be directly transferrable to the simpler configuration. This design strategy maximizes the research results of a single iteration while developing both modules simultaneously.

5.1.4. 1x1 Module exploration

The development of the 1x1 module focused on intra-module and inter-module connections and the relationship between them. A requirement of this design is to attach the end of a culm to the round body of the connecting culm to transfer compressive loads. The only way to achieve such a connection is by shaping the culm end into a concave shape that matches the curvature of the culm it is connecting to – a fish-mouth joint. This is the most traditional and structural bamboo connection: because the full cross-section bears against the surface of the receiving culm, it is the most reliable way of transferring compression between culms.

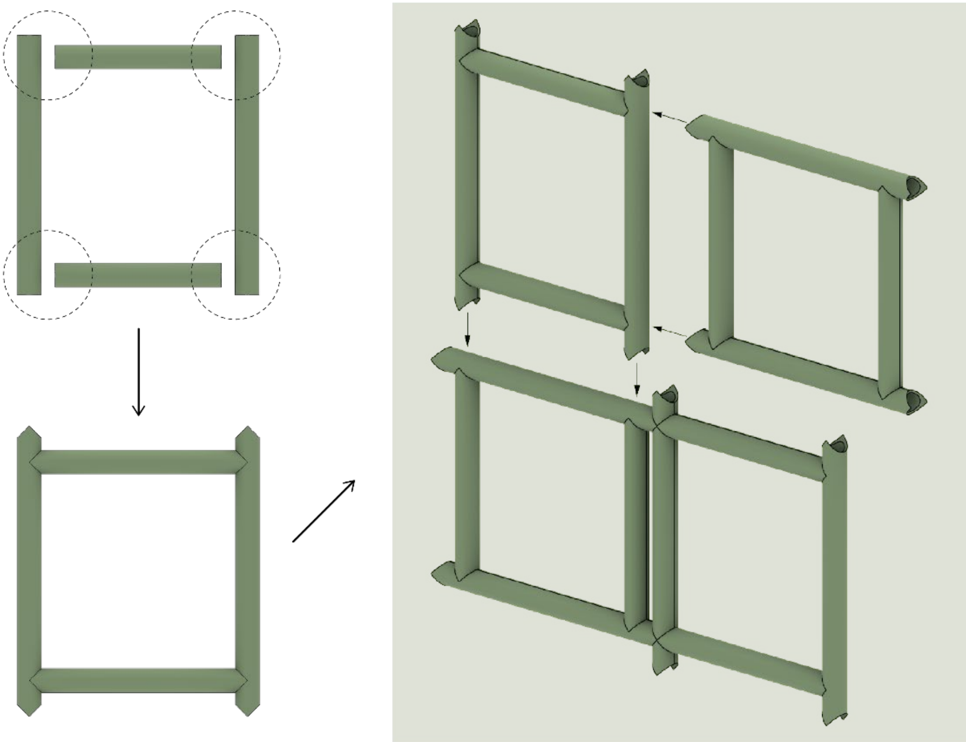


Figure 20 - Application of fish-mouth joint to intra- and inter-module connections

To decide on a suitable intra-module connection, diverse types of connections and connectors were arranged in a grid and qualitatively assessed based on their perceived buildability (B), availability (A), and how biobased (Bb) they are and repairability (R), (figure 21).

Based on these constraints, four joints were selected for their overall high rating in buildability, availability and repairability. Connection 1 scored the highest overall in each criterion as it is easy to connect, the materials are all locally available and as all the elements are accessible from the exterior, it is easy to repair. Connection 4 and 8 both require making sizeable holes in the culm wall which can critically weaken the culm under seismic conditions, leading to crushing and buckling. Connection 6 is a viable candidate and contemporary joining method which can be tightened to make the fish-mouth fit more firmly on the culm. Connection 1 is the chosen connection going forward as it aligns with the soft criteria to make the module as biobased as possible, in addition with the criteria for demountable connections which are accessible for inspection and repair. A plywood gusset plate has the additional advantage of being able to create holes wherever necessary, allowing to adjust the hole positioning closer to a node.

The gusset plate connection was explored in relation to the inter-module connection in **FIGURE X**. It was identified that for most of the options, a secondary gusset plate is required to connect the four modules together at the hashtag interface. This creates a simple interface on which the Ikra panel module could potentially be fastened.

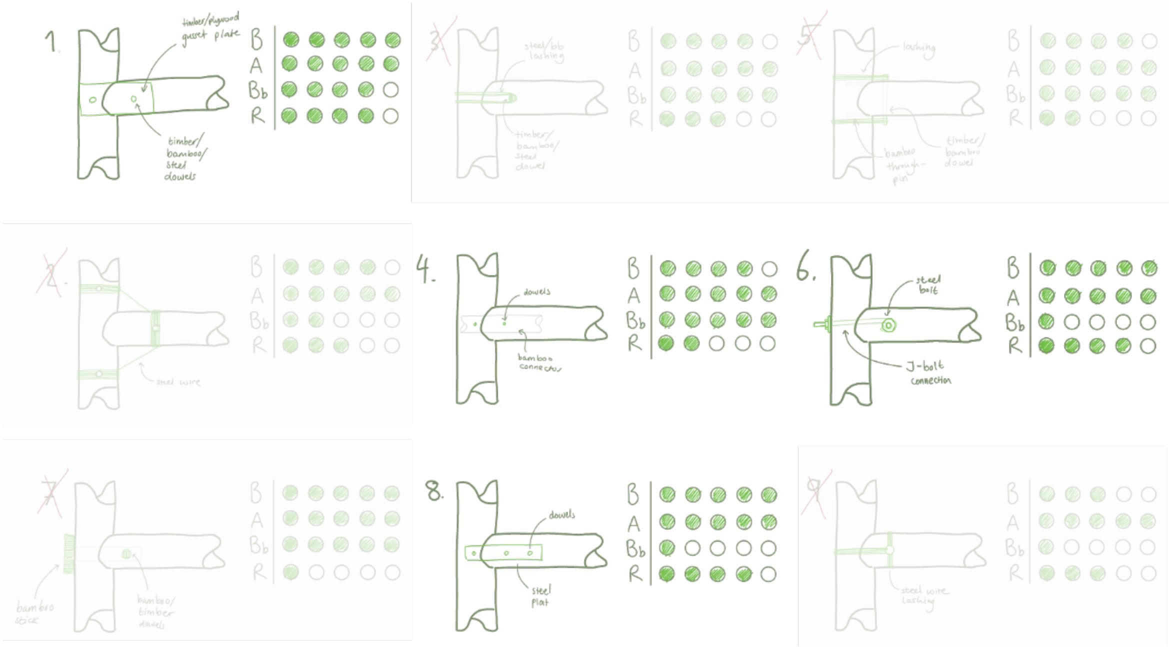


Figure 21 – Fish-mouth connection variations and selection

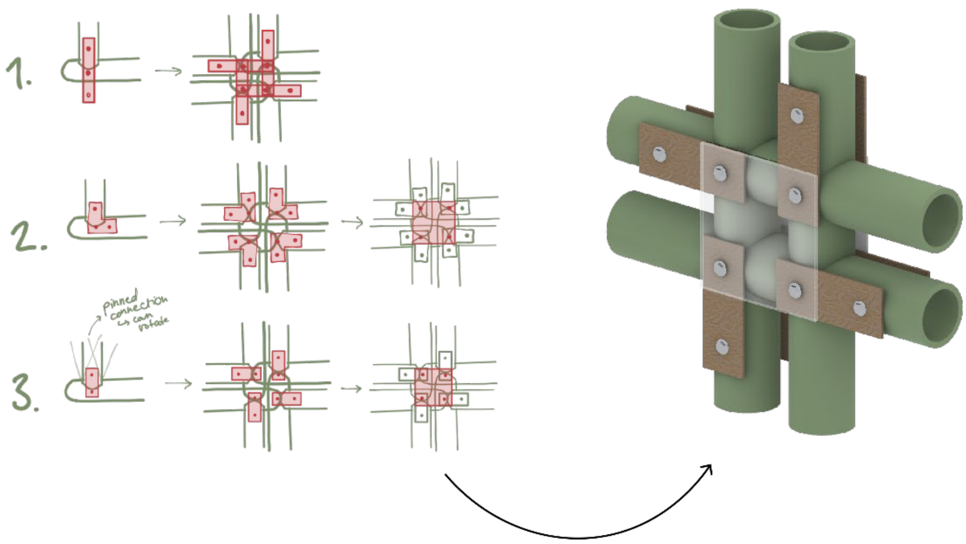


Figure 22 - 1x1 module connection detail example

There are a few issues with this design. Firstly, this is an idealized representation of the connection without any tapering of members, therefore, it does not accurately represent the real system. This diameter variations will have an impact on the fish mouth joint as the joint must be universally connectable to allow for repair and minimal on-site customizing. An exploration into the construction of a fish mouth joint demonstrated that the fish-mouth cannot join equally securely to a wide range of diameters **[TABLE X]**. The consequences are illustrated in **FIGURE** X.

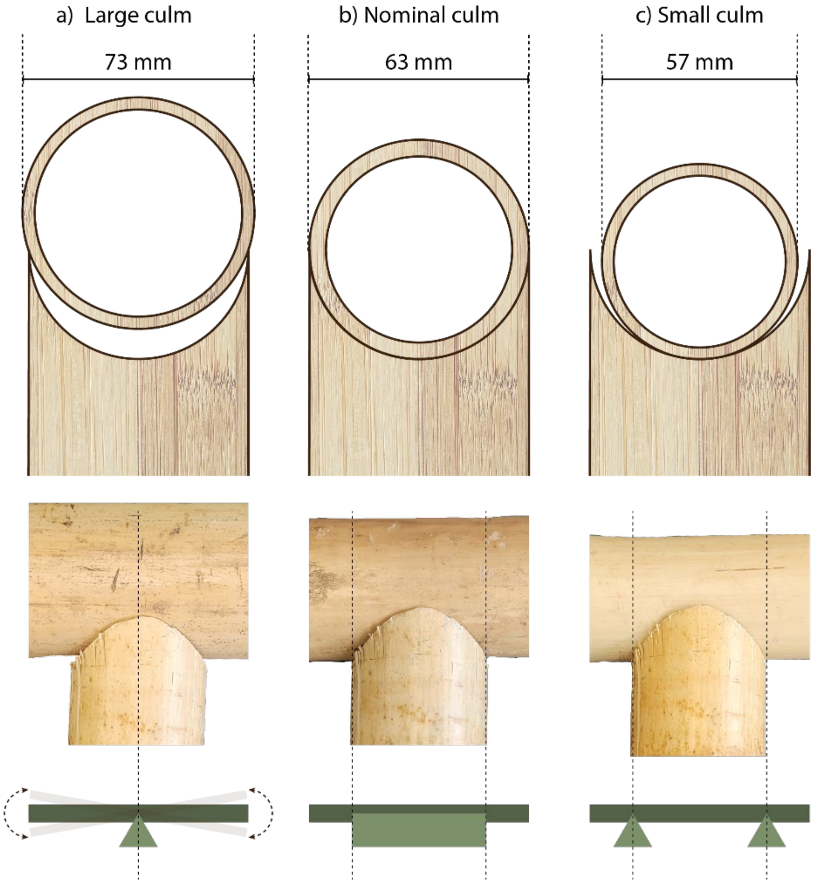


Figure 23 - Analytical representation of fish-mouth connection variability

When the cut has a smaller diameter than the attached culm, then the connection loses the benefits of full cross-sectional contact, instead, the culm would be offset from its connection and would act as a whip. To partially solve this issue, the cut would have to be sized to the largest allowable culm diameter to allow for universal compatibility. Consequently, the perpendicular culm of all other culm diameters would simply lie inside the fish-mouth, only supported by two contact points at the lowest point in the fish-mouth cut. This is a slight improvement but does not solve the issue of a secure connection. A fish-mouth connection can only work if it is customized for the culm that it is fitting, which is suitable for the intra-module connection. From this, it is concluded that a fish-mouth connection does not satisfy the modularity criterion for universal connectability and cannot work as the inter-module connection, therefore, this module variant becomes unfeasible.

5.1.5. 1x3 Module exploration

Due to the infeasibility of the 1x1 module, the 1x3 module is selected by default. The exploration of the 1x1 module revealed inconsistencies in the approach to producing a complete and coherent system as the critical interfaces were not systematically addressed. For the 1x3 module, the analytical approach was therefore restructured around the development of a complete seismically stable wall system and the subsequent connection typologies. The structural seismic models constructed by Chand et al. (2019) are overlayed onto the 1x3 module to complete the analytical system. Figure 24 illustrates the development of the seismic system and the decomposition of the connection typologies.

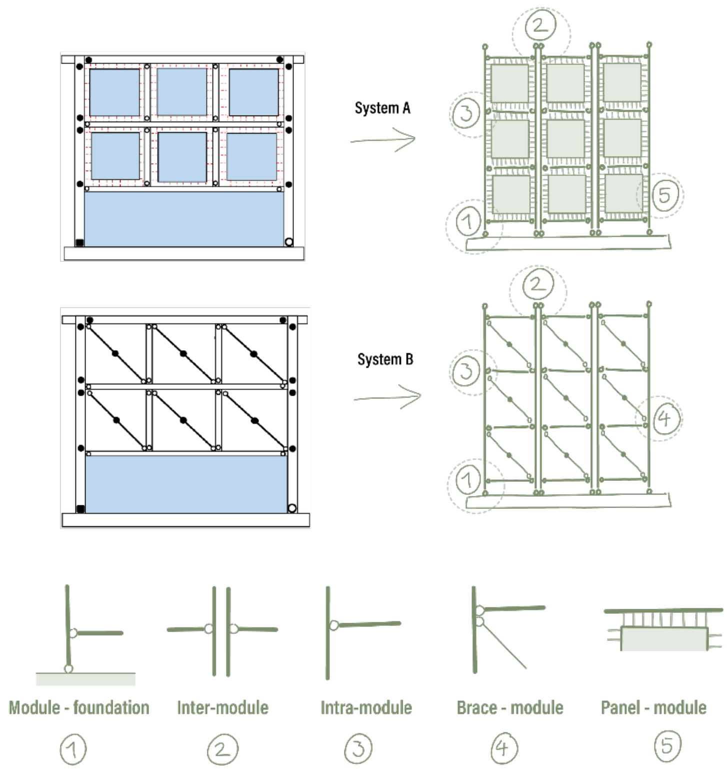


Figure 24 - Translation of analytical system from Chand et al. (2019) to 1x3 module

A diagonal brace was added as an additional component to the system which does not appear in the IMA. This is as a result of the analytical seismic models proposed by Chand et al. (2019) in the literature review; two models were created to represent the functional components of the seismic wall system, one of which replaces the ikra wall panel with an equivalent diagonal strut with a central plastic hinge. Both representations of the system were crossed with the analytical models, producing three system options; A, B, A+B. System A relies solely on the friction interfacing between the panel and the bamboo for energy dissipation and lacks predictable ductile mechanisms due to the absence of steel nails for plastic hinging, and that its failure mode is relatively brittle. Therefore, it was opted to develop system A+B as it combined both the vernacular logic with the hard criteria for designed and predictable ductile behaviour by including a steel diagonal brace. In the event that the friction link is not possible, the system can still always rely on the development of System B. As a result of the additional component, the MIM was reevaluated with the diagonal brace (figure 25). The outcome of the MIM revealed that the diagonal brace qualifies to be modularized, surpassing the score of the window/door frame module. The brace received such a high score on account of it acting as the primary fuse mechanism in the system. Therefore, it has to be replaceable, accessible and upgradable, all essential characteristics of a module.

		"I"	C2+3 Structural frame	C4 Ikra panel	C5 Plaster material	C6 Paint	C9 Window/door frame	C14 Diagonal brace
Development and Design	Carry-over	1	3	1			1	9
	Technical evolution	3	9	9	1	3	3	3
	Planned design changes	9	3	9	1		3	9
Variance	Scaling	9	9	3	1		3	3
	Styling	1		3	3	1	3	
Production	Common unit	9	9	9	9	3	9	9
	Manufacturing Variety	3	9	9			9	1
After Sales	Service & Maintenance	9	3	3	9	3	3	9
	Upgrading	9	9	9	3	9	9	9
	Recycling	9	9	9	1	9	9	9
9 = Strong Driver 3 = Medium Driver 1 = Some Driver	Sum Weight of Driver		435	436	222	226	364	453
	Module Candidates		x	x				x

Figure 25 - Module Indication Matrix (MIM) revision

All of the connection typologies in this new analytical model were categorized and organized to enable the systematic development of the first system iteration. The connections were organized based on the order of influence on the system; 1) foundation, 2) module-foundation, 3) intra-module, 4) inter-module, 5) diagonal bracing, 6) panel-module, and 7) panel configuration. An overview of the connections and results are presented in figure 26.

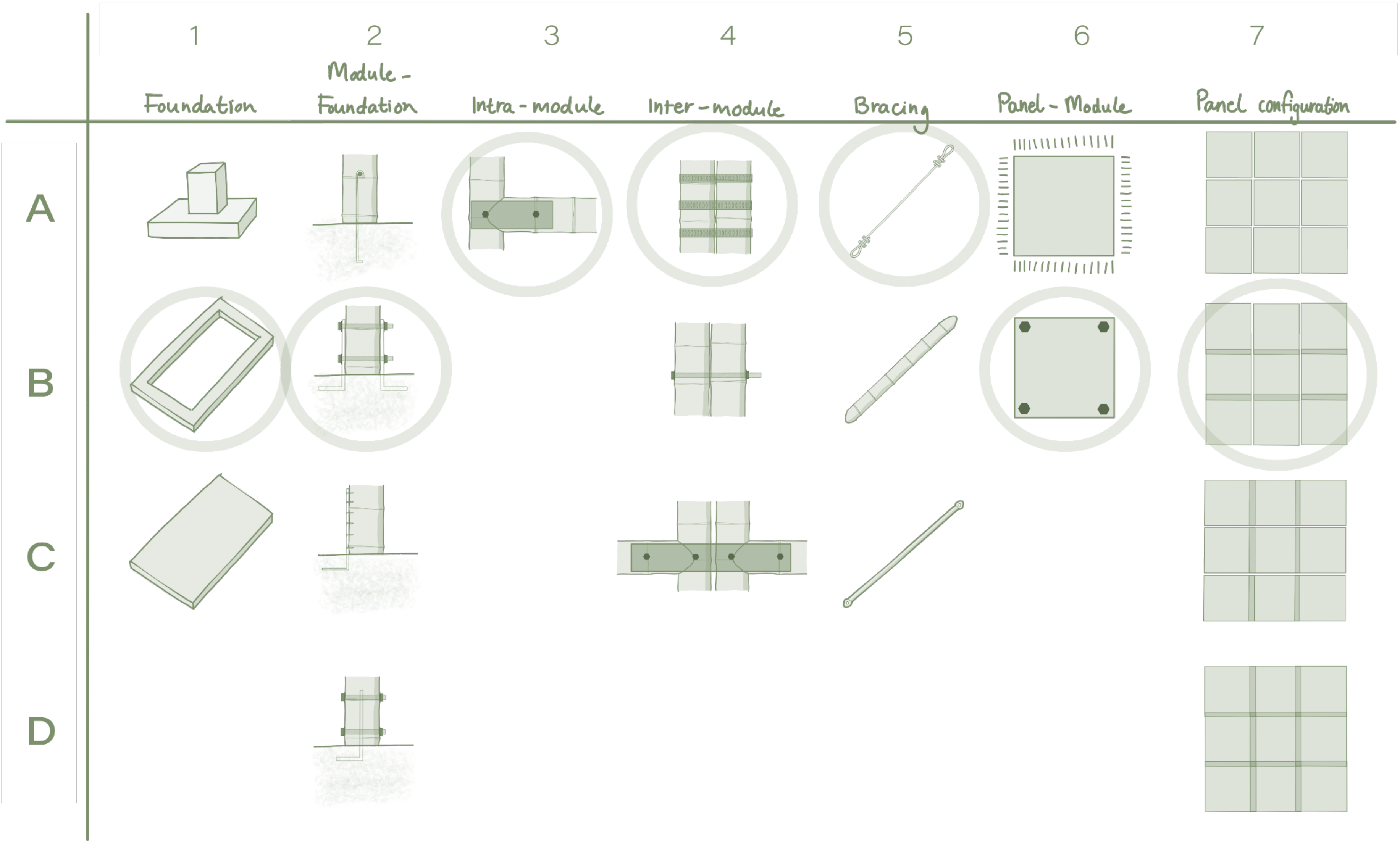


Figure 26 - Module Interfaces Exploration and Selection

1) Foundation

It was decided during the IMA that the foundation of the system falls outside of the system boundary for modularisation, therefore, the foundation is assumed to be identical to a traditional Assam-type house. Such a foundation is usually a shallow strip foundation which is poured in place. On top of the strip foundation, a brick or hollow concrete plinth is constructed that raised the house 600mm from the ground to prevent moisture contact. This is also essential for bamboo construction which is particularly susceptible to moisture damage.

