RE - CONNECTING BAMBOO

Development and structural evaluation of connections for construction of a prefabricated housing unit using engineered bamboo

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DEVELOPMENT AND STRUCTURAL EVALUATION OF CONNECTIONS FOR CONSTRUCTION OF A PREFABRICATED HOUSING UNIT USING ENGINEERED BAMBOO

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ABSTRACT

Today, the world is continuously looking forward towards sustainable solutions for building construction, thus the interest and the need for sustainability is continuously growing. With growing issues related to the environment and sustainability, Bamboo being one of the answers, is one such sustainable material which has a lot of potentials to be used as building material. This graduation research is a little step towards uplifting the material, improvising and changing the current perception of bamboo in the building construction sector by evaluating possibilities of using engineered form of bamboo in structural application. Today, bamboo is developed up to a level where it is structurally modified for improved strength , durability and performance. This research focuses on using this advanced form of Bamboo to develop a method of construction to build a housing prototype and investigate into connection techniques to construct the same using these materials. The connection design is inspired from Japanese interlocking joinery, with an aim to avoid use of external fasteners to connect the joinery .This semi-permanent prefabricated interlocking approach allows for future flexibility. The research also establishes and evaluates criteria's as an design rule for efficient joinery connections. The joinery design is validated by physical prototyping, testing and software validation of the proposed joinery design configuration. The project strives to gain validation for the potential of using bamboo is structural application.

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INTRODUCTION:

1.1 NEED FOR INTERVENTION:

Today, the world is continuously looking forward towards sustainable solutions for building construction, thus the interest and the need for sustainability is continuously growing.

Nowadays, building materials are not only judged on their functionality, mechanical properties, financial requirements but also based on their environmental impact (Van der Lugt, Van den Dobbelsteen & Janssen, 2006). When it comes to analyzing these materials based on sustainability, environmental impact and Energy consumption factors like carbon footprint, the life cycle of the building/ product, manufacturing process of the material, maintenance, recyclability criteria in terms of disposal and post-use of the material play a major role.

To keep up with global development in infrastructure, demand for more advanced sustainable material is continuously increasing, as these materials offer more easy and permanent solutions. With this increased demand and focus towards sustainable materials there has been a lot of focus on natural biodegradable materials like wood and Bamboo.

Bamboo is one such sustainable material which is gaining importance with respect to above-mentioned aspects. Bamboo is also one of the fastest-growing plants and has also proven useful in numerous ways in the construction industry. There have been examples of houses built using natural Bamboo. While bamboo is already used in traditional forms in construction, most of the building are temporary and are constructed using natural bamboo, using local treatment methods of preservation. It is a well-known fact that the durability of bamboo in its natural form is very low. The houses would need a lot of maintenance and sometimes they also reconstruct them within few years. With these issues there is a lot of development in engineered form of Bamboo. Currently, there is already a lot of research and development on use of more advanced engineered form of bamboo In construction. However structural use of these materials and developing effective connections using these advanced materials is still questionable.

This research focuses on using these advanced forms of Bamboo for structural use to develop a method of construction and investigated into connection techniques using these materials.

Figure 1 : Bamboo forest ,a shelter in itself.("The whole world is a playground," n.d.)

Figure 2: Evaluation On possibilities and scope of building houses with bamboo

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02 CONTEXT

02 CONTEXT:

2.1 HISTORY:

History of use of bamboo in traditional construction methods is well known. Traditionally, often in developing countries where new advanced materials are not yet introduced and availability of material is low and is expensive. There have been examples of houses built using locally available material like bamboo and mud.

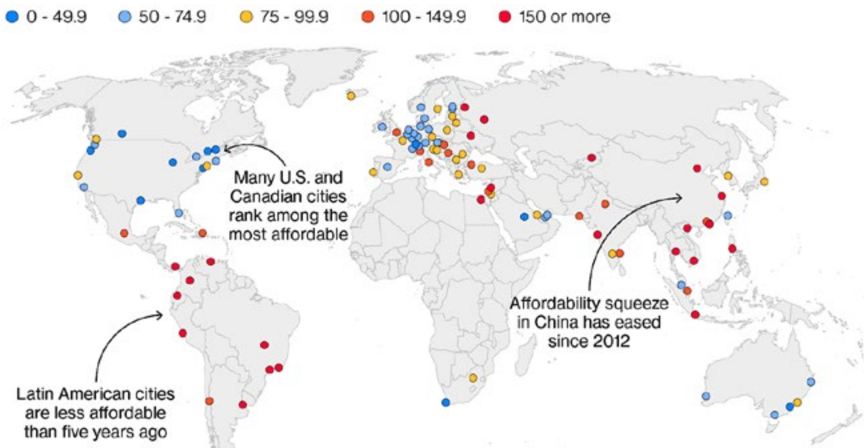
Houses being temporary and not durable

Figure 3 : Traditional bamboo houses("Ibuku," n.d.)

Till a decade ago traditional rural bamboo houses in Indian subcontinent were constructed with emphasis comfort and space. However for most of the rural populations, the once cozy bamboo house have now been reduced to flimsy and temporary structures. The maintenance and durability of which is a constant drain to time and money *(Dunham 1994* (Bamboo people and the environment.vol 3, 1995)*).*

2.2 GLOBAL HOUSING SCENARIO:

In developing countries specially owning your own permanent shelter might cost a lot of money. With more and more technological advancement in material as well as constructions, building a house is becoming a costly affair. Additionally owning a permanent shelter which would last longer and is durable, is becoming of prime importance all across the world. On the other hand the developed nations are turning towards advanced sustainable solutions for constructions materials.

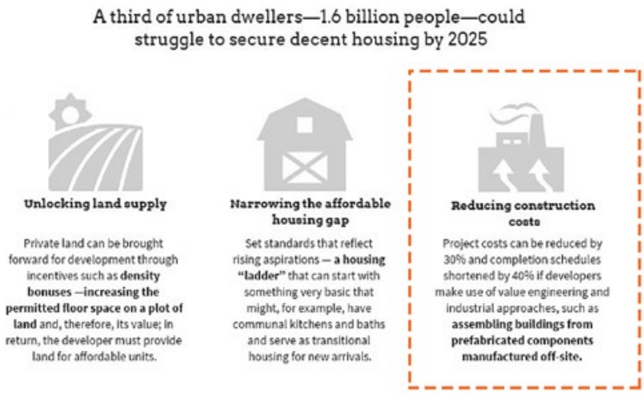


Global affordable housing Demand

Figure 4: The map from the Bloomberg Global City Housing Affordability Index shows that as bad as the housing affordability crisis is in expensive cities, it is even worse in the rapidly urbanizing cities of the Global South, where rents as a share of income average 100 percent, 150 percent, 200 percent, or even higher.("CITYLAB," n.d.)

Global affordable housing demand

Continuous new housing demand is a global scenario. According to the UN, by 2030, about 3 billion people – about 40 percent of the world's population – will be in need of proper housing. This translates into the need to complete almost 100,000 housing units per day from now until 2030. Additionally, home owners and potential homeowner face many challenges, including affordable housing and need for energy efficiency due to rising energy costs. For example Considering housing shortage in America which is considered to be a developed nation. Most of the housing shortage is in low cost & affordable homes. With the new Zero Carbon 2018 and Zero Net Energy regulations in California new housing is even rare and expensive Additionally, construction costs have increased 45% in the last 15 years despite cost saving measure. 6% of the cost increase is due to more restrictive energy saving regulations ("RDA," n.d.).



Global housing crisis

Figure 5: Showing global housing crisis and demands.

The issue of availability of materials to meet the demands of constructing two billion new homes emphasizes the need for countries to resource them as efficiently as possible. Government policies which encourage the sustainable design of new buildings to maximize future re-use, reduce carbon emissions and manage resources properly will be essential. Over the next 30 years, the countries which promote policies to help sustain and increase new housing provision will be more likely to avoid problems in sourcing materials and price hikes.

Need for sustainable housing design and material resource:

It is important to maximize the use of local materials and components in lower-income countries while striving for climatic appropriateness, energy-efficiency and environmental friendliness of the production processes of building materials, and for energy efficiency in their use. The use of imported materials should be systematically avoided.

Functional and cultural adequacy, energy efficiency, climatic and environmental appropriateness, affordability, flexibility for expansion and for upgrading of standards, and adaptability for future needs, should be maximized in housing design, both at the level of buildings and at the level of neighborhoods. Designs should also allow for possible economic activities in the dwelling unit to enhance income generating opportunities. Housing is to be mixed with other uses achieving appropriate densities to increase urban interaction, improve mobility and ensure the environmental sustainability of the urban fabric. As is the case of design, the aims in terms of technologies should be energy efficiency, environmental friendliness, cost-minimizing, allowing incremental expansion and improvement of standards, and enabling, where appropriate, owner building and use of local labour and contractors. Traditional technologies should be considered for local use and their adaptation for better performance, should be encouraged. ("UN-Habitat Global Housing Strategy," n.d.)

Some of the Main factors involved in the global housing requirements are:

High housing cost (which is usually not affordable for middle class population). Usually these housing costs are above their average income level. With most of the countries turning towards green building material and energy efficiency policies, new laws are passed thus increases global demand for new energy efficient houses.

2.3 MEETING THE DEMAND:

When we seek solutions to these problems across the globe, Bamboo is one such sustainable material which can be replenished within a very short time and is construction friendly when locally available. This natural material is available almost on all continents, except Europe, across the globe. Additionally, Bamboo has great economic potential when sourced locally. Building houses with this material would save a lot of capital investment in housing and would also help tackling sustainable issues. In order for a global system for housing, it is important to understand the potential of such system.

Some of the Criteria's are:

Determining the availability of raw material:

As discussed above ,for any housing model to be successful, easy availability of raw material is of prime importance. Sourcing the material locally, can drastically reduce the construction cost of a structure. Thus, it is of prime importance that the material is sourced locally and used within short transport distances. The figure 6 shows a map of availability of bamboo across the globe and it can be seen that the Bamboo is available almost on every continent except Europe.

Transportation:

Another reason of sourcing the material locally is that it has been observed that the transportation cost of the bamboo adds up to 30% to the cost of entire structure. With local availability of material would save a lot of transportation cost. Additionally, the transporting cost is considerably reduced due to weight of the Material.

Environmental impact:

The shipping cost and energy consumed play a major role in determining the environmental impact of the material .When the engineered product is developed it is important to initially take context with local availability of the material which would, in turn, decrease the additional expenses of transportation cost, recyclability, etc. The vast majority of bamboo's environmental load/cost is seen to be associated with transportation; assuming 1 kg bamboo culm, including transport from Costa Rica to the Netherlands as part of the production process, the load resulting from land and sea transportation was found to be approximately two times and 29 times greater than that of processing the material, respectively.

To determine the scope and limitations of the research and in order for the system module to work on global front some of the thumb rules are established based on the research above. The further research will be done considering these criteria as the boundary limits.

Summarizing the scope and boundary conditions which will form a base for further research:

Target Population : Housing for Middle Class

Based on Affordability and most needed population in the need of housing today (Please note that the Change in Target Population will also Change the scope and design of the research). Use of technology in this project is advanced and would come with a price. Thus, it is important that the technology should be affordable for people using it.

Use of Bamboo as indigenous material for construction: The context feasibility will be based on areas where Bamboo is locally available and can be locally sourced within limited distance, thus minimizing the transport of raw materials. So that the Transportation costs of components will be low, reducing the cost of the house.

Material efficiency: Based on Prefabrication of components: It Is assumed that the prefabrication will be done at a small scale local production unit. Transportation cost will be low resulting in cheaper cost and availability for the mass. Development of such a prefabricated system; a technology accessible and feasible for maximum number of population-

Environmental consciousness : The housing will be most suitable for countries with strict use of green building material and energy efficiency laws.

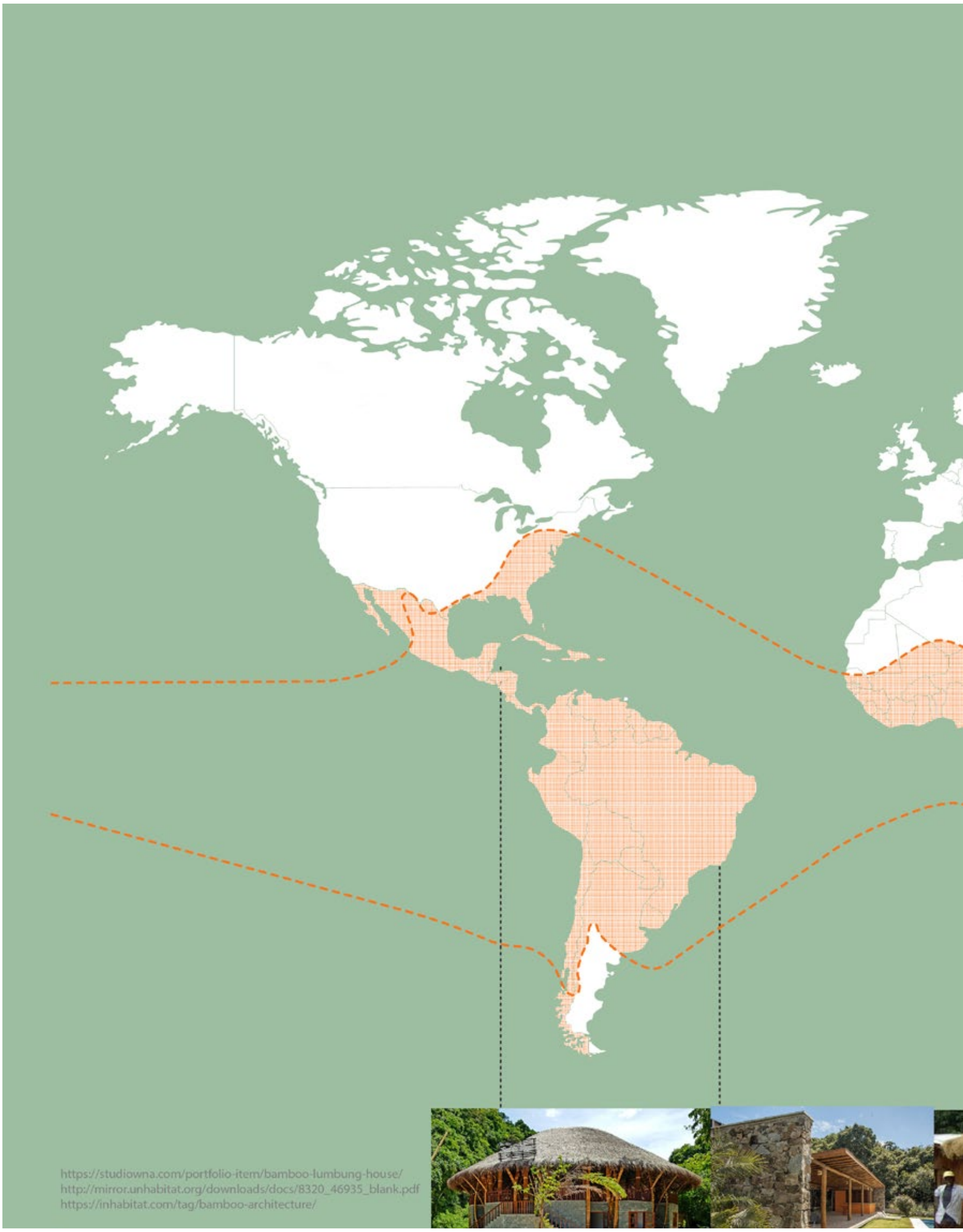


Figure 6 : Bamboo gro

wing areas across the Globe

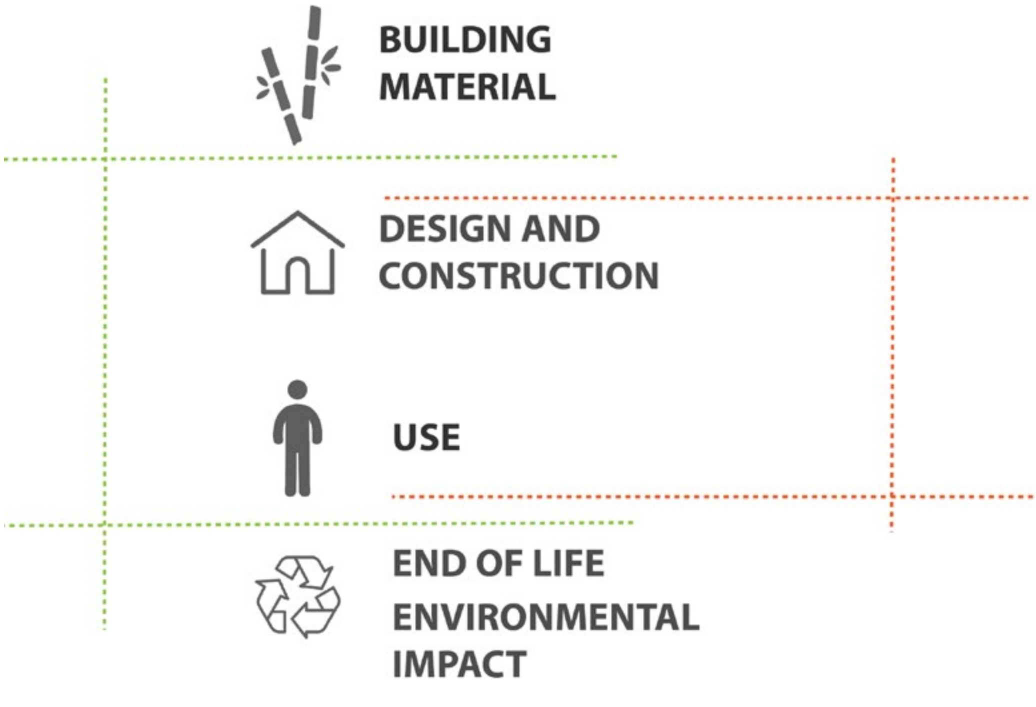


Figure 7 : Evaluation On possibilities using bamboo

03 BAMBOO

03 BAMBOO

3.1 BAMBOO : CREDITS

As one of the fastest growing plants in the word, bamboo is one of the key solutions to enable the transition towards a bio based economy. Today, sustainable materials can be briefly defined as materials which reduce dependency on fossil materials. Bamboo is a sustainable, natural source of material which is widely available almost on all continents except Europe. It is an incredibly rapid growing material and matures within a few years. If used in the right way benefits of using bamboo are enormous:

Availability: Bamboo is a rapid growing plant. During the growing season the bamboo shoots will sprout from the ground and reach their final length up to 30m height within a couple of months, with a maximum recorded spread of 1 meter a day. The growth rate of bamboo versus wood can be seen In Figure 9

Low processing required : even the engineered bamboo forms use 60 to 80% of the natural materials, making low processing criteria's for production of the material.

Strength: It is light weight and high in tensile strength as shown in figure 8

Light weight : Light weight of Bamboo is an advantage in terms of construction machinery required during installation, and also in terms of transportation .

Durability : If treated right , and especially after thermal modification of the properties of bamboo , the modified material can be very durable compared to the natural material.

Economic: The material can prove to be a highly economical solution when sourced locally, reducing a lot of transport cost.

Downcycling: As a nontoxic material Bamboo offers no issues, can be easily downcycled to various form like chip board etc

Environmental impact: Bamboo has a very low or negative carbon footprint even after considering the environmental damages caused due its transport and production process. It is highly sustainable due to its capacity of capturing co_2 from the environment . The Footprint is low even after a complete life cycle from production to use for more advanced forms.

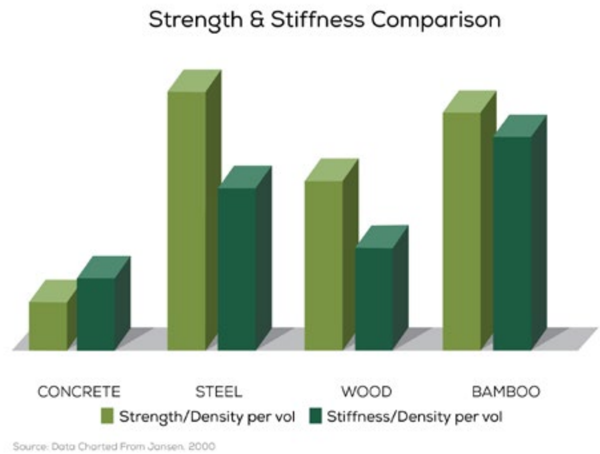


Figure 8 : Graph showing strength vs stiffness of Bamboo

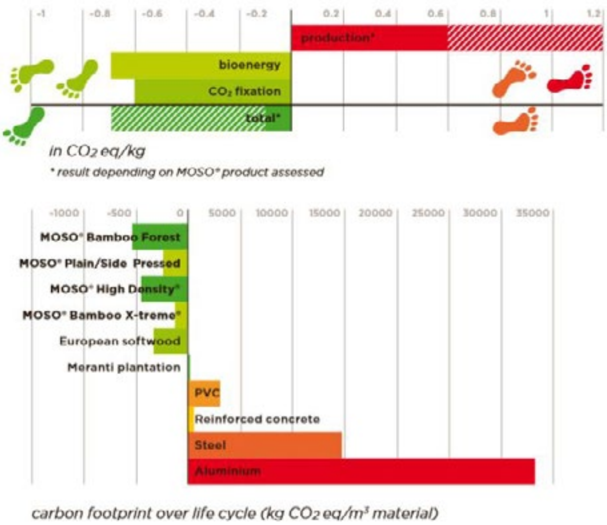


Figure 9 :Carbon foot print assessment.("MOSO International," n.d.)

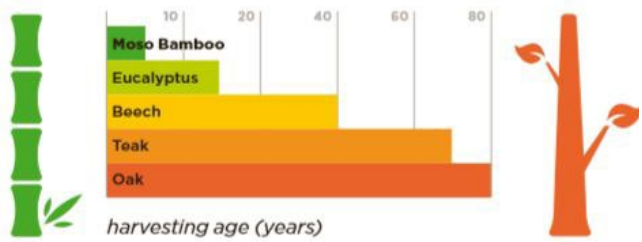


Figure 10 : Comparative chart of harvesting age of wood vs bamboo.("MOSO International," n.d.)

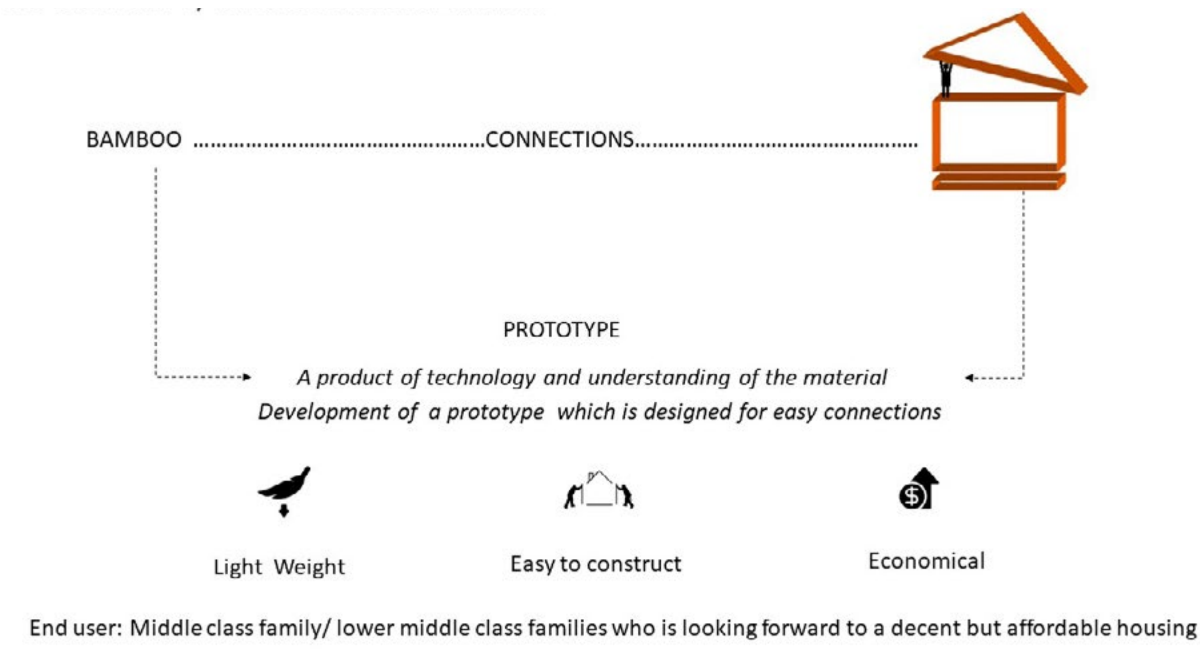


Figure 13:Overview of the research and methodology

04 RESEARCH DEFINATION

04 REASERCH DEFINITION

4.1 PROBLEM STATEMENT:

BAMBOO: DEBITS

Bamboo is a fast-growing, abundantly and locally available resource. It is available almost on every continent except Europe but is often seen used in construction in European nations. Traditionally, often in developing countries, the houses of poor have been seen built-in Bamboo. The reason being its local availability and it being cheap. *In the developing countries mostly in rural areas millions of people still live in bamboo houses.* But it has been observed that as soon as rural people have access to wood or other materials, they change to them because these houses are often built with a natural form of bamboo (using very low-tech methods).

Figure 11.Tradtional bamboo house found in India.

"Poor treatment and low construction techniques result in very low durability and performance of the material (temporary houses)."

With this poor performance and improper use of the material, some social factors are often put forward as the cause for shift in this attitude of changing to a more permanent shelter, among which is the fact that other materials give a sort of status to their user, while bamboo emphasizes their position as **poor members of the society.** (IR.O.A.ARCE-VILLALOBOS)

"The way the houses are built using in Bamboo needs to be rethought."

Research (anonymous) states that the building sector consumes the highest percentage of global resources in terms of manufacturing, disposal, and transportation. In acknowledgment of these issues and with increasing demand for sustainable material natural *resources* like wood *is becoming more and more scarce*, **Bamboo**, on the other hand unlike wood is a **highly renewable natural resource.** Although wood is also a natural resource, it is available in limited supply and the use also increases deforestation.

With growing interest and need for sustainability, there has been a lot of focus on the material used in the construction industry. The building construction sector consumes a very high amount of energy in the manufacturing of the material or executing these materials in the form of building.

"Today's need for a strong and Durable, SUSTAINABLE construction material."

In natural form each of the bamboo poles, even for the same species varies in size thickness and strength. Natural properties are quite comparable to those of wood, however the original geometrical shape of bamboo culms makes it difficult to be used in modern construction. (R.shreshtha & crews, 2014) The unevenness results in increased structural risk and needs experience and intuitions in construction, ultimately increasing the time and use of the material is excessive. Additionally, there are many factors which needs to be considered while dealing with the material in natural form like - not two bamboo poles are same, the shape of the bamboo makes it difficult to connect and often requires expert craftsmanship. The unevenness results in increased structural risk and needs experience and intuitions in construction, ultimately increasing the time and use of the material is excessive.

Figure 12: Connections Using natural form of Bamboo.

"The natural form is not the most effective and durable for structural purposes".

"Not enough research on the use of advanced bamboo for structural use."

With all these issues there has been a lot of research going on around the world towards the development of advanced engineered bamboo products. The technology works on altering the properties of bamboo to more durable and stable form. These products are quite new and are still not completely used in the construction industry. Thus, there are very few researches available on their use for structural purposes and it is important to evaluate these materials based on their structural properties and usability.

4.2 RESEARCH OBJECTIVE:

Having established the problem statement, the research objective can be described through some main points which are explained below:

Develop a more permanent, sustainable and durable housing solution.

Evaluate properties of advanced forms of bamboo and choose the right method and form of engineered bamboo in order to make to further process easier.

Check the structural feasibility of using the engineered form to build a G+1 structure from bamboo.

Develop a prefabricated approach of construction of a housing prototype which can be adapted globally.

Develop a set of connections that facilitates a prefabricated approach to building a G+1 structure (house).

Evaluate and Explore the structural capacity of the connections using an engineered form of bamboo.

Check the feasibility by Prototype and Testing the durability, and strength of the connections.

4.3 ASSUMPTION:

The properties of the engineered form of bamboo are assumed based on the data available from the literature and on the samples sourced from MOSO Bamboo. Assumptions are made on reliability and availability of equipment's to build the house.

4.4 METHODOLOGY:

The final aim of the research is to develop efficient connections using the engineered form of bamboo which would also facilitate prefabricated construction process in terms of production and buildability (for e.g. using standard premanufactured forms for components).

The assignment can be divided into three categories, which are interlinked to each other. The design proposal will be based on the analysis of the results of these categories.

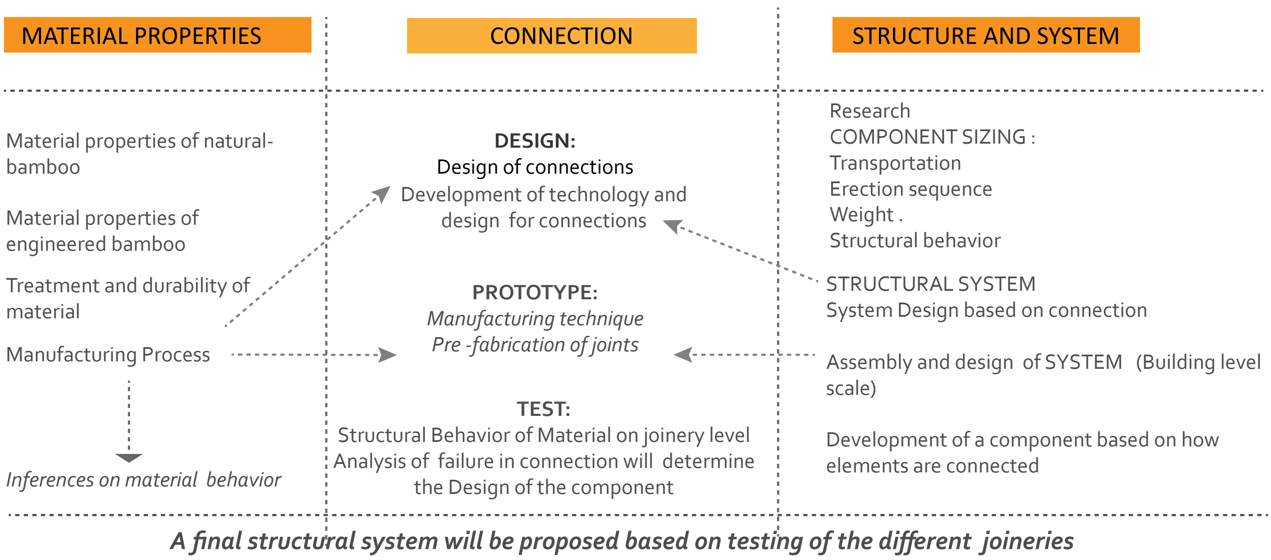


Figure 14:Description of the Methodology.