2) Module – foundation

Multiple options for the module-foundation connection were reviewed. A small collection of potential bamboo-foundation connections were illustrated by Kaminski et al. (2016) for the design of bamboo bahareque housing. This was the was the most proximate examples for potential connections of vernacular bamboo housing. This left four types of connections, A) a steel j bolt which hooks onto a bolt passing through the culm, B) two external steel brackets with a through bolt, C) a long steel strip screwed into the bamboo, D) a steel T/L plate which sits in the hollow section of the culm. All of these connection elements are embedded in hollow concrete blocks, filled with cement so that uplift is resisted. Before a decision can be made, culm alignment has to be considered as it has multiple implications on the rest of the system such as the inter-module connection and the panel offset. The foundation connections were placed side by side in a plan-section (figure 27) to compare the effects of centre-alignment and front-alignment would have on the foundation connection placement, inter-module connection and the panel alignment. The external steel brackets with through bolts were eventually selected for the reason that all the connection elements are accessible for inspection and repair and that the position of the culm on the axis is adjustable with another set of bolts and washers clamping it in place. In addition, a front-alignment minimised the adjacent panel offset and the panel interference with the inter-module connection. The only issue is that the internal face of the structure could possibly have large offsets.

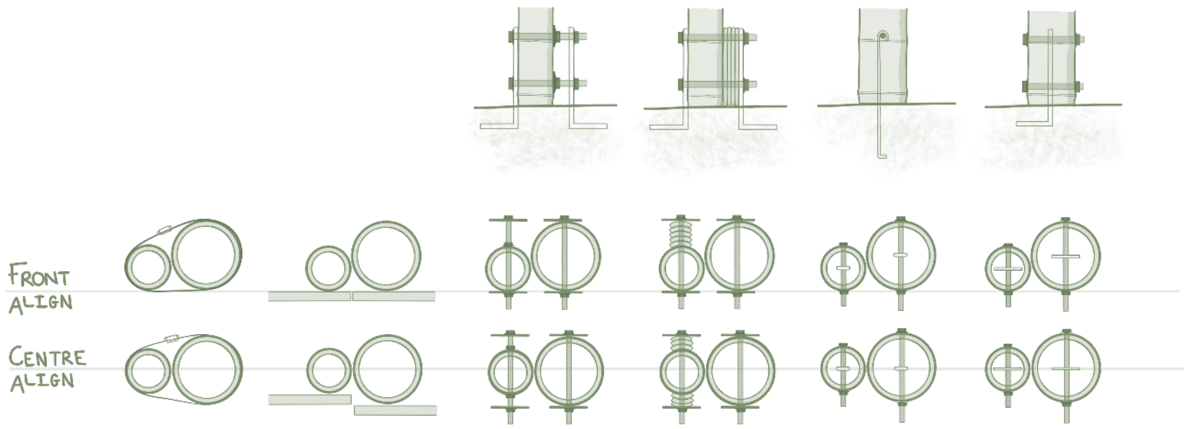


Figure 27 - Module - Foundation Exploration

3) Intra-module

The intra-module connection has already been considered in the development of the 1x1 module. The connection has therefore remained the same as with the 1x1 module - a fish-mouth cut with bolting using a plywood gusset plate. The fish-mouth cut can be customized to the culm in the prefabrication step.

4) Inter-module

The inter-module connection can be achieved through bolting, a strap/lashed connection or using another gusset plate. The bolt and gusset plate created a rigid connection between the two modules that are dependent on node spacing, while the strap connection is adaptable to culm diameters, is not dependant on node spacing and creates a non-rigid connection which allows for a friction slip connection, employing the same friction interfacing as in the Assam-type house.

5) Diagonal bracing

Three options were considered for diagonal bracing: bamboo culm, steel cable, and a steel bar. The steel cable complied with the most criteria as it has ductile behaviour, could be ordered and transported in bulk as a coiled spool, and it has predictable failure limits. The bamboo culm must rely on compression, cannot be pinned to the bamboo and has brittle failure, so it was quickly discarded. The steel bar complied with most of the criteria as well, however, its bulk transport capabilities were far more limited than the steel cable, in addition to the fact that its length could not be adjusted to absorb any tolerances, which the cable is capable of. The cable will have to be attached to the culm using a gusset plate, this can be either the same gusset plate that is used for the intra-module connection, or it could be a secondary gusset plate. Considering that intra-module connection relies on a plywood gusset plate which is relatively weak, the best option is to have an additional steel gusset plate which is attached to the bolt in the vertical culm.

5.1.6. Panel – module connection

The panel has a separate module typology which require a series of additional considerations such as composition, panel configuration and panel interfacing. Therefore, it is given additional acknowledgement as a separate sub-chapter.

Panel composition

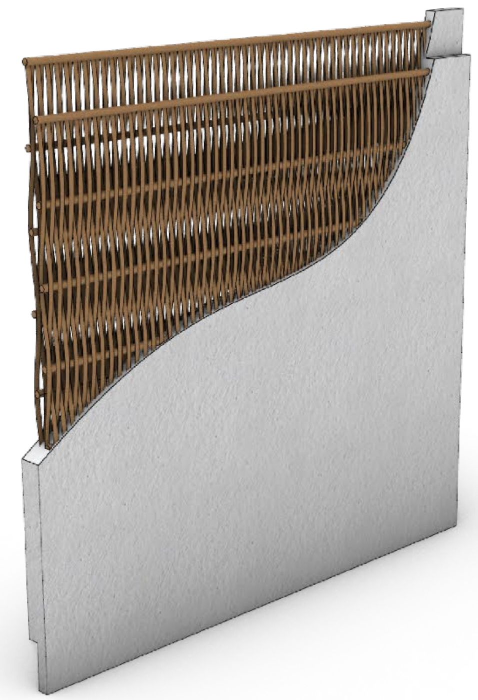
The panel will have the same composition as the ikra-panel in the Assam-type house for vernacular continuity. This composition consists of a bamboo/ikra mesh which is plastered with cement mortar.

Panel interfacing

According to system A, the panel should interface with the structural frame through friction. The Assam-type house allows this connection by embedding the frame in a groove made in the timber beams and posts. During a seismic event, the system could rack and the panels would slide along the groove creating friction between the two components. The possibility of a friction interface with bamboo was briefly explored through sketching, and it was determined that in this system it was not possible. Firstly, the clamping interface clashes with the modularity criterion of concentrated interfacing as it distributes the interface over a large area. Other structural issues also presented itself; making grooves in the hollow culm would lead to critical failure. The option to clamp the panel to the beams was also explored, however, this meant hanging the panels on the beams. The weight and seismic forces would be transferred onto the connections of the beams through shear, which could potentially lead to brittle failure. Clamping to the vertical culm would solve the issue of shear forces, however, it would no longer act as a friction dissipator. Lastly, the clamping interface requires a complicated set of components to achieve a proper connection. As a result of all of these factors it was decided that the simplest course of action, that is most in line with the criteria, is to bolt the panel to the column, no longer relying on a friction link between the panel module and the frame module. This means discarding system A, and solely focusing on system B for lateral restraint. It is important to note that panel module will still contribute to seismic dissipation through local crushing and shearing of the panels when the system begins to rack. It is the stiffest element in the system and will therefore, experience the first forces of the earthquake. Once it crumbles, the bracing will maintain lateral stability of the system. However, for the development of this system, the lateral stability will be assumed to come solely from the diagonal bracing.

Panel configuration

The panel will be situated as cladding on the exterior of the bamboo structure to prevent moisture ingress. There were multiple panel configurations considered (figure 27): A) adjacent modules, B) vertical overlap, C) horizontal overlap, D) Complete overlap. Configuration B was immediately discarded as such an overlap was impossible and led to a piling of surfaces. Configuration B was selected over the other two because configuration A and C required two bolts close together on the same culm which would weaken the culm alongside the fact that a nearby node for either one would not be guaranteed. Configuration C had the added disadvantage of failing to comply with the buildability criteria for dismantling. By having to remove one panel, the horizontal overlap means having to dismantle a panel that is horizontally adjacent to it. Configuration B had the highest interfacing concentration as it makes use of the bolt which is already present for the intra-module connection. In addition to this, the vertical overlap meant that water ingress was effectively prevented. Creating such a panel module is simple to achieve through the use of a mold in which to place the bamboo mesh and shape the ends for the overlap. A potential design concept was constructed based on the traditional Ikra panel weave and infill practices (figure 28).



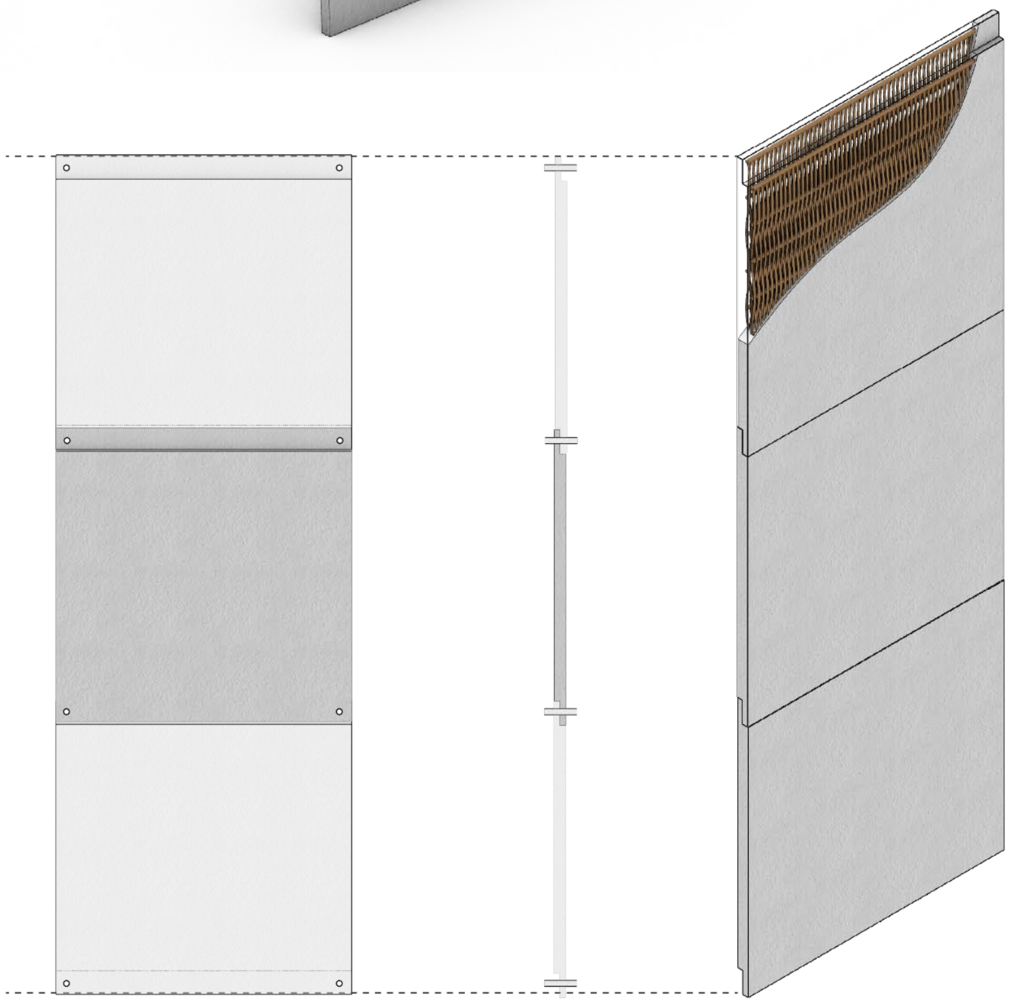


Figure 28 - Panel module, preliminary design concept

5.1.7. System assembly - First Iteration

Now that all of the interfaces are defined, the first system iteration can be assembled and evaluated against the established criteria. Due to a lack of resources, this was done using rhino to visualize the system as a whole, and 1:10 scale module was built to better understand the implications of building the structural frame module. However, some additional considerations must be made for the development of this system including design parameters, bamboo morphology and culm sizing.

Material conditions and assumptions

Given the morphological variability inherent to bamboo culms, a set of material assumptions and grading criteria must be defined to ensure that the design represents realistic and consistent conditions. These criteria and assumptions have been made using the International Standard (ISO 22156:2021) and National Standard (IS 15912:2018) for bamboo design.

- tapering must be no more than 5 mm/m,
- culm wall may be no less than 8mm thick on average,
- the culms are pre-straightened just after harvesting and will be assumed straight,
- diameter range of 30mm to allow for variability

Culm sizing

The culm range will be decided based on the minimum culm diameter. This will be determined based on buckling constraints using calculations provided by ISO 22156:2021 and the design parameters.

The minimum culm diameter was determined by working backwards from the critical buckling load using a goal seek approach in Excel. The effective buckling load was calculated by computing the dead and live loads in the system, with inputs including effective length (3m), minimum wall thickness (8mm), from which a nominal culm diameter of 70mm was selected as the design value. At the selected diameter, the utilization ratio under buckling is 7%, providing 1.6 mm of tolerance before the limit state is reached. ISO 22156 and IS 15912 do not specify which cross-section along the culm should govern diameter selection. Therefore, the 70 mm result was decided to be the most conservative estimate for the top of the culm, the narrowest point. With tapering included of 5mm/m, the base diameter is 85 mm. Assuming that culms are selected and cut such that the base of the structural culm corresponds to the base of the harvested culm, then 85 mm will represent the minimum culm diameter. This way, the culms will always have an added safety margin and will always satisfy the buckling load. By applying the 30mm diameter variability range, culms between 85mm and 115mm at the base are acceptable for use in the system.

3D Digital Modelling

To evaluate the structural performance across the full range of accepted culm sizes, the largest and smallest size culms in the diameter range 85 – 115 mm at the base were modelled as the governing limit states of the system. The 85 mm is the critical lower bound where buckling capacity is at its minimum, while the 115 mm culm represents the upper bound. If these two culms perform sufficiently, then any culm between these two bounds will perform sufficiently as well. This is combined with a maximum tapering of 5 mm/m.

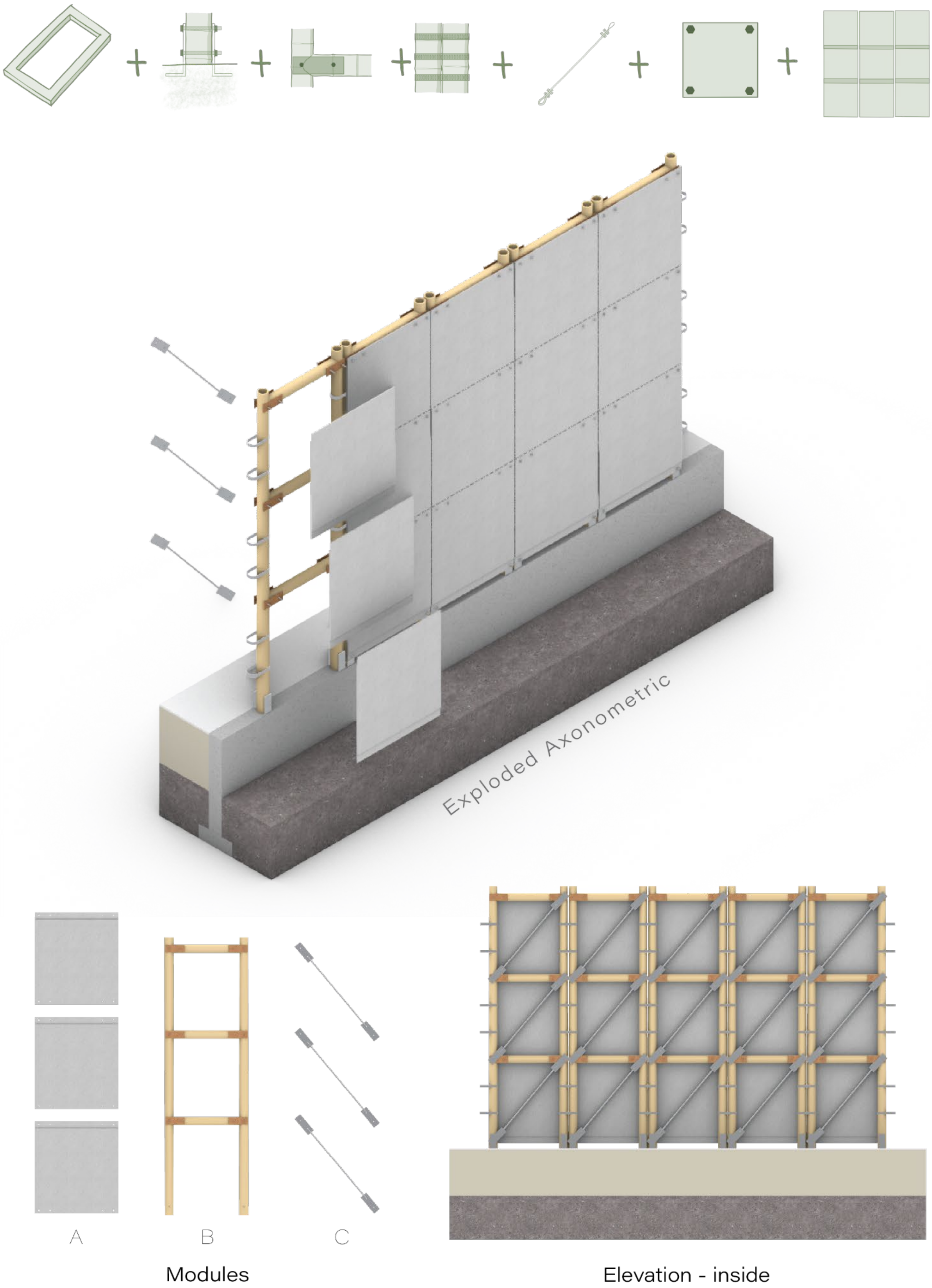


Figure 29 - System assembly first iteration

5.2. Evaluation – First iteration

In this section, the current iteration of this system will be evaluated through the lens of the established hard and soft criteria categories, modularity, buildability, structural design and seismic design. The input for the evaluations is from observations made during 3D digital modelling, rendering and prototyping, as well as through calculations for specific hard criteria. An overview of the evaluation is presented in **TABLE X**. A few criteria are omitted from the evaluation as they are currently not relevant.

Table 9 - Overview of Criteria and the results

Category	Criterion	Type	Result
Modularity	Scalability	Hard	Pass
	Universal connectability	Hard	Pass
	Grid alignment	Soft	Pass
	Tolerances	Soft	Fail
	Concentrated interfacing	Soft	Partial
	Minimal customisation	Soft	Partial
Buildability	Module size < (3.5 m x 1.8 m)	Hard	Pass
	Module weight < 50kg	Hard	Fail
	Demountable connections	Hard	Pass
	Module replacement	Soft	Partial
	Simple construction	Soft	Pass
Structural design	Pinned connections	Hard	Fail
	Measurable failure	Hard	Fail
	Moisture protection	Hard	Fail
	Lateral stability	Hard	Fail
	Axial loading	Soft	Fail
Seismic design	Plastic deformation capacity	Hard	Fail
	Vernacular seismic principles	Hard	Pass

5.2.1. Modularity

Grid alignment – *All modules and interfaces should align to the grid wherever possible*

In bamboo construction, bolted connections must be located at or near a node to prevent culm wall crushing. The position of each connection is therefore highly dependent on the natural node spacing of the culm rather than the original simplified 1x1 grid dimension. To ensure that bolts consistently land at or near a node, the grid spacing was adjusted to reflect the average internode distance of bamboo culms, which is approximately 340mm, almost exactly one third of the 1m module grid. This required only a minimal adjustment to the existing grid (figure 30):

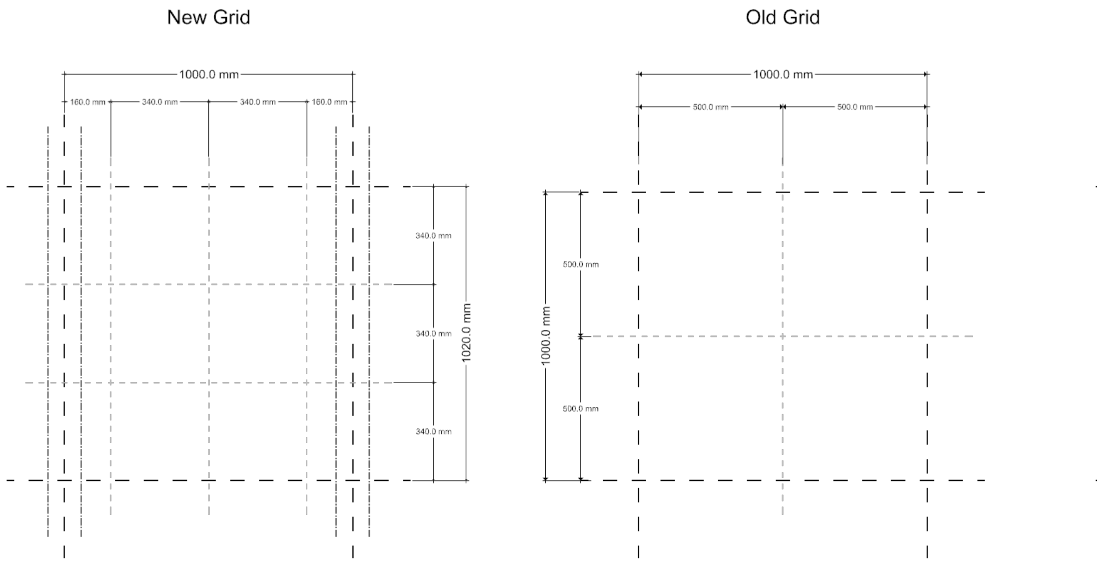


Figure 30 - Grid evolution

In the vertical direction, grid lines are spaced at 340mm intervals, corresponding to one internode length, so that horizontal connections along the height of the wall consistently fall at node locations.

In the horizontal direction, the requirement is different. Two connections must occur near the ends of each culm, one at each column position. The 340mm sub-grid is therefore centred within each 1m horizontal bay, placing one node at the centre and one node close to each end of the culm. This ensures that the two column connections are as close to a node as the natural internode spacing allows. The centre of the nominal culm is also illustrated as it is the line which aligns both the culms and the interfaces along the culm. Using this newly adjusted grid, the system was assembled and all interfaces align satisfactorily to the grid. The foundation brackets will be cemented in place at the given intervals to ensure that placement will always accurately take place.

Scalability – *Each module must be able to scale linearly across the grid*

The panel modules and the bracing modules scale along the structural frame module, so the scalability of the system is determined by the placement of the structural frame along the grid; if the structural frame module is placed in such a way that all adjacent culms are touching each other, then error accumulation will occur along the length of the grid. This is because when the largest culm (115 mm Ø) is positioned next to the smallest culm (85 mm Ø) then the offset will be 30mm. This is assuming that the beam length is always the same for the standardization of elements. Therefore, the centre axis of the largest culm determines the centre axis of all other culms. This is reflected in the new grid. All culm centres must align with that axis to allow for predictable linear scaling with minimal error accumulation. A consequence of this is the tolerances that form between the culms.

Tolerances - *Minimise the degree of tolerance as much as possible*

The variation in culm diameters creates upper and lower limits in the tolerances that exist in the structure. The upper limits are determined by the smallest culm diameter and its maximum taper while the lower limit is determined by the largest culm diameter and its minimum taper. A culm diameter of 85mm with a maximum taper of 5mm/m will lead to a gap of 30mm at the base, and a maximum gap of 46.5 mm at the height of 3.3m. These are large tolerances that hinder the inter-module connections as there exists no direct physical interaction between the culms (figure 30).

Universal connectability – *All inter-module connections must allow universal connectability*

The universal connectivity criterion was satisfied when doing the previous research on interfacing possibilities. The foundation, and inter-module connection both allow for flexibility in culm diameters; the strapping can be tightened or loosened to adjust to the diameters, while the foundation clamps are intentionally oversized and can be adjusted with an additional bolt and washer. The panel – module interface has predetermined holes incorporated in it, which only connect properly if each culm has an exact vertical and horizontal bolt spacing for the panel module. The internode spacing cannot be guaranteed; however, it can be vetted. It has therefore become a requirement that only culms are to be selected with an average of 340 mm, +/- 5 mm spacing, to guarantee the bolt placement required for a universal panel-module connection. The steel cable can be lengthened or shortened through the steel wire clamps, allowing it to be retightened and adjusted to variable conditions.

It is also important to consider the effect tapering has on creating a gap between the two adjacent culms. This gap could allow for swaying and a loosening of the connection between the two culms; therefore, this gap should be filled.

Concentrated interfacing – *Minimise and concentrate the number of interfaces in the system*

One of the principles of modular design is to minimize and concentrate the number of interfaces that exist in a system to reduce the complexity and improve the comprehensibility of the interfaces. This was achieved through the bolt placement along the vertical culm on which the interaction between all three modules meets. However, the use of the traditional bolt with a bolt head only allows modules to mounted from one end of the thread, meaning that the module, on the most inner part of the thread can only be accessed by removing all other modules first.

Minimal customization – *Modules should minimize the amount of customization necessary*

The only customization that appears in the structure, is the fish-mouth connection between the culm and the beam, and the plywood gusset plate connection. Both of these connections are made in factory, under controlled conditions, relocating the labour for customization away from the construction site.

5.2.2. Buildability

Module Size – *Modules cannot exceed 3.5m x 1.8m (L x W)*

Due to the adjustment of the grid, the structural culm module had to be extended in length from 3m to 3.3m, however, this still complies with the 3.5m x 1.8m size constraint. All other modules are far within the size constraints as they are sized to fit on the structural culm module.

Module weight - *Maximum module weight cannot exceed 50 kg*

For a preliminary check to see if the modules are less than 50 kg each, the weight of the modules have been calculated using their material densities and rough dimensions. The bracing module has been excluded from the check because its compliance is self-evident and falls well within the acceptable range. The structural culm module has been weighed at roughly 30 kg at a density of 772 kg/m3 for the module with the largest culm diameter (115 mm). The panel module is composed of a bamboo mesh and cement plaster, with a nominal density of 2000 kg/m^3. Assuming the panel has the same composition and thickness as that of the traditional ikra panel, the panel would be 1000 x 1100 x 45mm and would weigh approximately 88.19 kilos which far surpasses the module weight limit. This issue will be resolved in the module improvement chapter.

Demountable connections - *All connections must be demountable*

All connections comply with these criteria as they are all bolted, clamped or lashed. There are no permanent fixtures except for the foundation connection element which is cemented in place.

Module Replacement - *The modules should be able to be dismantled and replaced without impacting the horizontally adjacent modules.*

The bracing and panel modules can currently be detached from the superstructure by unbolting it from the frame. They have no influence on the adjacent structure during replacement. The structural culm module currently experiences a challenge in this area. The steel foundation brackets and the adjacent modules currently inhibit any movement along the X and Y axis once it is in place. There are currently only two options for removal. Firstly, the module could be removed vertically, however, this would be constrained by the roof structure. The second option would be to dismantle the module altogether by unbolting the beams from the columns and then to pivot and remove the elements individually. This is only an issue when a new replacement module has to be refitted into the system as it increases the work done by the consumer. However, all the interfaces will have already been prepared in-factory and assembly would only involve bolting the elements in place and lashing them to the adjacent modules, which costs relatively little time. This is an acceptable compromise as it still complies with the criteria for dismantling and replacement.

Additional criteria – *Simple construction, available tools and materials, bulk transport*

These criteria have been taken into account during the interface selection process. All of the tools and connections are simple and accessible in India under the assumption that suppliers in Guwahati source their materials from the online retail store *IndiaMART*. No interfaces require invasive processes and are simplified to simple bolting and strapping connections.

5.2.3. Structural Design

Pinned connections – *All bamboo connections must be pinned*

From the scaled prototype it was discovered that the fish-mouth connection is not a true pinned connection. Instead, when the system begins to rack, a friction moment is induced in the fish mouth connection (image is in the appendix). The beam rotates and creates shear stress perpendicular to the fibre, and a pull-out stress in the plywood gusset plate. This is an undesirable condition which could lead to brittle failure and will be addressed in the module improvement chapter.

Failure – *Failure must be measurable and predictable*

Global failure is assumed to be governed by the strength of the diagonal brace. The steel cable is assumed to be made of 7x19 S304 woven steel cable, which is available, and ductile and has predictable ultimate strength values. However, the system has lateral bracing in each bay, making many of the braces redundant and the entire system statically indeterminate, therefore, making the location of failure difficult to predict. This must be addressed. The sizing of these cables will be addressed in later chapters.

Moisture protection – *The bamboo structure must be protected from contact with moisture*

The external cladding and overlap prevent moisture from entering the system for the most part. However, the 3d digital model reveals that there is a gap at the bottom of the structure which will lead to moisture exposure. This is not acceptable and must be addressed.

Axial loading – *Loads on bamboo must only travel axially through the culm*

With the inclusion of the diagonal brace at the bolt and a stiff wall panel, there exists a horizontal force perpendicular to the grain which could lead to critical failure and cannot be allowed to exist without reinforcement. In addition, the 1-10 scaled prototype demonstrated that the fish-mouth connection is not truly pinned and creates a friction moment in the beam which could also lead to splitting. These two aspects will be addressed in the second iteration of the design. In the case of the panel, the bearing stress is distributed over a larger number of bolts for each module, therefore, the distributed bearing stress will be assumed acceptable for now.

Stability - *Each wall plane must be stable in both lateral directions*

Currently the bracing system only provides lateral stability for one direction, and each structural culm module has its own bracing making many redundant. The Karamba model demonstrates that when the system experiences a lateral load from the left corner, the bracing is loaded in compression which it is not capable of taking and will lead to collapse. The assumption could be made that a system derives stability from the parallel wall which is braced in the opposite direction. However, this modular system which is designed for replaceability and incremental construction cannot assume that the parallel wall is always present. At any given moment during construction, repair or expansion, a single wall plane may be standing without its counterpart. Alternate bracing layouts must, be explored to improve the lateral stability of the wall, and to reduce the number of redundant braces.

5.2.4. Seismic Design

Plastic deformation capacity – *the system must incorporate plastic deformation for a ductile system*

The chosen lateral bracing system is made of a steel cable which can deform plastically. However, due to the fact that the current system has lateral bracing in each bay the load path is statically indeterminate and therefore lacks predictable ductile failure mechanism. The system must be adapted so that the location of ductile failure and the size of the cable can be designed for.

Vernacular seismic principles – *the system must incorporate at least one principle from the Assam-type house*

Originally, the system aimed to incorporate seven different principles that were derived from the literature review:

1. Regular framing system
2. Lightweight-infill walls
3. Ductile steel connections for energy dissipation
4. Friction dissipation between elements through controlled slip
5. Leave a small gap between the bolt and bolt holes
6. Bolt the frame to the foundation using steel L brackets to allow for in plane rotation of the posts
7. Do not insert the frame into the foundation

Most of these principles were successfully incorporated, except for 3 and 4. Principle 3 alludes to the plastic hinging of the steel nails. Incorporating steel nails was not possible for this system due to the difficulty of repair and the risk of splitting. Instead, the main ductile mechanisms come from the steel bracing. Friction dissipation was also determined earlier to be infeasible at the moment due to the difficulty of connection.

5.3. Improve Module – Second Iteration

Problems to address in second iteration:

The problem list is organized in order of influence on the total system. For example, the panel calculations and the perpendicular force solutions where required in the calculations for the bracing configuration, therefore, they are preceding.

1) Tolerances
   a) Tolerances between culms too large — up to 60mm gap at 3m height
   b) Inter-module gap
2) Panel
   a) Reduce panel module weight to a maximum of 50 kg
   b) Gap at base of the panels structure exposes bamboo to moisture
3) Remove perpendicular forces
   a) Fish-mouth connection induces friction moment — not truly pinned
   b) Diagonal brace induces perpendicular force in the culm
4) Bracing configuration
   a) Lateral stability in one direction only — bracing configuration unresolved

5.3.1. Tolerances

Minimizing tolerances

In the first iteration (Figure 27 – A), adjacent culms taper upward, producing an increasing gap along the height of the wall. The smallest culm (85mm) at maximum taper (5mm/m) produces a gap of 46.5mm at its highest point.

The first improvement (Figure 27 – B) is to invert the orientation of one culm in each module pair, so that one culm tapers upward while the adjacent culm tapers downward. The opposing taper directions cancel each other out, eliminating the increasing gap along the height and producing a uniform gap of 38.3mm across the full culm height. While this is still a large tolerance, it is consistent and predictable.

The second improvement (Figure 27 – C) addresses the grid offset. In the first iteration, culm centres are placed at 57.5mm from the grid line, corresponding to the radius of the largest culm (115mm). Shifting the nominal design diameter from 115mm to 100mm brings the culm centre 7.5mm closer to the grid line, with a variability range of ±15mm. This has reduced the maximum tolerance to 23.3 mm uniformly along the culm height, equating to a 50% tolerance reduction. As a consequence, a culm at the upper limit of the range (115mm) will overlap the grid line and requires a smaller adjacent sub-module to accommodate the centreline offset.

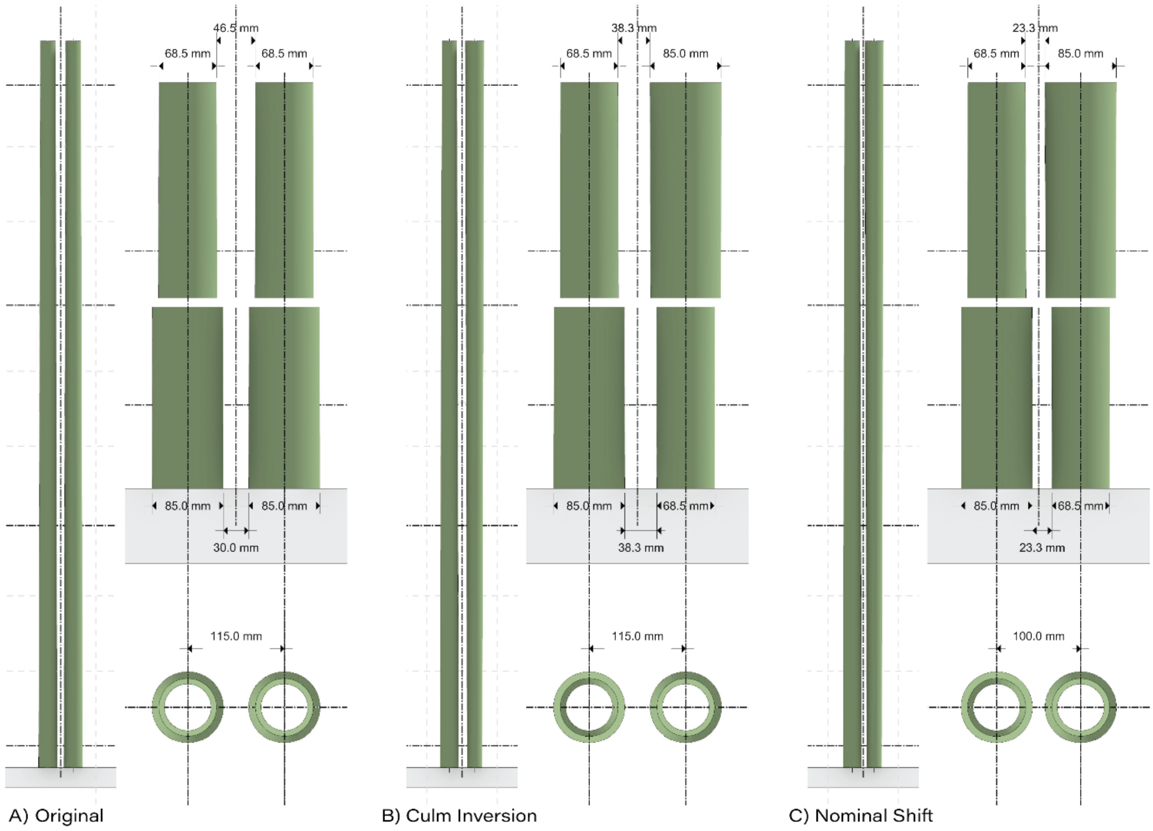


Figure 31 - A) First iteration, B) culm inversion, C) nominal culm shift

Filling the gap

The gap between the two culms requires filling. In this worst-case scenario, there exists a continuous gap between modules, allowing swaying and potential detachment of the straps. There is no body of literature which addresses gaps between bamboo, as traditional bamboo construction focuses on local accuracy instead of global accuracy. This renders gap filling unnecessary in vernacular bamboo construction. The gaps present in this system are a product of modularization, arising from the imposition of a standardized grid on a material with inherent dimensional variability.

There are other standard gap-filling methods that are used in other construction fields such as mortar, foam, timber packers, and sealants. Most of these involve using (semi)fluid materials to shape itself to the gap. Timber packers are the only material which does not bond, making it reversible without damaging the surrounding materials. A variation of this can be applied to bamboo construction through wedging. The benefit of the wedge is that it self-adjusts to the whatever gap width it encounters; a 20 mm and a 10 mm gap could receive the same wedge, just driven to a different depth. The friction between the wedge and the culm interface generates local compression between the two faces and prevents any lateral movement. In the event of module replacement, the wedge can be removed and repurposed for the following module.

A timber or bamboo wedge with a slight taper can be driven between the culms to fit the variable, and unpredictable gaps. The ideal location for this is at the inter-module strap connection where it can be prestressed. Such a wedge can be formed at the construction site from bamboo off-cuts or provided as a set of wedges with different standard sizes alongside the modules.

5.3.2. Panel improvements

Panel weight

The original panel from the first iteration weighed 88 kilograms, far surpassing the 50-kilogram hard criteria. The panel was dimensioned according to the ikra-panels used in the Assam-type house – a bamboo mesh with mortar infill, totalling 45mm in thickness. The panel material properties were modelled in excel to determine the optimal thickness to achieve a 50 kg panel. The dimensions of the panel remain the same at 1110 mm x 1015 mm (W x L). Based on the diagram from Chand et al. (2019), it is conservatively estimated that the bamboo mesh has a total surface area of 80% relative to the total surface area. The bamboo volume is calculated by multiplying the estimated average bamboo strip thickness by the calculated surface area. The subsequent volume of the panel is assumed to be filled with cement plaster with a density of 2000 kg/m^3. The remaining variables were calculated and filled in using preliminary assumption, including bamboo self-weight, mortar volume, mortar self-weight, and panel thickness. A goal seek function in excel was applied to the 'panel weight' which changes the 'panel thickness' cell until a goal of 50 kg was reached. This generated a maximum panel thickness of 27.64 mm which will be rounded down to 25 mm – 44.2 kg (figure 32 – B). Interestingly, there is a perfectly linear relationship between panel thickness and panel weight; with each 5 mm thickness increase, there is a respective 11.2 kg weight increase. The chart demonstrates how a half centimetre increase in weight can dramatically increase the weight of the panel. It is therefore, recommended to potentially reduced the panel thickness to 20 mm – 33.2 kg, to allow for a larger tolerance when constructing the panels.