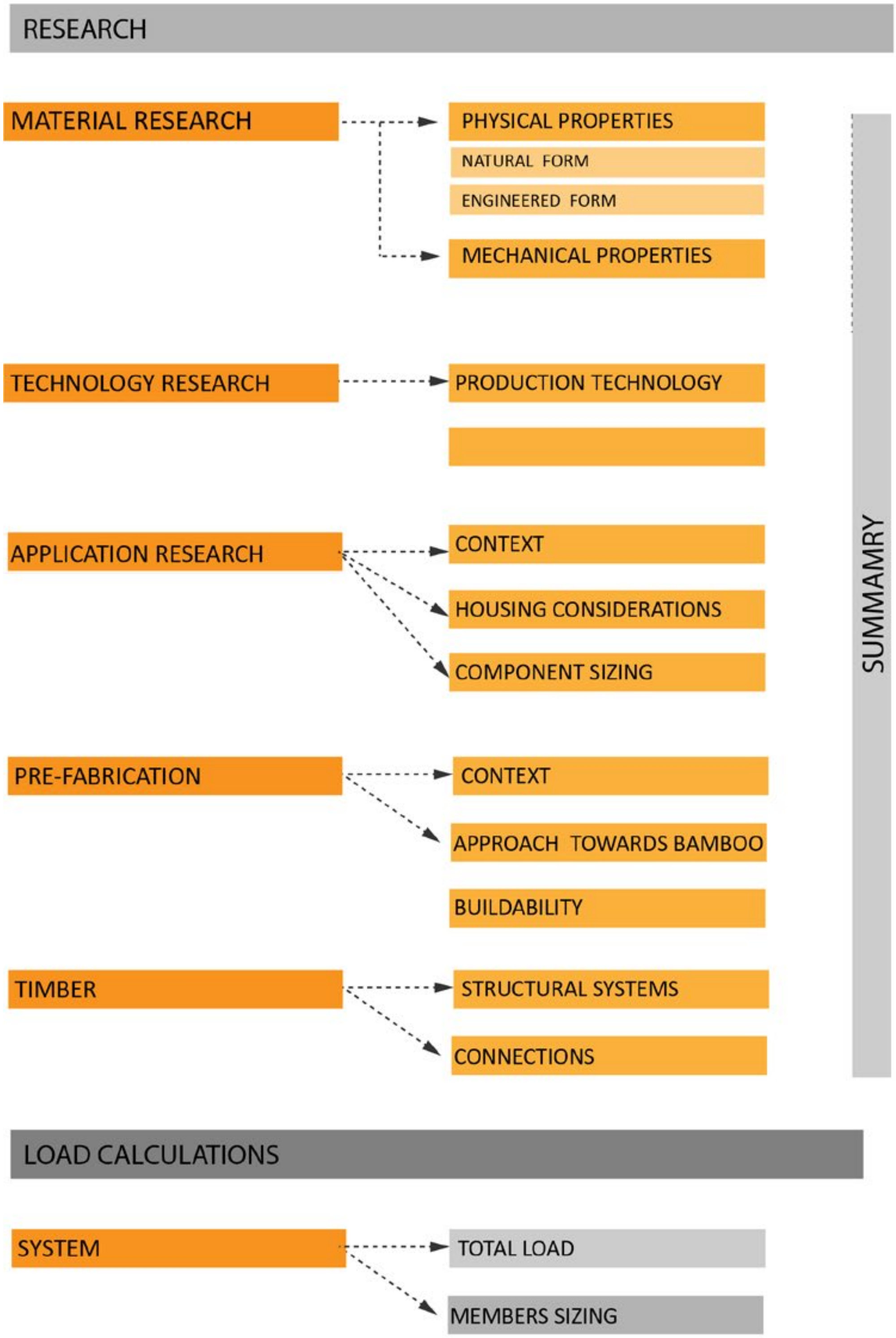


Figure 15: Flow diagram showing research methodology

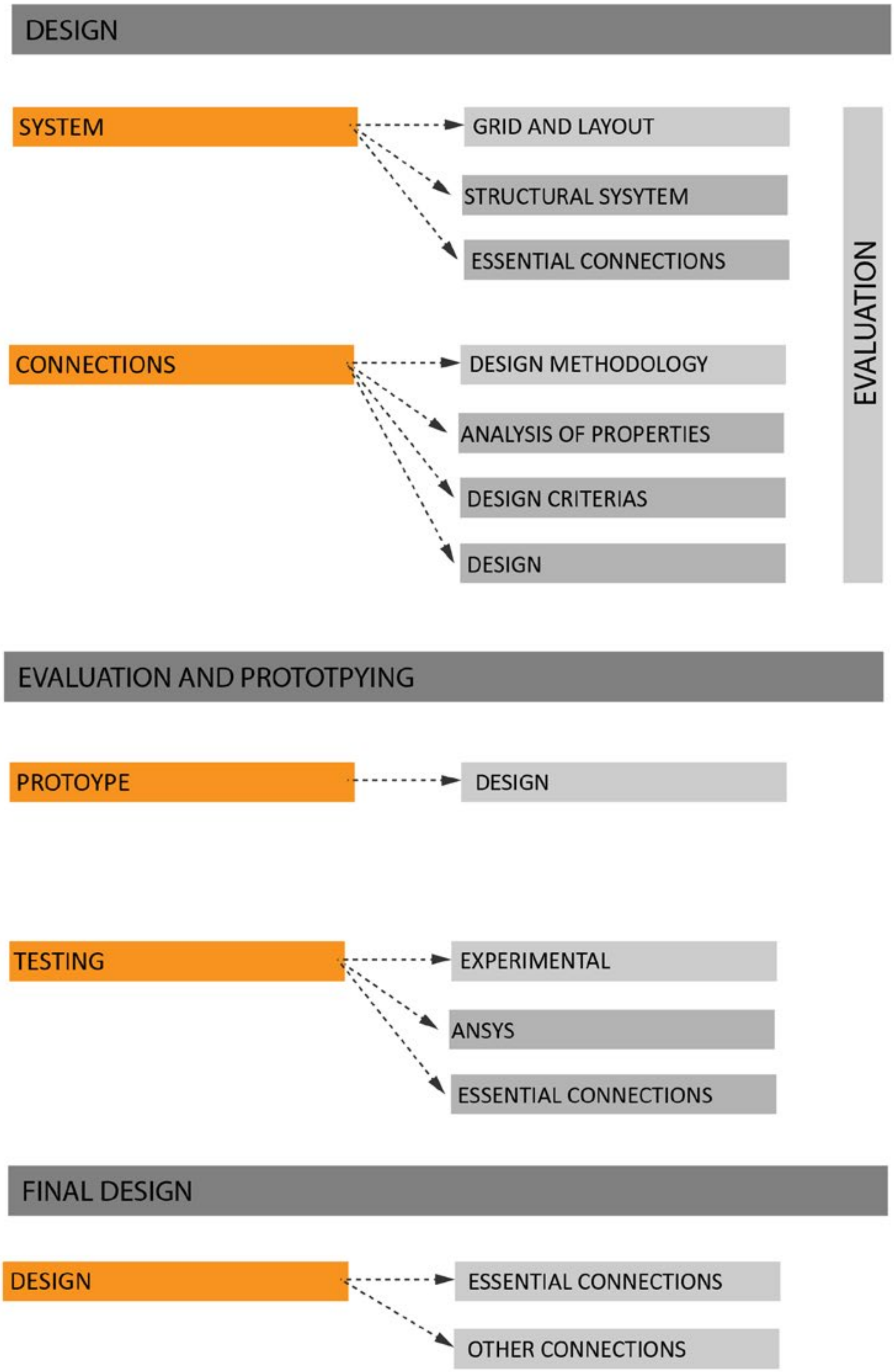


Figure 15.1: Flow diagram showing research methodology

4.5 RESEARCH QUESTION:

Having introduced the problem statement and research objective, the research question can be formulated. Based on the level of technicality the research questions can be divided in:

GLOBAL RESEARCH QUESTION:

Introduce a system backed up by a technique which will help ease the process of construction using bamboo and eliminate the limitations posed because of a lack of technical data and construction knowledge. Additionally, will help change the perception of the material from poor man's timber to a more technologically advanced material which is durable, lightweight and easy to construct and would not require expert craftsmanship.

In what way can we devise a system or an approach for use of an advanced form of bamboo in structural use to build a more permanent and durable global standard housing unit.

TECHNICAL/DESIGN RESEARCH QUESTION:

Based on the above considerations a technical research question is concerned to provide a scientific-technological solution on uses of an advanced form of bamboo in connections - to make it more durable and easy to build. Develop a method for connections through design, prototyping, and prefabrication techniques which can be replicated or adapted for other structural purposes.

"Is it possible to develop efficient, durable and structural connection system which use engineered form of bamboo for constructions for standard housing unit"

Some of the objectives are: Explore the structural capacity/feasibility of prefabricated engineered bamboo connections for the construction of a G+1 structure/house.

SUB RESEARCH QUESTIONS:

The main research is answered by various sub research questions.

What are extents of design considerations for a house?

Understanding prefabricated approach of construction and its relevance?

Exploring timber structural system and Japanese joinery connections and evaluating its relevance for connection in bamboo?

Establishing the type of system feasible for construction using bamboo?

What are the connections required to build the prefabricated structure using the above system?

Explore the properties of the material in natural and engineered form, for better understanding of physical properties during designing?

What kind of assembly/Prefabrication method needs to be adapted.

What methods suits the best in order to develop the connections?

Evaluate Feasibility in terms of strength of the connection?

How can the joinery be cast in order to develop the connections?

4.6 RELEVANCE:

Considering the history of bamboo availability and its temporary use in the construction, it is important to provide solution for construction using this material, which is easy to manufacture and are advanced eliminating the uses of expertise. The more advanced the technology of using the material the more it is accepted globally.

4.7 LIMITATION AND SCOPE:

The idea of the research is mainly to evaluate the feasibility of the use of an advanced form of Bamboo. Bamboo is available almost on all continents and thus this research intends to benefit any designer who wants to explore use of bamboo for structural purpose. Thus, as a Boundary condition all the design considerations are based on the global System. The intention is that the system should be easy to adapt or alter as per the purpose and requirement. For example, The species of Bamboo are not taken into consideration in this research. The type of bamboo used in fabrication will be based on local availability. The system will be evaluated for extreme climatic conditions and needs to be adapted for all the climate zone lesser than extreme. Any change in any of the parameters assumed would require reevaluation and calculations.

04 LITERATURE REVIEW

UNDERSTANDING OF MATERIAL PROPERTIES OF BAMBOO AND TIMBER

05 LITERATURE REVIEW:

5.1 BAMBOO IN GENERAL: NATURAL FORM

5.1.1 THE DISTRIBUTION OF BAMBOO PLANTS:

There are more than 1200 species of 50 genera of *Bambusoifead* in the world, mainly distributed in tropical and subtropical areas. China is one of the centers of the bamboo growth possessing about 400 species. There are a few indigenous bamboo species in North America, there are not naturally distributed plants in Europe. In recent years there has been a lot of research on introduction of bamboo plants in these continents.(Zhang Qisheng, Jiang Shenxue, 2001)

5.1.2 BAMBOO IN NATURAL FORM: ANATOMY:

Bamboo is an anisotropic material, having mechanical properties that vary in the longitudinal, radial and transverse directions.(Sharma, Gatóo, Bock, & Ramage, 2015)[1] The raw bamboo is a giant grass consisting of a hollow culm having longitudinal fibres aligned within a lignin matrix, divided by nodes (solid diaphragms) along the Culm length (Sharma, Gatóo, et al., 2015).

Following is the detailed description of anatomy of Bamboo shown in figure 16

***Culm**:*

Referring to the stem of the plant, bamboo has a varying cross-section across the length with a larger diameter in the bottom decreasing all the way to the top. The composition of the bamboo culm includes longitudinal fibres, aligned in the vertical direction of the bamboo, within a lignin matrix. (Bamboo, state of art). This anatomy turns the bottom piece of the plant into the most suitable *part for construction purposes.*

Nodes:

Nodes can be defined as a Diaphragm that divides the culm into internodes. They are characterized by a larger diameter than the internodes and provide additional strength and stability to the plant.

Internodes:

Are defined as the portion of the culm between two nodes. Bamboo culms are hollow tube comprising of a three layers: bamboo skin, bamboo timber and pith.

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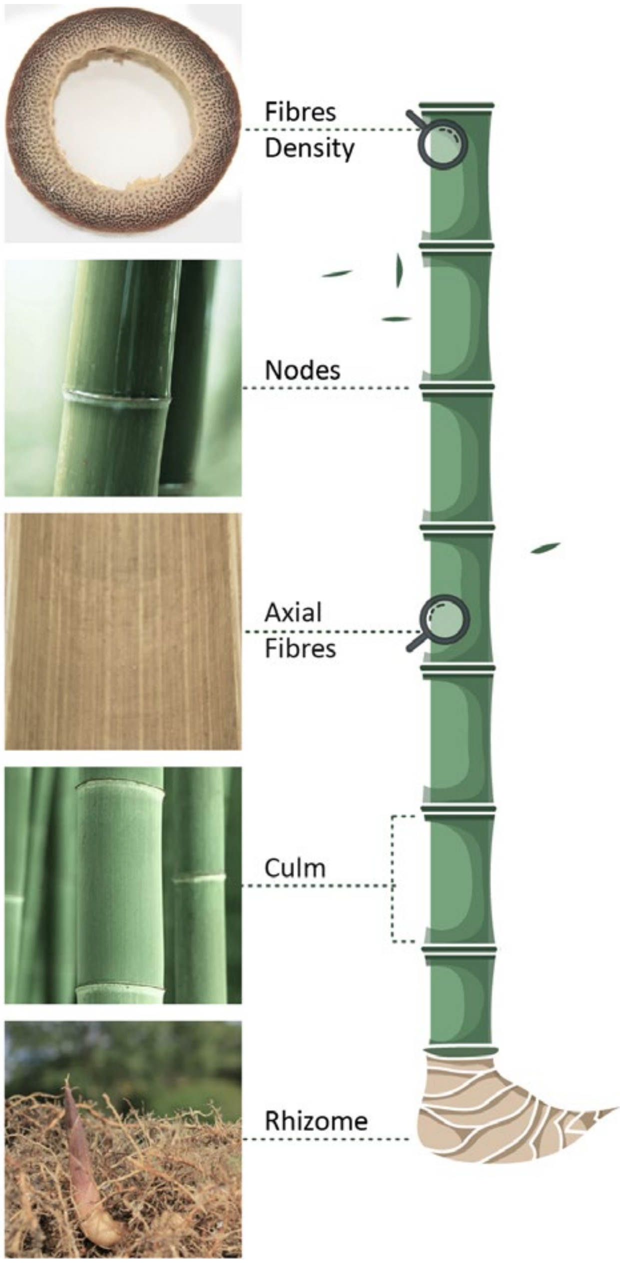


Figure 16: Anatomy of bamboo

Cross sectional data :

Bamboo skin is the outermost part of the cross section of stem wall which has no vascular bundles. Pith forms the inner part stem wall next to bamboo cavity and does not contain vascular bundles. Within the internode, the cellulose fibres are aligned parallel to the direction of the culm giving it increased strength in that direction. Lignin serves as the bond between fibres and gives the plants resistance in the transversal direction of the culm, however, it has a soft and brittle behavior. The vascular bundles lie within the skin and the pith. The vascular bundles decreases from outer region of cross section towards inner.

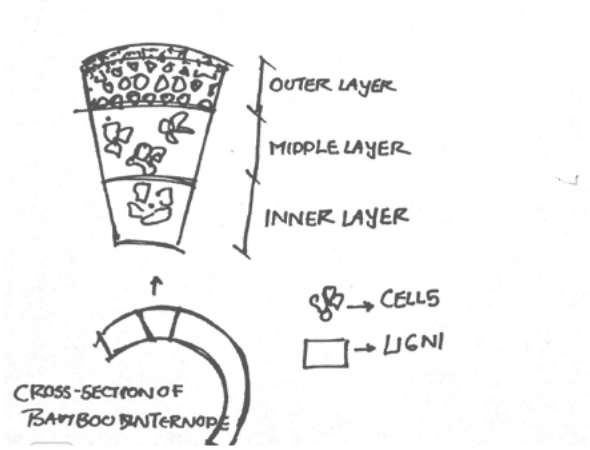


Figure 17: Density along the cross section of the bamboo culm

Fibre density:

Unlike wood, fibers in bamboo vary from the inner side of the culm to the outer side, being higher on the external wall giving the material an intrinsic structural behavior. The strength of the culm displays maximum strength on exterior and reduces toward inner core. (Sharma, Gatoo, Bock, Mulligan, & Ramage, 2015)

Average density (green bamboo volume) ranges from 0.40-0.80 g/cm³ depending on vascular bundles and their composition. As a rule density increases from the inside towards the outside of the culm wall at the internode and dense fibres display higher mechanical properties. (Zhang Qisheng, Jiang Shenxue, 2001)

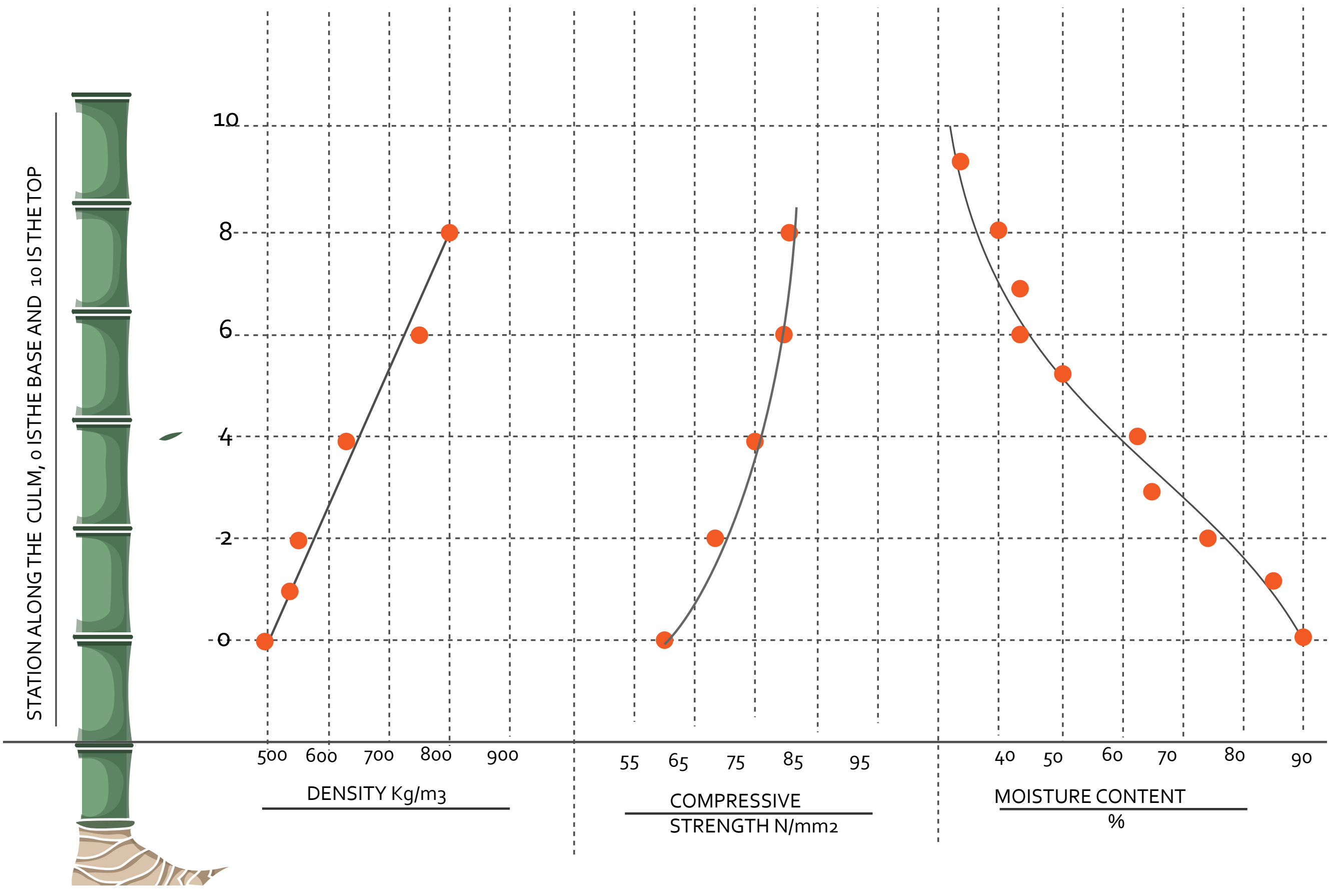
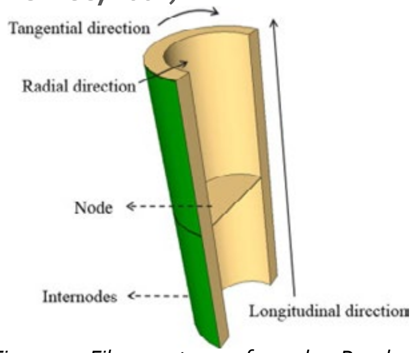


Figure 18:Graph showing Variation of compressive strength, density, Moisture content along the Culm. Retrieved from (Trujillo & López, 2016)

5.1.3 STRENGTH AND MECHANICAL PROPERTIES OF BAMBOO:

As discussed above in chapter 2.2.3, due to unidirectional fiber placement, bamboo behaves like an Anisotropic Material. The most important difference in the direction of microbial fibres of outermost layers of wood and bamboo are as follows**:**

Bamboo microbial fibres is vertical and wood microbial fibre is horizontal and spiral (Zhang Qisheng, Jiang Shenxue, 2001)



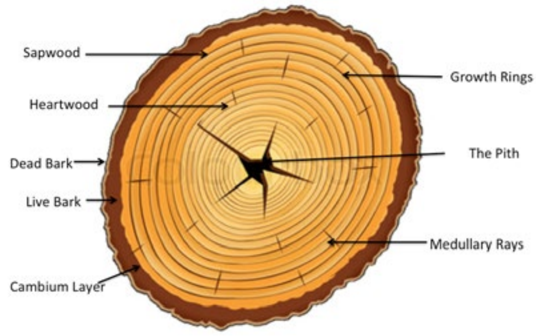


Figure 19: Fiber anatomy of wood vs Bamboo.

Being a natural material the strength of Bamboo is affected by various external and internal factors, some the important factors are listed below. According to the book (Arce-Villalobos, 2002) the strength of the Bamboo depends on various factors like:

Growing condition:

The growing condition of the Grass as stated by (Soeprayitno et al 1998) in (Arce-Villalobos, 2002) where an analysis was carried out of the physical and mechanical features for Species *Gigantochloa pseudoarundinacea* from two different localities and it was concluded that the strength of the Bamboo can vary with change in terrain.

Testing conditions:

The strength can vary based on whether the Bamboo is tested in Green conditions or dry condition, the age of the Culm, the height at which the Culm is used (the lower part of the culm has a different tensile strength compared to the upper part of the culm).

Moisture content:

The average moisture content of bamboo stem at cutting age is approximately 80%. The moisture content of the material after air seasoning changes to approximately 15.7%. The strength of bamboo increases with the decrease in moisture contents. As shown in Fig ___ when bamboo was tested in green versus in air dry conditions, there was an increase in compressive strength, tensile strength, elastic modulus, and modulus of rupture (MOR) by 37.6, 19.4, 48.2, and 47.7%, respectively. (Trujillo & Lopez, 2016)

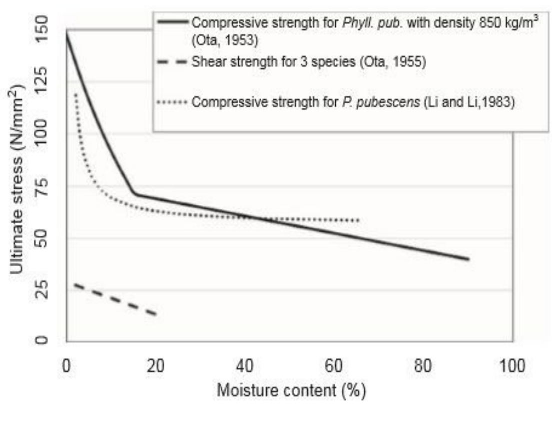


Figure 20:Effect of moisture content on strength, (Trujillo & Lopez, 2016)

In a similar manner as timber, the strength of bamboo is affected by the moisture content of the specimen (Trujillo & Lopez, 2016)

5.1.4 MECHANICAL PROPERTIES OF NATURAL BAMBOO

Tensile Strength of Bamboo:

There is a very strong relationship between density and the strength of the bamboo.

As shown in figure 21 .a .The density of stem wall increases from lower part to upper part consequently, the strength also improves in the same direction. As a kind of engineering structural material strength of bamboo mainly depends upon the mass of its cell walls, indicated by its basic density. Similarly, across the Cross-section of the culm in Radial direction the maximum tensile strength is seen on the outer layer and decreases towards the inner layer (Arce-Villalobos, 2002).

Tension Capacity	Average	270 N/mm^2
Youngs Modulus	In X-direction (Perpendicular to the Fibres)	2000
	In Y-direction (Parallel to the Fibres)	14000

Table 1: Average tensile strength of a bamboo pole.

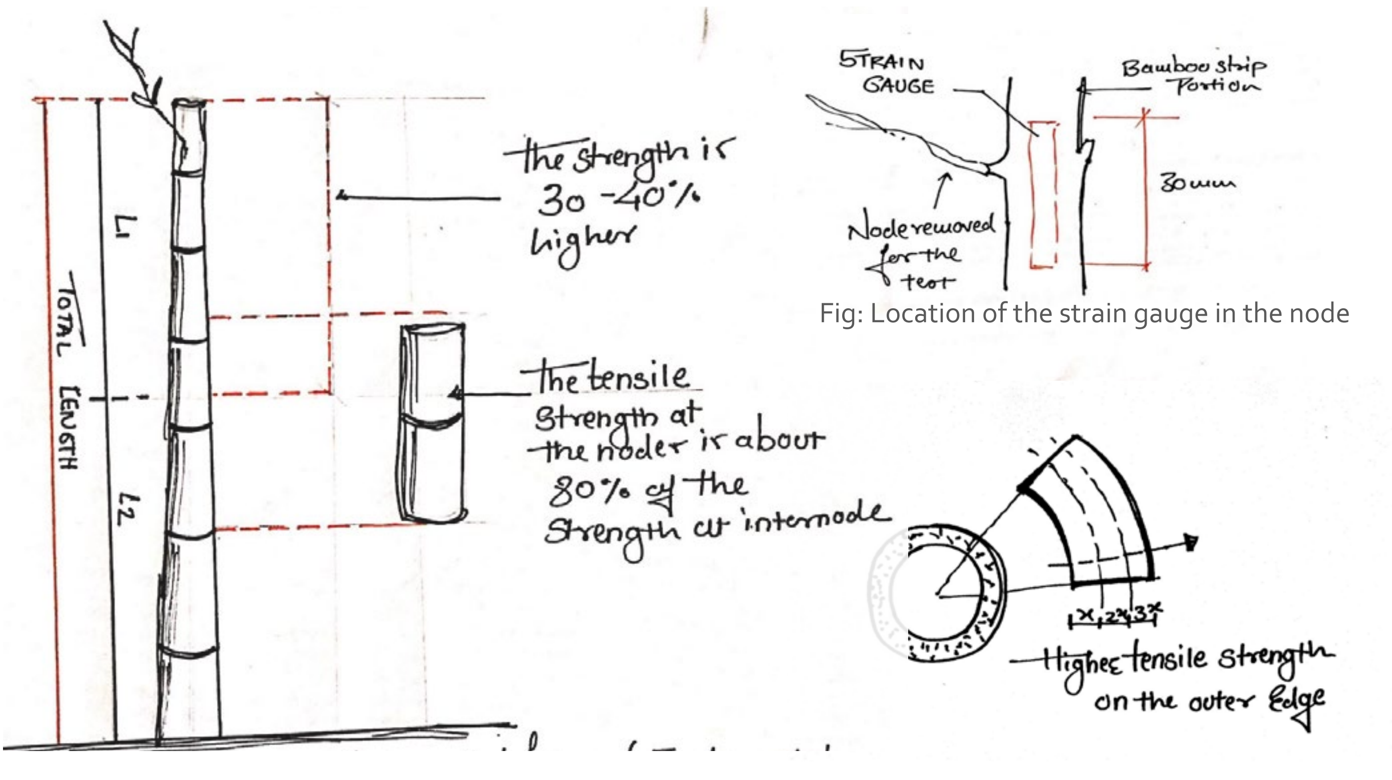


Figure 21: a. Showing tensile strength along the length of the culm. b. tensile strain gauge near the Node .c. Tensile strength along he culm cross section.

Bamboo has a higher tensile strength than compressive strength. There is a strong correlation between tension strength and density. As presented in (Arce-Villalobos, 2002), nodes are the weakest and the softest components of the culm. Average capacity is only about 30% of that of the internode, and the average elastic modulus is only 40%. Since they are the weakest link, their properties are of paramount importance in the definition of design capacities. Their influence in the elasticity of the members becomes very important as well. Tensile Strength varies from the inner layer to outer layer: 100-335 N/mm^2 outer layer, 150 -160 N/mm^2 for inner layer.

The capacity of the strips from the internode is very high - 270 N/mm². **The elastic modulus in tangential direction is 1/8 of elasticity in the longitudinal direction.**

Compressive strength:

A usual type of failure while testing compression strength of Bamboo is set of vertical cracks which open wider and wider with an increment of the load as reported in Meyer and Eklund (1923). The Youngs Modulus is much higher for the bottom position of nodes and position along the culm from the middle to top as per Limaye(1952). The conclusion from Author based on a very extensive literature review and a comprehensive set of test is that:

The moisture content plays a significant role. Presence of a node in the specimen doesn't not seem to affect the strength. The samples were tested with 15% - 18% moisture content and loading speed was set about 1.5 N/mm². Thenode and the internode do not play a significant role. Bamboo's compressive strength is proportional to the fiber density of the culm.

Compression Capacity	Average	60- 176 N/mm²
	In X-direction(Perpendicular to the Fibres)	

Table 2: Average Compressive strength of a bamboo pole.

Shear strength:

Lengthwise strength of bamboo is high and crosswise is low. The main reason why bamboo can be split easily.

Modulus of elasticity:

The variation to the modulus of elasticity is quite significant for green bamboo but relatively small for dry bamboo in comparison. The elastic modulus in tangential direction is about 1/8th elasticity modulus in tangential direction. (Arce-Villalobos, 2002).

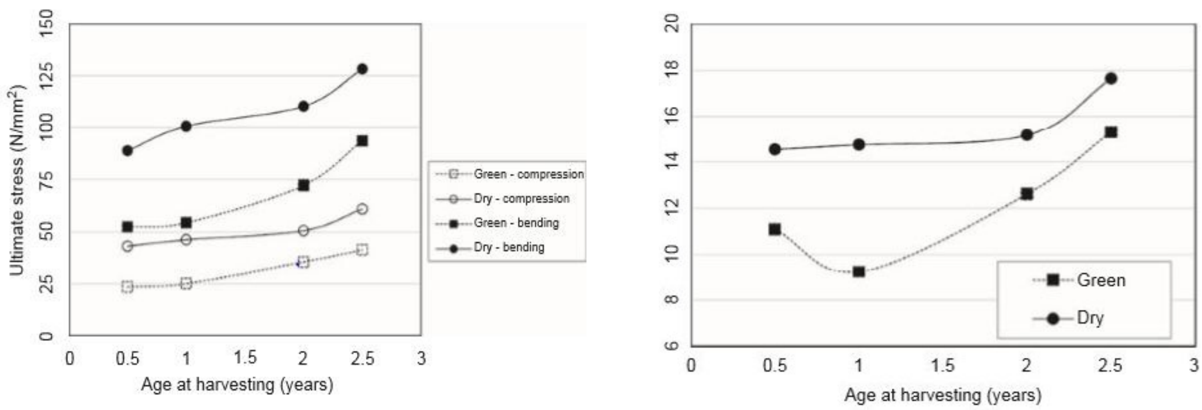


Figure 22: Effect of age on modulus of elasticity for Dendrocalamus strictus in green and dry condition, Limaye (1952) as cited in (Trujillo & Lopez, 2016).

	Guadua.s.p *N/mm²*	*Gigantochloa scrotechinii*	*Test on three years old*	*Phyllostachys pubescens*	Steel Kg/cm³
Average strength	2.608	2.445			
E modulus	2122.8	2444.7	1000-3000 kg/m³		
Maximum strain	0.001386	0.00111			
Average density	795.7	788.68			
Tensile strength			1000-4000		
Tensile strength parallel to the grain				2118	1805
Bending strength			700-3000	510	711
Compression strength			250-1000	149	153
Shearing strength parallel to the grain				1348	1544

Table 3: Table showing mechanical strength of Bmaboo pole. Compiled from different articles and papers (IR.O.A.ARCE-VILLALOBOS) (Bamboo people and the environment.vol 3, 1995)

Referring to table 3 the data about mechanical feature of *Phyllostachys pubescens* indicates that the pull resistance parallel to grain of about 10 %. The density of bamboo is only about 1/6th - 1/8th of the steel's Density, but its compression strength parallel to grain is 1/5th to ¼th of steel and the shearing strength parallel to the grain is ½ of the steel, therefore we can say bamboo is a material of high strength and low weight.

Summary of general properties and specific features of bamboo:

Here's a summary of important structural and mechanical properties of bamboo which are of primary importance while testing

DIRECTION OF FIBRE NOT LIKE WOOD:

Bamboo similar to wood is a kind of heterogeneous and anisotropic material and therefore the physio-mechanical properties are extremely unstable, in certain respects it is more unstable than wood. (Zhang Qisheng, Jiang Shenxue, 2001)

The most important difference between wood and bamboo is the direction of microfibril of the outermost layer of wood horizontal and spiral and that of bamboo is Vertical. *As a result of the above-mentioned features all the highly efficient method and equipment of woodworking cannot be applied to bamboo processing and usage directly.*

RELATION BETWEEN STREGNTH AND DENSITY:

The Strength of the Bamboo mainly depends on the mass of the cell wall, indicated by basic density.

MOISTURE CONTENT:

The moisture content in Bamboo plays an important role in the strength of the bamboo.

The tensile capacity of the node and internode differ. Samples tested without internode show higher strength.

5.2 BAMBOO IN GENERAL : ENGINEERED BAMBOO:

5.2.1 INTRODUCTION

As discussed above, Bamboo in its natural form displays high potential as a construction material in terms of strength, however, when it comes to buildability, it is difficult to use due to its round cross-section. Within the idea to simplify and enhance the structural quality of bamboo, the concept of engineered bamboo has emerged. In recent years there has been a lot of research and development in engineering Bamboo, The new form considers the limitations of using bamboo in its natural form. The research is inspired from woodworking industry, with professionals researching and manufacturing of bamboo-based components for exterior use. Also known as an engineered form of bamboo these components can be defined as -

"Engineered bamboo which refers to any modification made on natural bamboo to increase its durability and mechanical properties for flexibility of its use. The engineered bamboo process produces uniform composite bamboo sections from raw bamboo culms by fixing the units together with plastics, adhesives or thermal compression".

Figure 23: Types of Engineered bamboo("MOSO BAMBOO," n.d.)

Why engineered form of bamboo over natural bamboo ?

The concept of Engineered Bamboo has developed from removing and engineering longitudinal Splits strands and Fibres from a Bamboo Culm, which allows higher quality control in terms of physical and mechanical properties compared to the raw bamboo culm. Some of the most common forms available today are Glued Laminated Bamboo, Strand Woven Bamboo, Bamboo Scrimber. Details description of each of these are explained below in chapter 2.3.3. The engineered bamboo component compared to raw bamboo and other products in the market demonstrate specific features like :

The process allows the production of standard sections with more uniform properties *(Sharma, Gatoo, Bock, Mulligan, & Ramage, 2014)*.

Standardization in dimensions and size with a very small deformation.

Strength: High strength and rigidity, high wear resistance.

Increased Durability: Resistance against insects and rot.

A very high quality control is possible.

5.2.2 TYPES OF ENGINEERED BAMBOO:

Based on the research and development in recent years, there is a lot of focus on developing and improving the current forms of engineered Bamboo. The diagram in figure 24 below shows the available products in the market today. Considering the scope and limitations of this research, the most relevant types are studied in detail. Engineered Bamboo can be briefly divided into following types based on the process carried out on them.

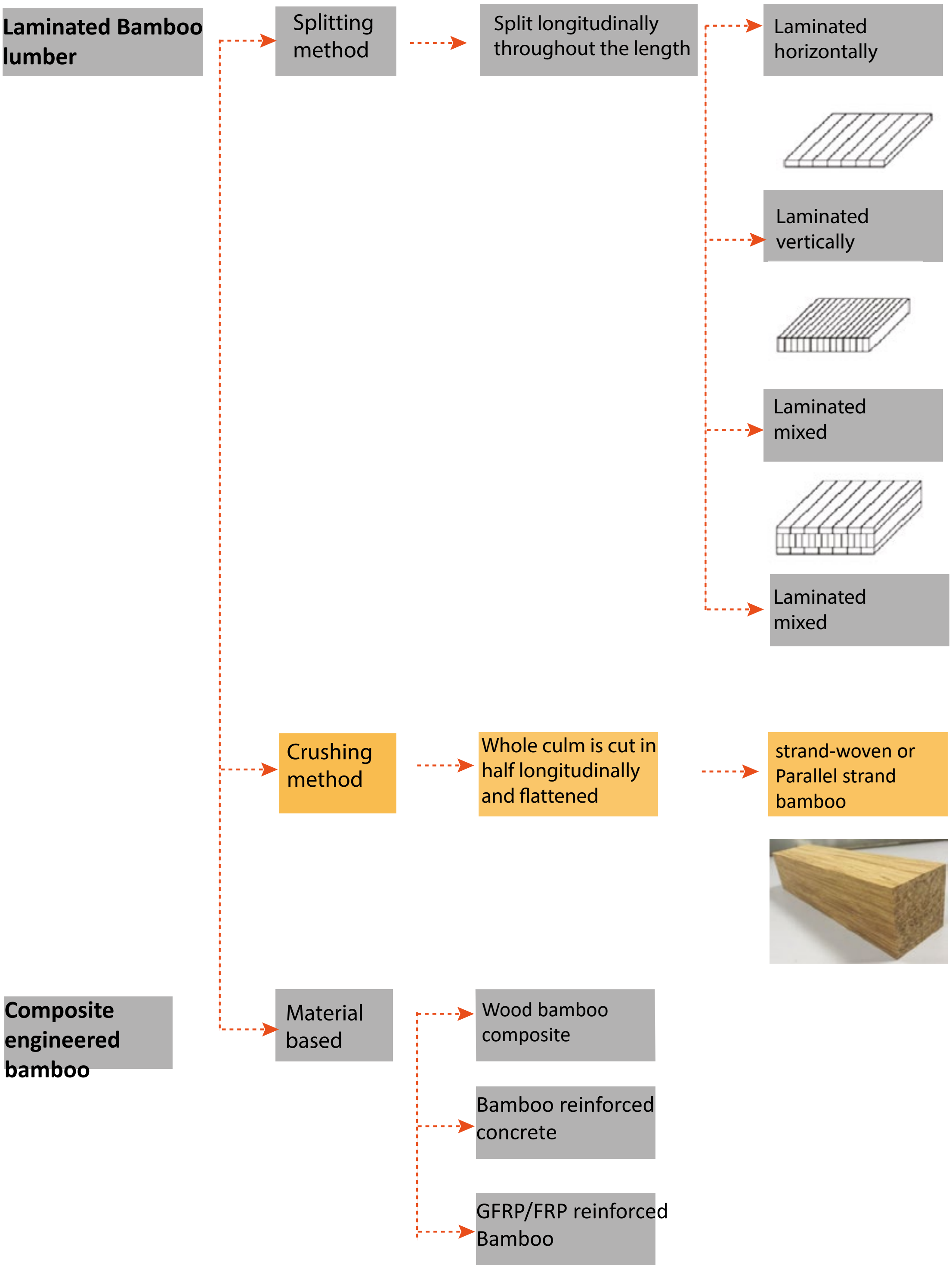


Figure 24: Types of Engineered bamboo

LAMINATED BAMBOO:

Laminated bamboo lumber is a relatively new concept that involves gluing together bamboo material in various forms (e.g., strands or mats) to form rectangular boards, similar to lumber. Based on the method of processing the laminated types can be classified into:

Strip Laminated bamboo:

Strip Laminated bamboo consists of bamboo strips which are compressed from the side and top of cross-laminated to form composites. The nodes in laminated bamboo products are clearly visible and the strength and flexibility of the product are not affected. The strips are glued and compressed against each other using special adhesives. (Sharma, Gatoo, et al., 2015) The bamboo culm is split, planed, processed (bleached or caramelized), laminated and pressed to form the board product. The orientation of the strip within the board, and therefore the direction of the radial fibre density, is randomly placed within the board. The final product uses only approximately 30% of raw material input due to large losses of material when the strips are planed to form the rectangular section. (Sharma, Gatóo, et al., 2015)

Laminated bamboo maintains both the longitudinal fibres as well as a portion of the original culm matrix.

Figure 25: Strip laminated bamboo beam("eco friendly," n.d.)

The strips can be arranged in multiple ways and the strength of the final product also varies depending on the arrangement of the strips. Types of arrangement for manufacturing of laminated bamboo lumber using strips can be seen in the figure----.

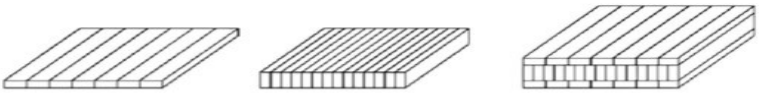


Figure 26:Strip laminated bamboo types beam(Rittironk and Elnieiri 2007; reprinted @ (Mahadavi, Clouston, ASCE, & Arwade, July, 2011)

This type of bamboo composite is of Prime focus in the thesis as it allows more versatility and strength in terms of Design and construction . Also known as strand woven bamboo, consists of raw bamboo strands saturated in resin and compressed under high pressure to form a new composite material in the form of a block, rectangular prism or panel sheet. Scrimber is manufactured by compression of the fibre bundles into a beam section. Although the fibre direction is maintained, the gradation is not maintained with the bundles crushed to form the section. When compressed it is important to maintain a continuous length of the fibre.

The strand laminated bamboo process is materially efficient, utilizing approximately 80% of the raw inputs and produces a product with a hardness that is acceptable for external applications.

Figure 27: Strand laminated bamboo beam("eco friendly," n.d.)

The density strand of woven Bamboo is higher than strip laminated bamboo beam. The process maintains the longitudinal direction of the fibres and utilizes resin materials to connect the fibres together (Sharma, Gatóo, et al., 2015) The bamboo scrimber are produced commercially using MOSO bamboo (Phyllostachys pubescens) along with phenol-formaldehyde resin, and the thermal treatment using saturated steam (SST) is also employed during the fabrication process. (Kumar et al., 2016).

Composite Engineered Bamboo: CLB

Consists of consecutive layers of bamboo alternating at 0 or 90 degrees forming a single monolithic element joined together by special adhesives. This product is currently developed at MOSO bamboo.

GFRP reinforced/ FRP reinforced composites:

For the above engineered products the processing techniques are similar to some extent, what makes them different is the heat/cold treatment and the quality of production.

5.2.3 PROCESSING PROPERTIES:

It is important to understand the current processing techniques used for making the engineered bamboo components as it provides information about the usability of the material and also on analysis of behavior of the material under different process carried out. The way the bamboo is processed may affect the strength and the behavior of the final product. Below is a general explanation of the procedure followed in each of the processing techniques. There are various methods involved while developing the final product and some of the processes alter the properties of the material.

Selection of raw bamboo: The most important step of selection of material as any defects may results in inconsistency in the strength of the final product. An advantage of the engineered bamboo product is that the varying properties of individual bamboo culms are eliminated and do not affect the final product by a large difference.(““How-Is-Bamboo-Lumber-Made”,” n.d.)

Based on the type the bamboo products the culm is either crushed or split into strips.

Crushing: In this process, the entire bamboo culm throughout its length is crushed using a crusher.

Splitting: In this process, bamboo strips are produced by feeding culms through a splitter machine that cuts bamboo culm into slender strips. The ways of splitting are shown in figure ----

The products are based on the method of splitting the bamboo into small strips .Splitting can be done in multiple ways. The figure --- show the methods of splitting the bamboo culm into strips by Entirely splitting the bamboo in strips throughout its length. By cutting the whole bamboo culm in half and flattening or based on the arrangement of the strips is another variation within this type. The bamboo is cut short according to the dimension of the press. The number of splitting pieces is determined by the diameter of bamboo. The larger the diameter of bamboo, the more the splitting pieces are.(Huang, Ji, & Yu, 2019).

Planning:

The process in which all outer and inner surfaces of the bamboo are removed or scarped in order to remove the wax and silica layers is called Planning. These layers contain wax and silica which weaken adhesive bonding of the material. This is an important process as described above, the outer skin and inner pith of bamboo have zero bonding capacity.

Drying

The moisture content (MC) of bamboo after defibering is usually above the fiber saturation point. The MC of bamboo bundles needs to be dried below 10% so that there is room for the resins to get in.

Boiling: Sometimes this process is used in order the aid the flattening process. In this process, the specimens are dipping in boiling water for about a minute. This process is more effective at low oppress temperature (between 150 deg – 180deg) compared to high press temperature (between 150 deg – 180 deg).

Carbonization: This is an alternative step for boiling. Products which demand high durability and strength, carbonization is followed.

Dipping/ Adhesive coating:

After the fibers or the strips are dried to the requited moisture content level they are dipped in the resin. Dipping is also the key process for manufacturing bamboo scrimber, as it determines the bonding performance. The resin which is currently used is the phenolic resin; and the impregnation amount of the resin is controlled by the solid content of the resin, the impregnation method (in vacuum or at normal pressure), the soaking time and the MC of bamboo units. In actual production, the impregnation is designed according to the requirements of bamboo scrimber's performance and use. For example, if the bamboo scrimber is used for outdoor purpose where high waterproof performance is required, the impregnation could be higher (> 20%) (Huang et al., 2019).

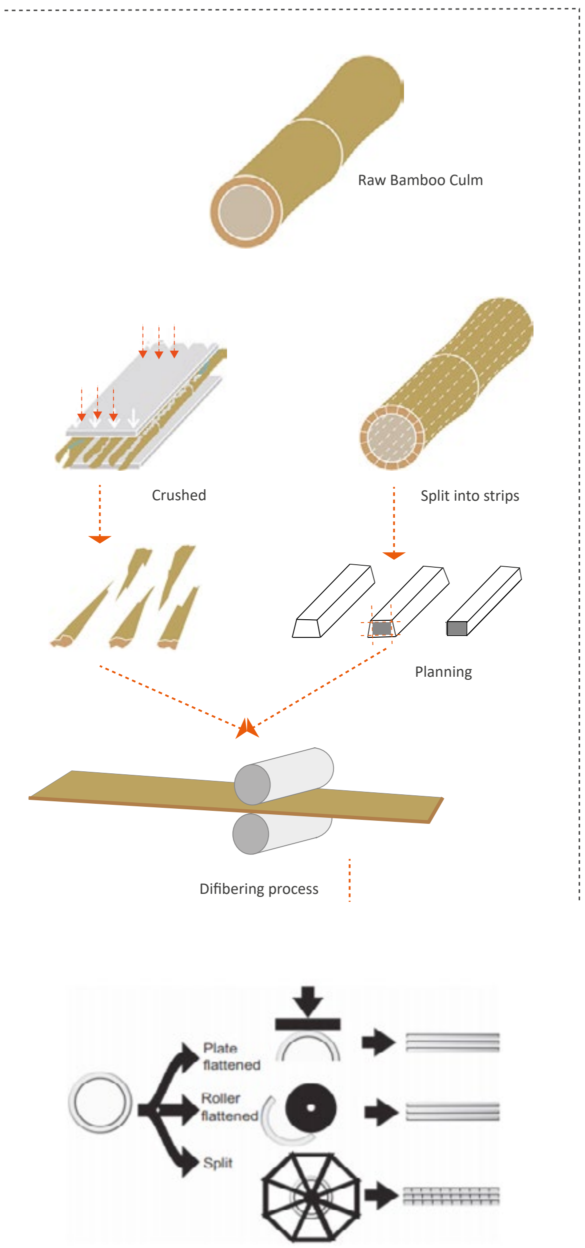


Figure 29: Methods of obtaining base material for laminated bamboo

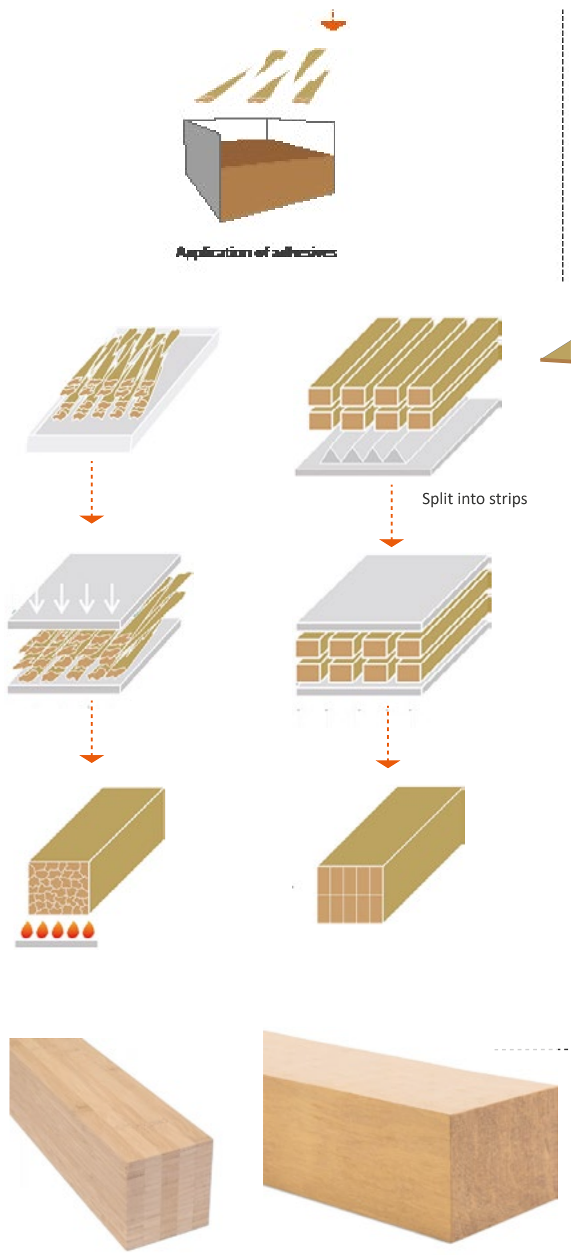


Figure 28: Production process of engineered Bamboo

Casting Process:

The Compressing of the strands to the shape is done by two methods. It is important to understand these methods as to give an understanding of the possible shape using these material.

Each of the two technologies has advantages and disadvantages. Cold-pressing and heat curing have relatively high production efficiency and low energy consumption. However, due to the need for high pressure, bamboo bundles are easily crushed by machinery, resulting in lower mechanical properties. In addition, the density of bamboo scrimber using cold-pressing technology could reach 1.2 g/cm^3. At such high density, there is a possibility that the resin does not remain on the surface of the bamboo bundles, which leads to starved joints and further reduces the bonding strength. Although the hot-pressing method has made up the shortage of the cold-pressing to some extent, there are also two problems. The slab needs artificial paving, leading to large diffidence in the density of boards. The maximum density deviation could exceed 20%. On the other hand, "cold-in and cold-out" process is needed for the hot-pressing technology, which requires large consumption of water and energy, **and the hot-pressing efficiency is low**. Without the water it is easy to cause defects such as bubbling. (Huang et al., 2019)

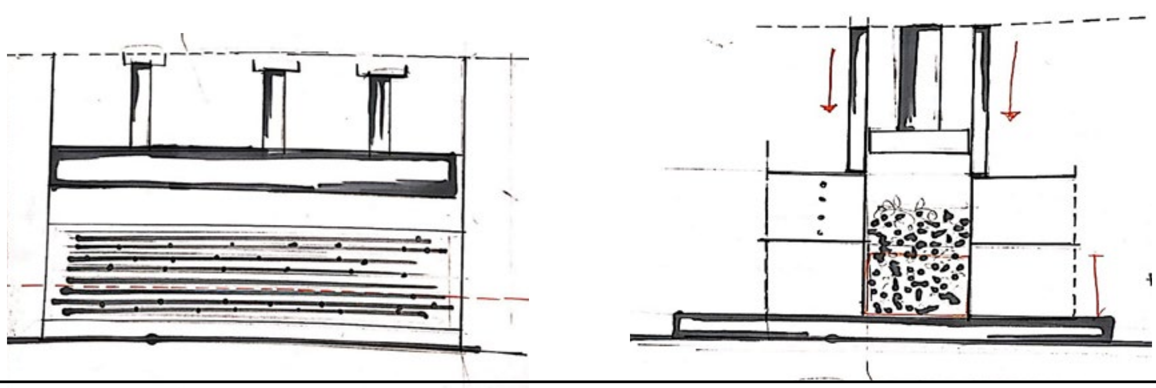


Figure 30: The Figure shows the method of the compressing. The diagram is interpreted from anonymous sources.

Cold-pressing and hot-curing:

After drying the resin-impregnated bamboo bundles to 12–15% MC, they are directly molded and shaped at high pressure of 70–80 MPa. Then, the mold is locked and sent to the curing channel for resin curing. Cold-pressing process is mainly used for manufacturing the square-edged bamboo scrimber with thickness of 15–18 cm. The commonly used size (length × width × thickness) for the square stock is 193 × 10.5 × 15.0 cm or 200 × 14.5 × 15.0 cm. (Huang et al., 2019)

Hot-pressing:

Hot pressing is a method in which the material is compressed under high heat which may vary between 150 deg – 180 deg in order to achieve a smooth surface with lesser irregularities and to avoid voids during adhesive bonding. The unit pressure is 4–6 MPa, far below than that used for cold-pressing. The commonly used size (length × width × thickness) for the bamboo scrimber board is 244 × 122 × 1.5–4.0 cm. (Huang et al., 2019)

Summary of important criteria of the production process:

The quality of the raw material and low defects should be analyzed before sourcing the raw material ,as it may affect the strength and quality of the final production order to design effective connections, understanding the process, anatomy and the strength of engineered bamboo is important. Some of the factors which should be considered while designing are summarized below.

Bonding between the fibers is Dependent on the precision , quality control , type of adhesive used during the productions process. The fibers are compressed to a shape in a unidirectional way and are only bonded by the glue based a adhesives. To conclude even the engineered material does not behave as a homogenous material and should be used in the fiber directions , reduce stressed on the adhesive connections the fibers ,thus the direction of the fibers while designing is important.

Molding process: Understanding the casting process would allow more versatility in the shape and form of the final bamboo components used in joinery. In order do so process of press molding should be kept to primary processing as far as possible in further design process

Flexibility in Sizing : It can also be concluded that, with further analysis of density concentration and bonding strength it is possible to customize the beam to any desired shape. Thus allowing Versatility in development of possible sizes for design . It is very easy to develop varied sizes of the components.

Engineered can completely reduce dependency on the properties of natural form like moisture content relative strength , durability and quality control .

Material properties : Post-processing:

It is important to analyze the mechanical properties of Bamboo scrimber and laminated bamboo to assess the potential for structural application. A basis of comparison usually adopted is comparison with the properties of timber. There are no set-testing of the engineered bamboo as the material is still under research and development. However, the most common practice is to follow standards of timber testing. The test results also vary depending on the type of bamboo Species used and based on the production method. The research on understanding the structural properties of the engineered material is still very new and inadequate. There is not much literature available considering the limitation on access, so in order to understand the potential and properties, data will be collected from different research papers and summarized for further designing. For better understanding, results from the test conducted and discussed are the research paper by (Sharma, Gatóo, et al., 2015) are studied.

Type : Bamboo Scrimber

The test was carried on a commercially used bamboo scrimber product from the China comprised of Phyllostachys pubescens (MOSO) with phenol-formaldehyde resin. The process of manufacturing bamboo scrimber uses bamboo culm with minimal processing. The resulting commercial product is tested as a final product with no additional modifications.

Average density of the bamboo scrimber is 1160 kg/m^3

Moisture content of 7%.

In comparison, MOSO as a raw material has a relative density of approximately 0.5–1.0. (Sharma, Gatóo, et al., 2015)

Type : Laminated Bamboo

Two orientations were tested: radial horizontal and radial vertical, which refer to the orientation of the original strip within the beam. Laminated bamboo sheets are also manufactured from MOSO bamboo strips using a soy-based resin and discussed in the previous section. The structural specimens are built up from a commercial sheet (2440 _ 1220 _ 19 mm). The sheet was cut and the section laminated into the desired dimensions using polyurethane adhesive (Purbond HB S309). The adhesive was applied manually with a glue proportion of approximately 180 g/m^2 (final product) and the lamina pressed using manual clamps to apply the required pressure of 0.6 MPa for 4 hours (Sharma, Gatóo, et al., 2015).

Average density of 686 kg/m^3

Moisture content of 6%.

All specimens are conditioned in a constant temperature of 23 degC and relative humidity of 55% for 2 weeks before testing.

Test Method:

To obtain the material and mechanical properties, tension, compression, shear and flexural tests were conducted based on BS 373. Methods of testing small clear specimens of timber Tension, compression and shear tests were conducted in a universal testing machine. (Sharma, Gatóo, et al., 2015)

Understanding of the results :

Tensile Strength :

According to the test ,In tension parallel to the grain, both bamboo scrimber, and laminated bamboo show similar and straight behavior prior to failure. The tension perpendicular to the grain results shows the low strength of the bamboo scrimber and the laminated bamboo perpendicular to the fibre direction. Most of the failures are seen at various locations within the fibre and *through the length of bamboo rather than within the adhesive* for both materials. (Sharma, Gatóo, et al., 2015)

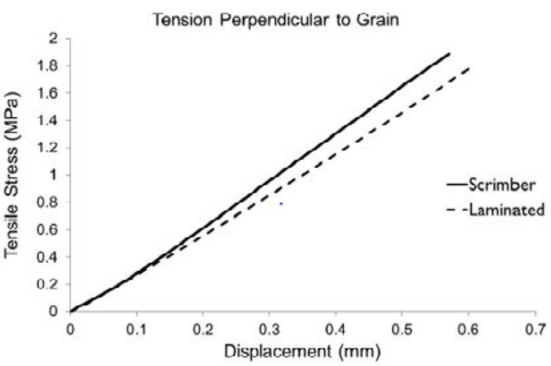


Figure 31: tension parallel to grain (Sharma, Gatóo, Bock, & Ramage, 2015)

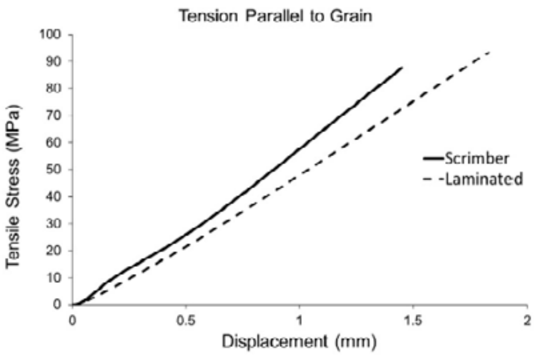


Figure 32: tension perpendicular to grain (Sharma et al., 2015)

The parallel tensile strength was more than forty times the perpendicular strength.

Compressive Strength :

The failure mode of the bamboo scrimber was overall section buckling of the specimen. Similar failure was noted by Huang et al. [14] in larger (105 _ 105 _ 315 mm) bamboo scrimber specimens. All of the laminated bamboo specimens failed in overall section buckling with no shear failures observed. It is also noted the buckling failure in larger samples (100 _ 100 _ 300 mm) in compression parallel to grain, specimens that were manufactured from the upper portion of the bamboo with laminates of approximately 4 mm in thickness, similar to the specimens tested here (4–6 mm). (Sharma, Gatóo, et al., 2015).

The representative curves show that both materials exhibit bilinear behavior. Because specimen buckling dominates behavior, the compressive strength is determined at the proportional limit in all cases (the knee in the bilinear curve).

Thus this value must be interpreted as the strength for the sample dimension used rather than the compressive capacity of the material. The materials had reduced strength in compression perpendicular to grain, in comparison to the parallel to grain direction. Both displayed bilinear behavior. The failure mode for both materials was fracture of the matrix and bamboo fibres. For a parallel to the glue line. In comparison, the laminated bamboo showed no influence on the direction of the glue line. (Sharma, Gatóo, et al., 2015)

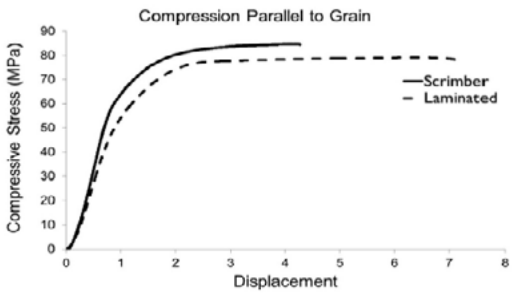
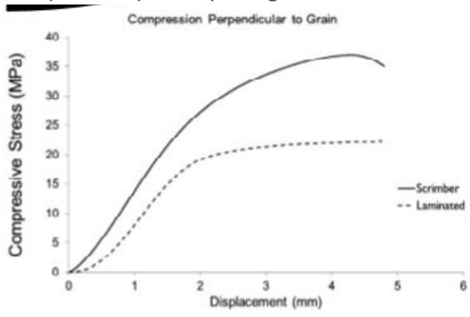


Figure 33: : Compression parallel to grain (Sharma et al., 2015)



Compression perpendicular to grain. (Sharma et al., 2015)

The bamboo scrimber achieved twice the load at similar displacements before failure.

Shear Strength :

In shear parallel to the grain, the behavior of the two materials is quite similar, however the laminated bamboo is able to withstand increased load and displacement before failure. The laminated bamboo is noted to have higher compressibility before the shear failure occurred within the fibres. The failure surface of the bamboo scrimber was much rougher.

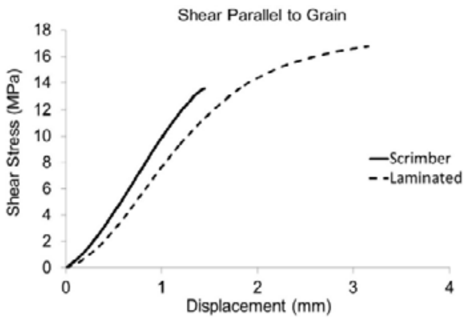


Figure 34: Shear Parallel to Grain

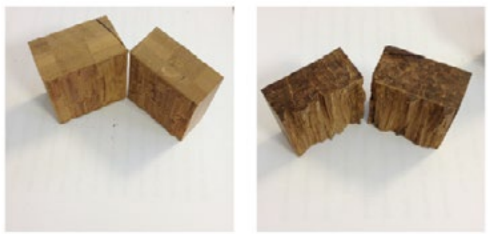


Figure 35: results; specimen failures in laminated bamboo and bamboo scrimber.(Sharma et al., 2015)

The average shear strength, however, was comparable with the laminated bamboo, slightly higher (16 MPa) than the bamboo scrimber (15 MPa).

Bending:

The results indicated that a large displacement was achieved in the specimens before failure. The failure occurred at the tension faces of the specimens at mid-span. Similarly, the laminated bamboo failures occurred near mid-span, although these were characterized as longitudinal shear failures (i.e. VQ/I failures) within the depth of the beam for both the edgewise and flatwise oriented specimens(Fig. 00). All of the laminated bamboo specimens demonstrated brittle failure. Although micro-cracks within the material were audible and are also observed in small drops along the load-displacement curve (Fig. 00), no cracks were visible before failure. Comparison of the two orientations indicates that while achieving similar maximum loads, the flatwise orientation had an increased modulus of elasticity with a gain of approximately 18% over the edgewise orientation.

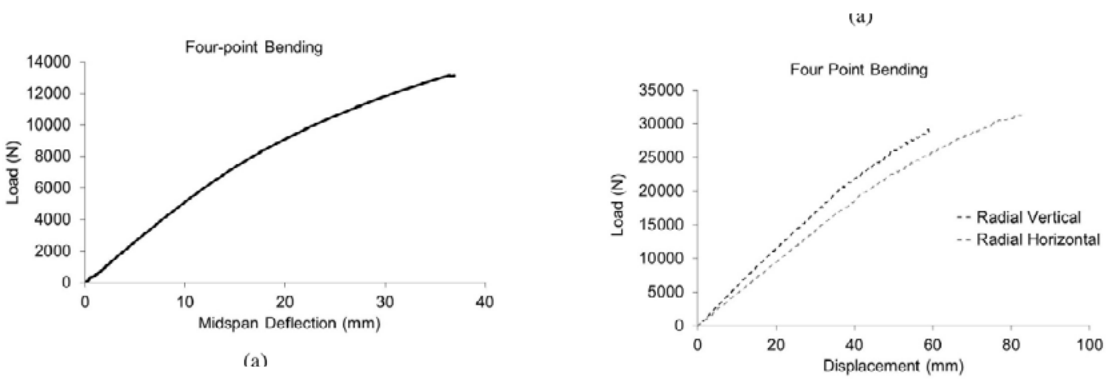


Figure 36: Bending results for the bamboo scrimber are shown(Sharma et al., 2015)

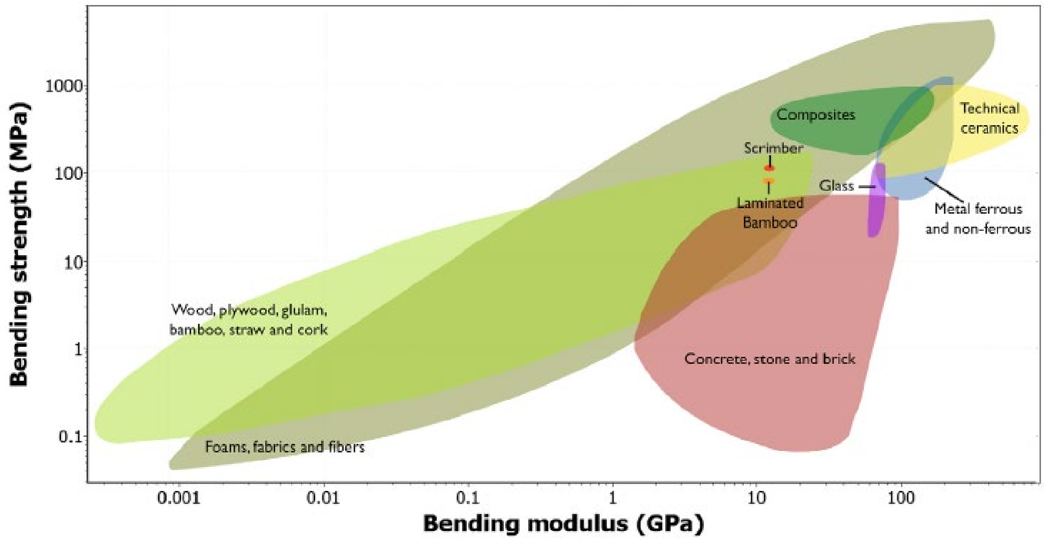


Figure 37 : Bending modulus vs. bending strength for various construction materials

Results from other research: Here is a compilation of properties for different material tested by researches Strip laminated bamboo, also known as Glubam. According to (Xiao, Shan, Yang, Li, & CHen, Glue Laminated Bamboo(glubam) for structural apllications) Below is the table of mechanical properties of glubam: The table is a compilation of experimental studies done by various researchers and aims to show the potential of engineered bamboo as a structural material.