Panel gap

The panel gap at the top and bottom are simply addressed by including an additional panel variation which extends to fill the gap between the floor and roof (figure 32 - A). The gap between the panels of adjacent structural modules will be addressed alongside the finish plaster layer applied to the house. A layer of tape will be adhered over the gap from top to bottom, with a slight extension left at the bottom. A thin final plaster/pain layer will be applied over the entire surface area to equalize the surface, covering the tape and all other overlapping panel connections. In the event a panel needs to be replaced, the tape extension at the bottom acts as a location identifier and can be pulled to strip the plaster from the gap.

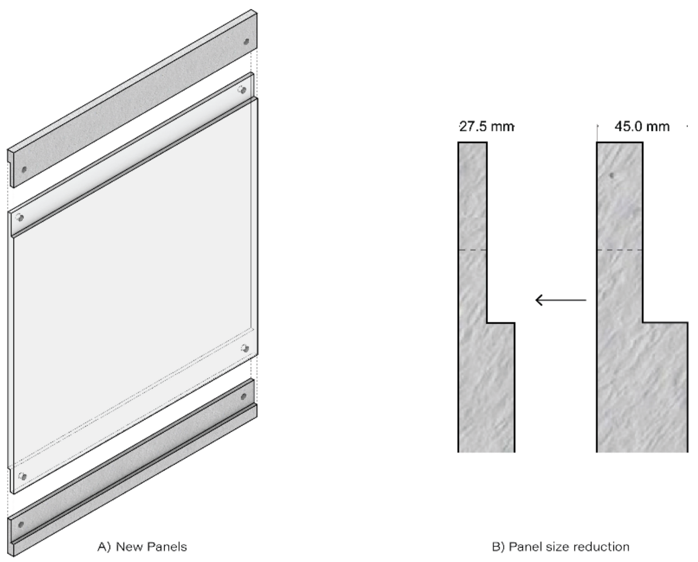


Figure 32 - A) New panels, B) Panel size reduction

5.3.3. Remove perpendicular force

Fish-mouth connection solution

As demonstrated in the evaluation, the original fish-mouth connection still creates a friction moment in the connection during racking. The design solution would be to remove the contact between the beam and the culm so that the beam can rotate freely under lateral forces. This prevents any perpendicular forces from propagating in the beams and allows it to only carry purely axial forces. This beam is also quicker and easier to make, requiring no precision cutting or fitting, except for the bolt placement. Furthermore, it further segregates the functions of each module – the structural culm carries purely axial forces, while the bracing and panels carry lateral loading. An additional benefit is that the structural culm module becomes a collapsible structure which can easily be transported and carried from the factory to the construction site, maximizing the volume of material that can be transported in one trip. This is demonstrated in **FIGURE X**.

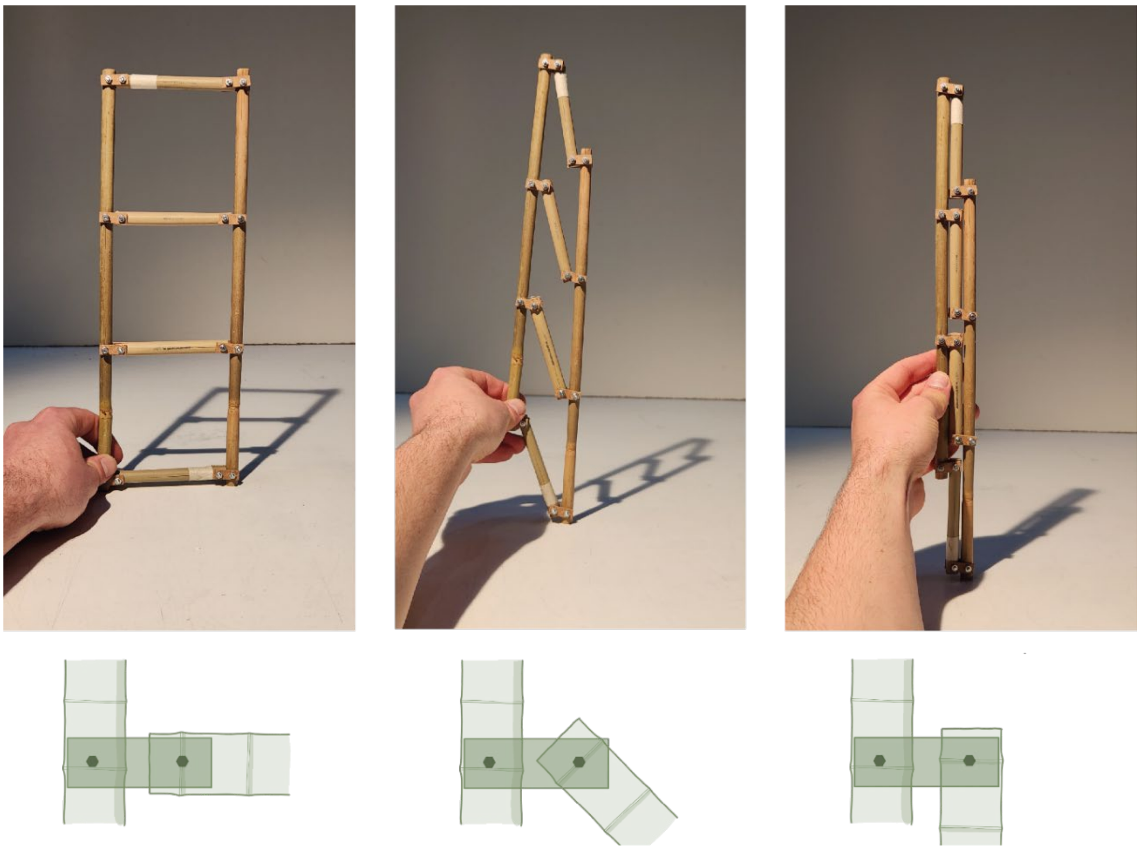
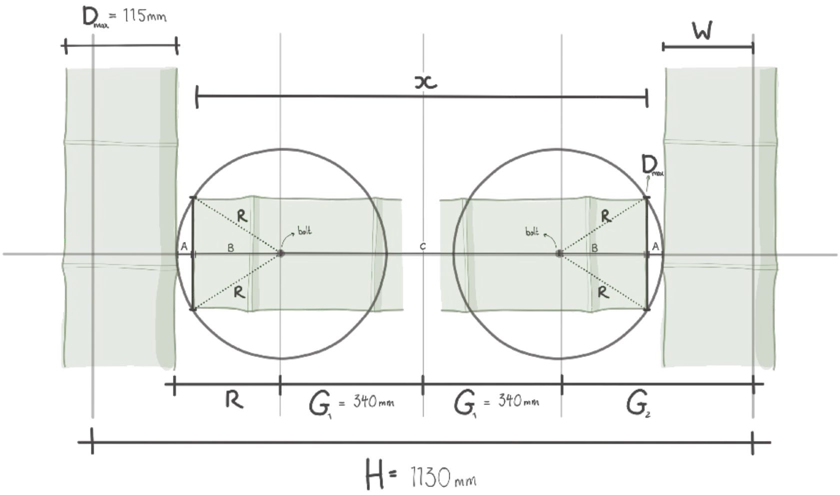


Figure 33 - Illustration of collapsable module

In order to properly standardize the beams so that only one beam length has to be cut, and a free 180˚rotation can occur on each culm diameter, the minimum radius of ration must be assessed. The calculation diagram is illustrated in figure 33, which shows the relationship between the radius of rotation from the bolt, the beam length and the minimum offset of the beam from the column. This includes a simplified two step calculation to find the maximum beam length (x). The calculations to finding the value to each of the variables, as well as how the calculation steps that have been derived, are in the appendix. The limit of the radius of rotation is determined by the maximum column and beam diameter of 115mm, assuming they are the same diameter. With the diagram it was calculated that the minimum offset (A) is 15 mm, with a beam length of 885 mm. This beam length and minimum offset (A) will satisfy all culm diameters



$$1.\quad R = \frac{1}{2}\left(H - 2G_1 - D_{max} - D_{nominal}\right)$$

$$2.\quad x = H - D_{max} - D_{nominal} - 2\left(R - \sqrt{R^2 - \frac{1}{2}D_{max}^2}\right)$$

Figure 34 - Calculation of beam length and offset based on minimum rotation radius from the bolt holt

A = beam offset from culm wall

B = distance from node end to bolt

C = distance between bolts on the beam

D = beam diameter

R = radius of rotation

G_1 = grid distance 1

G_2 = grid distance 2

H = main horizontal grid distance

W = culm wall distance from main grid

x = beam length

Diagonal brace load transfer

The diagonal brace that is attached to the bolt in the culm, creates a horizontal force perpendicular to the grain of the bamboo. Without reinforcement, the culm will definitely split under bolt bearing stress from the seismic loads, leading to global failure. There are two methods possible to avoid this; 1) reinforce the culm using a timber or mortar fill so that the bearing stress is distributed over the entire cross section of the culm, instead of the two culm walls, 2) move the diagonal brace to a pipe clamp so that the force is translated to radial compressive stress on the culm, which is significantly stronger (figure 35). There are a few implications for each decision:

1. Mortar fill connection

The mortar cannot be filled into each of the nodes with a connection because that would increase the weight of the module beyond 50kg, therefore, diagonal bracing in each bay of the structural frame module would not be possible. Instead, a single diagonal brace could be placed that goes directly from the top node, diagonally to the foundation. The top and bottom node will be filled with mortar to strengthen the connections locally.

2. Pipe clamp connection

The pipe clamp connection does not require reinforcement and has a flexible placement, however, it must still be placed near a node and not in the middle of the internode, to ensure the stress is transferred to the node diaphragm. The downside to this connection is that the maximum radial stress of the Guadua bamboo species has not been documented and therefore cannot be calculated for.

The mortar fill connection is the preferred connection method as it complies with the criteria to concentrate interfaces. The strength of the connection can also; be mathematically verified, therefore, satisfying the criteria for measurable and predictable failure. Lastly, it simplifies the construction, ensuring that the diagonal transfers its load directly to the foundation. Any horizontal loading is minimal due to the steep angle of the diagonal. Most of the diagonal force can be deconstructed into a vertical load which is ideal for the bamboo.

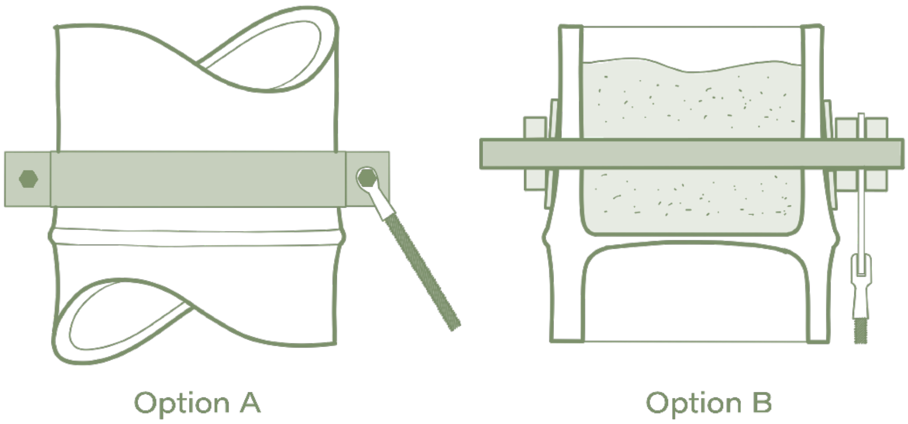


Figure 35 - Option A) pipe clamp induces radial pressure, B) bolt with cement mortar infill

5.3.4. Diagonal bracing configuration

The original diagonal bracing configuration was only stable in one direction, and it left the construction statically indeterminate which made it impossible to design for the location of failure. The wall was modelled in Karmaba3D in order to iteratively find the optimal bracing configuration (figure 36). In order to do so, the system had to be simplified in a number of ways as Karamba cannot take certain variables into account. These simplifications are listed in table 10:

Table 10 - Simplifications applied to the Karamba model

	Simplifications
1	No culm tapering
2	Inter-module connection occurs adjacent to the intra-module connection
3	Inter-module connection is modelled as a roller to show friction slip
4	Only use nominal culm diameter
5	Lateral stability of the panels is not taken into account, only weight
6	Monotonic Loading

This simplified Karamba model also assumes certain perfections in the system; therefore, the model does not accurately represent how the structure would respond in an earthquake. However, the values that are extracted from each configuration can be compared against each other to determine which is the most favourable and to check whether they are within the same magnitude as expected. To apply proper loading, the dead loads, live loads and seismic design force had to be calculated. The loads are 90.60 kN, 0 kN, and 27.18 kN respectively. The calculations will be further elaborated on in Chapter 5.3.5. The cells that are highlighted red indicate that the values exceed the suggested stress limits of the material. IS 15912 stipulates that the allowable compressive stress of bamboo cannot exceed -15.5 MPa. The 7x19 steel cable has a minimum allowable tensile stress of 1770 MPa. To model this in Karamba, dimensional material values had to be assumed for the preliminary calculations. These values are shown in Table 11 and will be adjusted based on the checks done in Chapter 5.3.5.

Table 11 - Assumed values for Karamba3D calculations

	Assumptions		
Bamboo	Diameter	100.00	mm
	Thickness	10.00	mm
Steel cable	Diameter	9.00	mm

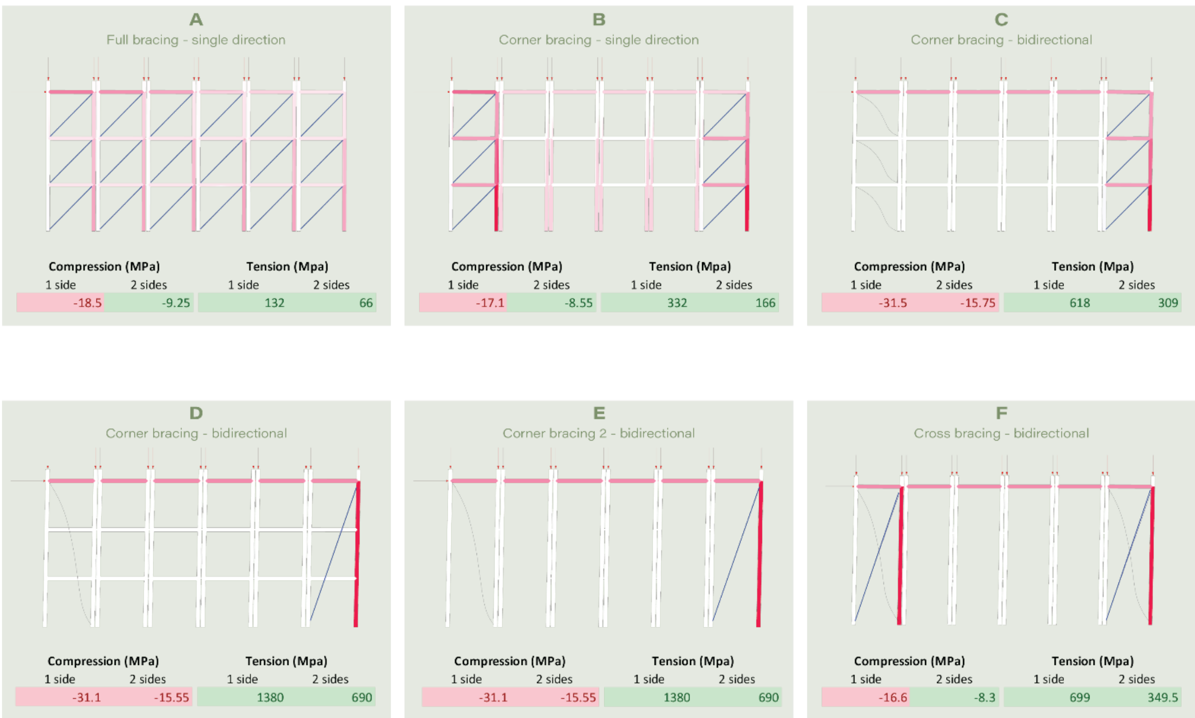


Figure 36 - Diagonal bracing configurations

Configuration A is the original system which has diagonals in each bay, bracing the wall in only one direction which was redundant and statically indeterminate. This was the motivation for exploring the alternative bracing configurations.

A side-by-side comparison of each bracing illustrated a few insights. Firstly, the comparison reveals a natural material-based load separation where bamboo elements carry compression in all configurations, while the steel cables carry tension. This aligns with the axial loading criterion and confirms that the structural logic of the system is good across all configurations.

Secondly, there is a trade-off between redundancy and stress concentration. Configuration A has the lowest maximum tension due to the dispersal of stress across each diagonal, while having the most redundant members. On the other hand, configuration E has the highest tensile stress concentration and is also the most determinate due to the single active diagonal. It is clear that fewer diagonals concentrate loads but create predictable, designable failure. Despite this, all of the diagonals are well within the breaking strength of 1770 MPa. The limiting factor is the allowable compressive stress on the bamboo. All configurations exceed the allowable compressive stress of 15.5 MPa when assuming a one-walled system (1 side). Only configurations A, B and F fall within the allowable compressive stress margin when it assumed that an identical parallel wall shares the lateral load (2 sides).

Configuration D revealed that the intermediate horizontal beams had no function anymore when a single diagonal spans from top to bottom. The intermediate beams were originally required to provide lateral restraint at the connection with the brace, which exerts a horizontal force at the connection point. When a single diagonal spans the full wall height, the intermediate beams are no longer required to provide that lateral restraint to the columns. Therefore, the horizontal beams have been removed from Configuration E to identify that the removal of the beams had no effect on the compressive and tensile stresses on the system. Configuration F adopts the same beam-free structure, retaining only the top rail.

Configuration F – cross-bracing in both corners – was selected going forwards because it now satisfies the wall plane stability requirement and no longer relies on a parallel wall to be stable. Additionally, it has the best balance of compressive stress in the culms and tensile stress distribution. Having the cross bracing in each corner of the building means that each pair of parallel walls has 4 steel cables that brace the same direction. These 4 braces share the seismic load, reducing the concentration of stress in any one particular component while allowing for an acceptable amount of redundancy in the system. By confining the potential failure location to the corners of the building, post-earthquake inspection and replacement is simplified, as damage assessment and module removal are always performed at the same known locations. The maximum horizontal displacement value of configuration F was computed to be 5.18 cm. This could be used to calculate monotonic drift of the structure, by dividing the displacement (5.18 cm) by the height of the displacement (3060 mm) which equated to a drift of 1.57%.

5.3.5. Calculations

There are many checks that could be done to ensure that the entire system works together, however, due to the limitation in time, only a few checks will be prioritized based on their importance to the system. This includes the primary lateral loading element and its related connections, the culm buckling and the module weights. Figure 37 illustrates the members with the largest normal forces, representing the members that will be checked and sized.

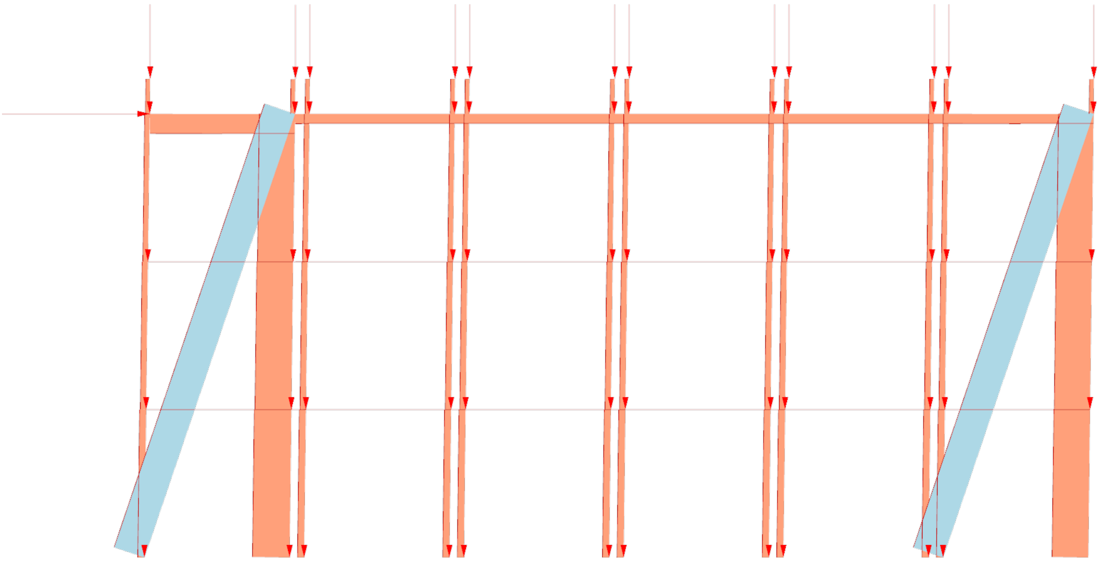


Figure 37 - Normal forces in members

Design parameters

The system is governed by fixed design inputs such as building dimensions, loading, and seismic zone. These had to be determined before sizing and structural checks can be conducted. These design parameters are assembled in Table 12. The building dimensions were an average length and width value based on the values provided by the World Housing Encyclopaedia Report on the Assam-type house. These building dimensions are thereby the representative value of a house in the Assam region. It was assumed that the building would support a clay tiled roof with bamboo rafters, an ikra panel wall and that the structural frame is made of Guadua bamboo. This species was chosen as a proxy for native Indian bamboo for the large amount of research that was conducted on its mechanical properties, and due to its availability in the area of where the research was conducted.

Table 12 - Parameters

Assumption	Value	Unit	Notes
Building Length (long)	9	m	(H. B. Kaushik & Babu, 2009)
Building width (short)	6	m	
Eave Height (story height)	3	m	
Roofing (clay tile)	0.65	kN/m^2	IS 875 Pt1; (Clay tile - 65 kg/m^2)
Bamboo rafters	0.20	kN/m^2	Estimated - Spaced 500 mm
Ikra panel (bamboo + cement)	0.39	kN/m^2	Lath and plaster (Bhavan & Marg, 1987)
Guadua Bamboo			Guadua is used as a proxy for Indian bamboo species as it was the only available structural species in the area

Seismic design load

The seismic design load was calculated using IS 1893 which specifies all of the related values required to complete the calculation. The main calculation is expressed as:

$$V_b = A_h \times W$$

V_b = Seismic design base shear

A_h = Design horizontal seismic coefficient

W = Seismic weight of the structure (dead load + live load)

The inputs and calculation steps are all expressed in the appendix. The calculation was based on the most unfavourable situation including the results showed that the building had a total dead load of 90.36 kN and a design seismic base shear (V_b) equated to 27.18 kN. These values were later used to complete the succeeding steps and the Karamba model.

Diagonal Sizing

The diagonal brace is sized based on the translation of the horizontal seismic shear force to the vector of the diagonal. The structure has four active diagonals for each direction of force; therefore, the total shear force is divided equally over the four braces. This is expressed in this formula:

$$F_d = \frac{V/n}{cos\theta}$$

F_d = Diagonal force (kN)

V = Base shear design force (kN)

n = number of diagonals concurrently active

θ = angle from horizontal

The total seismic base shear of 27.18 kN is distributed equally across four active diagonals, giving a horizontal force of 6.80 kN per diagonal. Resolving this horizontal force along the diagonal axis, which is inclined at 71° from horizontal, gives a diagonal tensile force of 21.5 kN per brace. This value was cross-referenced with the minimum breaking load of a 7x19 steel cable provided by Carl Stahl, with a minimum tensile strength of 1570 MPa. The 7 mm cable has a minimum breaking load of 25.5 kN, leaving a utilisation factor of 0.84 at the worst case.

The yield limit and elongation of the steel cable, which represents the plastic deformation point, was not provided by manufacturers, merely the working load limit and the minimum breaking load. The working load is 20% of the minimum breaking load so that the cable can remain elastic under realistic conditions. It is thereby assumed that the yield limit of the cable is at 50% to take into account the safety factor that is applied. On the basis of this assumption, it is calculated that the yield limit for the 7 mm cable would be at around 10.23 kN. This value and the elongation length of the cable requires further testing for verification.

Figure 38 - 7x19 cable rope

Bolt Sizing

In the previous chapter, it was determined that the culm requires reinforcement for the diagonal brace so that it can withstand the perpendicular bearing stress produced by the threaded rod. Two limit states govern this connection: shear in the rod itself and bearing on the material surrounding the bolt hole. The infill material which surrounds the thread could be either timber or mortar infill. A timber plug is the original infill due to its replaceability and its biobased nature, satisfying those criteria. Steel is significantly stronger than timber in both shear and compression, therefore, the bearing stress of the bolt on the timber perpendicular-to-grain is the governing limit in the connection. The required diameter was calculated using the bearing equation:

$$\sigma_{bearing} = \frac{F_{compression}}{d_{thread} \times t_{member}}$$

The infill material distributes the bearing stress across the entire diameter of the culm, therefore, t_{member} can be substituted with d_{culm}. The bearing stress has to remain below the compressive strength of timber perpendicular-to-the grain.

$$\sigma_{bearing} = \frac{F_{diagonal}}{d_{thread} \times d_{culm}} \leq f_{c,perp}$$

$f_{c,perp}$ = compressive strength perpendicular-to-grain (MPa)

This is rearranged to become:

$$d_{thread} \geq \frac{F_{diagonal}}{f_{c,perp} \times d_{culm}}$$

The Indian Standard for timber design specifies that the maximum allowable stress perpendicular to the grain is 5.88 MPa. The resulting thread diameter became 69.7 mm, which is significantly larger than any generally available thread diameter. The allowable timber strength was clearly too small and results in the necessity for a mortar infill. The same calculation was repeated with a minimum mortar compression strength of 15 MPa. This resulted in a minimum thread diameter of 20.9 mm. This is rounded up to an M22 thread.

The shear capacity of the bolt is checked against the shear force produced by the diagonal using the Eurocode table of bolt standards. An M22 bolt for a single shear plane, has a shear resistance of 58.2 kN at the lowest grade (4.6) which is more than twice the shear force applied by the diagonal. This means that any grade thread at 22 mm is sufficient to withstand the expected shear forces in the structure.

Gusset plate sizing

Steel gusset plate

The steel gusset plate used for the diagonal brace is sized to resist the bearing stress of the bolt. This calculated using the bearing resistance formula from Eurocode 3 (EN 1993-1-8) which checks that the steel plate will not tear or crush at the bolt holes:

$$F_{b,Rd} = \frac{2.5 \times f_{u,plate} \times d \times t}{\gamma_{M2}}$$

$F_{b,Rd}$ = bearing resistance (kN)

$f_{u,plate}$ = ultimate tensile strength (MPa)

d = nominal diameter (mm)

t = thickness of gusset plate (mm)

γ_{M2} = partial safety factor

Given a standard S235 steel and a force of 21.5 kN and an assumed plate thickness of 6mm and a safety factor of 1.25, the bearing resistance of the plate is 82.5 kN. This gives a U.R. of 0.26 which is extremely satisfactory.

Plywood gusset plate

The plywood gusset plate is used to connect the beam to the column in the pinned connection. The top beam shares the full lateral seismic load with the parallel beam in the parallel wall. It transfers 13.59 kN of force to the bolt with the attached diagonal. This plywood plate must be sized to withstand the bearing stress of the bolt. This can be expressed using the traditional bearing stress formula ($\sigma_{bearing}$) that was used earlier.

The lateral load is distributed over two gusset plates, therefore, the formula can be expressed as such:

$$\sigma_{bearing} = \frac{V}{d_{thread} \times t_{plate} \times 2} \leq f_{c,0}$$

The compressive strength ($f_{c,0}$) of plywood is between 31.0 and 41.4 MPa (*Wood Handbook*, 1990). Assuming a plate thickness of 12mm and an M22 bolt, the experienced bearing stress on the plywood is 25.7 MPa. This gives a U.R. of 0.83, given the most conservative plywood compressive strength of 31 MPa. This is a satisfactory value, and therefore any plate above 12 mm thickness will be suitable for use with the top beam.

Culm buckling

The diagonal brace also produces a vertical force which is carried by the culm directly down to the foundation, along with the dead loads of the roof and the panels. The culm should therefore be checked for buckling. The buckling check was done using IS 15912 which provides the necessary calculations. The roof rests at the top point of each column. Each module has two columns with an effective length of 3.06 m. The smallest culm (85mm) with a taper of 5 mm/m has an average diameter of 77.5 mm. There is a total of 30 modules in a 6 x 9 m house, equating to 60 columns. With a total dead load of 88.72 kN, each column carries only 1.5 kN. The vertical force applied under seismic load was calculated to be 20.4 kN. The panels collectively add another 0.75 kN to each culm. The resulting vertical force experienced by the culm was calculated to be 22.65 kN. However, each column is braced against the adjacent one effectively doubling the buckling capacity of the culm. The Euler buckling limit was calculated to be 4.7 kN which is significantly less than the 22.65 kN it does experience and will therefore surely buckle.

The intermediate beams were reintroduced in order to reduce the effective length of the culm to 1.02 m. As a result, the Euler buckling limit rose to 42.6 kN, which is double the vertical load and keeps the culm well within safety against buckling.

Foundation uplift

The structure experiences uplift in the opposite culm to the one which experiences compression. The uplift is equal to the vertical force from the brace ~ 20.4 kN. The foundation will easily be able to withstand the vertical uplift force, as the bottom of the culm will also have a mortar infill, and the bolts have already been sized to resist a shear force of up to 58.2 kN.

Module weight

With the addition of a heavy mortar infill at all the bracing connection points, the weight of the module has to be reassessed. The volume of mortar is determined by the limit weights of each module. The heaviest module – assuming no tapering and continuous wall thickness – is a module with 115 mm culm diameter with a wall thickness of 24 mm, which weighs 49 kilograms. Each module has an average open internode of 250 mm at either end which is open to be filled by mortar.

The inclusion of mortar infill at each bolt connection adds mass to the structural culm module. To determine whether the module remains within the 50kg weight limit, the mortar volume was calculated as a function of the number of connection points and the internode fill volume at each exposed node. Since culm diameter varies between 85mm and 115mm and wall thickness has a minimum of 8mm, the inner diameter and fill volume per node varies across the accepted culm range. The largest culm (115mm outer diameter, 8mm wall thickness) produces the largest inner diameter of 99mm and therefore the greatest mortar volume per connection. This represents the worst case for module weight and was used as the governing circumstance. The remaining weight was determined first, establishing the maximum allowable mortar mass. The mortar volume corresponding to this mass was then calculated using a density of 2000 kg/m^3, giving the maximum allowable fill volume per module of 0.01 m^3. This volume of mortar can fill up to 1.28 m of culm, allowing for each culm end to be filled by 32 cm. This almost the entire length of the average internode at the worst case and is an ideal volume.

5.3.6. System Assembly - Second Iteration

The assembly of this system will use the same parameters and assumptions used for the calculations. All sizing and calculations of bolts, gusset plates and cables have been considered in the illustration of the second iteration system assembly. All additional elements such as the steel cable connection have been sized using the manufacturer's loading limits.

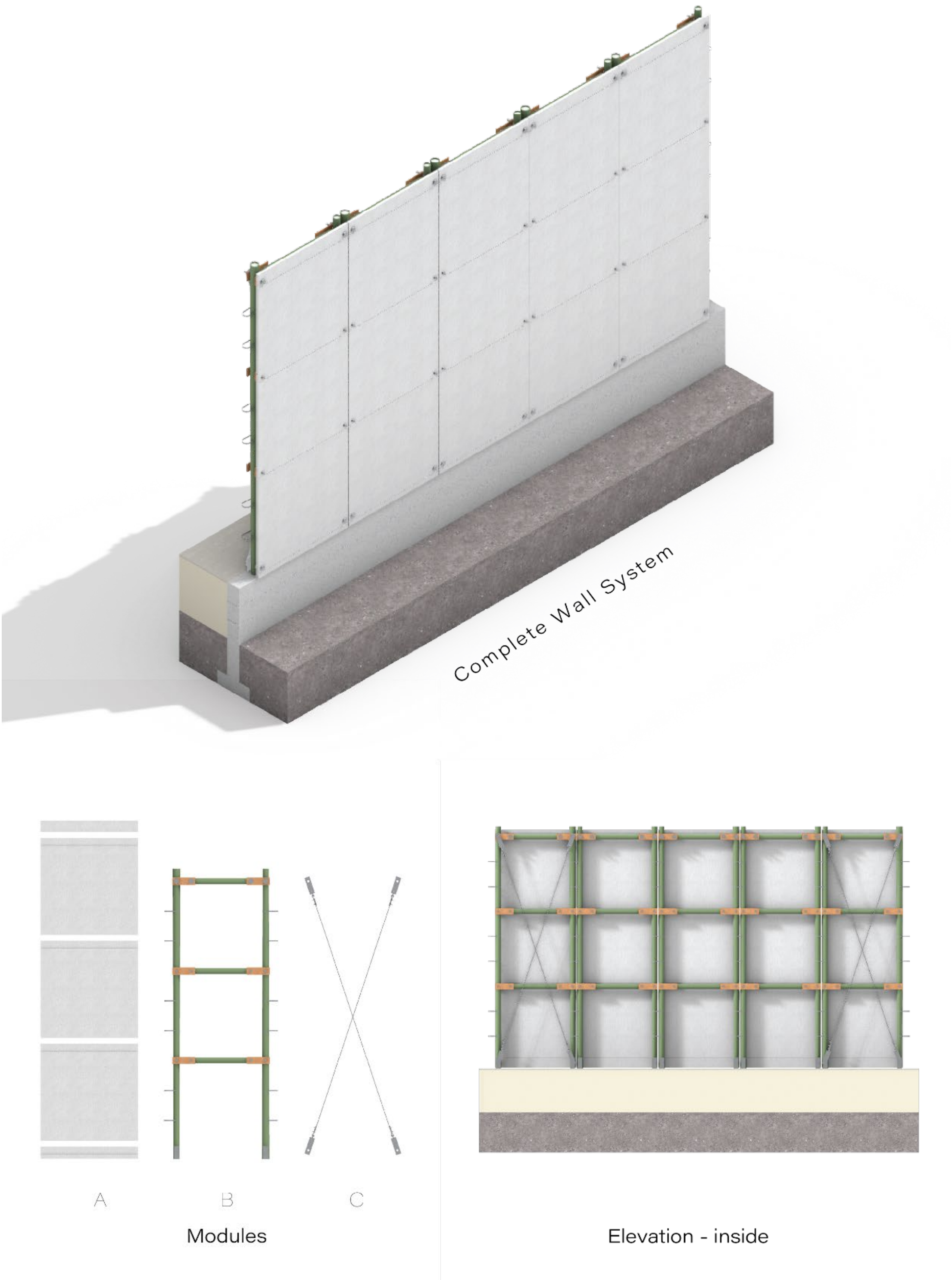


Figure 39 - Second iteration system assembly

5.4. Evaluation – Second iteration

Criterion	Type	Result	Second iteration response
Modularity			
Linear scalability across grid	Hard	Pass	Nominal diameter shifted from 115mm to 100mm, reducing maximum tolerance by 50% to 23.3mm uniformly along culm height
Accessible interfaces	Hard	Pass	All connections remain bolted or clamped, bracing confined to corners for predictable access locations
Universal connectability	Hard	Pass	Unchanged from first iteration - straps, clamps and cable clamps all adjustable to diameter variability
Grid alignment	Soft	Pass	Culm inversion and nominal diameter shift reduce tolerance accumulation along the grid
Minimise tolerance	Soft	Partial	Reduced from 46.5 mm to 23.3mm through culm inversion and nominal culm shift. Residual gap filled with bamboo wedge at strap connection point
Concentrated interfaces	Soft	Pass	Mortar fill connection preferred over pipe clamp = concentrates diagonal interface at existing bolt location
Minimal customisation	Soft	Pass	Fish-mouth removed. Beam now requires only bolt placement, no precision cutting. Beam length standardised at 885mm for all culm diameters
Buildability			
Module size ≤ 3m × 1.8m	Hard	Pass	Unchanged. Structural culm module at 3.5m × 1.8m remains within limit
Module weight ≤ 50kg	Hard	Pass	Panel reduced from 88kg to 44.2kg at 25mm thickness. Recommended 20mm for construction tolerance margin = 33.2kg. Structural module confirmed at 49kg worst case including mortar infill
Demountable connections	Hard	Pass	All connections remain bolted, clamped or wedged. Wedge is reversible and reusable. Use of open thread to allow two-sided mountability
Module replacement	Soft	Partial	Panel and bracing modules fully replaceable independently. Structural culm module must be dismantled element by element. Alternatively, roof module must be removed for vertical dismantling. Collapsible beam connection improves transport and reassembly
Simple construction	Soft	Pass	Collapsible module simplifies transport. Panel gap sealed with tape and finish plaster, no specialist skill required. Only simple tools used. Wedge gap filling requires no tools
Minimal on-site alterations	Soft	Pass	Beam standardised at 885mm fits all culm diameters without on-site cutting. Mortar fill done in factory at connection nodes

Structural design			
Pinned connections	Hard	Pass	Fish-mouth contact removed; beam rotates freely about bolt, eliminating friction moment. Joint now truly pinned
Masonry restricted to foundation	Hard	Pass	Mortar infill confined to bolt connection nodes only; not a structural masonry element
Measurable and predictable failure	Hard	Pass	Configuration F concentrates failure at corner bracing modules. Mortar fill connection mathematically verifiable. Cable breaking load confirmed within allowable stress
Moisture protection	Hard	Pass	Extended panel variant closes base gap. Tape and finish plaster seals inter-panel joints. Wedge fills inter-module gap
Both lateral directions stable	Hard	Pass	Configuration F: bidirectional cross-bracing at corners = achieves inherent wall plane stability in both directions without relying on parallel wall
Compressive stress ≤ 15.5 MPa	Hard	Pass	Configuration F satisfies compressive stress limit assuming two parallel walls share the lateral load. Intermediate beams reintroduced to reduce effective buckling length to 1.02m = Euler limit rises to 42.6 kN against 22.65 kN demand
Axial loading only	Soft	Pass	Fish-mouth removal eliminates beam perpendicular shear. Mortar fill distributes diagonal bearing stress across full culm cross-section. Steep diagonal angle minimises horizontal force component at connection
Seismic design			
Plastic deformation capacity	Hard	Partial	Configuration F reduces indeterminacy — four cables share load with acceptable redundancy. Precise yield threshold of 7×19 cable not published by manufacturers; estimated at 50% of breaking load. Physical testing required to verify
Drift ≤ 8% of Assam-type drift	Hard	Pass	Karamba model gives 1.57% storey drift under design seismic load, far below 8%. Panel stiffness contribution not modelled — actual drift likely lower. Further analysis required
Incorporate vernacular principles	Soft	Pass	Five of seven Assam-type principles incorporated. Steel nail ductility replaced by cable brace. Friction dissipation deferred to future development

Modularity

The most prominent change was the removal of the fish-mouth joint. This allowed for the beam to be standardised at 885 mm, minimised customisation and improved the transportability of the structural module by becoming collapsable. The tolerances were reduced by 50% through culm inversion and shifting the nominal culm diameter to 100 mm.

Buildability

All modules now fall within the weight limit of 50kg; the panels were reduced from 88kg to 33 kg. The structural culm modules are 49 kg in the worst case scenario with the inclusion of mortar infill. All connections are visible and demountable using simple tools and minimal skill, and the collapsible module has improved transportation. The only partial pass is module replaceability. Each module is individually replaceable, however, the structural culm module must be dismantled element by element under the assumption that the roof cannot provide space for vertical translation.

Structural design

Removing the fish-mouth connection made the connection truly pinned, removing unpredictable perpendicular forces in the structure. The only perpendicular force is now reinforced with a mortar infill and the threads have been sized to minimise the bearing force on the culm and mortar. The intermediate beams were reintroduced to reduce the effective buckling length of the columns.

Seismic design

Configuration F gives a monotonic storey drift of 1.57% under the design base shear. This is far below the 8% benchmark set by research standards, and incorporates five of the seven vernacular Assam-type principles. The two partial passes are the most important caveats of the whole design: the yield threshold of the 7×19 bracing cable is estimated rather than measured, as it is not published by manufacturers, and the modelled drift excludes panel stiffness. Both require physical testing to confirm, which is the principal recommendation carried into future work.