		Compressive stress Mpa		Tensile stress Mpa		Shear stress Mpa	Flexural			
	Density kg/m3	Parallel to grain	Perpendicular to grain	Parallel to grain	Perpendicular to grain	Parallel to grain	MOR Mpa	MOE Gpa	G Mpa	
Bamboo Scrimber	801	-	-	41	7	-	102	2		From 1.0
Lamninated Bamboo	577-750	63-64	20	102-191	3-4	4	78-88	1-12		
Phyllotachys pu-bescens	666	53	-	153	-	16	135	-		
Sitka spruce	383	36	-	-	-	9	67	8		
Douglas fir LVL	520	-	-	49	-	-	68	13		
GLUBAM	800-900	51	-	82	-	801	99	ex - 10.4 ey- 2.6	Gxy - 4.6 Gyx- 7.2	From 2.0

Table 4: This table presents the properties of the material of bamboo in its natural form compared to engineered form. (Sharma et al., 2015) (Sharma et al., 2015)

SUMMARY AND CONCLUSION FOR FURTHER DESIGN :

The table clearly shows that the strength of bamboo scrimber is higher in strength than that of laminated bamboo. The strength of the material increases with an increase in the amount of processing.

The utilization ratio of bamboo is increased to more than 90%, which greatly reduced the cost of the production of bamboo scrimber.

The properties remain similar to the properties of natural form bamboo. The shear failure in natural Bamboo is depended upon the natural glucose present in bamboo , is now dependent on the adhesives used to bond the fibers.

Following are some of the advantages and disadvantages of using engineered bamboo .

***Advantages**:*

- There is a small variation in the strength and properties of the material compared to the test conducted on different raw bamboo. This observation is of significant importance to us as a smaller variation in properties of bamboo means that there is inherently higher reliably in these properties which can lead to standardization of the products, leading to improved confidence for designers. (R.shreshtha & crews, 2014)
- The results have demonstrated that by reconstituting bamboo with adhesives, it is possible to overcome shortcomings in the properties of natural bamboo which make it difficult to put into an engineered application such as high variability in properties and undesirable shape. The study demonstrates the potential of using bamboo as an engineered product by using a relatively simple fabrication technique. (R.shreshtha & crews, 2014)
- For bamboo, the production efficiency varies by manufacturer and is approximately 80% for bamboo scrimber and 30% for laminated bamboo. (van der Lugt, 2008).

Disadvantages :

- Bamboo is strongest along the length of the fibres and is usually glued along its longitudinal length.
- Closer inspection of the some specimen from tests show that the splitting occurred at or close to the adhesive layer. The shear splitting is usually followed by tensile rupture of the bamboo strips at the soffit of the specimens. The primary failure mode by shear splitting is **attributed to the fabrication technique** where the bamboo strips were laid out in layers in the formwork. (R.shreshtha & crews, 2014)
- During testing of laminated glued bamboo (strip glued together) It has been observed that irrespective of the type of adhesive used, generally fail by horizontal shear splitting which initiated close to one of the supports and near the Centre of the cross-section.

5.3 TIMBER:

5.3.1 SYSTEMS IN TIMBER CONSTRUCTION:

To imply and understand the working of prefabricated systems, study of systems implemented in wood constitution was done as numerous advantages have contributed to an ever larger proportion of prefabricated timber construction worldwide. (Egarac & Leskovar) One of the most favorable aspect of timber is faster construction, due to a high degree of elements' prefabrication. Timber prefabrication systems can be categorized on approach to planning and designing a particular system. Based on y, based on size and complexity Also with respect to labor/machinery availability on site. The systems can be massive timber construction systems or light weight timber construction system.

The systems can be categorized based on the components:

Log structures: Log construction is a traditional method of wood construction, especially in countries where there is a plentiful supply of cross-sectionally suitable and straight wood. In a log house, the building's load-bearing structures at least are made of log.

Precut materials: Are pieces of material customized and fabricated through a manufacturing process. The pieces, once finished, are transported to the site for assembly. Compared to the conventional method of cutting timber on-site, this system is more accurate and waste production is minimized. (as cited in (Schaik, 08 April 2016))

5.3.2 PREFABRICATED COMPONENTS:

Prefabricated components are relatively simple building blocks which can be handled by two or three men without using machinery. Examples of prefabricated components include Lightweight Timber Structural Systems, (Schaik, 2016) As described in (Leskovar, esna Žegarac, 2013) Prefabricated systems in light weight be further divided in :

Planar/ panelized system:

Balloon frame:

In balloon frame system the function of the main load-bearing part is taken by the frame composed of beams and pillars following a continuous bottom-to-roof pattern. the load-bearing timber frame consists of storey-high preassembled studs with square sections. Individual load-bearing frame elements are assembled at the prefabrication stage and transported to the construction site as self-contained elements. (Leskovar, esna Žegarac, 2013)

Platform frame:

The basic vertical load-bearing elements in the frame-panel construction, which is nowadays typical of Central Europe, are the panel walls consisting of the load-bearing timber frame and the sheathing boards, while the horizontal floor load-bearing function goes to slabs made of the floor beams and the load-bearing wood-based sheathing boards connected to the upper side of the floor beams. In the frame-panel construction, the entire wall assemblies, including windows, doors and installations, are fully constructed in a horizontal plane in the factory and then put in vertical position. (Egarac & Leskovar)

Modular structures:

Are volumetrically prefabricated structures that enclose usable space. Modules are structurally independent and completely finished at the factory. Modules can refer to one-room modules but also to larger modules consisting of multiple rooms. (Schoenborn, 2012) This prefabrication method has the shortest erection time at the site, but it requires the use of heavy transportation and crane. (Schaik, 2016)

Linear skeletal systems (timber frame construction):

Timber-frame construction, is one of the traditional forms of lightweight timber structures. Timber-frame construction shows first signs of prefabrication The vertical loads are transferred directly via contact faces between various timber members. Deplazes Frame construction could be regarded as the second type of linear skeletal systems where all loads are transmitted via vertical (studs), horizontal (beams) and diagonal elements. The load-bearing structure thus functions independently of the enclosing elements, such as façades or sheathing boards.

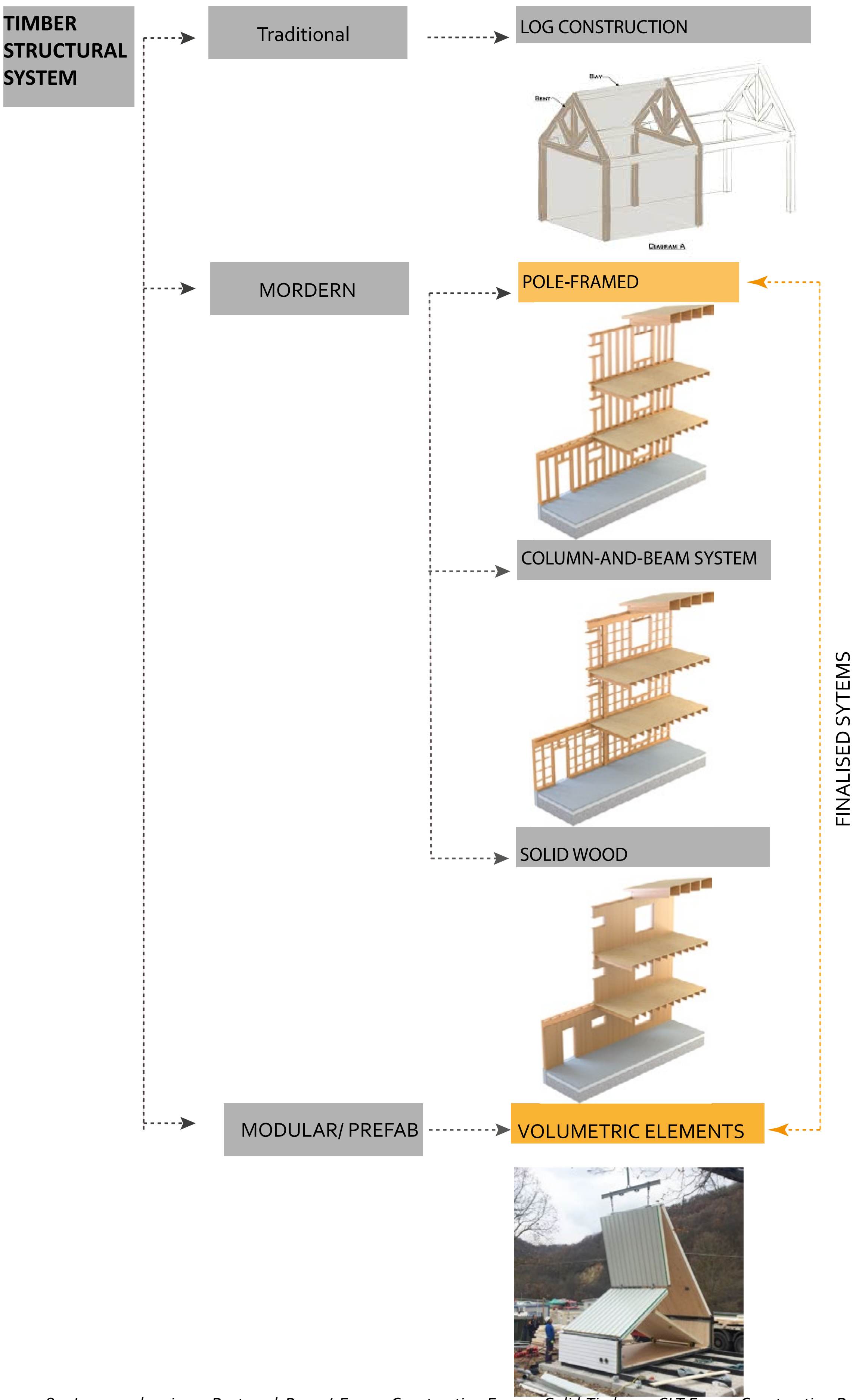


Figure 38: Images showing : Post and Beam/ Frame Construction,Frame- Solid Timber – CLT,Frame Construction.Retrieved from https://www.shutterstock.com/search/new+construction(Leskovar, esna Žegarac, 2013),https://woodendreamhomes.com/section.html?section=13&category=timberframes

5.3.3 RESEARCH IN TIMBER JOINERY:

Relevance, history and research in interlocking connections:

Historic wood construction in different parts of the globe widely used interlocking joints before metal connections. In timber framing, what historically has concerned the housewright is how timbers are fastened together—the joinery. In wood joinery different types of joints are used to deal with the stresses and the concentration of different wood members. (Sobon, Jack A., 1984)

Additionally, how timber members are assembled also needs to figured out in the joinery. In modern construction, two main contexts in which wood construction might exhibit interlocking connections are: (1) in low-rise structures built in the timber-frame tradition, or (2) in unique structures (e.g. Yusuhara Bridge Museum, 2010, Kengo Kuma and Associates; Tamedia Office Building, 2013, Shigeru Ban Architects).

Since the revival of timber framing, just a few years ago, new and non-traditional (Sharma, Gatoo, Bock, Mulligan, & Ramage, 2015) joints have come into use. This is often the result of someone misunderstanding the construction of the old joinery. (Sobon, Jack A., 1984)

Timber-frame specialists, today, typically build such joints at the low-rise residential scale, relying on a combination of traditional craft and modern specialized analysis. The potential benefits of using joinery connections in mid-rise scale buildings are multifaceted. The elimination of metal joints could further drive down the embodied energy of structures. Using joinery connections may offer new implications in construction assembly speed of timber structures. Innovations in digital fabrication suggest that the cost of milling joinery could become competitive with that of fasteners. (Fang & Mueller, 2018)

Historical interlocking timber connections can be seen in Japanese Architecture. In wooden architecture, the majority of construction employs straight lines primarily because of the characteristics of the wood and nature of its growth Joinery is the heart of timber framing .

Some of the most common and relevant timber joineries are discussed below.

Perpendicular frame connection:

One of the most important is the mortise-and-tenon joint and the most basic timber framing joinery is mortise and tenon joint. The joint is designed to carry light load . It has another job in timber-frame construction, and that is to position timbers. Anchor beam joint is variation of tenon and mortise. A simple dovetails is commonly used to join the smaller members. The joint is also deigned to support the load. The Dovetail Lap Joint: This joint is named because of its resemblance to the flared tail of the dove. It is truly a remarkable joint. It is used where great strength is needed to resist pull-out tendencies. This joint is strongest when the grains of the two timbers are at right angles to each other.

5.3.4 CASE STUDY:

Interlocking joint:

Interlocking joint are more advanced form of connections derived from basic joineries shown above. Here are some examples of interlocking connections:

Case Study: Kengo Kuma Architects Works

Kengo Kuma is one of the architects who incorporated new joinery techniques in his design that involves wood structure. As we all know, he is an architect who is famous for pursuing and experimenting on new materials during his design process. The Yusuhara Wooden Bridge Museum built in Sept, 2010 is a fascinating wooden structure project designed by Kengo Kuma. The use of large-scale steel or concrete elements was avoided in favor of the small members of glue-laminated local cedar. In order to achieve its 47 meter span, an innovative system of interlocking beams was developed, reinterpreting the traditional Japanese cantilever. (Building, n.d.)

In the project of GC50th Anniversary Memorial built in 2010, chidori-patterned grid consisted of thin timbers, carries a high hall of 9 meters. Experiments prove that the timbers can bear 1 ton of weight by grappling each other at the cost of only 4 percent of volume. (Building, n.d.)

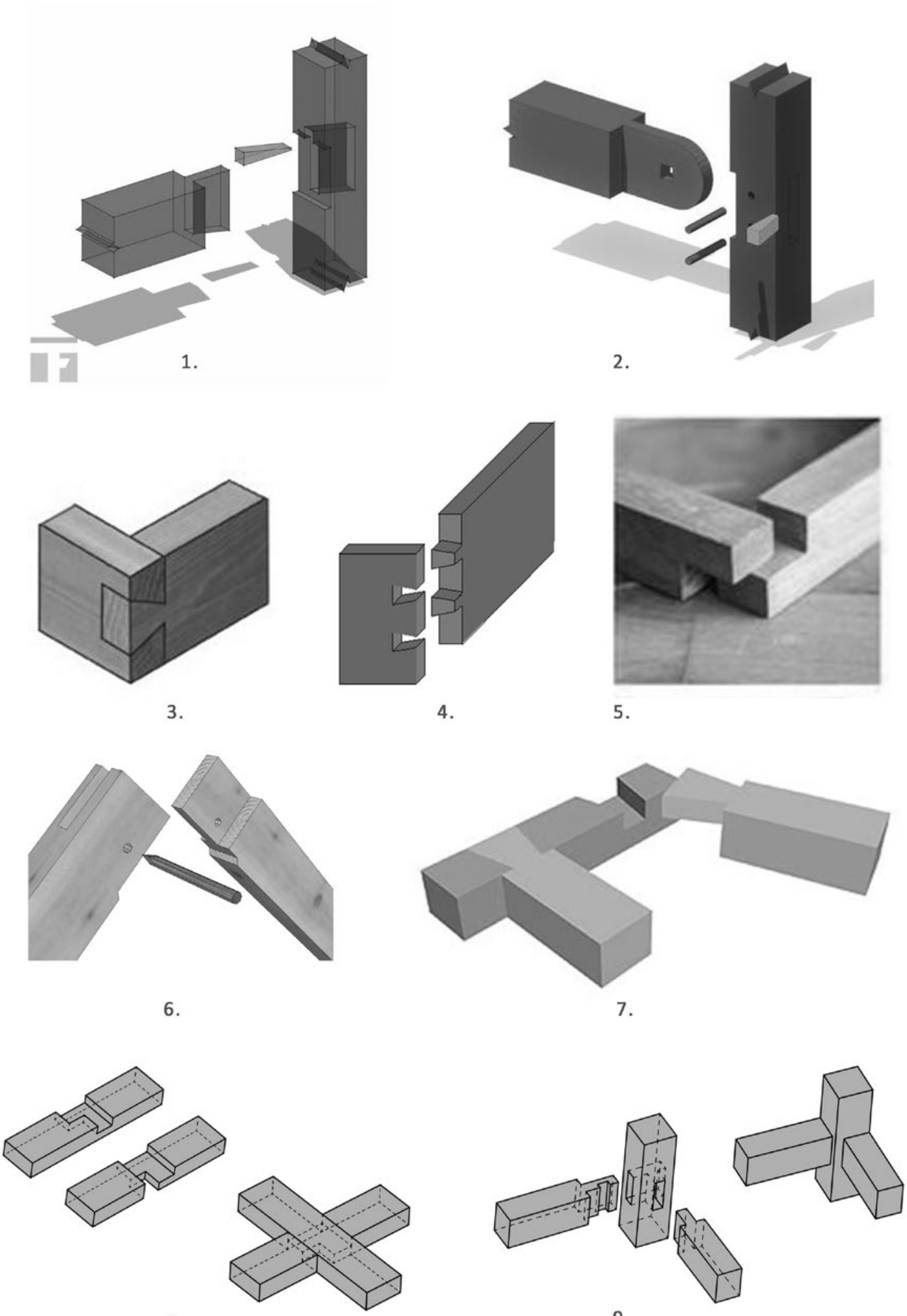


Figure 39: Images showing possible joineries for a timber frame construction.(Sobon, Jack A., 1984)("Timber joinery," n.d.)

Figure 40: Image showing works of Kengo Kuma architects(Building, n.d.)

Case Study : Tamedia Office Building

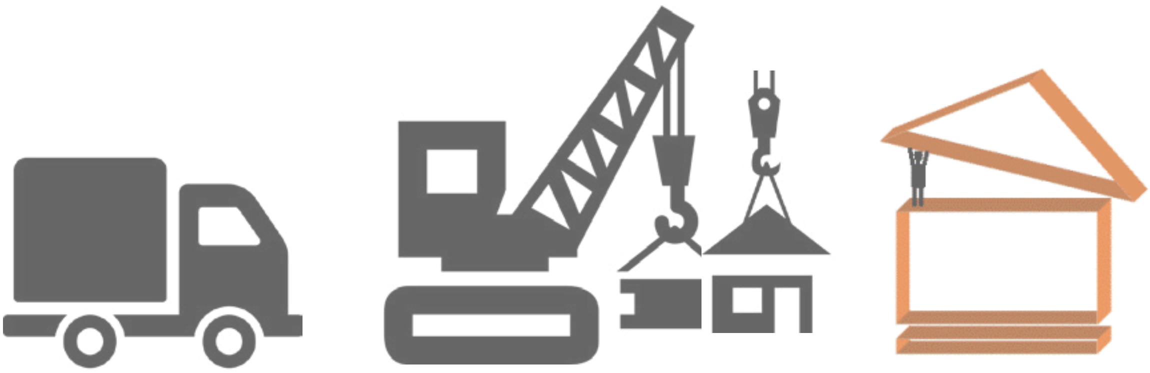
Shigeru Ban Architects.

The construction was done completely without steel reinforcement and consists solely of prefabricated, precision milled timber elements assembled on site. The Japanese tradition of carpentry – as represented in the new building in Zurich – do not require the use of glue, nails or screws. The load bearing timber components are simply interlocked and their pin connections are additionally stabilized by a secondary structure. Zurich's Tamedia building shows that timber construction technologies have matured. The result is now in the hands of innovative architects, engineers and builders to rediscover wood construction for large, inner city buildings that are architecturally exciting: Wood is not only a renewable resource and thus, if it comes from sustainably managed forests, an environmentally friendly material.

Figure 41: Image courtesy of Shigeru Ban Architect("Tamedia Office Building," n.d.)

RELEVANCE OF TIMBER IN BAMBOO CONSTRUCTION:

Same like bamboo timber is natural material which is also designed based on the parameters required for for joinery design. Additionally the splitting behavior of timber ,the defects in the natural materials, and the grain direction of timber will help in designing the joineries using bamboo.



05 PRE FABRICATION

06. PRE-FABRICATION AS AN APPROACH:

6.1.INSIGHT TO PRE-FABRICATION:

Today, due to time limitation and emphasis on fast construction process, usually a prefabricated approach is adapted. In order to implement prefabricated approach it is important to understand the concept of prefabrication in construction.

A pre-fabricated housing unit is the one given by Craven (2015):

'prefab is used to describe any type of home that is made from easy to assemble building parts that were manufactured offsite'.

According to The Free Dictionary (2015) 'prefabricated' means: 'To manufacture (a building or section of a building, for example) in advance, especially in standard sections that can be easily shipped and assembled'. Prefabrication comes with multiple benefits of accurate installation, standard tested and reliable components which eliminates the current problem faced by bamboo construction industry. The method allows you to installed the components to before taking them to the site. Prefabrication is not something of the last decades; it has been around for a long time. There are many different traditional prefabrication examples in developing countries, like thatched roofs or bamboo panels. However, industrial building prefabrication was introduced in the last decades, which increased the use of prefabricated building elements. There are multiple factors that have to be taken into account when transferring a prefabricated building system as a module.

Some of them are :

Modularity,Transportation Ease,Cost,Easy Assembly,Physical non-adaptability.

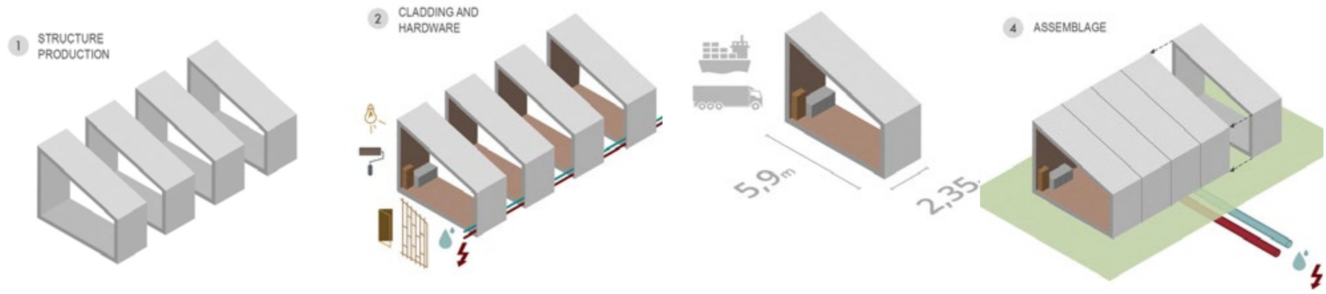


Figure 42: Image showing Prefab design configurations.

Adaptable Prefabrication Motives :

Flexibility:

Modular construction can be easily disassembled and relocated to different sites. This significantly reduces the demand for raw materials, minimizes expended energy and decreases time overall. Also, modular construction allows for flexibility in the design of the structure allowing for a limitless number of opportunities. Since prefabricated construction units can be used in different spaces, its neutral aesthetics is able to blend in with almost any building type.

Consistent quality:

Since prefabricated construction occurs in a controlled manufacturing environment and follows specified standards, the sub-assemblies of the structure will be built to a uniform quality. Construction site-built structures are dependent upon varying skill levels and the schedules of independent contractors. These all contribute to the craftsmanship and overall quality of given structure. With prefabrication, each sub-assembly is built by an experienced crew in a weather-resistant factory, with multiple quality checks throughout the entire process. Some components of the building are constructed using precise machine equipment to ensure conformity to the building code.

Reduced site disruption:

Since many components of a building are completed in the factory, there is significantly less truck traffic, equipment and material suppliers around the final construction site. This limits the disruption of traditional job sites that suffer from noise, pollution, waste and other common irritants. This streamlined approach to construction provides a far more efficient atmosphere for productivity, and eliminates unnecessary distractions and interference that are typical of construction sites.

Shorter construction time:

Portable construction takes significantly less time to build than on-site construction. In many instances, prefabrication takes less than half the time when compared to traditional construction. This is due to better upfront planning, elimination of on-site weather factors, subcontractor scheduling delays and quicker fabrication as multiple pieces can be constructed simultaneously. Shorter construction times allows construction companies to take on multiple projects at once, allowing businesses to grow rather than putting all their focus and resources on one or a few projects at a time.

Safety:

Since subassemblies are created in a factory-controlled environment utilizing dry materials, there is less risk for problems associated with moisture, environmental hazards and dirt. This ensures that those on the construction site, as well as a project's eventual tenants are less likely to be exposed to weather-related health risks. Also, an indoor construction environment presents considerably fewer risks for accidents and other liabilities.

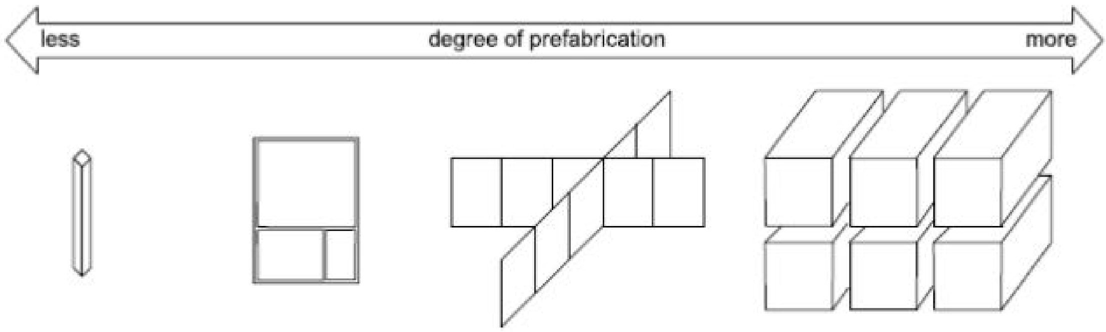


Figure 43: Degree of prefabrication for offsite construction. (Retrieved from Prefab architecture: a guide to modular design and construction.)

There are strict factory processes and procedures that protect the worker from on-the-job injury. At a construction site, although safety is of utmost importance, workers are subjected to weather-related conditions, changing ground conditions, wind and other crew members who are at the site. ("7 Benefits of Prefabricated Construction," n.d.)

The classification of various off-site construction methods is based on the degree of completion during the manufacturing process. As the figure shows, materials, components, panels, and modules are the general categories in which architectures are produced and assembled. Generally, the advantages of prefabrication would increase with a greater degree of prefabrication.

Large-scale heavy component of prefabricated systems are not flexible to change use in a later stage of the buildings lifetime. Being able to replace or change components of the building is essential to successful functioning of the design. When a building can comply with these needs success is more viable.(Schaik, 2016) Prefabrication technology has not transferred easily compared to other technologies because it is a production technology and not a consumption technology. (Smith, 2006) Production technology requires more background knowledge compared to consumption technology.

6.2 RELEVANCE OF PREFABRICATION IN BAMBOO CONSTRUCTION:

Bamboo can be a complicated material to work with due to its certainties when it comes to biology and utilization. In order to utilize bamboo effectively it is important to simplify and standardize its usage under scientific and technological conditions. Bamboo components being light in a weight are more of an advantage for this technique as the components can be erected in larger dimension just with a few equipment's because they are very low in volume/ weight. It is also easier to transfer the prefabricated components to remote areas due to their lower weight ratio, they can be erected with human interventions or a fewer light weight / easily accessible local machineries.

Standardization, a major advantage of prefabricated approach allows the user to employ local contractor, who could easily follow the assembly manual to build the house. With prefabrication only site execution is exposed to the weather conditions (as water to rains can pose a problem for bamboo structure. (Shrestha & Crews, 2014)

Pre-fabrication as an approach to design:

How to build with bamboo, a prefabricated approach which can be developed in categories as mentioned below:

Prefabricated approach toward : As a system of building,

Prefabricated approach toward: the connections

Here are some reasons which led to process of standardization and prefabricated use of material.

Uncertainties in properties: Bamboo being used in natural form no two poles of Bamboo are same. As the currently sourced bamboo grows in natural environment, All bamboo poles have different and challenging angles.

Dependency on skilled workmanship: Because no two bamboo pole are similar, human interventions becomes an important factor. Unevenness in material increases structural risk, needs experience and intuition ultimately resulting in excessive use of material and labor.

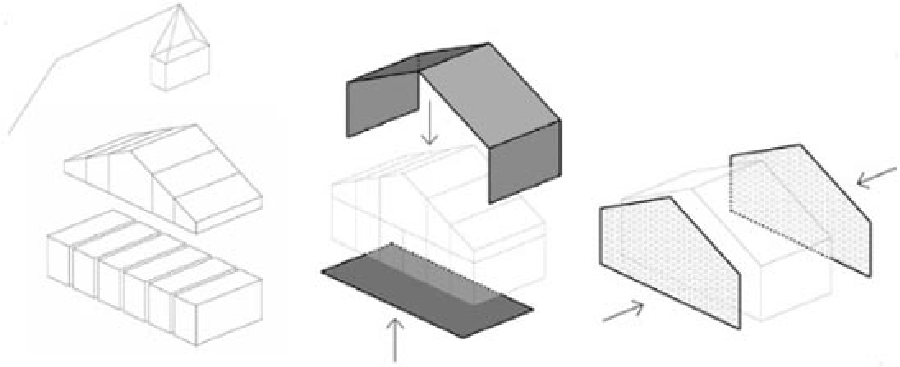
Easy construction/Construction efficiency: Pre fab involves a more faster and efficient construction process and offer a promising alternation to traditional stick / pole building.

Standardization: Standardization of components used in construction facilitate increased durability strength and material quality. Pre-fabricated elements have potential to be treated and increase the capacity of bamboo for a longer life.

Simplified Joinery: Standardized bamboo components gives opportunity to innovate design connections, eliminating use of dependency on skilled labor.

Saves time and capital: Efficient construction process saves construction time. Can be expensive than traditional stick and pole construction techniques.

Transport: Transportation can be a major issue, transporting hollow bamboo stems as they take up a lot of space but are low in weight. The long distance transportation can be extremely unprofitable. Prefabricated components are produced off site and can be assembled on site with ease. Are light in weight and thus easy to transport in separate parts.



Compared to conventional Prefab shelters, a bamboo prefab house can prove to be 20-25% cost efficient.

Figure 44 : Diagram showing Category of materials, components, panels, and modules for the off-site construction. (Retrieved from Prefab architecture: a guide to modular design and construction.)

07. APPLICATION:

7.1 SUMMARIZING DESIGN BRIEF

CONTEXT:

A sample context for further designing

TARGET POPULATION

Middle class families looking for a affordable more permanent solution.
With an initiative to cater the need for housing as a global issue. With increasing issues of housing the most issues with housing are faced by middle class families.Middle Class population just above mid income group.
With more and more technical an global advancement people are looking for a affordable but permanent solution based on the location
Majority of the people who wish to improve the standard and quality of living about cheaper

Figure 45 :Image showing an overview of the design brief for further research and development .

PROTOTYPE: HOUSE

A permanent housing solution.
Simplified and standard- available for the mass population.
Sustainable in terms of energy efficiency and green building material foot print.
Prefabricated for affordability and reduced dependency on workmanship (business model).
DESIGN
Standard design with a globally accepted layout and grid dimension.
Larger floor plan to make it user friendly.
Lower middle class family live in. a general grid and area analysis can be inferred.

STRUCTURAL SYSTEM

CONSTRUCTION APPROACH

Prefabrication as a system
Modular Construction , Off site component fabrication and assembly.

CONNECTIONS

Prefabricated connection system
in terms of Assembly and component production

FEASIBILITY AND ECONOMICS

Cost -effective
Production
transportation
Assembly

Figure 46 : Figure showing the construction layer of the typical structure / building

08 SYSTEM DESIGN

08. DESIGN SYSTEM:

Before starting any structural design, it is important to understand the end user, housing type from the perspective of architecture feasibility and construction easy.