6. Conclusions

6.1. Sub Research Questions

6.1.1. *Modularity*

How can modular design principles be applied to create self-supporting, stable panels or modules that enable efficient assembly without requiring complex connections or highly skilled labour?

The adapted Modular Function Deployment method (MFDA) proposed by Sonego et al. (2016), combined with the Interaction Matrix Analysis and Module Indication Matrix, provided a systematic framework for deconstructing the Assam-type house and identifying modules for redesign. The application of these tools produced three modules: a 1×3 structural culm module, an ikra cladding panel module, and a corner bracing module.

A 340mm sub-grid, derived from the average bamboo internode spacing, organizes all module interfaces and ensures that bolted connections consistently land at or near a node. All interfaces are bolted, clamped, or strapped, requiring no on-site customisation. Universal connectability is achieved through adjustable pipe-strap connections and well-defined connection points that accommodate the full culm diameter range of 85 - 115mm.

Inter-module tolerances were reduced by 50% (from 46.5mm to 23.3mm) through culm inversion and a nominal diameter shift from 115mm to 100mm. Remaining gaps are filled with bamboo wedges at the inter-module strap connection, providing local compression and preventing lateral movement between adjacent culms. All elements within each module are standardised to allow efficient prefabrication and assembly.

6.1.2. *Buildability*

To what extent can the module be fabricated and assembled/disassembled using low-tech tools and minimal skill?

All connections are reversible using bolts, clamps, straps, or wedges — tools and materials confirmed as available to rural Assam populations through cross-referencing with IndiaMART as a proxy for suppliers in Guwahati. Any precision work is isolated to in-factory prefabrication under controlled conditions, ensuring that on-site assembly requires no specialist skill, no on-site customisation, and no wet trades. Mortar infill at connection nodes is applied during factory prefabrication and arrives on site ready to install.

The system follows a defined assembly sequence: foundation brackets → structural frame modules → bracing modules → panel modules. This sequence reverses for disassembly, ensuring each module is accessible at the correct stage without disturbing elements that have already been installed. Each connection and module is exposed for inspection and repair in the event of degradation or seismic damage. Module replacement can be achieved without disturbing any horizontally adjacent modules. Panel and bracing modules attached to the face of the structural frame must be unbolted first to allow access to the structural frame module behind them. The interior of the wall is currently entirely open, its structural frame, bracing, panels and interfacing all visible and inspectable from the inside of the house.

Two options exist for replacing the structural frame module itself: the elements of the module can be disassembled individually and removed, or the roof module can be designed to be temporarily lifted/pivoted, allowing the structural frame module to be removed as a whole unit without element disassembly. The second option is identified as a priority for future development as it significantly reduces the repair effort required after a seismic event.

Beams are standardised at 885mm to fit all culm diameters within the accepted range, with a minimum column offset of 15mm ensuring free rotation and collapsibility for transport. The worst-case module weight is 49kg, satisfying the two-person carrying limit. Assembly requires only bolting and strapping on site, with no precision fitting required.

6.1.3. *Structural design*

Which combinations of bamboo reinforcement and locally available materials are suitable for producing a modular building unit with sufficient cohesion and dimensional stability?

The structural system uses Guadua bamboo as a proxy for locally available species due to the availability restrictions and its well-documented properties. The system combines Guadua-grade bamboo culms as the primary axial load-carrying element, woven bamboo lath panels as lateral cladding, mortar-infilled nodes at bolt locations for bearing reinforcement, and 7×19 stainless steel cable as the ductile diagonal bracing element. Each material is selected for a specific structural function that is in-line with the material's strengths. Bamboo carries purely axial loads, the cable carries diagonal tension, and the mortar distributes localised bearing stress at connection nodes.

The mortar infill is confined exclusively to the internode cavity at each bolt location for the diagonal brace, preventing culm wall crushing under the perpendicular bearing stress induced by the threaded rod and bracing combination. The volume of mortar per module was confirmed to fall within the 50kg module weight limit under the worst-case culm geometry of 115mm outer diameter and 8mm wall thickness.

The woven bamboo lath panel was redesigned from the original 45mm ikra panel thickness to 25mm, reducing the panel weight from 88kg to 44kg and satisfying the two-person carrying limit. A further reduction to 20mm is recommended to provide a construction tolerance margin, bringing the panel weight to 33kg. The panel contributes to lateral stiffness through composite action with the structural frame, though this contribution was conservatively excluded from the Karamba model and is identified as a secondary lateral brace, requiring further research and testing.

Lateral stability is achieved through Configuration F which has cross-bracing that is confined to the two corner modules of each wall plane. This configuration was selected from six alternatives modelled in Karamba3D as the optimal balance between compressive stress in the bamboo culms and tensile stress concentration in the cables. Confining the bracing to the corners reduces redundancy, concentrates the potential failure location at known and accessible points, and achieves inherent wall plane stability in both lateral directions without relying on the parallel wall.

Together, these material combinations produce a modular building unit with sufficient cohesion and dimensional stability for the seismic and climatic conditions of Assam, using materials and processes available within the local supply chain.

6.1.4. Seismic Design

How does the module and its interlocking system behave under simplified lateral or cyclic loading representative of earthquake-relevant actions?

The Equivalent Static method from IS 1893 produced a design base shear value of 27.18 kN. This force is distributed equally across four active diagonal cables per load direction, producing a diagonal tensile force of 21.5 kN per cable. A 7 mm, 7×19 stainless steel cable satisfies this demand, transferring the force into the bamboo culm through an M22 threaded rod bearing against a mortar-infilled node. The vertical component of 20.4 kN is carried in compression by the column culm alongside the dead load demand. Bamboo structural design codes from IS 15912 and ISO 22156 were used to check the limits and compliance of the bamboo structure under the design load. Intermediate beams reduce the effective buckling length from 3.06 m to 1.02m, raising the Euler buckling capacity from 4.7 kN to 42.6 kN against a combined demand of 22.65 kN.

Under this loading, Configuration F was modelled in Karamba3D under static conditions and produces a storey drift of 1.67%. This is well below the 8% drift capacity of the traditional Assam-type house calculated by Chand et al. (2019), confirming that the modular system remains within the lateral deformation capacity of its vernacular precedent while introducing a predictable and designable failure mechanism.

The yield strength and elongation from the plastic deformation of 7×19 stainless steel cable are not published by manufacturers, as cables are conventionally designed to remain elastic under service loading. As a result, the precise threshold at which the cable enters plastic deformation could not be determined analytically. The cable was therefore sized to satisfy the minimum breaking load, confirming that the diagonal force of 21.5 kN remains below the fracture threshold. It is assumed that the yield strength lies below the breaking load, meaning the cable will undergo plastic deformation before fracture under extreme loading. Physical tensile testing of the selected cable diameter is identified as a priority for future experimental development to verify the yield threshold and confirm the plastic deformation capacity under cyclic loading.

6.2. Research Question

To what extent can a modular, bio-based bamboo hybrid building unit provide adequate seismic performance, buildability for low-income housing?

The research demonstrates that a modular bamboo wall system, can be designed to meet the theoretical structural, modularity, and buildability criteria established for low-tech seismic construction in Assam. However, a fully bio-based system is not feasible under the extreme lateral loading conditions which require strong connections with predictable limits that can be designed.

Under analytical, physical, and digital evaluation, the system satisfies almost all hard and soft criteria. The modularisation methodology successfully deconstructed the vernacular system, identify potential modules, and guide the process of modularisation. This produced a system with an organised structural logic, set of standardised elements, defined interfaces, predictable failure thresholds and assembly sequences, and localised damage potential.

However, the extent to which the system performs under real construction or seismic conditions remains unverified. The ductile behaviour of the steel cable bracing, the composite lateral contribution of the ikra cladding panels, and the cyclic performance of the mortar-infilled bolt connections have not been physically tested. The system therefore demonstrates feasibility at the preliminary design level, but it still requires full-scale mechanical testing and iterative refinement before it can be considered a validated seismic-resistant system. In terms of modularity and buildability, the system is theoretically capable, however, full scale testing with unskilled labour and Assam-local materials and tools, are still required to validate the potential for integrating this system into the context.

6.3. Construction Sequence

The wall system is assembled in four phases. Phases 1 to 3 take place at a centralised facility located close to the bamboo source; phase 4 takes place on site.

Phase 1 — Harvesting and treatment

Step 1. Selection and harvesting. Mature bamboo culms of 3-5 years are harvested and graded against IS 15912 Group A, Special grade: minimum wall thickness 8 mm, maximum taper 5 mm/m, maximum curvature 75 mm over 6 m, and outer diameter within 70–115 mm. Culms outside this group are rejected.

Step 2. Treatment. Within 24 hours of harvest, culms are boron-treated using the modified Boucherie method in parallel to each other. Treatment is completed in approximately 4–5 hours per culm and gives the bamboo an indoor service life of 50 years or more when shielded from weather exposure.

Step 3. Straightening and drying. While the culm is still green, any curvature within tolerance is removed by heat straightening: the culm is heated until the outer surface softens, held in a jig until the lignin rehardens, and then transferred to a drying rack. Culms are dried for a few weeks until a moisture content of below 5% is reached.

Phase 2 — Factory fabrication

Step 4. Sizing and grading. Culms are sorted into groups with of a range of ± 2 mm from between 85 mm and 115 mm at the widest end. Culms within a group are paired with their closest similar culm so that adjacent culms in a module can be connected with opposite taper directions, this cancels-out the increasing tolerance along the height.

Step 5. Cutting to length. Vertical culms are cut to the storey height of 3.3 m. Beams are cut from culms within the same group to the standardised length of 885 mm.

Step 6. Bolt-hole drilling at nodes. Bolt holes are drilled through each culm at internode positions, on the 340 mm sub-grid derived from average internode spacing. Just above and below each bolt hole a pipe strap will be lashed around the culm to minimise splitting risks from any bolt bearing on unreinforced sections.

Step 7. Mortar infill at bolt nodes. At the top and bottom internodes, where bolts will receive diagonal cable bracing forces, the internode is filled with cement mortar before assembly. The mortar fill distributes bolt bearing stress across the full cross-section of the culm rather than across two thin wall sections, preventing splitting under seismic load.

Step 8. Panel weaving. In parallel, infill panel modules are produced. Split bamboo lath is woven in flat rectangular moulds, then plastered with cement mortar on both faces, following the traditional Ikra panel composition. Two panel variants are produced: standard panels and an extended variant that closes the gaps between the structural module and the foundation, and the gap between the structural module and the roof.

Step 9. Cable bracing modules. Corner bracing modules are pre-assembled. Each consists of two pre-cut lengths of 6 mm 7×19 galvanised steel cable fitted with end connections (d-shackles, thimbles and cable clamps).

Phase 3 — Module assembly and transport

Step 10. Structural culm module assembly. Two prepared and pre-selected vertical culms are placed parallel on the workbench. The standardised 885 mm beams are positioned between them at the designated spacing. The plywood gusset plates are positioned and drilled so that bolt holes are located at the location of a node.

Step 11. Quality check. Each module is checked against the criteria recorded for that batch: beam length, mortar set, and overall module mass (≤ 50 kg). Modules failing any check are reworked or rejected before leaving the facility.

Step 12. Stacking and loading. Structural modules are folded flat and stacked. Panel modules and bracing modules are bundled separatel-y. All modules and bundles are loaded onto a tractor trolley and stacked with appropriate protection layers and filling between modules to prevent sliding and abrasion.

Step 13. Transport to site. The trolley delivers the modules to the construction site.

Phase 4 — On-site assembly

The concrete strip foundation, raised at least 600 mm above grade, with embedded steel module brackets, is constructed in advance and is not part of this sequence.

Step 14. Placement of the first structural module. Two workers lift the first folded module from the trolley, carry it to the corner of the foundation, unfold it into its rectangular configuration, and place its base into the embedded foundation brackets. Bolts are inserted through the bracket and the lower bolt nodes and hand tightened. Intermediate bolts are fit to clamp the varying bamboo diameters to the foundation bracket. Steel cross bracing is immediately fitted to the top and bottom threads in the structural corner module to provide the wall with immediate stability.

Step 15. Placement of the second structural module. The adjacent module is placed in the same way. Both modules are now standing but not yet laterally connected.

Step 16. Inter-module connection. A steel pipe strap is wrapped around the culms of the two adjacent modules at each beam level and tightened. Any residual gap between the culms is closed with a tapered bamboo/timber wedge driven into the strap.

Step 17. Repeat to complete the wall plane. Steps 14 to 16 are repeated along the length of the foundation until the full wall plane is erected. The last structural corner module is also fitted with the steel cross bracing.

Step 18. Panel module attachment. Panel modules are lifted by two workers and organised along the wall. Panels are fitted to the wall from bottom to top, starting with the smaller base panel. Each panel is slotted onto the existing intra-module thread and bolted with a washer and rubber gasket to prevent moisture ingress.

Step 19. Inter-panel sealing. A continuous strip of tape is applied vertically over the gap between adjacent panel modules, from roof to plinth, with a short extension left at the base of each strip. The extension acts as a location marker for future panel replacement: pulling the tab strips the finish layer cleanly from the gap, exposing the panel-to-panel joint without disturbing the surrounding wall.

Step 20. Finish layer. A thin layer of clay or lime plaster (or paint, depending on local preference and budget) is applied across the full external face of the wall. The finish equalises the surface, covers the inter-panel tape and any overlapping panel edges, and provides the final moisture barrier.

7. Discussion

7.1. Interpretation of results

The theoretical exploration of such a system, where morphological variations must be standardized, requires the simplification and generalization of variables to create conformity within a regular system. The organization of this system is based on the average internode spacing of Guadua Bamboo of 340mm. It is important to consider that this average has a large margin of variation, which cannot be predicted for, merely managed against by assuming the average. In practice, the success of this system is contingent on many such variables that are inherently difficult to control. In the case of grid alignment, only culms which correspond with the average inter-node spacing, with only a small margin of variation, can be used, minimizing the proportion of harvest which can be included in this system. The straightness of a culm also determines the connection tolerance between the panel and the structural module. Although there are methods that can straighten the culm, which are described in the chapter on contextual constraints, it is extremely difficult to ensure that it is perfectly straight. Modularity is a field which works best when the components have predictable and modifiable properties and dimensions. This is not the case with bamboo, which is the defining component for the rest of the system.

Digitally modelling the system also required simplifications and the assumption of certain perfections which do not exist in practice. To model the wall system in Karamba3D, many elements of the system could not be included in the calculations which has a drastic effect on the values that were produced such as the compressive and tensile stress, and drift percentage. This was taken into account so that the results did not rely on the significance of any individual value. They were instead used comparatively to assess the relative differences between the bracing configurations, and to check the global accuracy of the input values. The one reliance was in the 1.57% drift of Configuration F used to assess against the seismic design criteria of 8% drift. The Karamba model can only simulate elastic monotonic loading, which has a completely different effect on the structure than the cyclic loading experienced in earthquakes. The drift value can therefore not be entirely trusted. However, as it falls far below the 8% drift criterion, and that the increased stiffness provided by the panels, it can be safely assumed that the criterion is still satisfied.

The end result of is a wall system with an architectural language which has evolved into something entirely different from its Assam-type predecessor, shaped by the constraints that governed the design. Figure 40 shows a side-by-side comparison of the two wall systems. The structural language of the Assam-type house is exposed to the exterior, whilst, the modular bamboo wall required the panels to hide the frame, protecting it from moisture. From the interior, the frame systems have a similarly regular rhythm, however, the bamboo system has a clearly exposed and layered structural system, adding a visible engineering complexity which the Assam-type house lacks – its joints are all hidden at the interface between the panel and the timber frame. What unites them now is not their appearance, but their underlying principle: a lightweight system built from local materials, by local hands.

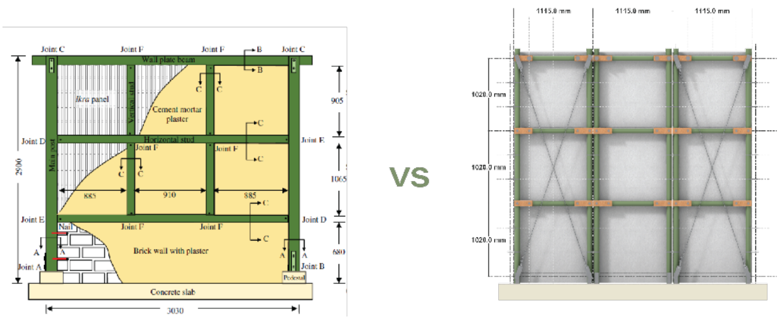


Figure 40 - Comparison between Assam-type wall and Modular wall system

7.2. Limitations

Results

The results of this research are entirely analytical and digital, supplemented only by a few scaled prototypes. No full-scale physical testing was conducted, creating a large gap between the design's theoretical performance and its real-world validity. The structural model in Karamba3D is linear-elastic and monotonic, meaning it cannot capture the effects of culm tapering, cyclic degradation, friction slip between elements, pinching behaviour, or post-yield response, all of which are relevant to seismic performance. The yield threshold of the 7×19 stainless steel cable could not be sourced from manufacturer datasheets and was estimated rather than measured, introducing uncertainty into the ductile fuse design. A large limitation was the exclusion of the panels as part of the calculations for the lateral loading system. The panels have a noticeable influence on the structure's stiffness and the calculations will benefit from empirically modelling the contribution of the panels. Originally, mechanical tests were intended to be performed which is why Guadua bamboo was selected as a proxy for native species, as Guadua was the only bamboo species available for testing. However, this doesn't accurately reflect the performance of the native species which could have very different characteristics.

Design

Bamboo durability has not been properly addressed. Although the bamboo is treated against biological attack, the structure could still use proper plinth detailing and a protocol which manages decay. The additional panel module variant does minimise the opening at the base, however, the structure must still be fully sealed off to prevent insects and moisture from penetrating the structure. The exposed bolt head on the panel surface has not been addressed for the potential of moisture ingress or weathering. Interfacing with the roof and potential corner connections are also entirely undeveloped and could have completed the structural language of the wall system by creating a completely confined enclosure. To further the completeness of the system, construction details with accurate sizing and illustrations should still be made. Due to time limitations only two system iterations could be performed despite more problems which have been identified which require solving in future iterations. The use of Guadua as a proxy species determined the average internode spacing and interface designation, which should have instead been decided by the native species. However, Guadua is one of the few structural bamboo species which have had extensive research done.

Context

This research suffers also from contextual limitations which could have strengthened the design; no on-site validation could be conducted in Assam, no analysis was conducted on cultural acceptance, local skill availability, and the substitution of Guadua with native species such as Bambusa balcooa or Dendrocalamus hamiltonii. Finally, a cost analysis was not conducted within the scope of this research, limiting the ability to compare the economic benefit of this construction system with the conventional systems.

7.3. Implications

Sustainability and societal impact

The proposed system directly addresses the current issue facing low-income, informal housing in earthquake-prone regions in Assam, India and the transition it is experiencing away from the established vernacular. The system achieves this by capitalising on locally available resources and workforce to achieve a low-cost alternative to both the current vernacular system and their concrete/masonry replacements. If development of a complete housing system is continued and validated through physical testing and construction trials, the system has the potential to offer an affordable, locally buildable, and repairable alternative.

The use of bamboo as the primary structural material carries significant sustainability advantages. Bamboo is one of the fastest-growing plants on earth, sequesters carbon during growth, and is abundant in Assam. A bamboo-based modular system that extends the service life of the material through replaceability and reuse contributes directly to circular construction principles. The inclusion of steel elements and mortar infill at critical connections is a compromise that was required to offer seismic strength and ensures the long-term durability of the structure.

Cultural context and contribution to the built environment

This research attempts to extend the traditional building practices that surround the Assam-type house rather than replace it. Although the architectural language has evolved into something entirely different from its Assam-type predecessor, the vernacular structural knowledge is still translated into a system that can be produced and maintained by the communities that inhabit it. Any modular system introduces the risk of imposing a uniformity that conflicts with local practices of construction and aesthetics. However, the development of this modular system, using local materials, tools, and people, makes an honest attempt to bridge the gap between a standardisation and tradition.