As an example a basic general house was designed based on the idea of Prefabrication. The figure shows a diagram for the layers of offsite construction, the building accompanied by off-site construction usually follow the prototype which contains five factors from outside to inside, namely foundation, skin , structure, service, and interior finishing. Considering adaptability to the context, the façade can be varied based on the context, the structural system would be the primary focus.

The grid and size was decided based upon the numbers of considerations including the end users, prefabrication concept, transportation and availability of the material which is discussed in detail in further chapters.

As a structural system a frame timber structural system will be adapted into design.

Some of the Factors which influence the design of the structural system are

Manufacturing: Easy offsite manufacturing. The homes need to be manufactured and assembled by manual labor or minimum machinery, since machinery can be expensive and often unavailable.

Transportation: Within the transportation size and weight limit.

Assembly: Easy assembly with minimum tooling.

The system design should allow Easy Maintenance and repair of the

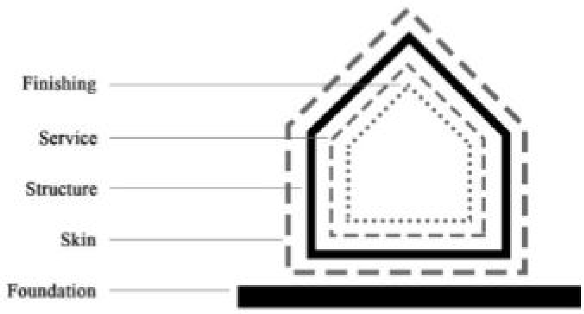


Figure 46 : Figure showing the construction

8.1 GRID AND COMPONENT SIZING:

The grid needs to be developed on a standard global grid module. The prefabricated components need to be manufactured and transported to the site form the factory. Thus the size of the components needs to be standard, easy to handle. The size for the component is directly correlated to the grid of the house. The grid is also an important aspect as it will allow extension of the house only in multiple of the basic grid sizes, spanning capacity of the material and loading above also are important factors in determining the grid size.

Following are the criteria's considered in determining the grid size of the house:

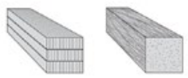
Timber references

Research in timber is advanced and there are several examples of the prefabricated construction using timber as disused in chap ---. The prefabricated timber construction has evolved since history and follows a standard grid dimensions for structural members based on spacing of the structures and openings.
Also the standard prefabricated timber components come in 6-8-10m long components.

standard grid size is **500-600-800 mm.**

Sizes in engineered bamboo components:

In order to gain a practical insight, research was done on the current engineered bamboo components available in the market. 'The data was retrieved from MOSO company who work in design and installation of bamboo structures and furniture.



Dimensions (mm)			
Thickness	55	60	72
Length	2440	2440	2440
Width	55	120	120
Strip width			
Style			
Plain Pressed (PP)	-	-	-
Side Pressed (SP)	•	•	•
High Density* (HD	-	•	•

Standard length of the beam available at MOSO is **2440 mm.**

Shipping data:

Shipping container size
Standard frame size used in the timber Construction
Frame - Panel timber structure :4m -8m
Truck Sizes
10' x 8 ft

Weight Allowance :
11.300kg

2.43 x 2.99 m

Standard House Dimensions

Considerations:
Span: a large floor span to build user-friendly
Target Population based on income group.
Lower Middle class , Middle Class families

Prefabricated / repetitive elements easy to assembled
To be build by local contractors with minimum requirement of machineries.

Minimum standard span

4 x 6 m

Natural bamboo pole size

It is important to understand the available length in Bamboo.The product length is defined based on the uniform strength available in natural bamboo.

Current standard length available **2000- 2500 mm**

Grid size dimensions for a prefabricated component can vary between 2000mm to 2500mm

Table 5:Table showing the a summary of criteria's for determining the final grid size of for the structural system and layout.

8.2 GRID DIMENSIONS AND HOUSES LAYOUT:

From the above analysis a basic grid of 2000 mm was taken into consideration. Considering standard 4m and 6m clear spans and following a standard center to center dimension of 2000 mm a layout is designed. For bamboo beams of more than 4m in length, timber joinery extension techniques like finger, lap joint are used, the downside of this 4 m length is that it makes the component weaker. For better and more accurate results a standard grid of 2000 mm will be followed as much as possible. 2m grid sizes also facilitate further paneling and window and door openings.

All the livable spaces in a house such as living room, kitchen, bedroom, toilet, staircase can be covered within the combination of the 2000 mm grid. Based on the grid and standard sizes for room dimensions, these are basic layout which are possible. Thus, for this research the grid have been analyzed to produce layouts shown below.

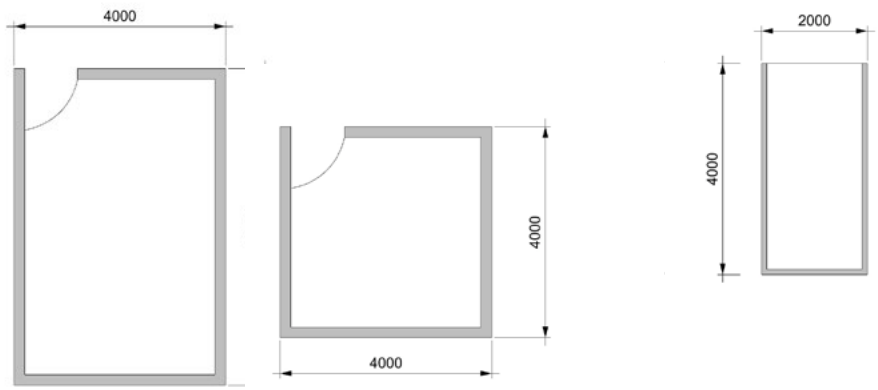


Figure 47 : Drawing showing possible sizes for different types of habitable rooms

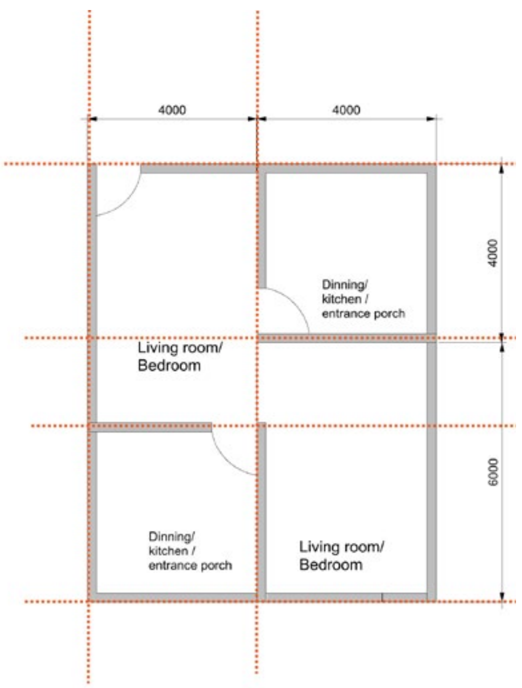


Figure 48: Drawing showing possible floor layout using above configuration.

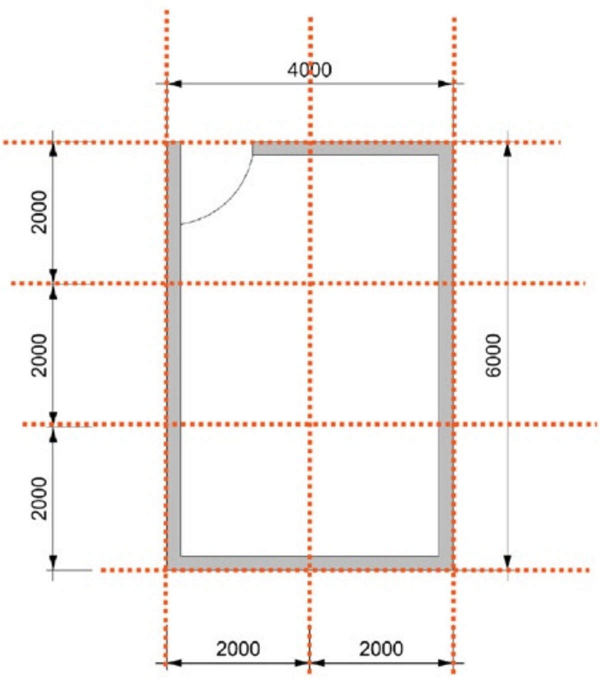


Figure 49: Diagram showing final grid size categorization of 2000 mm

8.3 HOUSE – STRUCTURAL COMPONENTS DESIGN:

The image50 below shows a finalized structural system using frame components is proposed for further designing of the joinery. The facade panel can be installed with the frame or can be installed after the entire structure is erected. The structure should be able to resist lateral loads without installation of the facade frame for lateral support.

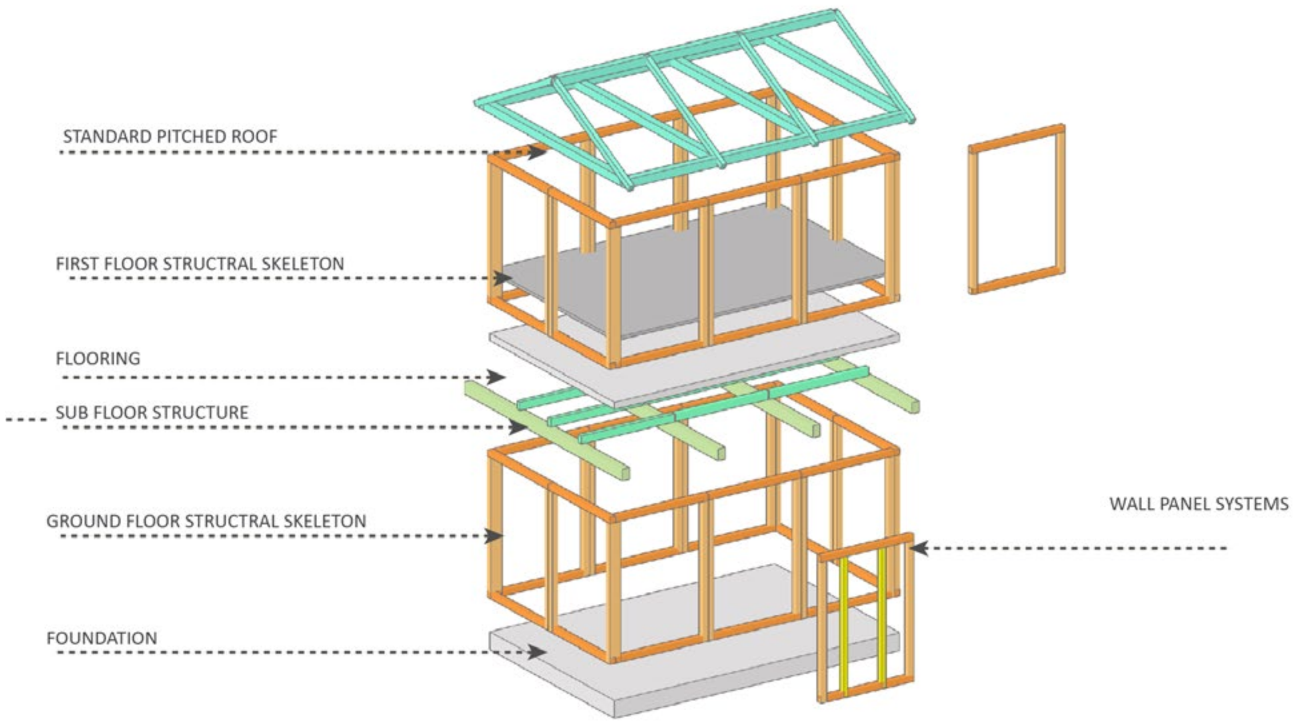


Figure 50: Final structural system comprising of a Frame system proposed.

09 STRUCTURAL LOADING ANALYSIS

09. STRUCTURAL LOAD ANALYSIS:

LOAD CALCULATIONS FOR SIZING OF STRUCTURAL COMPONENTS:

9.1. INTRODUCTION:

After determining the structural system to be used the components which form the main load-bearing structural members are identified. The frames form the most important part of the structure and it is important to determine the sizing of the column and beam based on the load calculations. Also the weight of the prefabricated components play an important role in buildability analysis of the material. There are no fixed standards available for the use of engineered bamboo in structural use like column and beam thus majority of structural sizes and thumb rules are adopted from timber standards. There are two approaches that will be adopted in order to determine structural sizing:

1.References based on timber standards and codes (BS and NEN codes),

2. Evaluating the size based on the test carried out on the engineered bamboo samples (based on the maximum allowable stress values of those samples).

Wind loads, snow loads, live load and self-weight of the structure are taken into consideration. While the seismic loads are not considered in this calculation, due to unknown factors like the location of the housing unit. These factors can be taken into consideration in future references and work on the thesis. The material used for Framing is sourced from Company called MOSO which bamboo-based firm in Nederland's. All bamboo components of MOSO were manufactured in China from MOSO species bamboo. The following data is the detail specification of the material sourced which will also be used in further calculations for structure as well as input for software and e experimental testing of connections.

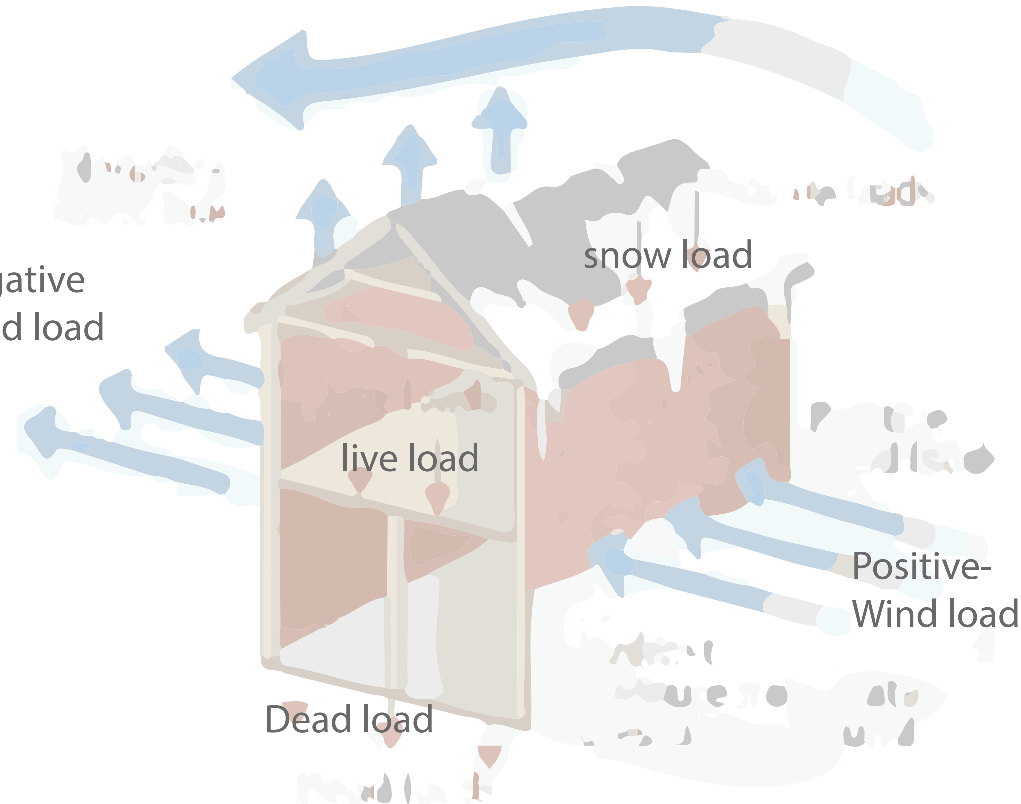


Figure 51 : Abstract figure showing type of loads acting on a typical house

9.2 MATERIAL SPECIFICATIONS:

Type: MOSO* Solid Beam: A is a very regular material in terms of stability and structure and also easy to process. The standard length of the beam is 2440mm but by using finger joints any length can be created.("MOSO International," n.d.)Asshown in fig -- the MOSO® Beams are available in the colors caramel and natural, in the extra hard High-Density ® version (tropical hardwood look - random line pattern).

Natural	Caramel	Style	Construction(mm)	Dimensions (mm)
	BL-DT260-244	HD	1X 100	2440x120x100
BL-DT211-244	BL-DT261-244	HD	1X72	2440x120x72
	BL-DT262-244	HD	1X60	2440x120x60

HD: high density

Table 6: Table showing current available sizes in the Beam("MOSO International," n.d.)

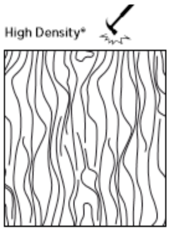


Figure 52 : Showing the Beam and the Grain Pattern. ("MOSO International," n.d.)

Specifications	
Density (Product):	**+/- 1050 kg/m³ (HD)**
Shrink/Swell bamboo	0.14% per 1% change in Moisture Content (SP)
Equilibrium MC	10% at 20°C and 65% rel.
Air Humidity	8% at 20°C and 50% rel.
Air Humidity (SP)	- ≥ 9.5 kg/mm² (HD) (EN 1534)
Resistance to Indentation	
Reaction to fire	Class B-s1-do (HD) (EN 13501-1) not Easily flammable
Formaldehyde emission:	Class E1 (< 0.124 mg/m³) (EN 717-1)
Modulus of Elasticity:)	+/- 12505 N/mm² (HD) (mean value - EN 408
Bending strength:	65.4 N/mm² (HD) (characteristic value - EN 408)
Use Class	Class 1 (EN 335)
Glue:	D3 water-resistant

**CO2 neutral: LCA report TU Delft (ISO 14040/44) (www.moso.eu/lca)*

Table 7: Table showing Material specification for the Moso Bamboo scrimber material used for further calculation Fig : Technical characteristics and certifications for the Sample Material .("MOSO BAMBOO," n.d.)

9.3 DETERMINING THE LOAD CASE:

A basic structural member sizing is considered based on the preliminary concept design inferred from current available sizes and Timber Construction Technology Studied in the chapter 3. The main concept of the design the structural sizing is assumed based on the timber standards for sizing for a G+1 structure.

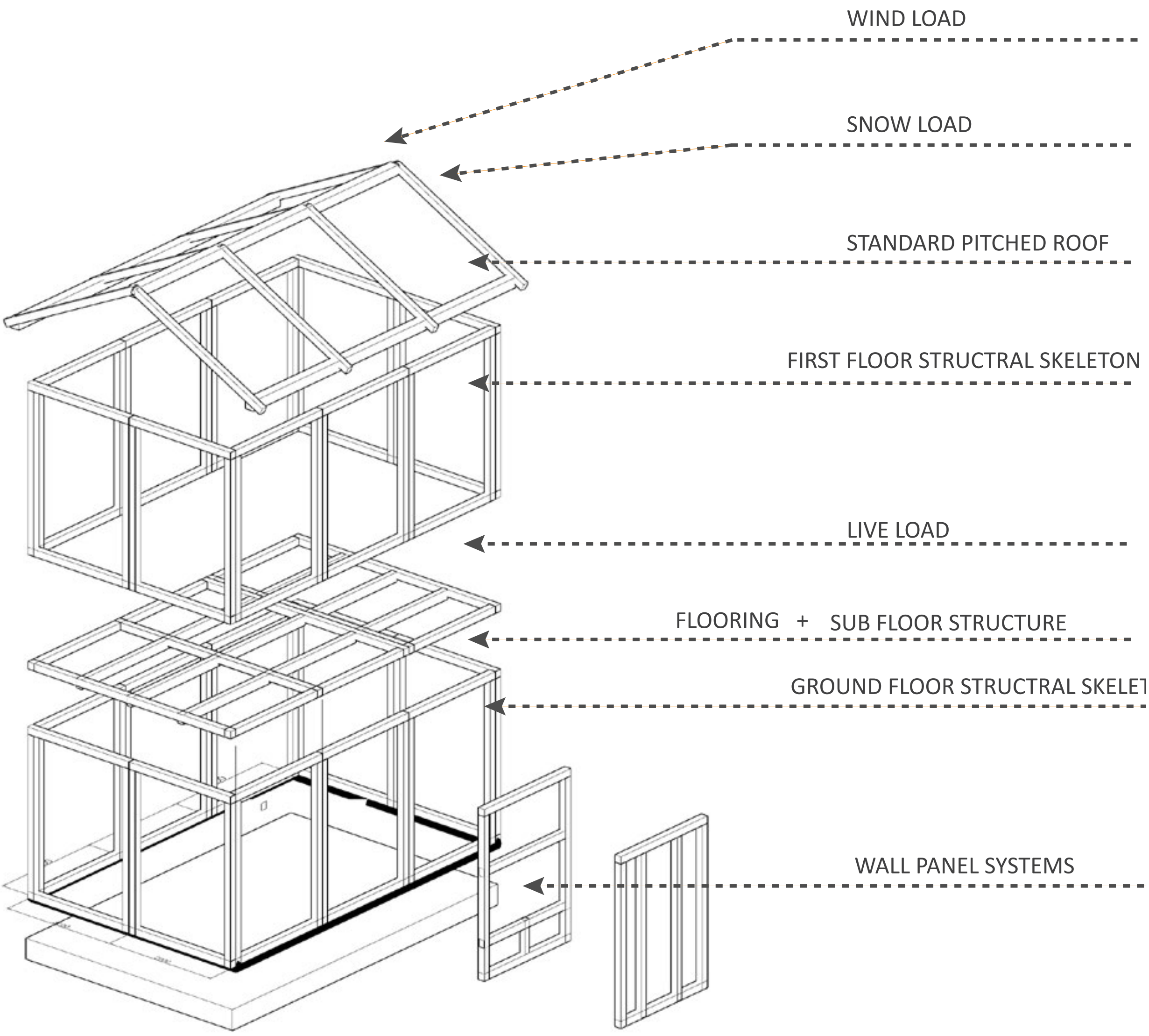


Figure 53 :Load Diagram for calculation for dispersion of weight.

Component 1: FRAME

The frame forms the most important structural aspect of the Design. The frame is comprised of 2 sets of columns and Beams. The beams in frame will act as primary Beam. The standard column size is assumed for first iteration based on references from Timber construction. As per standards of timber structural system, the structural system and testing the frame structure will be Investigated for

Bending strength

Maximum horizontal Shear

Deflection

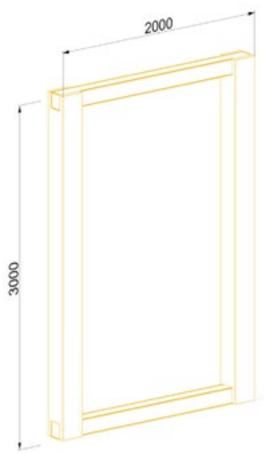
COLUMN	Size	**200mm x 200mm**	
	Volume of each column= cross-sectional area x length	200 x 200mm x 2940mm **=11760000 mm3** ==0,01176 m^3	0.1236 KN
	Self-Weight = Volume x Density	0,03528 x 1050	
	Self-Weight of one column	**12.6 kg**	
BEAM 	Size	**140mm x 120mm**	
	Volume of each Beam = cross-sectional area x length	140 x 120mm x 2000mm **=336**00000 mm3 =0,033 m^3	0.03452 KN
	Self-Weight =Volume x Density	0,033 x 1050	
	Self-Weight of one Beam	**3.52 KG**	
FRAME 	Total Weight of ONE Frame: Self-Weight of one column x2 + Self-Weight of one Beam	**16.12 KG**	0.1581 KN

Table 8: Table showing calculations for the total self-weight of frame component .

Component 2: FLOOR

Assuming a grid size of 2000 mm, based on the size of the frame. The floor consists of primary Beam, secondary

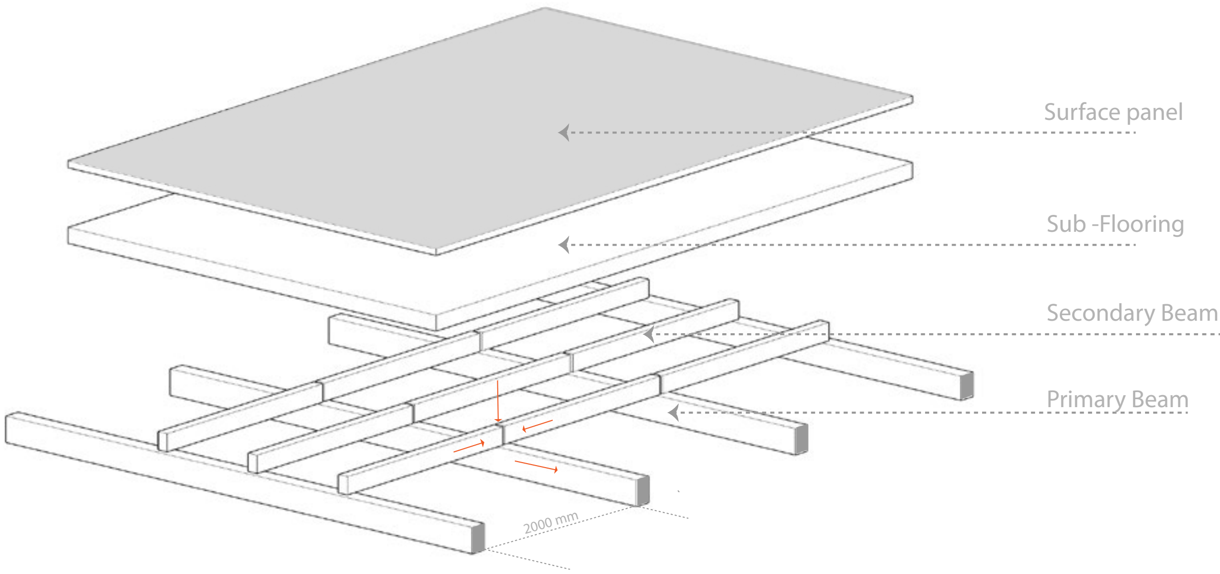


Figure 54 : Diagram showing the composition of the floor structural members.

FLOOR Size -4000 x 6000 mm			
Type	*Volume of each beam: cross-sectional area x length*	*Self-Weight =Volume x Density(kg/m³)*	*Dead load (KN)*
Primary floor beam(short)	120 x 100mm x 4000mm x 4 =0.26 m³	= 0.26 m3 x 1050 = **282.24 Kg**	**6.104 KN**
Long primary beam (6000 mm long)	120 x 100mm x 6000 mm x 2= = 0.144 m³	=0.144 m³ x 1050 = **151.2 kg**	
Secondary floor beam	100 x 100 x 2000 x 9 = 0.18 m³	= 0.18 m³ x 1050 = **189 kg**	
Floor Panel	2000 x 4000 x 100 x3 =2.4 m3	=2.4 m3 x 700 **1680 kg**	**16.48 KN**
Total Load of slab		**2302 KG**	**22.584 KN**
*Safety factor of 2 is considered			**45 KN**

Table 9: Table showing calculations for the total self-weight of the Slab .

beams and flooring material: floorboard in this case.

Component 3: wall panel

The wall paneling will act as additional bracing to the existing framework. The idea is to keep the wall panel separate for ease of construction, replaceability and also for easy adaption based on different geographical location and climatic conditions. Certain assumptions are made for load calculations of the wall Panel. It is assumed that wall panel is a CLT wall panel with a destiny of 40 kg/m² .The panel includes diagonal bracing and beam and window opening.

Component 4 : ROOF

A standard timber pitched is considered for load calculations *Standard Specification for timber Pitched Roof.

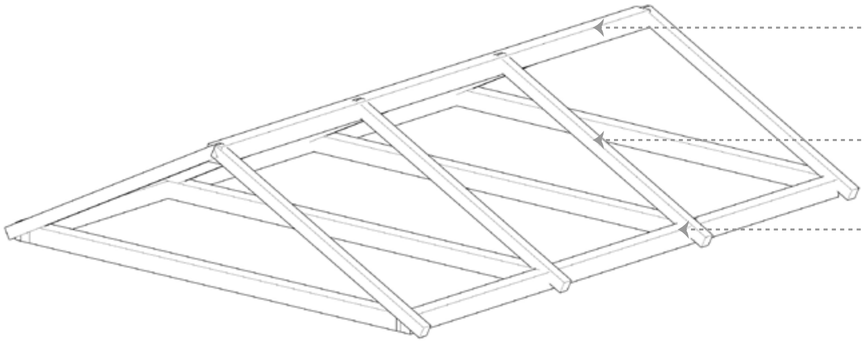


Figure 55 : Diagram showing the composition of the Pitched roof structural members.

WALL PANEL Size =3000 x 2000 MM			
Type	*Volume of each beam: cross-sectional area x length*	*Self-weight =Cross-section area x density*	*Dead load (KN)*
Wall Panel first floor	3000 x 2000x 10 =60000000	40 240 Kg	23.54 KN
Total Number of Panels on ground floor	3000 x 2000x 10 = 60 m³	60 x 40 240 kg	23.54 KN
Safety factor of 2 for each floor			**47.54 KN**

Table 10: Table showing calculations for the total self-weight of the Wall Panel .

Cross's sectional area of Roof =4000 x 6000 mm =24 m²

Total Weight of Rafters	*(Timber Trussed Rafters)	0,25 *kN/m²*	6 KN
Total Weight of Ceiling Joist	(*Ceiling Joists)		2,4KN
Total Weight of Roof cover	(*9.5mm Plasterboard + Skim)		3,6KN
TOTAL ROOF WEIGHT			**12 KN**
Safety factor: 2			24 KN

Table 11: Table showing calculations for the total self-weight of Roof.

Component 5 : Snow load and Wind Load

The snow load and wind load can differ a lot with the region. For the calculations simplicity snow and wind load based of Nederland's are assumed. According to Dutch National Annex of NEN-EN 1991-1-3 the complex calculations are substituted by one value for the whole country (s, = 0,7 kN/m2). For other countries and areas respective country codes need to be consulted.

Snow can cause considerable loads, as it doesn't run off like rain. It is therefore important to check whether a load combination containing snow loads is leading

Snow load is given by :

S= J.l; c_e. c_t . $s_{k,}$

Where, S= Characteristic value of the snow load on the ground [kN/m²] (0.7 kN/m² in the Netherlands), Shape coefficient, depended on roof angle, c_e = Exposure coefficient (1 ,0 for most cases) c_t =Thermal coefficient (1 , 0 for most cases)

= 0.8 x 1 x 1x 0.7 = 0.56 N/m²

From Table, ----- Total roof area is 24 m²'

=0.56 x 24 = **13.44 KN**

For design purposes a simplified version of the code such as the one below is used. For a detailed analysis or for building with an irregular shape, r regional national codes for definite wind values need to be referred.

Wind load is calculated as follows:

$F_i = A_{ref} \times C_e \times C_{d} \times C_{f} \times q_{p}(z_{e})$

= 24 x 1 x 0,8 x 0.98 = **18 .816 KN**

Where, F =Wind force on a structure or structural component [kN), A = Reference area on structure or structural component (m2] Roof area is considered for wind load, C_f = Force coefficient for structure or structural component[-],$C_e \times C_d$ = Structural factor' [-], $q_p(z_e)$ = Peak velocity pressure at reference height z. [kN/m2]. 1

Assumptions

1, The structural factor $C_e \times C_d$ can be taken as 1 for regular, low-rise buildings, as per NEN-EN 1991-1-4

2. Force coefficient for structure : The force coefficients corresponding to the different wind zones depend on the geometry of the building.

Building parameters

h = highest point of building [m] = 7.6 m , d = dimension in wind direction[m] = 6 m , b = dimension in crosswind direction = 4 m, e = b or 2h, whichever is smaller = 4 m

Based on the Wind Zone Table from NEN codes , Refer appendix , $C_{f = -}$0,8

3. Peak velocity pressure at reference height F z

Based on the Wind Zone Table from NEN codes , Refer appendix , for $z_{e =}$ 8 m , $q_p(z_{e})$ = 0,98 , Assuming mid-level wind pressure in rural areas.