More broadly, the research contributes to the largely underdeveloped field between modular design theory and low-tech seismic construction. This is a gap with global implications, beyond Assam; this is relevant to any context where the problems of seismic risk, low-tech construction and material scarcity coincide.

7.4. Recommendations/future work

- Full-scale cyclic shake-table or quasi-static cyclic test of one corner-braced wall plane.
- Material characterisation of Guadua (or native Assam species *Bambusa balcooa*, *Dendrocalamus hamiltonii*) for radial compressive strength and bolt-bearing capacity.
- Full structural check of each element
- Hide externally exposed thread connection
- Development of corner connection and roof modules
- Development of panel-module configuration with weave pattern and mould design
- Development of window-door openings and interfacing in the structural culm
- Field pilot with local builders in Assam, capturing assembly times and error modes.
- Cost benchmark vs. unreinforced brick.

7.5. Reflection

Position within the graduation studio

My mentors are in the fields of product design and structural design with a focus on biobased construction. By producing bamboo modules with seismic performance requirements, this topic directly overlaps with both fields and the focus.

Research approach – process and outcomes

My original research approach up until the A2 was entirely exploratory with minimal systematic development of results or proper constraints. This was due to a lack of proper understanding of the scientific fields I was involved in. My approach had drastically shifted since the A2, resulting in a revision of the literature review in search of measurable and definable criteria with which to structure my work and asses my design on. This resulted in the entire current methodological structure of this paper. I have very nearly reached the results I had set for myself in the A1 – to create a full biobased structural wall system which could withstand earthquake loads. This result was achieved but not in the manner that was originally thought with many compromises to the strong, yet naïve principles I had set for this project. I had wanted to conduct some more mechanical testing, but was advised against this multiple times by an expert who asserted that bamboo was not appropriate for testing – the value of the obtained results would be outweighed by the costs in time, effort, and resources in preparation for the tests. Testing would only be feasible at the PhD scale with funding and proper resources. Additionally, more physical prototyping was originally expected but it turns out this research was more logistically focused than prototyping. In hindsight this makes sense considering that modularity is fundamentally a systems problem which prioritizes the system logic and not any individual component or connection.

Strengths and limitations of the methodology

The methodology was structured based on the MFDA principles outlined by Sonego et al. (2016). They were sufficiently universal with clear steps and tools provided so that any system with various levels of complexity could employ this methodology to their own research. The steps were used more for the global structure of the research, confining certain research elements to appropriate stages. However, with the MFDA being so globally oriented, its structure lacked the necessary nuance for the design development and testing of architectural systems. This was supplemented by the hard and soft criteria which were essential for guiding decision-making and organizing relevant constraints. Overall, the current methodology of this research has allowed me to structure my work well and create a coherent story of development and evaluation.

The relationship between research and design

Research was equal parts literature review, digital design and quantitative modelling. Each part informed the other continuously through checks. When a design decision was made, digital modelling was used as a qualitative test, which was then confirmed or grounded by quantitative checks using excel, which was supported by a literature review for standards and values.

Ethical considerations

The moral dilemma of assuming practices and behaviours of a people from a context I have no first-hand knowledge about was considered. While stakeholder interviews would have strengthened the contextual grounding of the research, the logistical difficulty and time required were weighed against the added value at this preliminary design stage. It was decided that this would not have been worthwhile enough for this research. A more holistic research program with adequate time for an in-depth preliminary study, with a participatory design method, would benefit significantly from such research.

8. Glossary

Glossary of Terms

Assam-type house — The vernacular timber-and-bamboo framed housing of Northeast India, characterised by a light timber frame, brick masonry to sill level, and woven Ikra panels above. Also called Ikra-type construction.

Axial load — A force acting along the longitudinal axis of a structural member. Bamboo is strongest in axial loading and weakest perpendicular to it.

Bahareque — A vernacular Latin American construction system using a bamboo or timber frame infilled with a woven mesh and plastered with mud or mortar. Functionally analogous to Ikra panel construction.

Base shear (V_b) — The total horizontal force at the base of a structure produced by a seismic event, calculated per IS 1893

Bearing stress — The compressive stress at the contact surface between two elements, such as between a bolt and the wall of a culm. Critical in bolted bamboo connections where it can split the culm.

Bolt-bearing failure — Failure mode in which the bolt crushes the wall of the surrounding material under compressive contact stress. Mitigated in this system by mortar infill at the bolt nodes.

Boucherie treatment (modified) — A bamboo preservation method in which boron solution is pressure-displaced through the vascular tissue of a freshly harvested culm, replacing sap and protecting against fungi and insects.

Brittle failure — Sudden, low-deformation failure of a material at its strength limit, without prior yielding. Characteristic of unreinforced masonry and concrete under seismic loading.

Buckling (Euler) — The lateral instability failure of a slender member under axial compression, where the member deflects sideways before reaching its compressive strength limit.

Configuration F — The diagonal bracing configuration selected for the final design after comparative Karamba3D analysis; consists of corner-located steel cable bracing.

Culm — A single stem of bamboo. Tapered along its height, hollow except at the nodes, and the primary structural element of the system.

Cyclic loading — Repeated alternating loading, characteristic of seismic action. Cannot be represented by linear-elastic monotonic models such as the Karamba3D analysis used in this thesis.

Design for Disassembly (DfD) — A design strategy that prioritises non-permanent, reversible connections so that components can be separated, replaced, or reused at end of life.

Diaphragm — The cellular partition inside a bamboo culm at each node, with cells oriented perpendicular to the culm axis. Prevents local buckling of the culm wall.

Drift (storey drift) — The horizontal displacement of one floor of a building relative to the floor below, expressed as a percentage of the storey height. Used as the principal seismic performance criterion in this thesis (8% ceiling).

Ductility — The ability of a material or system to deform plastically without fracturing. Provides slow, predictable failure and dissipates seismic energy as heat.

Energy dissipation — The mechanism by which seismic energy entering a structure is converted (typically through plastic deformation, friction, or yielding) and released, protecting the rest of the system from that energy.

Fish-mouth joint — A traditional bamboo connection in which the end of one culm is cut with a concave saddle profile matching the curvature of the receiving culm, so the two surfaces bear against each other.

Friction slip — Relative movement between two surfaces in contact, dissipating energy as heat. A key energy dissipation mechanism in the Assam-type house at the panel-frame interface.

Function-Behaviour-Structure (FBS) — A design framework that describes a product in terms of what it should do (function), how it does it (behaviour), and what it is made of (structure).

Gabled roof — A pitched roof with two sloping sides meeting at a central ridge, with triangular vertical end-walls. Standard for the Assam-type house due to monsoon rainfall.

Group A bamboo — Per IS 15912:2018, the highest structural grade of bamboo culms, defined by wall thickness, taper, curvature, and diameter limits.

Gusset plate — A flat plate (steel, plywood, or composite) used to join multiple structural members at a single node by transferring load through fasteners in shear.

Hard criteria — In this thesis, the non-negotiable performance requirements that any design iteration must satisfy (e.g. module size ≤ 3.5 × 1.8 m, weight ≤ 50 kg, storey drift < 8%).

Ikra panel — The traditional infill panel of the Assam-type house: a woven bamboo or reed mesh plastered with mud or cement on both sides, typically 45 mm thick.

Inter-module connection — A connection between two adjacent modules in the system. In the final design, achieved through a steel strap and bamboo wedge.

Internode — The hollow tubular section of a bamboo culm between two nodes, with axially oriented fibres. Vulnerable to wall crushing under bolt bearing if not reinforced.

Interaction Matrix Analysis (IMA) — A matrix tool that maps the interactions between every component of a system (functional, physical, energetic, informational) and identifies which interactions warrant modularisation.

Intra-module connection — A connection between two elements within the same module — in this system, between a vertical culm and a horizontal beam.

IS 875 — The Indian Standard governing dead and live loads on buildings.

IS 1893 — The Indian Standard governing seismic design, used in this thesis to calculate the design base shear via the equivalent static method.

IS 15912 — The Indian Standard governing the grading and structural use of bamboo culms.

ISO 11228-1 — The International Standard governing manual lifting limits in occupational settings; provides the 50 kg per-module weight ceiling used in this thesis (two-person lift).

ISO 22156 — The International Standard governing the structural design of bamboo.

Karamba3D — A linear-elastic finite-element analysis plugin for Rhino/Grasshopper, used in this thesis to compare bracing configurations under the design base shear.

Linear-elastic — A material model in which stress is proportional to strain and no permanent deformation occurs. Cannot represent post-yield, cyclic, or friction-slip behaviour.

Modular driver — In the MIM, a category of reason for modularising a component (e.g. common unit, upgrading, recycling, separate testability), assigned a weight reflecting its importance.

Modular Function Deployment Adapted (MFDA) — The methodology proposed by Sonego et al. (2016), adapting the original MFD method to projects of different complexity and novelty. Structures this thesis into a three-step process: generate concepts, evaluate, improve.

Module Indication Matrix (MIM) — A matrix tool that cross-tabulates system components against modular drivers to identify which components warrant being grouped into a module.

Monotonic loading — Loading applied in one direction without reversal. The loading regime of the Karamba3D model in this thesis; contrasts with cyclic loading.

Mortise-and-tenon — A traditional timber joint in which a projecting tongue (tenon) on one member fits into a corresponding socket (mortise) on another. Used in the Assam-type beam-to-post connection.

Node (bamboo) — The thickened ring along a bamboo culm at the location of a diaphragm. Locally stronger than the internode and the preferred location for bolt connections.

Pinned connection — A connection that transfers axial and shear forces but allows rotation, transferring no moment. The design intent for the beam-to-culm connections in this system.

Plinth — The raised base of a building, typically 600 mm above grade in Assam-type construction, that protects the timber/bamboo frame from monsoon flooding and ground moisture.

Plastic hinge — A location in a structural member where plastic deformation concentrates under load, allowing rotation while continuing to transfer force. Sites of energy dissipation in the Assam-type frame.

Quincha — A vernacular Andean construction system using a timber or cane frame infilled with woven cane and plastered with mud. Functionally analogous to bahareque and Ikra.

Racking — The in-plane shear deformation of a rectangular frame into a parallelogram under lateral load.

Radial compression — Compressive force applied perpendicular to the longitudinal axis of a culm, compressing the culm wall radially. Considerably stronger than perpendicular-to-grain bearing on the wall section.

Soft criteria — Performance requirements that are desirable but not absolute, evaluated on a relative scale rather than pass/fail.

Supersystem — In MFDA terminology, the broader system within which the target system is embedded. For this thesis the wall is the target system; the roof and foundation are supersystem components.

Tooth-and-groove — A traditional timber joint in which a projection (tooth) at the end of one member slots into a continuous channel (groove) in another. Used in the Assam-type stud-to-beam connection.

Universal connectivity — In modular design, the requirement that any module of a given type be interchangeable with any other module of the same type, independent of position in the system.

Wattle-and-daub — A general term for traditional construction systems in which a woven lattice of organic material is plastered with mud, clay, or mortar. The family to which Ikra, bahareque, and quincha all belong.

7×19 cable — A steel cable construction with seven strands, each made of 19 wires. Provides flexibility and fatigue resistance suitable for ductile bracing elements.

9. Appendix

Fish mouth variation analysis

Table 13 -Analysis of fish mouth connection variability

Small Culm (D = 57mm)		
Medium Culm (D = 63mm)		
Large Culm (D = 73mm)		

Friction moment in fish-mouth connection

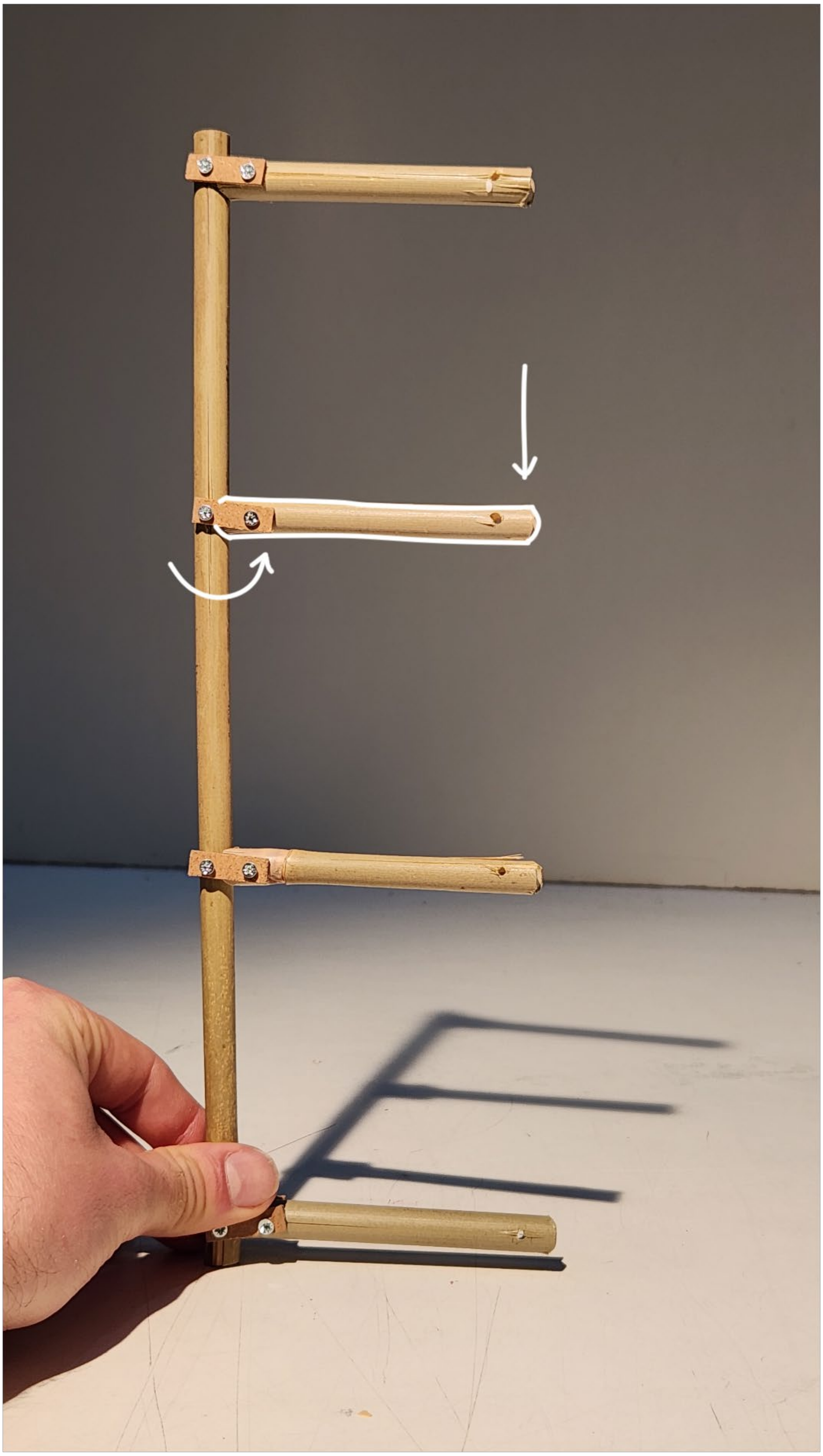


Figure 41 - Friction moment in fish-mouth connection

Relationship between panel thickness and weight

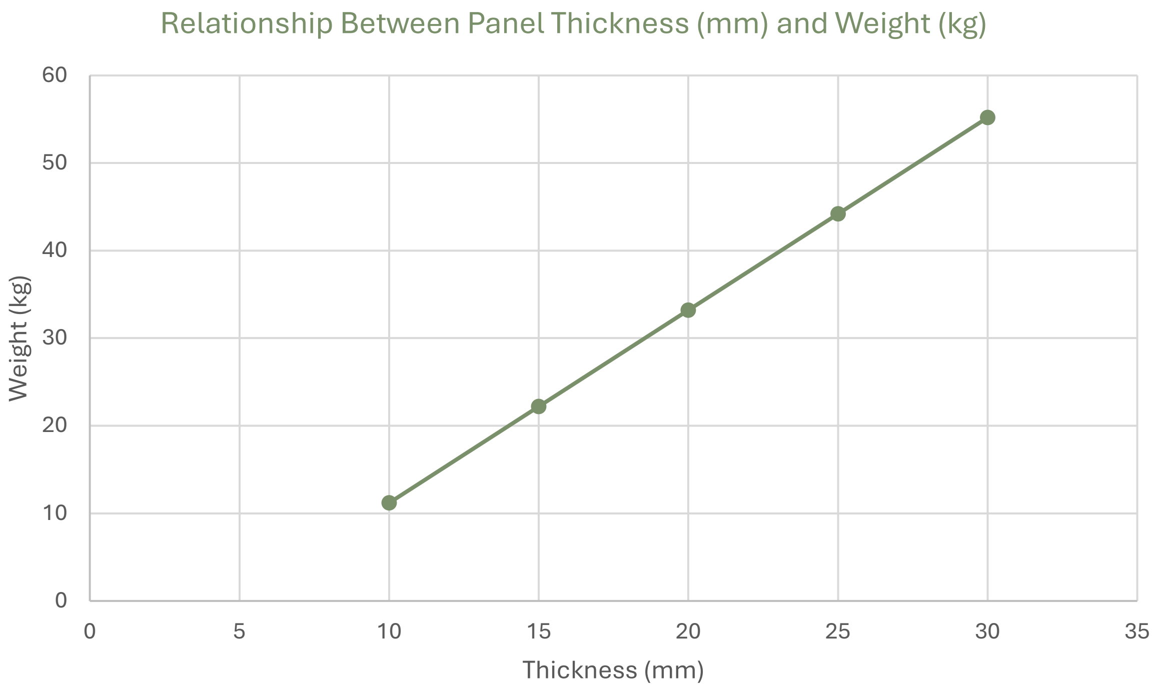


Figure 42 - Chart representing the linear relationship between panel thickness and weight

Beam rotation calculations

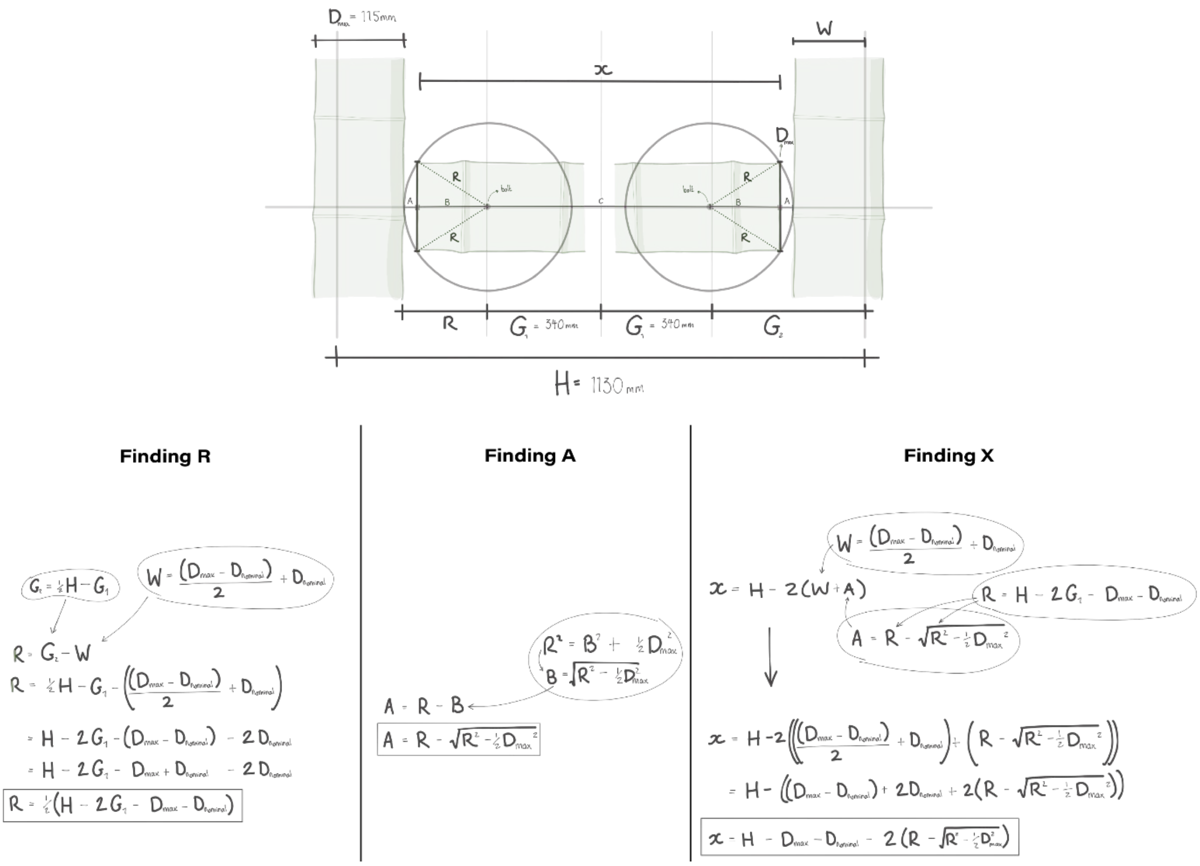


Figure 43 - Beam rotation calculation with all intermediate steps

A = beam offset from culm wall

B = distance from node end to bolt

C = distance between bolts on the beam

D = beam diameter

R = radius of rotation

G_1 = grid distance 1

G_2 = grid distance 2

H = main horizontal grid distance

W = culm wall distance from main grid

x = beam length

Table 14 - Excel calculation for beam length

Parameter	Value	Unit
D_max	115.00	mm
D_nominal	100.00	mm
H	1130.00	mm
G_1	340.00	mm
G_2	225.00	mm
W	107.50	mm
R	117.50	mm
A	15.00	mm
B	84.82	mm
C	715.37	mm
x	885.00	mm