Component 6 : LIVE LOAD

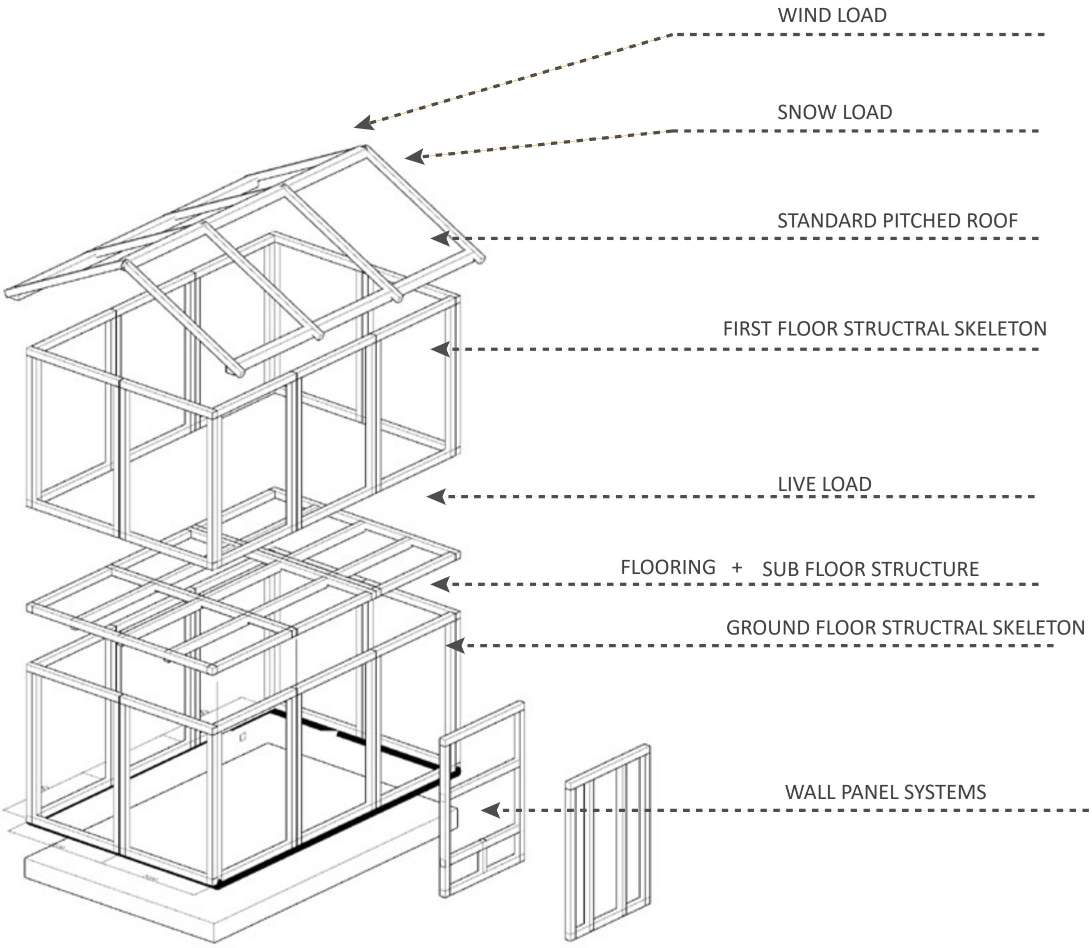
The value of uniformly distributed loads for corridors, passages, staircases including fire escapes and storerooms, which is maximum under the residential buildings has been considered for the overall purpose of load design, however prescribed loads for room is 2 KN/m2. (National Building Code, Table 1 (clause 3.3.1)("Krittika Agarwal | 1," n.d.)

Total First Floor area : 4000 x 6000 mm =24m² = 24 x 2 kn/m² =**48 KN**

Total load summarized :		*KN*	
Wind load		**18 .816 KN**	
Snow load		**13.44 KN**	
Live load		**48 KN**	
Roof		**24 KN**	
First floor	Frame : 1,221 x 10 =12.21 Wall panel =240 x 10 = 23,53	**35.74 KN**	*139.99 KN*
Total slab load		**45 KN**	*184 .99 KN*
Ground floor	Frame : 1,221 x 10 =12.21 Wall panel =240 x 10 = 23,53	**35.74 KN**	
TOTAL LOAD		**220 KN**	

Summarizing Total load Case on the structure refer Figure 53

Table 12 : Summary of Total load acting of the structure and diagram showing stages of loads for further calculations.



9.5 COLUMN STRUCTURAL SIZING:

Figure 56 shows the composition of the structural system, where the slab and beam rest on the column. The load from the slab and beams are transferred into the column. It is important to note that for calculation the central column along the longer 6m length is considered as it carries maximum load compared to the column in the perimeters.

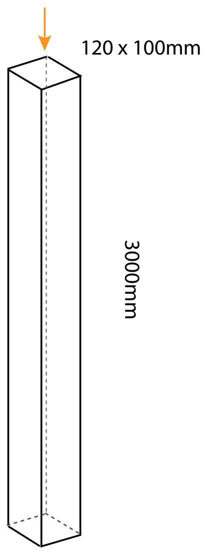
Although the column is essentially a compression member, the manner in which it tends to fail and the amount of load that causes failure depends on:

1. The material of which the column is made.
2. The shape of the cross-section of the column.
3. The end conditions of the column.

It is assumed that the beam directly rests on the column and the connections are pinned connection. For the ease and rough idea of calculation the modifications factor are referred from timber structural standards described in the appendix section –

Solid columns shall be classified into short, intermediate and long columns depending upon their

slenderness ratio (S/d) as follows:



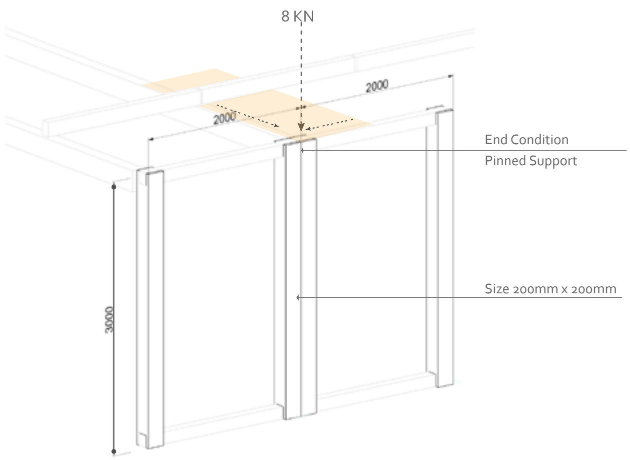


Figure 56 : Diagram for column size and the area of Load acting on the column

Size	D =160mm	D =180mm	D =200mm
S/d slenderness ratio S=3000mm	18.75	16.6	15
Classification of columns based on k_g value	Long column	Long column	Intermediate column
	11<18.75 >15.1	11<16.6 >15.1	11 <1 5 <15.1
Fc_c in N/mm²	3.83 n/mm²	9.34 N/mm²	12.4 N/mm²

Table 13: Table showing slenderness ratio for different Column sizes

a)Short columns — where S/d does not exceed 11.

b)Intermediate columns — where S/d is between 11 and K_g,

c) Long columns — where S/d is greater than K_g.

According to Fig---- S/d= 3000/200 = 15...........................(1)

k_g is constant which depends on the slenderness ratio and the material used.

Size	D =160mm	D =180mm	D =200mm
Cross sectional area	26500	32400	40000
Allowable load = F_c *cross section	101495 =10.1 KN	318816 =31.8KN	49.6 KN
Safety factor compared to actual load on the column whixh is 8KN	1.2	3.9	6.2

Table 14: Table showing calculations for final allowable load for different Column sizes

$K_{g=}$ 0.584 √E/f_{cp})

Where, E = Modulus of Elasticity and F_{cp} is the permissible stress in compression. From Table ---

E=12505 N/mm² and $F_{cp=}$ 18.5 N/mm2.

=0.584 √(12505/18.5) =

K_g =15.1

24

....eq (2)

For intermediate columns, the permissible compressive stress is calculated by using the following formula:

$f_{c=}$ f_{cp}[1- 1/3 (s/dk_g)⁴] ....eq (2)

Where, $F_{cp=}$ 18.5 N/mm2,

= 18.5[1-1/3(3000/200)⁴] = =12.4 N/MM2

Allowable load is Fc * Cross section area

= 12.4 x 200 x200=496000 = 49.6 KN

For example :Actual Load on the column is 8 KN.So the compressive strength in the chosen cross-section willbe

σ_c= F/A

=8000/

=0.2 Mpa................which is much less than allowable.

9.6 LOAD CALCULATIONS FOR BEAM:

As shown in Figure 57 Beam which is part of the frame form the primary beams in the Structure. It is assumed the structure needs to be stable and withstand the Maximum load without any need of wall panel. The panels which will form additional bracing. The highlighted beam along the longitudinal length of 6m is taken to consideration as the Central beam will take higher load compared the perimeter beam (including the weight of the roof and support reaction from adjoining beams)

The Beams are investigated for the structural sizing and safety limit towards the span of 2000 mm which is already defined based on the material availability and Grid dimensions above. The general design criteria for Beam is dependent on:

Magnitude and type of loading

Duration of loading

Clear span

The material of the beam

The shape of the beam cross-section

Based on the load calculations the Beam will be investigated for

Bending strength

Maximum horizontal shear

Deflection

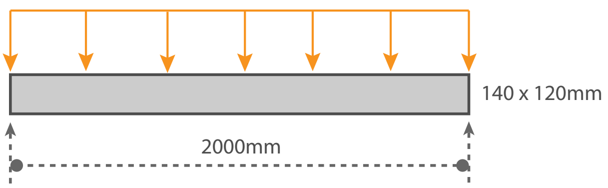


Figure 57: Structural Diagram for loading of beam

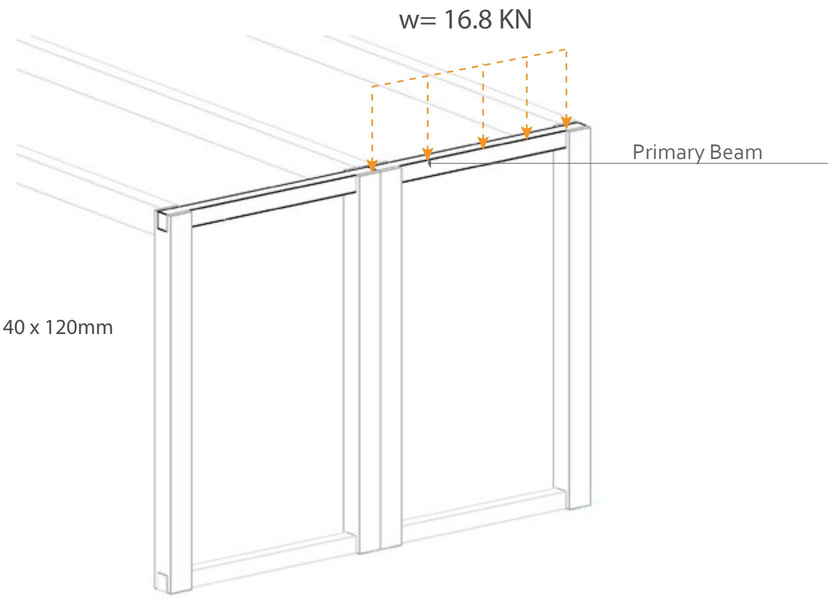


Figure 58: Structural Diagram for loading of beam

9.6.1 Permissible Stresses

As discussed earlier in assumptions there are no fixed standard permissible stress values available for use of Bamboo for structural purposes. There have been some attempts to calculate values for engineered bamboo based on the timber standards. These values cannot be completely relied upon and further research is required, but for current research calculations these values are expected to give basic idea of the structural behavior of Bamboo beam. In future, further more detailed research is required for actual implementation.

When compared to values for the timber the strength values of Bamboo are high for the facts that there are very low natural defects in bamboo scribers as knots crackle etc.

The following table is a compilation of values from timber and from the research done on a Bamboo scrimber beam.

Material Strength Character	**Timber (Minimum permissible)**	**Timber Permissible stress)**	**Bamboo scrimber (Maximum permissible)**	**Bamboo**
Density	**815**	**815**		
Bending and tension along grain	12.0	18.2	25	
Shear 2) Horizontal	0.64	1.4	7.5	7.5
Along grain	0.91	2.0	7.5	7.5
Compression perpendicular to grain	7.8	10.1	18.5	
Compression parallel to grain	2.5	4.4	35	21
Modulus of elasticity (×103 N/mm2)	9.8	12.56	13	9
Flexural			39.66	

Table 15 :table showing compilation of values from timber and from the research done on a Bamboo scrimber beam.

The values of horizontal shear to be used only for beams. In all other cases shear along grain to be used.

Fig Minimum Permissible Stress Limits (N/mm2) of Structural Timbers and Bamboo Scrimber

Effective Span :

The effective span of beams and other flexural members shall be taken as the distance from face of supports plus one and half of the required length of bearing at each end except that for continuous beams and joists the span may be measured from centre of bearing at those supports over which the beam is continuous.

9.6.2 Flexural Strength :

The maximum compressive stress (fc) will occur in the cross-section area of the beam where the bending moment (M) is greatest. Size and shape of cross section, i.e. its section modulus (Z), must be selected so that the fc does not exceed an allowable value.

F_{ab} M/Z ≤ f_b

Allowable working stress values are currently referred from the test carried out on the Bamboo specimen.

where:

f_{ab} = allowable bending stress , f_b = actual bending stress, M_{max} = maximum bending moment , Z = section modulus

Form Factors for Flexural Members

Square Cross Sections — For square crosssections where the load is in the direction of diagonal, the form factor KG shall be taken as 1.414.

M_{max} = WL/8 = 16800 x 2000 /8 = 4200000 N mm

Where L= 2000 mmm, W= 16800 N, Beam cross section : 120x 140 mm

Z =bd²/*6 =(140* x120)²/6 = 392000

So,

F =M/Z = 8400000/392000 = 25000

= 10.7 N/mm²

According to table----- the maximum allowable bending for a bamboo scrimber is 25 N/mm2

In this case f > f_b , actual bending stress is much less than allowable bending stress, thus it is safe with respect to flexural load.

9.6.3 Horizontal shear

The horizontal shear force (Q) at a given cross-section in a beam induces shear stress that acts tangentially to the horizontal cross-sectional plane.

The maximum horizontal shear, when the load on a beam moves from the support towards the centre of the span, and the load is at a distance of three to four times the depth of the beam from the support, shall be calculated from the following general formula:

For rectangular beams:

H = 3V / 2bD

Where,

V -Resultant shear force ,b – Beam Width = 120 mm , D = Depth of the cross section = 140mm

For Uniformly Distributed loads resultant Shear force:

V =W/2 [1 – (2D/l)] ....eq (4)

Where,

W: UDL acting on the beam in N = 16800 N, D- Depth of the cross section = 120 mm

L – length of the beam = 2000 mm

Thus

V = 16800/2 [1- (2x 140/2000)]

= 6212.64 N/ mm2

Substituting values of V

Horizontal shear Stress = 3 *7392/2*120*100 ....from eq (3)

H = 5.547 N/mm²

According to table ---- a safe permissible shear stress for Bamboo Scrimber is 7.5 N/mm2 , thus actual Horizontal shear is within limits. **9.6.4 Maximum Deflection**

Most building codes limit the amount of allowable deflection as a proportion of the member's length, i.e. 1 /180, 1 /240 or 1 /360 of the length.

Thus ,allowable deflection can be defined as

Span/ 240 =2000 /240 =8.3 mm

Maximum allowable deflection he the Beam is 8.3mm

Usual formula for deflection is given by:

δ = K x(WL^3/ EI)

(ignoring deflection due to shear strain)

where: δ_{max} = maximum deflection (mm), K_c = constant depending on the type of loading and the end support conditions = For UDL loaded simply supported beams: 5/384

Load Calculations

Self-weight of the beam + load on Beam

W = total load (N) = 16800 +360 = 17160

L = effective span (mm) = 2000, E = modulus of elasticity (N/mm²) = 13000

I = moment of inertia (mm4) = 27.4 x 10^6

Deflection is greatly influenced by the span L, and that the best resistance is provided by beams which have the most depth (d), resulting in a large moment of inertia.

=5/384 * 17160* (2000)^3/13994* 27.4*10^6

2.68 mm

The Permissible deflection is higher than actual deflection which is 2,68 mm < 8.3Mm

10 CONNECTION DESIGN

10.CONNECTION DESIGN

10.1 INTRODUCTION:

Joinery is said to be the heart of any structure. Most failures that occur in timber frames, new and old, are at the joints. Rarely does a timber break in half. Irrespective of how strong the material is the way these materials are connected defines the strength of a structure. Also in a loadbearing structure, the joinery takes the majority of the load(Sobon, Jack A., 1984)

In the course of time, a number of joints have been developed to connect natural bamboo poles together and since the development of an engineered form of Bamboo, there has been continuous research and updates on designs on connecting these engineered advanced forms together. Additionally, The joinery from timber construction forms the main Source of inspiration for these developments in joinery. It has been observed that it is not always that the joinery being adopted from the timber construction is the most appropriate for connecting engineered bamboo.

Unlike steel construction where connections are welded, or reinforced concrete construction where beams and columns are poured, like timber design requires that a portion of each timber be cut out to receive the other, same applies to Bamboo , as the main characteristics for Bamboo working as still like timber

Thus, it has been noted that Irrespective of the success in altering the properties of Bamboo suitable for construction, the relationship between new components, connections and structural performance of theses connections remains unexplored developing a gap in research of design feasibility and strength of connections when these materials are put to structural use.

Thus this research intends to understand the working of material holistically (based on the fallback and positive aspects of connecting the material) and Additionally analyze and learn from what has been done before, in terms of traditional bamboo connections and modern bamboo connections.

The research also briefly intends to understand the traditional and modern connections using timber, as they can already give an understanding of the connections systems.

The design of efficient simple connections using bamboo becomes an essential factor in the prefabricated system and construction making it important to analyze factors which would affect the performance of the connections.

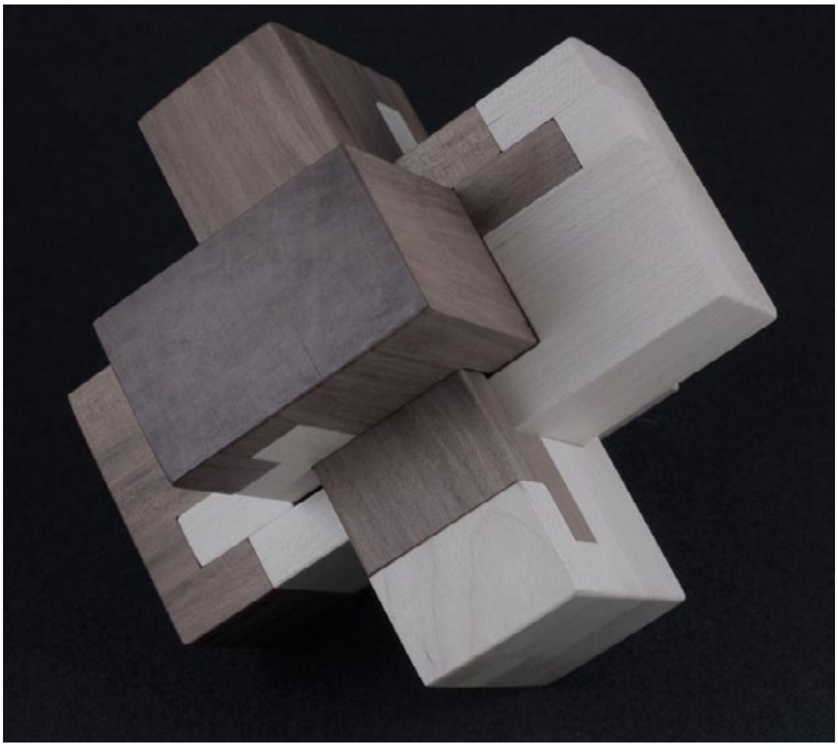


Figure 60: Inspiration from Japanese joinery system

"The techniques for constructing wooden buildings in the past greatly surpass those of today" - Shoji Matsuura

10.2 DESIGN METHODOLOGY:

A systematic design approach is given in Figure 11. The actual application of the approach is discussed in further chapters.

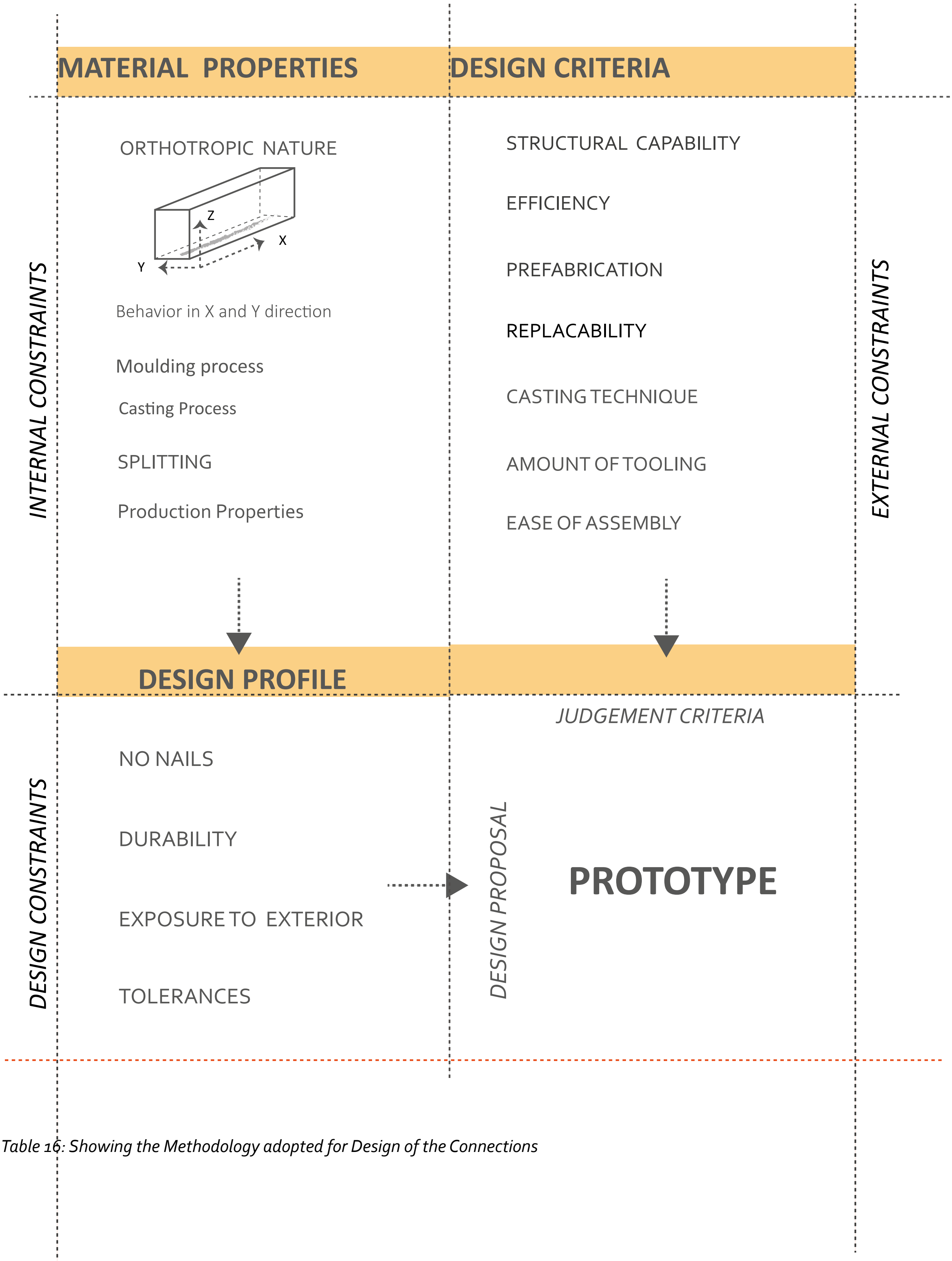


Table 16: Showing the Methodology adopted for Design of the Connections

10.3 ANALYSIS FOR FEASIBILITY OF CONNECTIONS:

The following section briefly discusses the design principles and design constraints to be considered.

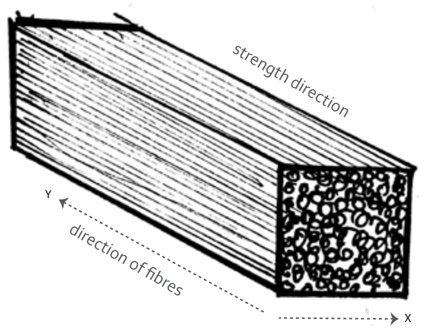
INTERNAL CONSTRAINTS

Analysis of Material properties.

As discussed in chapter 4 bamboo properties possess some different characteristics than wood and thus for using the materials right, right of methodology for connections would take understanding some important aspect of the material. Here is a summary of internal constraints which need to be understood before designing with the material.

Orthotropic nature

The engineered material almost behaves similar to a natural Bamboo Pole. As discussed before, bamboo behaves like an Orthotropic Material, which means it behaves differently in X and Y direction. The figure shows that orientations and direction of the fibers becomes a very important factor in design, as the properties may vary a change in the orientation. The engineered composite like natural bamboo is unidirectionally reinforced, with less shear strength and little tensile capacity in the direction parallel to the grain.



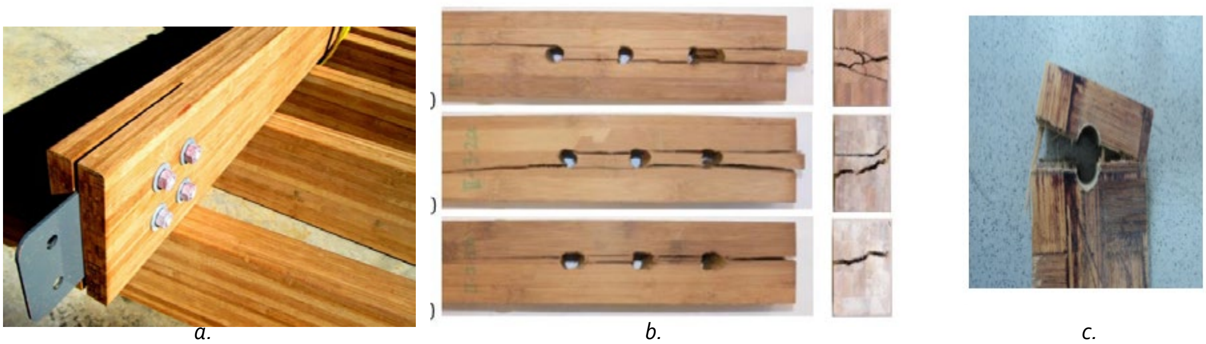
The engineered composite like natural bamboo is unidirectionally reinforced, with less shear strength and little tensile capacity in the direction parallel to the grain.

Figure 61: Figure showing direction and placement of Bamboo fibres

Splitting

To understand the splitting phenomenon some the existing joinery connections were studied. For Example, refer fig 62In traditional joinery, the lashing technique is one the most common and the whole reason to lash is horizontal splitting. The modern bamboo connections techniques are usually inspired from timber joinery, The most common method adopted as shown in fig: is screwing through the material, which results in failure due to splitting.

In the Bamboo Scrimber beam, the arrangement is such that, the Bamboo fibres are arranged longitudinally in length. Introduction of metal fasteners / drilling a hole through the material may cause splitting of the material across the length. As discussed in chapter 4 the node is the strongest due to the higher density compared to the culm, thus in case of drilling holes, it is important to drill holes close to the node and use the strong spots.



a. *b.* *c.*

Figure 62: a.An image showing typical method of connection Bamboo components b.diagram showing the arrangement of fibres and splitting analysis when a hole is drilled. C.A diagram showing the splitting of natural Bamboo beam
(Xiao, Shan, Yang, LI, & Chen , Glue Laminated Bamboo (GluBam) for Structural Applications)
https: //continuingeducation.bnpmedia.com/article_print.php?C=1548&L=517

Some of the solutions to be considered while designing are The option of using wood or bamboo inserts instead of metal. Arrangement of fibers in a particular way to avoid screwing while assembling the structure would give better results, as drilling holes may create shear failure resulting in the splitting of bamboo along its longitudinal length.

'The Problem of splitting across the cross-section still remains '

Design considerations with respect to material Properties :

For longer durability of the material, keep the bamboo away from the ground to prevent moisture entering the material.-Which can be done by providing some form of concrete / steel casing or foundation before it comes in contact with the ground. It is also helpful to cover the structural components using external cladding

EXTERNAL CONSTRAINTS :

Certain design criteria's need to be take into consideration for effective design of joinery.

Based on Material feasibility

Maximization of the use of bamboo structural capacities: The orientation of the beam parallel and perpendicular to grain can change the capacity of the material.

Cost-effectiveness :Connections are one of the highest cost components in a structure. For example with simplicity and repetitive connections, the structural costs can marginally go down.

Replaceability

When working with a natural material, there is always a small percentage of uncertainty in terms of performance and durability, thus in case of failure of any component, the failed component should be easily replaceable without disturbing most of the structure.

Stability and durability

The connections should be stable in relation to time. The design must take durability into account, in terms of life expectancy of the connections. The maximum percentage of engineered bamboo is still in natural form, which means the material would still need extra care when subjected to extreme weather conditions.

Simplicity

In terms of skill and equipment's required which are involved in the production. These conditions are very important because solutions to a building problem may sometimes involve unskilled labor. Thus simplicity can also affect cost-effectiveness. Minimizing the amount of tooling required.

Strength predictability

There is no literature available for the design of connections as a thumb of rule. Thus the analysis needs to be done on the analysis in software or by prototyping and physical testing.

Prefabrication

Connections should not be complicated. The idea is to make easy to assemble connections which facilitate prefabrication based on easy manufacturing and assembly.

DESIGN PROFILE:

The analysis of internal constraints indicates that certain elements should be present in the design profile.

No penetration in terms nailing/ screwing or bolting

As indicated before the uses of pins screws bailed entails some drawbacks and poses more disadvantages to the structure The argument made above also explains why traditionally the original natural bamboo has been commonly connected using ropes. Thus with restriction screwing, there some very apparent restriction on load transfer.

Shape

The casting process in the material allows modifications in terms of shaping of the beam within limitations of casting.

Tolerances

Standard permissible tolerances used in timber joinery are followed. Permissible tolerances in measurements of cut sizes of structural timber are as follows:

For width and thickness:

Up to and including 100 mm = 0 3– + mm

Above 100 mm =3 6– +mm

10.4 DESIGN OBJECTIVE:

Innovations in an engineered form of bamboo have opened new horizons for bamboo construction. Historically, there are have been numerous examples of the use of interlocking joint in low rise structure built-in Timber. Referencing from historic timber structures which feature joinery connections which geometrically interlock, are rarely seen in modern construction methods which uses steel fasteners for connection details.

Use of interlocking joint can be seen in Japanese carpentry which is strong as well as they help in earthquake resistance. Today the use of interlocking connection can be seen in contemporary works of Kengo Kuma and Shigeru Ban. Timber frame specialists typically build such joints at the low-rise residential scale, relying on a combination of traditional craft and modern specialized analysis. (FANG & MUELLEr)

With the analysis above and research on Japanese Timber joinery connections in Chapter ___ in the literature review, the idea is to develop connections inspired by timber and specifically Japanese interlocking wood joinery. The potential benefits of using these joinery connections in mid-rise scale buildings are multifaceted. With biological properties of bamboo: ability to split easily using as fewer metal connectors as possible is beneficial The elimination of metal joints could further drive down the embodied energy of structures. (FANG & MUELLEr)With innovations in production techniques, the cost of casting these joint to form may become competitive to CNC milling and cutting techniques.

Summarizing Design objective

Explore and design the interlocking connections in bamboo-inspired from techniques used in timber construction, evaluate the prefabrication feasibility and test structural capacities of these connections.

In Further Chapter :

The Design will be evaluated based on

1.Evaluation criteria (Table established above)

2.Analysis of design profile

3.Prototyping (Within limitations)

4.Testing:

a. Experimental

b. Using Software (ANSYS)

10.5 DESIGN AND EVALUATION:

Joinery evaluation :

In order to compare different design options for connections, the following table 17 will be referred which based on the parameters explained above, so that the decisions on the quality and functionality of the design can be made effectively. At the end of the assessment of the different joinery, a final design proposal will be proposed.

01 MATERIAL ANALYSIS Physical Material Properties	CASTING PROCESS Mould simplicity Cast connections in place Primart moulding process Complexities would involve undercuts , secondary level of processing techniques	
02 STRENGTH ANALYSIS Physical Material Properties	DIRECTION OF FIBRES	Parallel
	TYPE OF CONNECTION	Parallel
03 PRE-FABRICATION	ASSEMBLY EXPERTISE Assembly expertise willl be decided on the the skill of workmanship and amount of tooling and equipments required.	WORKMANSHIP SKILL TOOLING
	MODULARITY A joinery module which repeats will be cost effective easy to transpot and assemble.	LEVEL
04 STRUCTURAL SYSTEM	POSITION IN THE JOINERY The position of he joinery in the structural system will determine the number of connecting members and the loading condtion.	
	ESSENTIAL CONNECTIONS	NUMBER OF CONNECTING MEMBE
05 LOAD CALCULATIONS AND STRUCTURAL STRENGTH	CONNECTION STRENGTH Connection strength based on strutural analysis for deflection , shear and bending done using experimental tesing and is the software ANSYS.	ANSYS EXPERIMENTAL

Table 17: Table showing criteria for analysis and validation of further joinery designs

10.6 IMPORTANT AND ESSENTIAL

CONNECTIONS:

When designing the connections it is important to simplify the connections as much as possible. The idea is to test the feasibility, workability and strength of the connection. Thus simplifying the joinery would help in a design by research approach and would further help in elaborating the connections with more number of components Based on the system chosen the basic connections are outlined. Basically there are three -four types of connections which are required to build the house with the engineered bamboo: **Afte**r the basic connections are established the connections would need to be elaborated based the number of components joining.