Seismic Design Base Shear Calculation

Inputs

A. BUILDING GEOMETRY

Parameter	Value	Unit	Notes / source
Building length (long direction)	9.00	m	
Building width (short direction)	6.00	m	
Eave height (storey height)	3.00	m	*Floor to eave; single storey*
Total floor plan area	54.00	m²	*L × W*
Total wall area (4 faces)	90.00	m²	*2(L+W) ×H*

B. DEAD LOADS (IS 875 Part 1)

Element	Unit load	Unit	Area ref	Load (kN)
Roofing	0.65	kN/m²	*IS 875 Pt1; (Clay tile - 65 kg/m²)*	35.10
Bamboo rafters + purlins	0.20	kN/m²	*Estimated - Spaced 500 mm*	10.80
Wall infill panels (split bamboo)	0.44	kN/m²	*Trad. Lath + Plaster (-19mm); rep. bamboo lath and plaster*	39.85
Bamboo floor (splits on joists)	0.00	kN/m²		0.00
Structural columns + beams (lump)	4.67	kN	*Estimated - based on calculations D and E*	4.67
TOTAL DEAD LOAD W_DL	**90.42**	kN		
UNIFORM DEAD LOAD	**1.67**	kN/m		

C. LIVE LOADS (IS 875 Part 2)

Element	Unit load	Unit	Factor for seismic W	Load (kN)
Floor live load	0.00	kN/m²	*0.25 × LL included in seismic W (IS 1893 cl.7.4.2) - Assuming future addition*	0.00
Roof live load (inaccessible pitched)	0.75	kN/m²	*0.0 × LL for roof in seismic W*	40.50
SEISMIC WEIGHT W = W_DL + 0.25×LL_floor	**90.42**	kN	*IS 1893 cl.7.4.2*	

Seismic ESM

EQUIVALENT STATIC METHOD — IS 1893 (Part 1): 2016

Linked to sheet 1.

A. SEISMIC ZONE & SITE PARAMETERS

Parameter	Value	Unit	Basis
Seismic zone factor Z (Zone V)	0.36	-	*IS 1893 Table 3 - Zone V*
Importance factor I	1.00	-	*Residential - IS 1893 Table 8*
Response reduction factor R	1.50	-	*1.5 for bamboo braced frame (Kaminski et al., 2016)*
Soil type	2.00	-	*1=Hard, 2=Medium, 3=Soft (IS 1893 cl.6.4.2)*

B. NATURAL PERIOD & SPECTRAL ACCELERATION

T_a - RC MRF	0.17	s	*0.075h^0.75 IS 1893 cl.7.6.2a (RC MRF)*	Using the RC and MRF calculations as conservative values - **all are T < 0.4 therefore Sa_g = 2.5**
T_a - RC steel Composite MRF	0.18	s	*0.08h^0.75 IS 1893 cl.7.6.2a (RC Steel composite MRF)*	
T_a - Steel MRF	0.19	s	*0.085h^0.75 IS 1893 cl.7.6.2a (Steel MRF)*	
T_a - long direction (L)	0.090	s	*0.09h/√d IS 1893 cl.7.6.2b (RC)*	

T_a - short direction (W) ← governs	0.110	s	*0.09h/√d - shorter dimension gives longer T*
Governing T_a (longer period)	0.110	s	*Conservative - use longer*
Spectral acceleration S_a/g	2.50	-	*IS 1893 Fig.2 - plateau for T<0.4 s (all bamboo single-storey cases)*

C. DESIGN SEISMIC COEFFICIENT A_h			
A_h = (Z/2) × (I/R) × (S_a/g)	**0.300**	-	*IS 1893 cl.6.4.2*

D. BASE SHEAR V_B			
Seismic weight W (from Sheet 1)	90.42	kN	
TOTAL BASE SHEAR V_B = A_h × W	**27.13**	kN	*IS 1893 cl.7.6.1 Single storey - all at roof level*

Diagonal sizing calculations

Inputs:

Variable	Value	Unit	Source
V_wall	27.18	kN	seismic check
w (bay width)	1,015	mm	grid
h (wall height)	3,060	mm	grid
L_d (diagonal length)	3,162	mm	Pythagoras
cos θ	0.316	—	w / L_d
n (active diagonals)	4	—	config. F

Max volume reinforcement

This is the calculation to determine the maximum volume of mortar that could be used to reinforce a module before the maximum weight of the module is reached of 50 kg. The larger the culm wall thickness, the heavier the module, and the less mortar that could be used. A wall thickness of 20mm is roughly the maximum allowable thickness, assuming no tapering and continuous thickness throughout the culm.

Maximum volume of mortar		
Diameter	115.00	mm
Wall thickness	20.00	mm
Module weight	42.65	kg
Mortar Density	2000.00	kg/m3
Max mortar volume	0.0037	m3
	3675320.15	mm3
Surface area	4417.86	mm2
Length of culm able to fill	831.92	mm
	0.83	m
Each	**0.21**	m

Buckling Check

CULM GEOMETRY			
Parameter	**Value**	**Unit**	**Notes / IS 15912 Reference**
Outer diameter (D)	77.50	mm	*Mean outer diameter — Cl. 3.2.31 (blue = user input)*
Wall thickness (w)	8.00	mm	*Min 8 mm for load-bearing — Cl. 5.4.5*
Culm length	3300.00	mm	*Min 6 m preferred — Cl. 5.4.2.2*
Taper (diameter diff. over length)	5.00	mm/m	*Max 5.8 mm/m — Cl. 5.4.3*
Moisture content	18.00	%	*Target ≤ 20% — Cl. 5.3*
Age of bamboo	4.00	years	*Min 4 years — Cl. 5.1.1*

LOADING PARAMETERS			
Parameter	**Value**	**Unit**	**Notes / IS 15912 Reference**
Beam span (L)	0.00	mm	*Unsupported span for beam check*
Uniformly distributed load on beam (w_beam)	0.00	kN/m	*Total UDL including self-weight*
Column height (unsupported)	1020.00	mm	*Unsupported length — Cl. 7.7*
Axial load on column (P)	21.90	kN	*Design axial load*
Effective length factor (K)	1.00	—	*1.0 pinned-pinned / 0.7 fixed-pinned / 2.0 cantilever*
Number of culms in bundle	2.00	—	*Bundle column — Cl. 7.8*
Deflection limit (L/x)	250.00	—	*Timber deflection formula - IS 883 Cl. 7.5.9.1*

SECTION PROPERTIES (per culm)				
Property	**Formula / Value**	**Unit**	**IS 15912 Ref.**	**Notes**
Inner diameter (d = D − 2w)	54.00	mm	Cl. 4	
Cross-sectional area (A)	1558.23	mm^2	Cl. 4	
Moment of inertia (I)	761195.33	mm^4	Cl. 4, 7.6.2	
Elastic section modulus (Z)	21748.44	mm^3	Cl. 4	*pi/32 * (D^4 - (D-2w) ^4)/D*
Radius of gyration (r = √(I/A))	22.10	mm	Cl. 4	

COLUMN CHECK (axial, Euler buckling)

Check	Value	Unit	Limit	Status	Notes
Effective length (Le = K × L)	1020.00	mm			
Slenderness ratio (λ = Le/r)	46.15	—			
Euler buckling load (Pe, 90% I)	21316.30	N		Cl. 7.7.3 (90% I for taper)	
Euler buckling load per bundle	42632.60	N			
Applied load (P)	21900.00	N			
Buckling check (P ≤ Pe)	21900.00	N	42632.60	PASS	51%
Axial stress (σc = P / (n×A))	7.03	N/mm^2			
Permissible comp. stress (fcp × dur.)	23.25	N/mm^2			
Compression check (σc ≤ fcp)	7.03	N/mm^2	23.25	PASS	
Shear stress					
Utilisation ratio	49%				

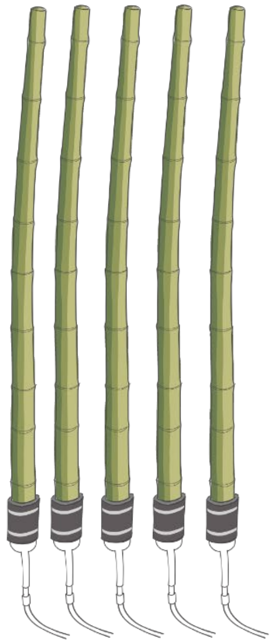
Final Iteration Construction details

Figure 44 - Steel cable connection

Construction Steps:

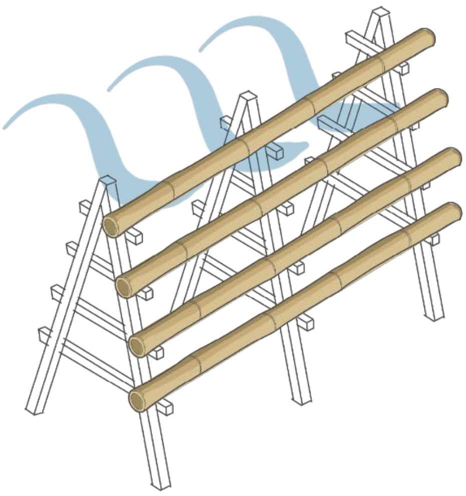
1. Culm harvesting

Culms are harvested at 3-5 years of age when they have reached full maturity and are structurally at their strongest.



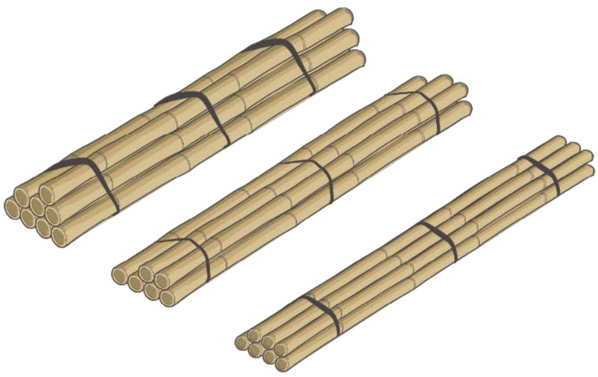
2. Culm treatment

Culms are treated using the modified boucherie method within 24 hours of harvesting while they are still green



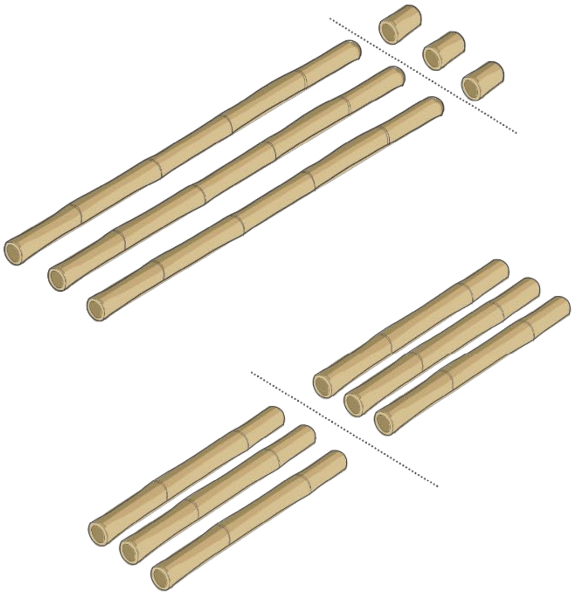
3. Straightening and drying

Any curved culms are heat straightened directly after the treatment. The now straightened culms are laid on racks or leaned vertically in a dry well ventilated space to allow for airdrying.



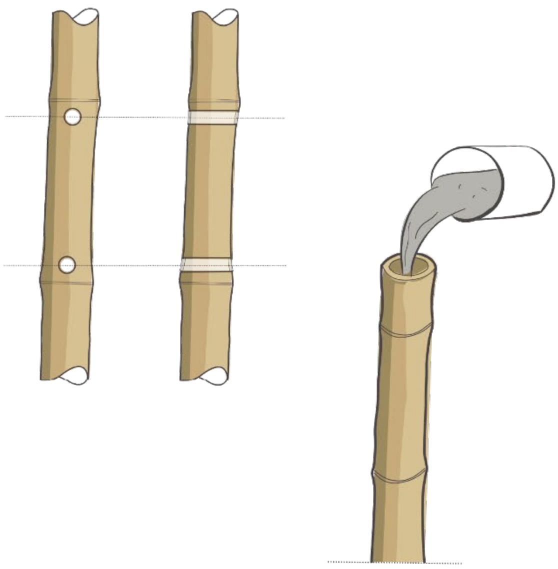
4. Grouping

Once the culms have been dried they can be grouped into their designated diameter bands for later processing.



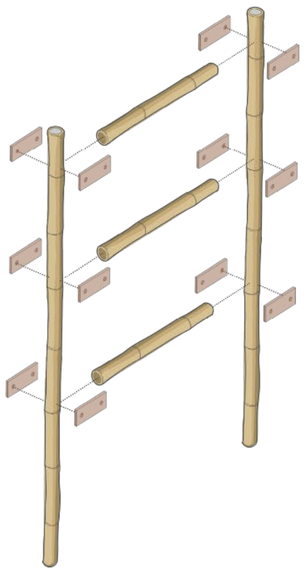
5. Sizing

Culms within the same group are graded and cut to the required standardised sizes



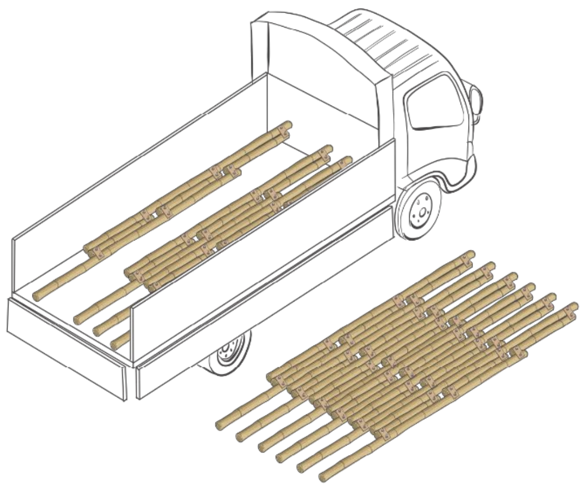
6. Preparation

Culms are prepared for assembly by drilling holes at the required intervals based on the grid and subgrid and column ends are filled with mortar grout for reinforcement



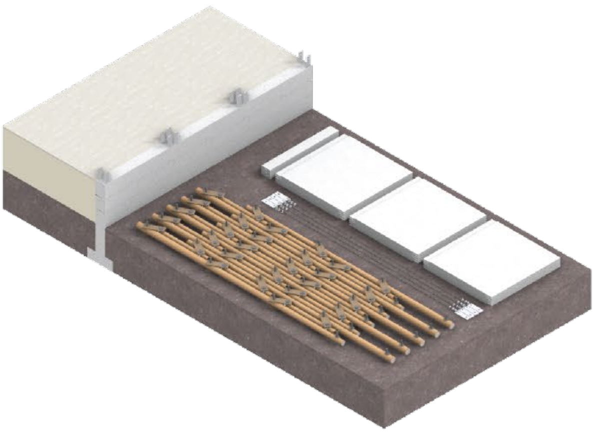
7. Module assembly

Structural frame modules are assembled with the plywood gusset plates and required bolts



8. Transportation

The structural frame modules are collapsed and organised, along with the other two modules - the brace module, and panel module - into the tractor trolley to be transported to the construction site.

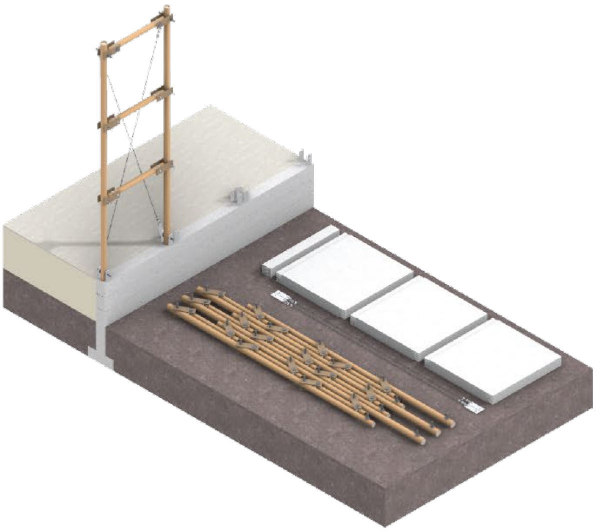


9. Construction preparation

All the modules are arranged at the construction site where the foundation has already been layed with the embeded foundation plates.

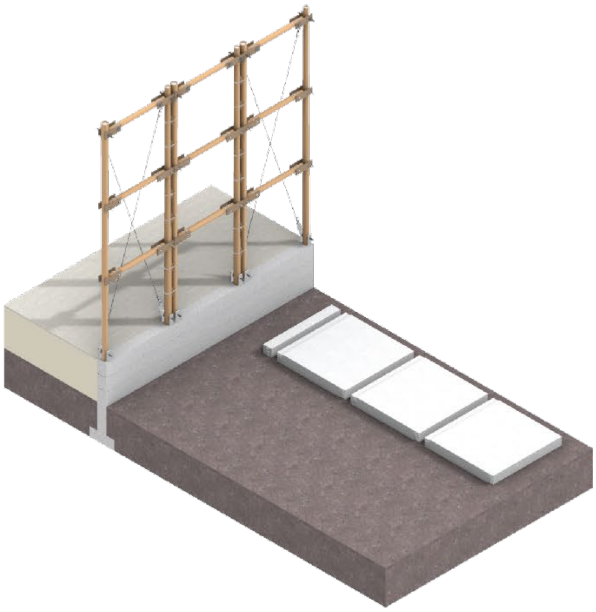
10. Structural frame placement

The first structural frame is folded out into the foundation footings and a bolt is extended through the designated holes.



11. Bracing

The first structural frame module is imediately braced to provide immediate stability for the additional structural frame. The bracing is placed on the interior of the future structure.



12. Complete structural assembly

The complete structural system is now assembled and the inter-module connections are strapped. Residual gaps are filled with a bamboo or timber wedge.

13. Panel placement

Ikra panel cladding can now be placed, going bottom to top. Panels are slotted onto the threads and then the final nut with integrated rubber gasket completes the placement.

14. Finishing layer

Gaps between panels are taped with a small extension label at the bottom for future identification and removal. A final plaster/paint layer is applied to equalise the surface.

15. COMPLETE SYSTEM

The wall system is now complete and structurally reliable against earthquakes.

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