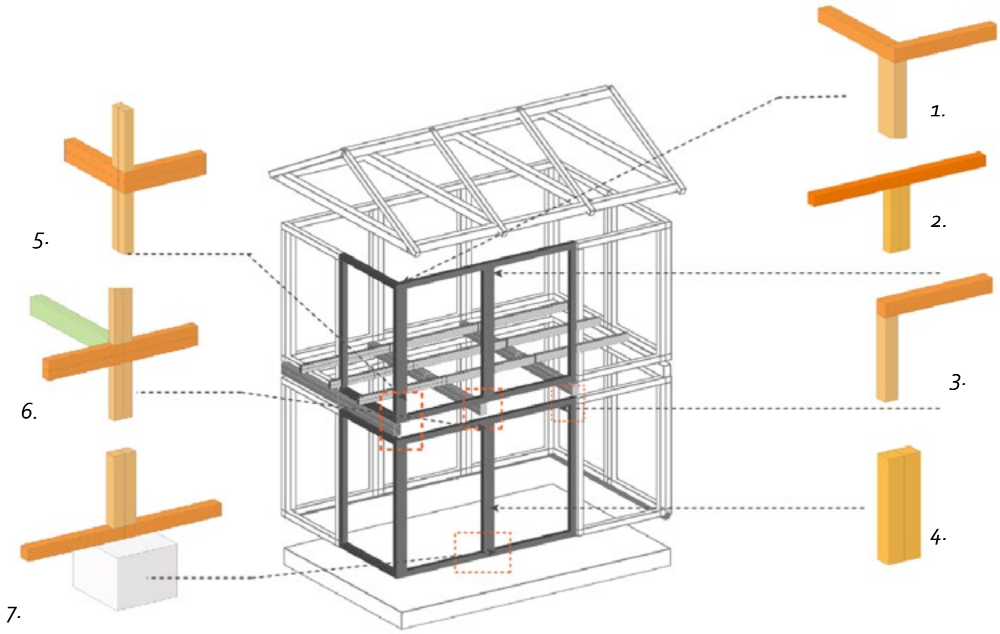


Figure 59: Diagram showing placement and essential connections to be designed

Basic /essential connection to connect frame components to each other

1.Corner connections Perpendicular connection between two frames

2.Connection of two frames in parallel direction connection between beams

3. Connection of frame component in Perpendicular direction

Further elaboration of connections :

Furthermore after the basic connections are established the connections would need to be elaborated based the number of components joining

4..Connection of two frames in parallel direction Connection between post/ column

5.Connection of frames and floor members in parallel

6.Connection of frames and floor members - Perpendicular

10.7 DESIGN EXPLORATION

The initial designs are explored through sketching and prototyping based on the understanding of the traditional timber joinery design.

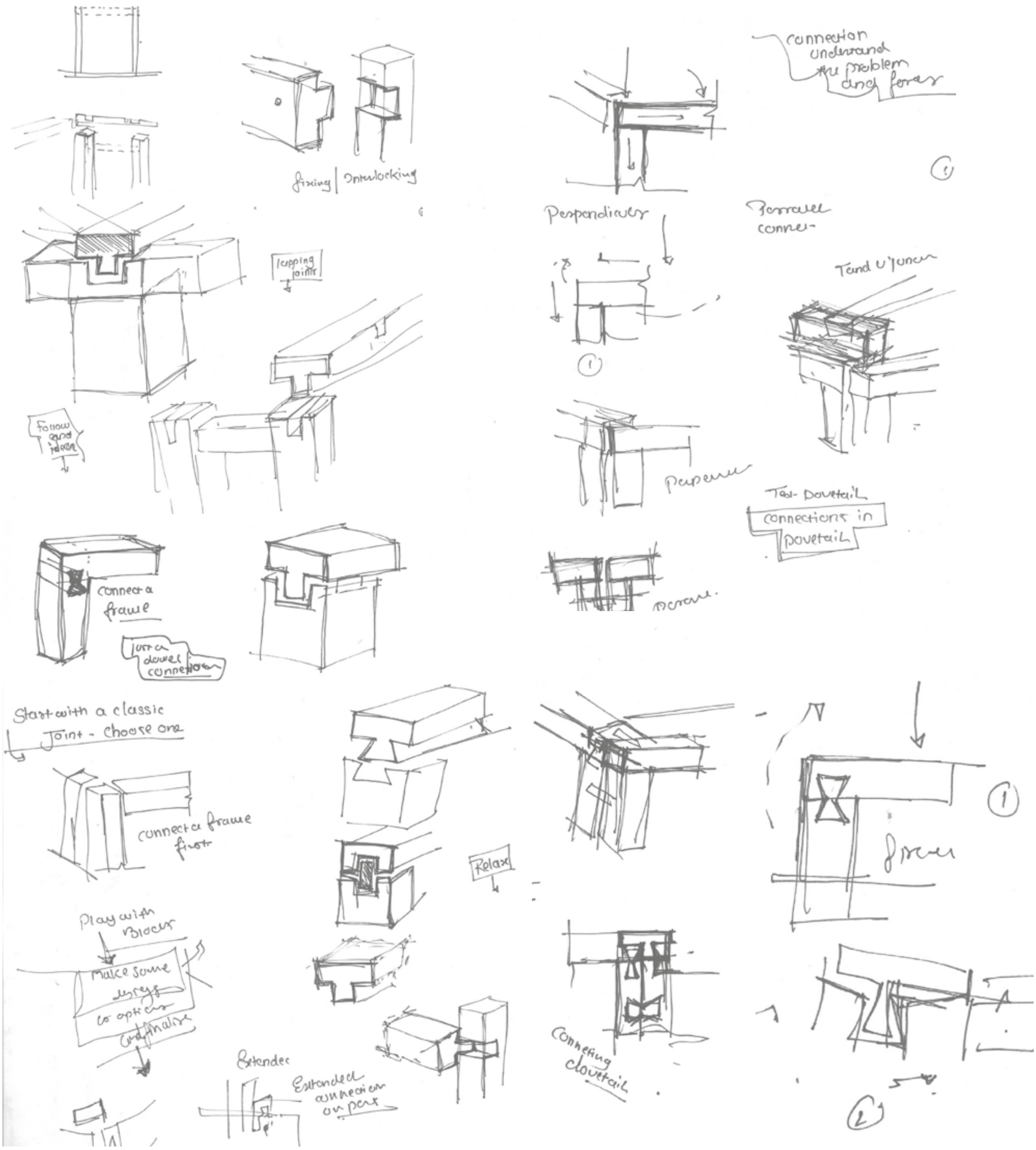


Figure 63: Figure showing Various design options explored through prototyping using foam and sketching

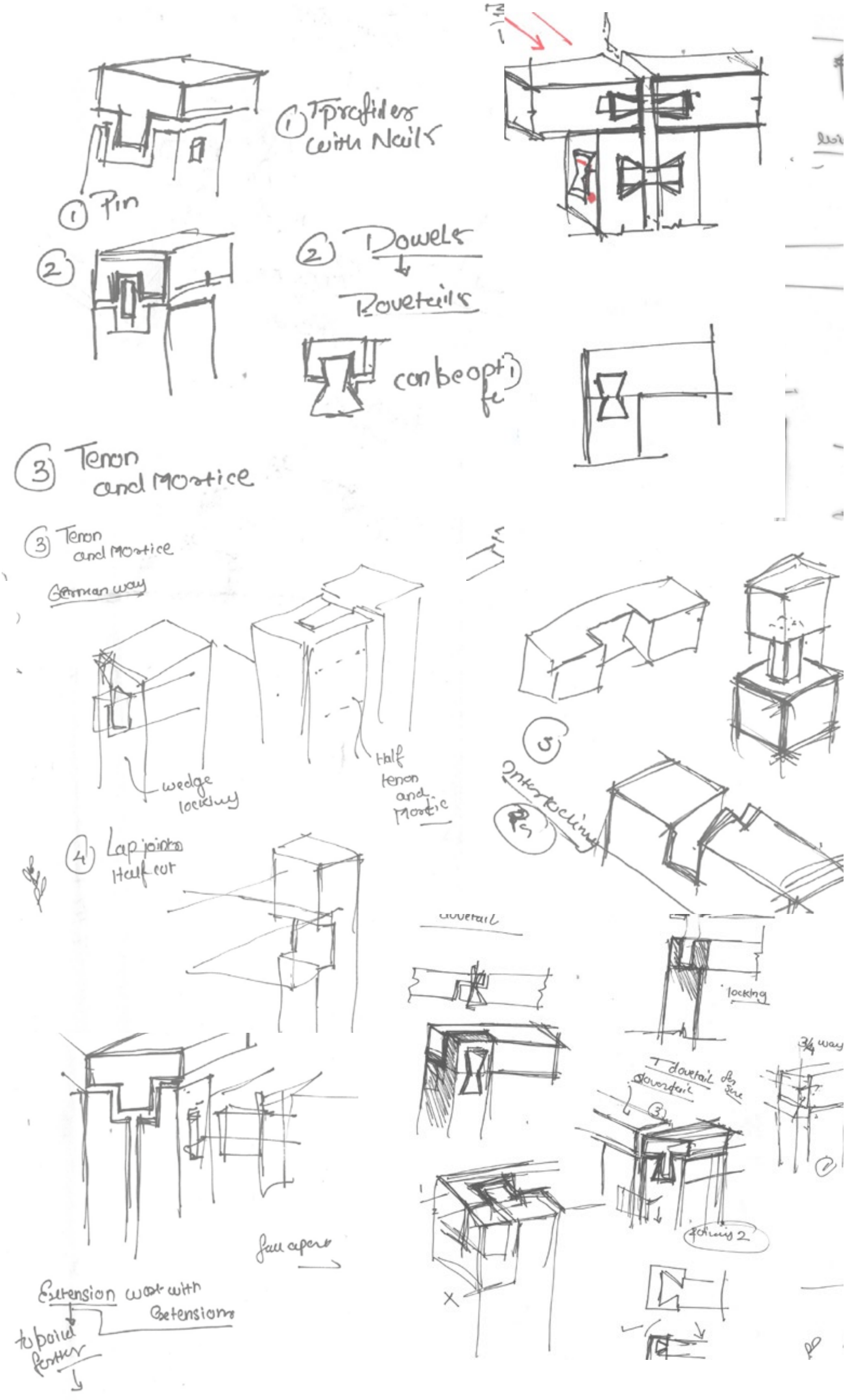


Figure 63: Figure showing Various design options explored through prototyping using foam and sketching (continued)

10.8 DESIGN PROCESS

After understanding the possible design options which can be implemented from timber joinery. The type of joinery evaluated is categorized and shortlisted based on basic and the most workable types of joinery. In order to analyze them further in terms of structural design and functionality, a basic perpendicular essential connection is elaborated. Usually, traditional joineries are used in wrong application without understanding their actual properties. If the joints are designed to resist stresses in a certain direction, they may fail if used in any other direction. In further elaboration a basic essential connection is designed and elaborated further to understand the effects of the stress and behavior of the material and also to analyze if the same joinery can be used in multiple connections.

Design Proportions

Where and at what distance are the joints connected can play an important role in the overall strength of the joinery. additionally, design proportions can also be one of the crucial reasons for joinery to fail. Proportions of the components in the joint are also important. A tenon that is too thick can cut too much material out of the component into which it is mortised. Too large a notch cut in a joist can cause failure. A dovetail with excessive flair is weak. Thus, studying proportions from the old timber joinery is important.

For the traditional and Japanese design standards, the design proportions are based on the 1/3rd and ½ Notch rule as shown in Figure 64.

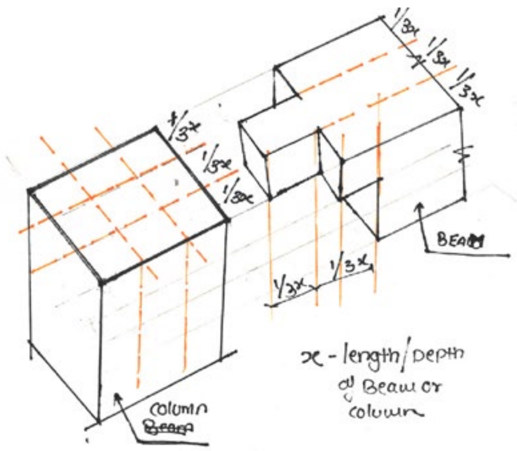


Figure 64: Figure showing design proportions followed for further development of joinery.

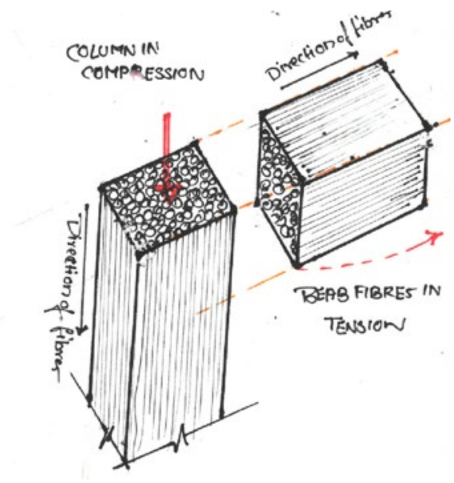


Figure 65: Figure showing the direction of fibers for column and beam components.

For understanding the performance of the joinery the weak spots need to be analyzed, as they are where the joinery first fails. The way the members are connected and directions of the fiber of each member can increase or reduce the strength of the joinery. As a rule for initial analysis, the direction of the fibers is determined as shown in figure 65. From the analysis above in Chapter 4 the column is in compressions in fiber strength direction and the beam is in the tensile fiber direction

Design tolerances

Tolerance is generally the permitted variation value which can vary from a given dimension. The immediate reason to specify tolerances is to ease the construction without the need of later modifying building elements to fit together.

A more long-range reason is to ensure that the structure will perform as designed, particularly with respects to safety. The design becomes more critical for the interlocking connections, as the strength for the connections is highly dependent on snap fitting and frictional contact between the elements. A not so well fitted connection that lacks precision and has a high tolerance value will fail in this research case. According to the timber construction standard (Section, Definitions, and Period n.d.), the design tolerance for timber components is +- 2 millimeters.

Furthermore, tolerance also closely depends on the production techniques or on the category skills. This is one of the drawbacks that very precise machinery or expertise will be required to produce or cut these components to shape.

Generally, different types of joinery are used to deal with different types of stresses. In the following chapter different types of joinery connections and their usability in the connections, the design is analyzed. All the design proportions and properties using the same joinery are evaluated using intuitive analysis, evaluation criteria. For structural analysis a small test prototype is evaluated using is ANSYS software.

10.8.1 ANSYS - STATIC STRUCTURAL ANALYSIS

Setup for further testing

A three-dimensional model was built using RHINOCEROUS computer modeling software for each Design configuration tested in the preceding chapter. The geometry from the 3D model built in RHINOCEROUS was imported into ANSYS Workbench 19.5. The material properties for the Bamboo Scrimber joinery were defined as orthotropic behaviors based on the understanding of the material behavior from chapter 3,.The properties are defined on the x , y and z-direction as shown in fig The Poisson ration is based on the research done on comparison on Poisson ratio for different types of engineered bamboo in research.

Mechanical properties setup in Ansys:

Young's Modulus X direction MPa	Young's Modulus Y direction MPa	Young's Modulus Z direction MPa	Poisson's Ratio XY	Poisson's Ratio YZ	Poisson's Ratio XZ
13994	6500,	6500,	0,32	0,32	0,32

Shear Modulus XY MPa	Shear Modulus YZ MPa	Shear Modulus XZ MPa
71,	71,	119,

bambooo > Constants	
Density	1,05e-009 tonne mm^-3

Table 18: Properties of Material entered for Static structural analysis in ANSYS analysis software.

The following table show the material properties data entered in ANSYS.

Meshing

Quadratic elements, which are well suited for meshing sure and rectangular geometries with a 20mm sizing, were used for meshing. In the areas where the connections were located, a refined method was applied to provide more comprehensive contact information. Two types of contacts were defined: frictional and bonded. The frictional contact shows more realistic behavior between the surfaces in contact. For example, frictional contact was identified dovetail and the beam connection. On the other hand, for simplification purposes, the contact between the test joineries was assumed to be bonded. The boundary conditions corresponded to a uniform load applied along the top surface of the Beam for initial analysis. Fixed support is attached only at the bottom face of the Beam, for simplification of the analysis a small scale prototype is analyzed with half of the calculated actual load and a cantilever beam model. The symmetry region function applied for more advanced final design analysis and structural validation.

Simulation

The main objective of the simulation was to find the most effective design configuration for each type of joinery shape and connection. Two modes, at times three of the analysis of the joinery configurations were compared to achieve the main objective. First the maximum deflection of the beam was determined, then the stress concentrations in the beam were identified.

10.8.2 Design exploration

Type 1: Using an external Connector

This particular type of joinery uses and external connector to hold the members together.In this type of joinery, the connections are mainly dependent on the shape and sometimes on strength of the external connector. The main purpose of the connector is to keep the two components in place and not take load. In this joinery a simple dovetail connector is used. The material for the connector is Bamboo, although it can also be replaced by wood or any other compatible material. The analysis intends to understand the behavior of the beam utilizing the functions of the connector. With this type of joinery multiple types of connections are possible using the same joining technique. A manual is analysis is done based on all the factors and tests studied above is chapter 4.

Advantages: Joinery is simple and repetitive. In terms of the production process it is also easy to cast due to no undercuts.The assembly expertise of the joinery is easy but execution in terms of construction at higher heights above ground can be difficult. Also, due to dovetail inserts the replaceability of a component is easy. A dovetail or wedged-shaped joint is used where great strength is needed to resist pull-out tendencies.

Disadvantages: The manual analysis based on study and understanding of the material shows the weak part in the design where the strength of the fiber is lowest due to discontinuation. At some points, the fiber direction is not continuous.

The tolerances and production precision for this type of connection needs to be accurate.In this joinery, it is possible to use the connector in multiple ways and is the most advantageous point of the joinery system.

Two dovetail insert options were evaluated. In which he dovetail is Inserted parallel to the direction of the Fibre and b. In Perpendicular to the direction of the fibre.A manual and structural analysis is done.

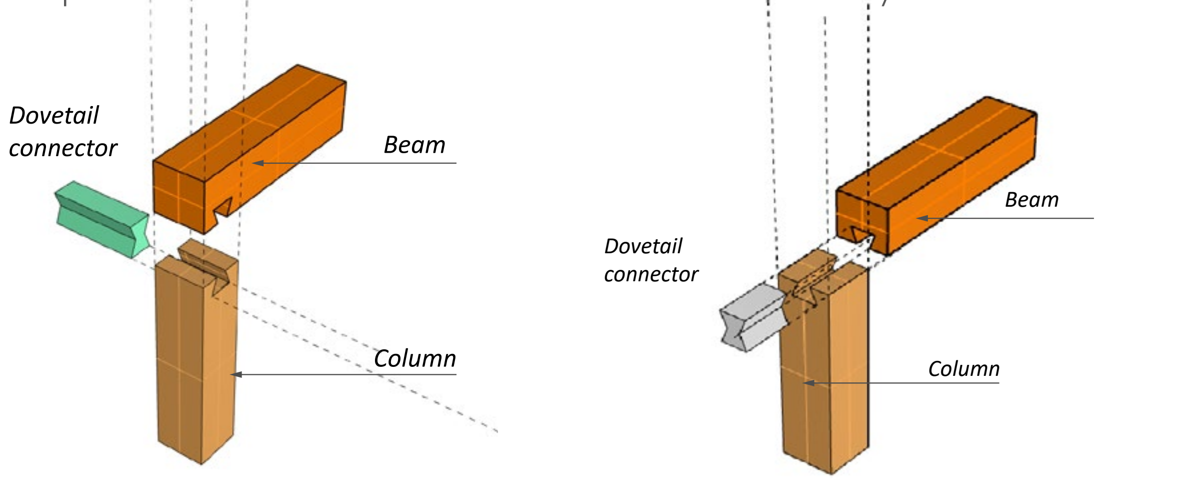


Figure 66: Figure showing the basic perpendicular connection alternatives. a. With dovetail insert in direction of the fiber. b. With dovetail insert in the cross direction of the fiber.

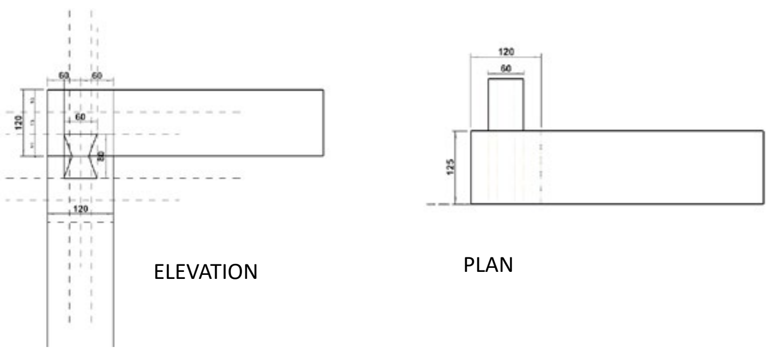


Figure 67: Figure showing a plan and section of joinery type a.

Structural Performance Validation :

Both the insert options were evaluated for Maximum Shear stress in ANSYS Static analysis.The analysis was to understand the performance of the joinery keeping the fibers continuous and effect of discontinuation of the fibers.The result shows a comparatively higher concentration of stress near the edge of the dovetail.The software does not evaluate stress based on the adhesion of the fibers and thus further manual understanding is required.

Manual analysis

It can be seen from the figure that the Placement of the dovetail can affect the strength of the joinery.It is clearly seen that in the manual analysis of option the low strength and maximum shear is at the point where the fibers are broken and discontinuous.

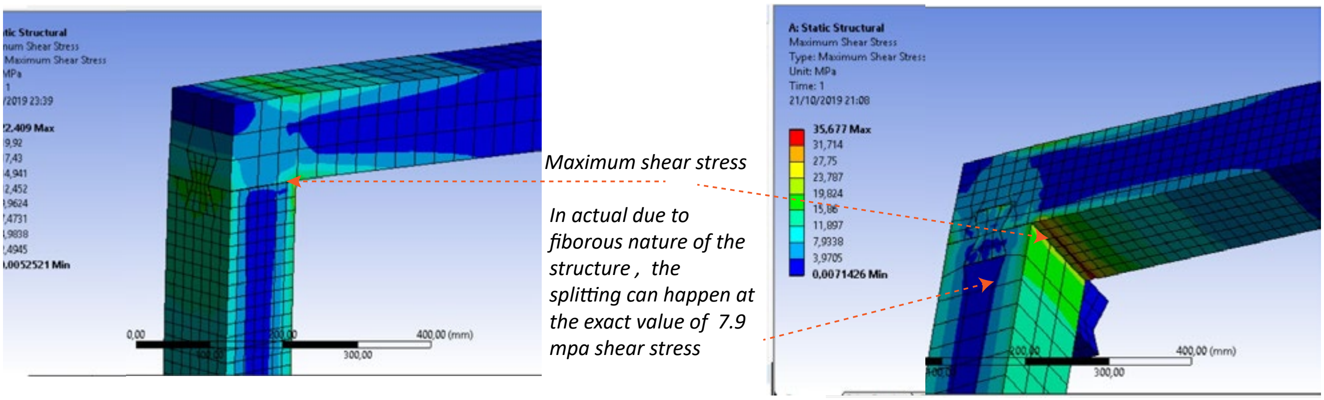


Figure 68: Showing the Maximum Shear Stress area for Type and b joineries.

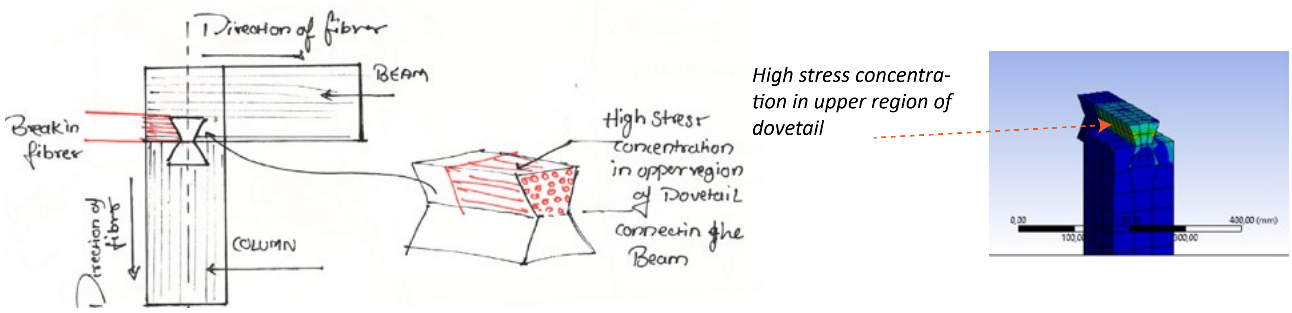
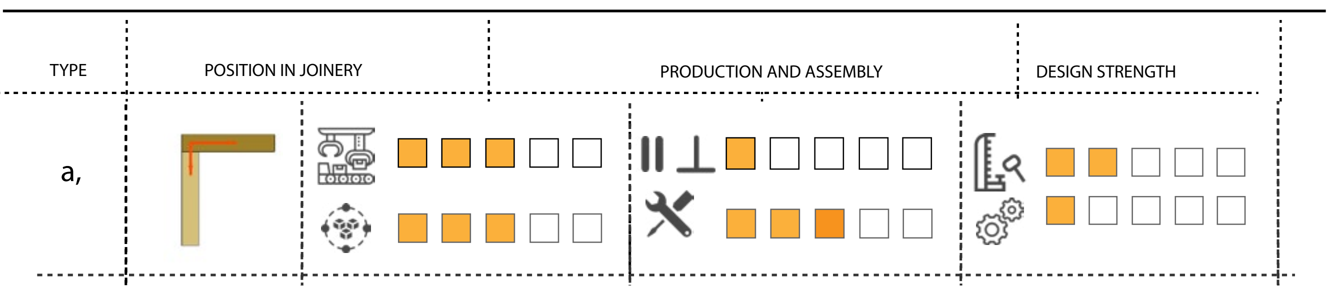


Figure 69: Showing the manual analysis diagram for type a and b joinery.



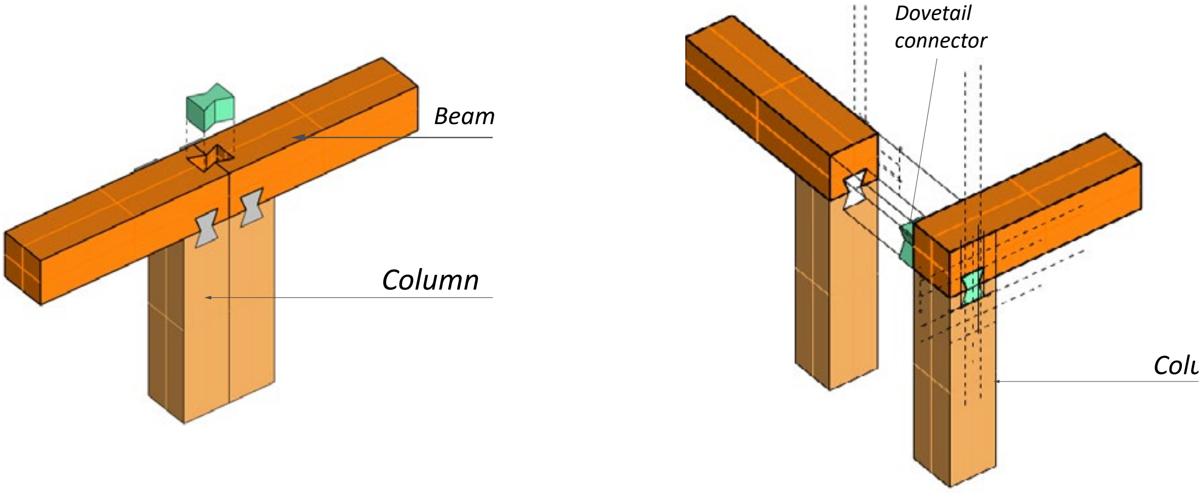


Figure 70: Figure showing the elaborate Frame connections. c. Corner perpendicular frame connection. d. Parallel frame connection.

Further designing of possible connections using a dovetail connector was done. The external connector can be used for multiple ways in terms of assembly making the assembly process easier.It can be seen in Figure 70, the possible configuration for perpendicular and parallel connection of frame components. It is possible to use this connection in case of a single storey structure.

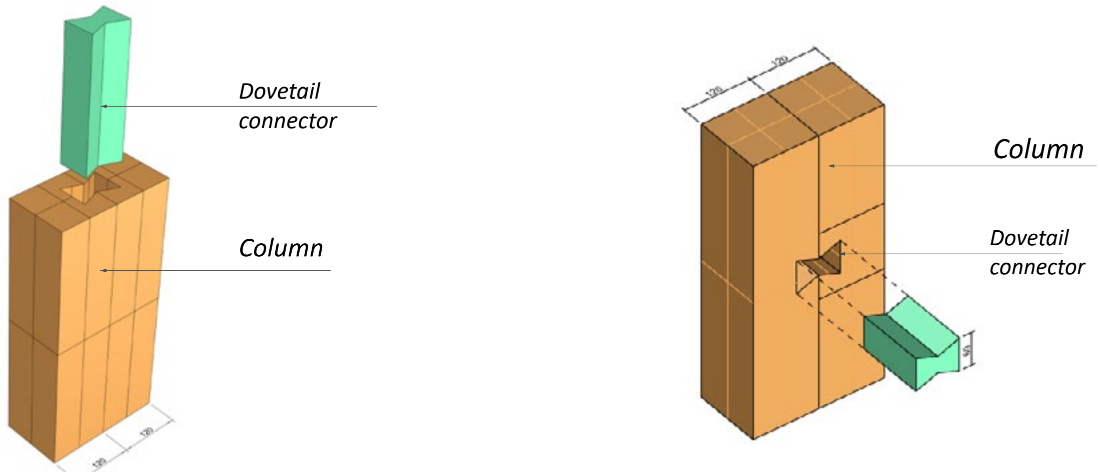
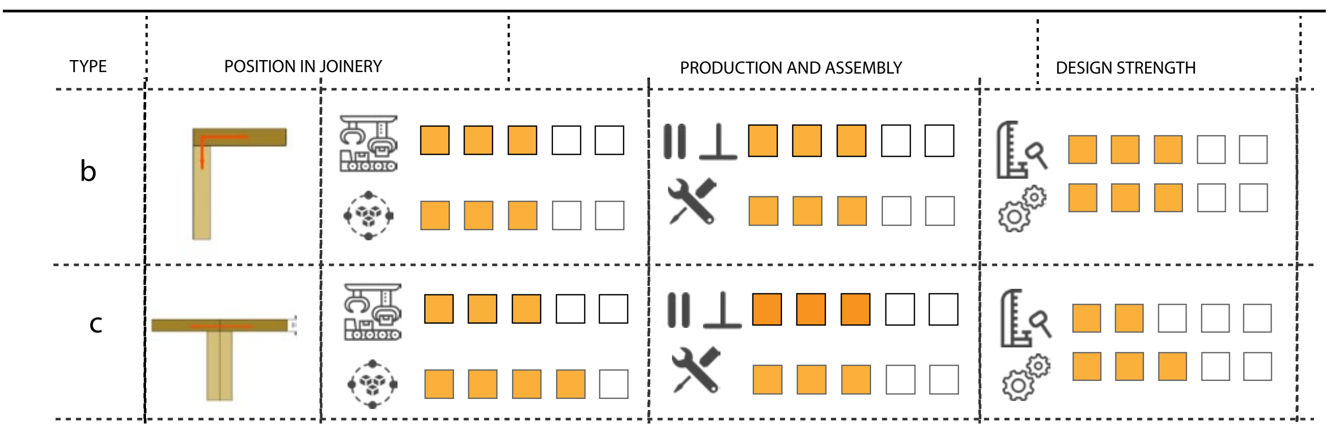


Figure 71: Figure showing the Frame – e,f Column connections alternative



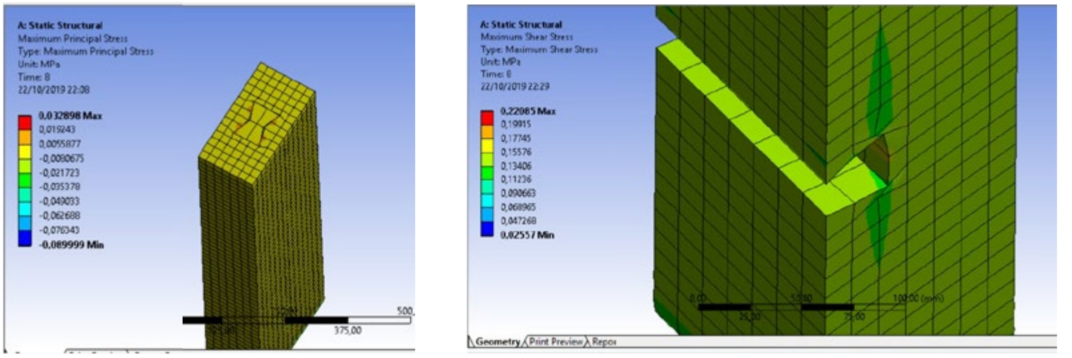
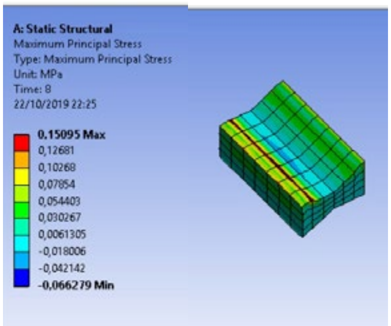


Figure 72: Figure showing Principal stress analysis for joinery configuration type e and f.



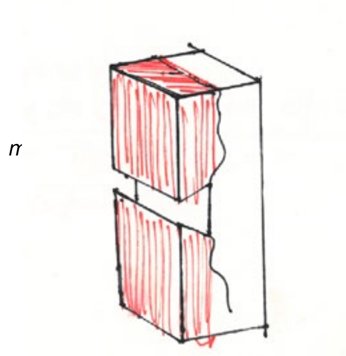


Figure 73: Figure showing Shear stress concentration and values

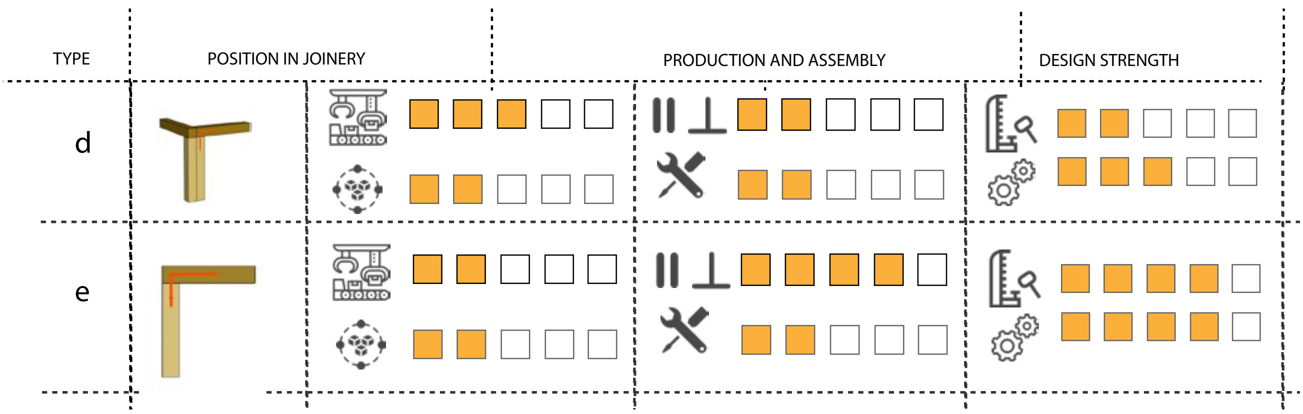
Figure 74:Diagram showing stress concentration area in the dovetail insert.

Connection Between the Adjoining Column :

The joinery for connection between two adjoining of column of frame component was evaluated .Figure 72 shows the possible configuration using dovetail.In Type c: The dovetail is inserted in cross-fiber direction and in type d :the dovetail is inserted from top in the direction of the fibers.Both the joineries were evaluated if Ansys static structural analysis for Maximum stress and Shear.

It can be observed that for type c it is high possibility that dovetail can be crushed due to high weight.As an alternative material in need to be used. Additionally as shown in figure 73 the highlighted area is more vulnerable towards shear stress as the fibers are not in continuation is that area. In type d. All the members are in equal loading in compression and the dovetail exhibits low stresses compared to type c. For cross fiber insert of dovetail other material with higher compression strength should be considered instead of bamboo peg.

In conclusion joinery type a and type b with fiber direction maintained have higher structural performance compared to type b and c.



10.8.3 Type 2 : T and U type joint profiles :

T and U Joinery connection system is the most commonly used design in the timber connection system. The system works on embedded interlocking connections. Often wedges are used to secure and strengthen the Joint. Combining these wedges in the joinery components forms a more advanced form the joinery, in which the T and U profile are wedge-shaped and help in the Interlocking of the joint. It must be noted the connection is used in combination with a cross insert as shown in Figure—.. For the easy of assembly In further elaboration, it is also possible to use external inserts. Multiple options and arrangements of T and u profile are analyzed. In Timber joinery design cross dovetails are inserted in order to interlock the beam into a column, but in this case, it not possible to insert a cross peg and thus it is important to find other alternatives for interlocking.

Advantage: The advantage of this joinery is that the direction of the fiber is positively used and the fiber continuation remains intact. The joinery can be adapted in multiple ways with slight alteration. The wedge-shaped connection as it can resist the pull out fore of the beam for the column.

Disadvantages: It is difficult to interlock the joinery as we cannot insert any cross dowel for interlocking, increasing the risk of the beam pulling off from the column due to deformation.

Different types of joineries adapted from timber construction are evaluated. A basic perpendicular frame connection is designed In T and U profile connection and further advanced to the design of a Wedge-shaped T and U Connection the better interlocking. Figure 73 shows the design configuration for type g.

The wedge-shaped configurations are analyzed structurally for shear stress connection and total deformation using ANSYS static analysis followed by a manual understanding of the stress concentration in the joinery.

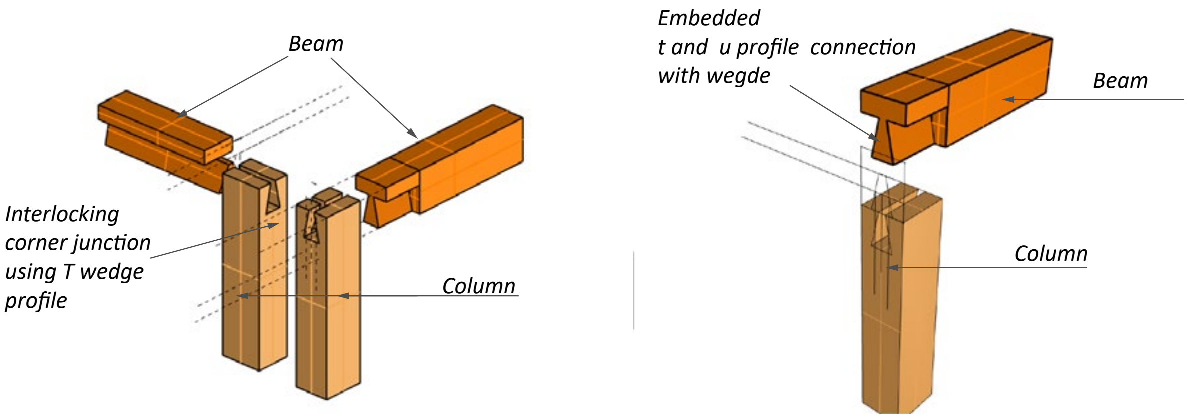
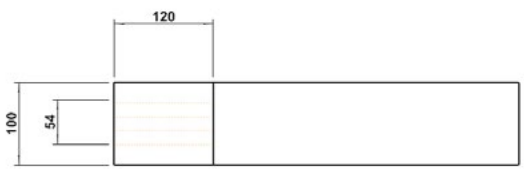


Figure 75: Figure showing the embedded Frame connections. g. With T shape flat tenon insert. h. With T shape wedge tenon insert.



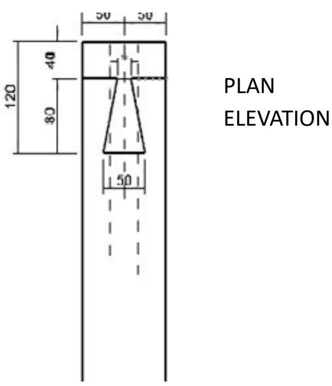
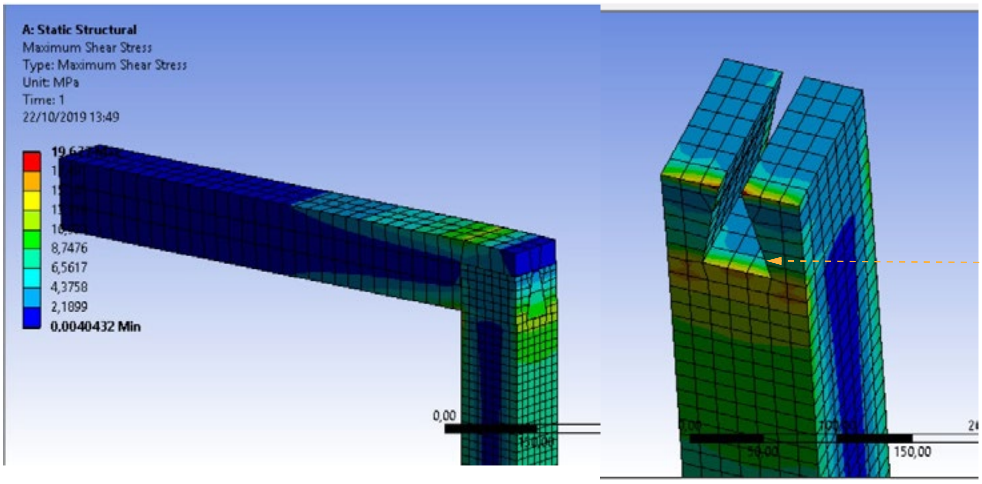


Figure 76: Figure showing a plan and section of joinery type h.



High stress concentration at the corner edge of the dovetail / embedded wedge

Figure 77: Figure showing Shear stress analysis for joinery configuration type h

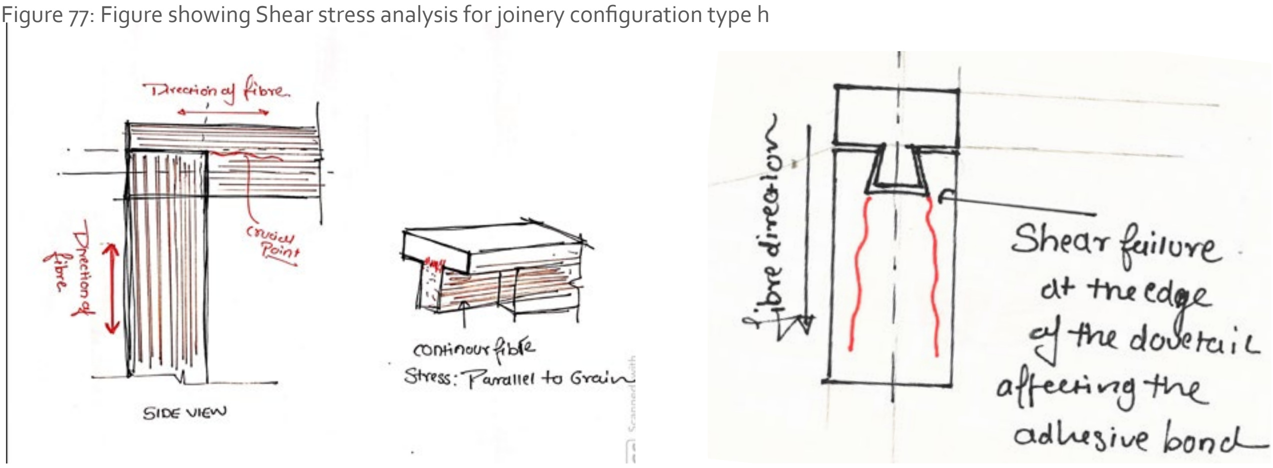
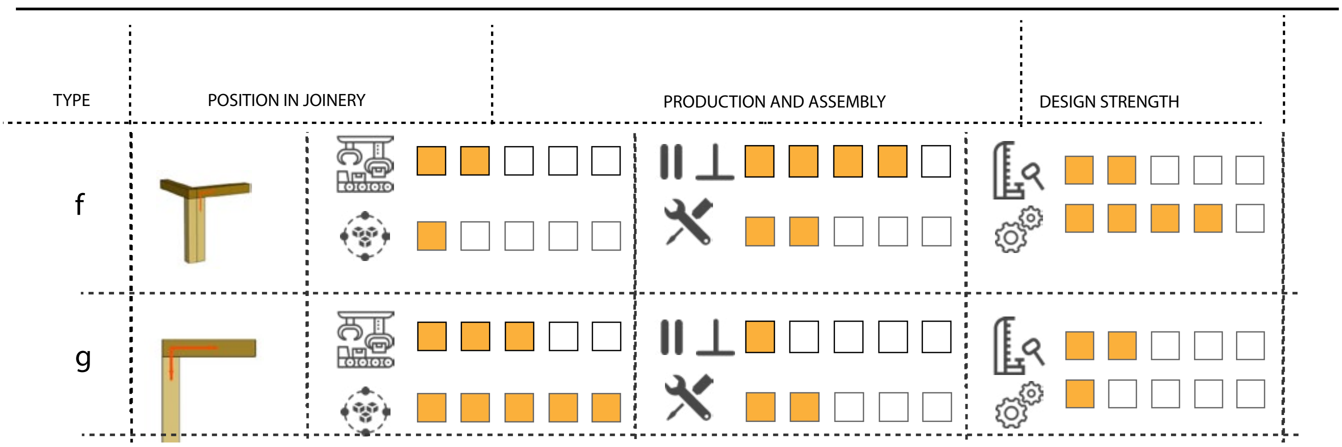
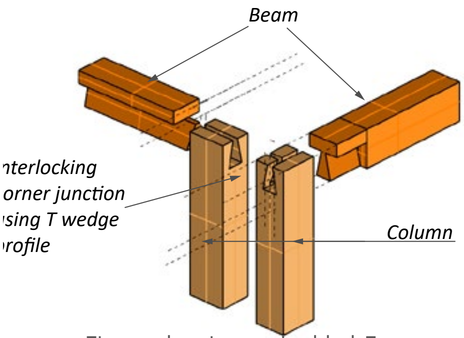


Figure 78:: Showing the manual analysis diagram for type h joinery.

It can be observed that in this case because the dovetail is embedded in the beam and inserted in the Column. As shown in figure 78..the Shear stress line changes at the edge of the dovetail and there is a high possibility of the shear failure due the debonding of fibers at that point.

The further elaboration of designing possibilities is done. The corner connections can be difficult using this t and U embedded connection. The image shows a possible alternative using a wedge-shaped connection and a basic t connection. With on Cross-connection , the Basic t shaped can easily be pulled out of the column profile.





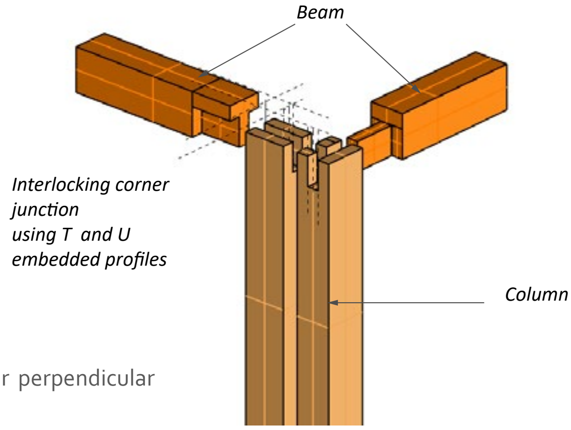
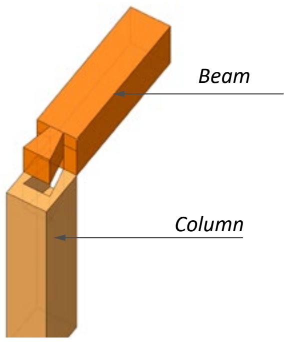


Figure 79: Figure showing embedded Frame connections. i. Corner perpendicular frame connection. j. Parallel frame connection.

In joinery type k, the wedge-shaped connection is made across beam width instead of beam depth. This connection would help in lateral loading, but the drawback of this connection would be that the beam can easily come out in Z direction. But in case of vertical loading it is efficient to use this type of connection.

In conclusion, the embed connections are strong in terms of the strength as the direction of the fibers is maintained. The wedge-shaped t profile connections can be a very effective connection.A drawback in this type would be in terms of assembly. Inserting the members in the column can be very difficult as extra force would be required due to the wedge shape of the beam.



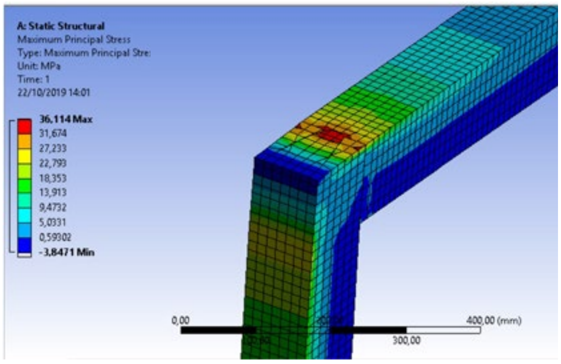
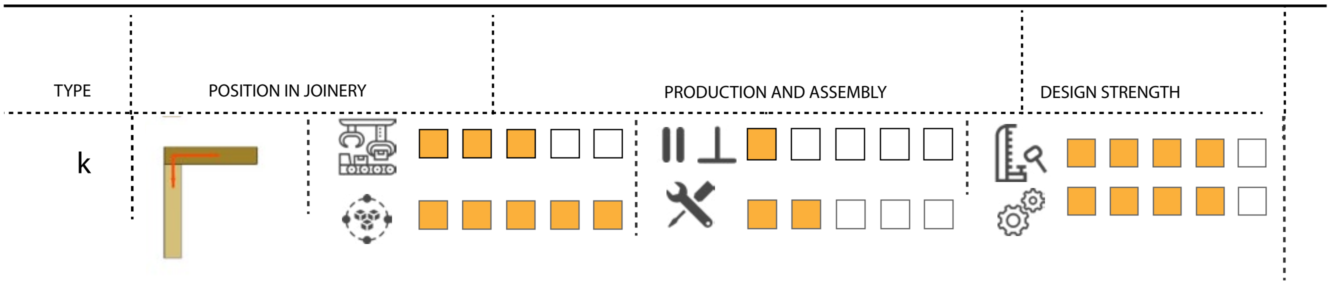


Figure 80: Figure showing the embedded Frame connections. . k With wedge shape flat tenon insert.

Figure 81: Figure showing Shear stress analysis for joinery configuration type k



10.8.4 Conclusion on the type of joinery studied above

Basic conclusions and comparative analysis of the type of joineries are done. It can be concluded that.

Analysis of Continous fiber vs Break in fiber

Dovetail is the direction of the dovetail in cross direction for the fiber can make a lot of difference.Dovetail in directions, doe not s discontinuation any fibers, hence show high strength and lower stress concentration .Members used in fiber direction without +discontinuation of fiber displayed higher strength.

The chart below compares Total deformation for type b, g,j compared based on same loading and end conditions. It can be observed that the joinery with embedded connections shows the lowest deformation values. The data is retrieved from ANSYS analysis, refer appendix for further details of deformation

Table 19 gives an overview of all the joineries studied above and their performance in terms of the evaluation criteria predefined from the research and the joineries most satisfying all the evaluation criteria for joineries design can be considered in designing any single storey house.

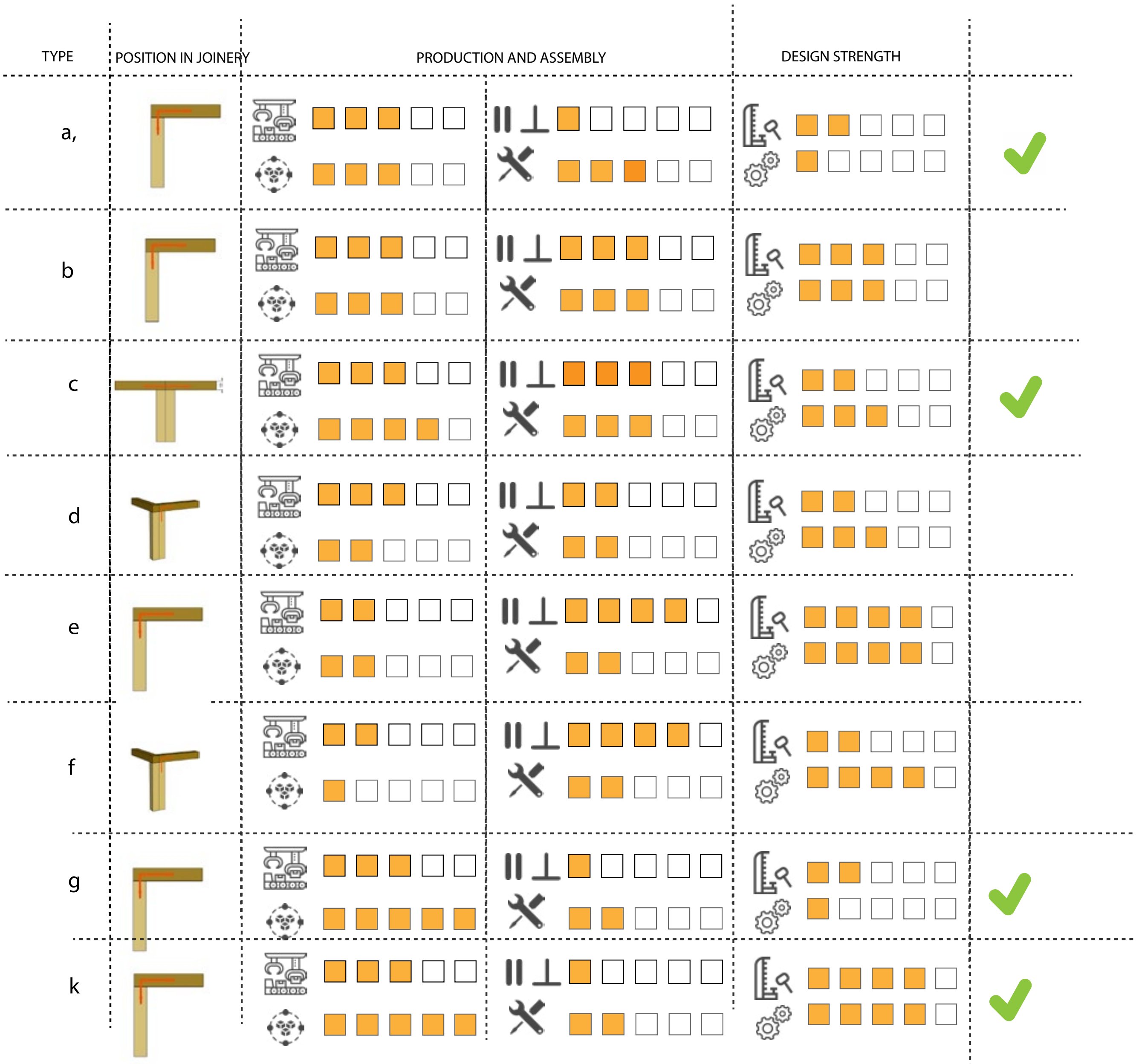


Table 20 : Show an overview of all the type of joinery studied above and their performance based on the evaluation criteria

The research helped understand the concentration of stresses in an area inadequate and adequate to deal with them. And need to be acknowledged in further designing. Thus, once the weak spots are known for the simpler version of the joinery, This research will be taken forward for further design elaboration. Each of the joinery types above has its advantage and disadvantages' In order to elaborate on the design further the most important factors are pointed out.

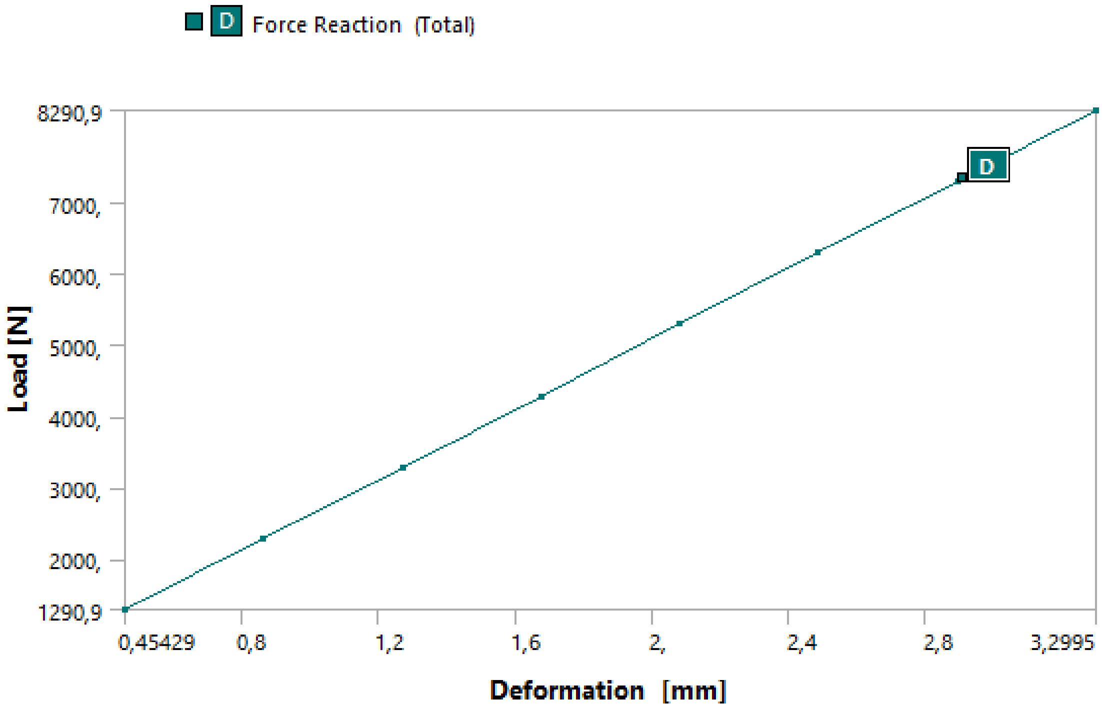


Figure 82: Graph showing Total deformation joinery configuration type b,h, k

PROTOTYPE EVALUATION:

Prototype 1: Joinery detail with an external dovetail connector.

In order to understand and analyze the Structural behavior, the prototype connecting two beams was made within limitations of test setup (Four-point Bending test) and the available size of the Material. The objective of the test is to understand the stress behavior of the material and determine maximum load capacity and deflection. The joinery is prototyped using traditional wooden tools like saw and dovetail router.

Tolerances: The tolerances are very low within 1=-1mm only enough, for the dovetail connector to be hammered in. Snap-fitting of the joint is important for the connector to stay in place and make to connection more rigid and stable.

Dovetail: The direction of the Fiber of the Dovetail connector is the same as the direction of the fiber in the beam.

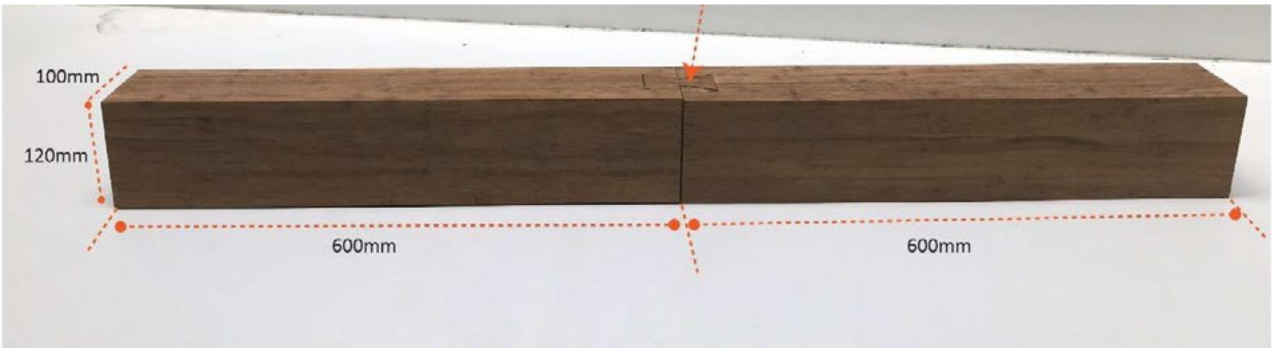


Figure 83: Image showing the sample prototype beam tested

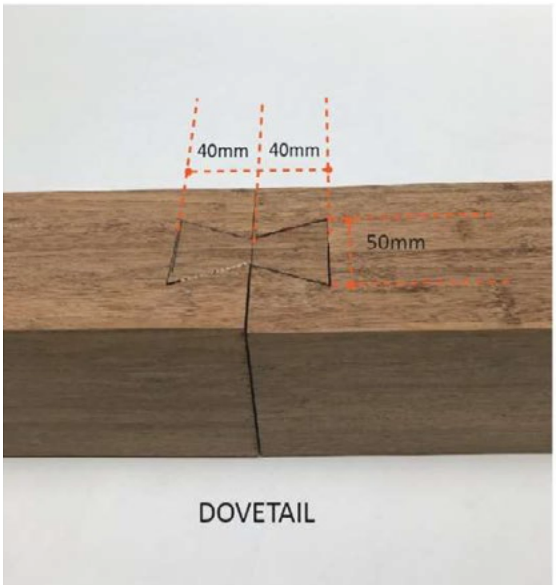


Figure 84: Image showing the sample prototype beam tested- dovetail detail

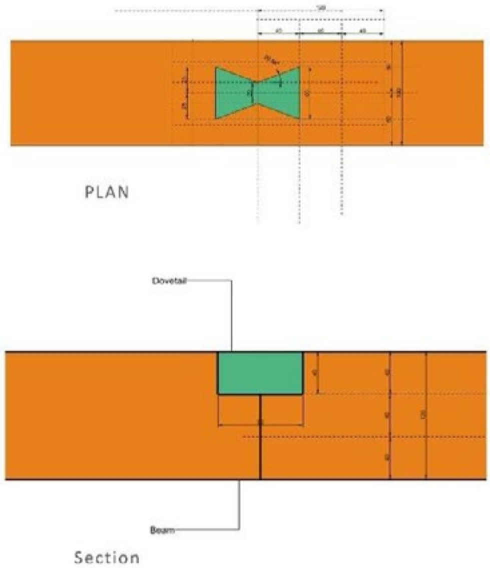


Figure 85: Figure showing design drawing for the sample prototype beam tested

8.2 TESTING:

After the design and evaluation of possible joinery, the most efficient and promising joineries are further prototyped and experimentally tested as well analyzed in ANSYS. The way in which forces are transmitted from one structural member to another very much depends on other types of structure and predominance of one force type upon another.

The detail STRENGTH ANALYSIS of the connections is done In further chapters. The analysis is done in two ways :

1. ANSYS static structural analysis
2. Prototyping and experimental testing of the design.

8.2.1 EXPERIMENTAL INVESTIGATION :

Laboratory Test Set up :

The experimental testing is done at the Mechanical Department of the Delft University of Technology.

Material and Size of the Specimen:

For all the prototypes, The material used were commercially sourced bamboo scrimber Bema sourced from Moso Bamboo comprised of *Phyllostachys pubescens (Moso)* with phenol-formaldehyde resin. The average density of the bamboo scrimber is 1050 kg/m3 with moisture content of 10%.The size of each Beam was 600 x 120 x100 arranged as shown in the Figure above.

Test Procedure:

All specimens were tested under four-point bending loading in Four-point bending test setup. Tests were undertaken to investigate flexural properties (bending stiffness and strength.)of the fabricated engineered bamboo connections. The beams are supported at the ends and loaded at two points across the length (L) as shown in figure---. The distance between the specimen is determined before carrying out the test Initially the specimen is loaded with an initial force of 95 kN with loading speed at 5mm/min with a constant increase on the force. The force is applied at an equal distance from the supports. Fig below shows the principle used during the experiment.

Test Method	Test Schematic	Direction	Specimen Size	Loading Rate
Four Point Bending	Refer figure -----	Parallel to the Grain	Two Beam : 600x 120x 100 Refer fig -	5mm/min

Table 21 : Showing the details of test method used.

PROTOTYPE 1 : Joinery detail with an external dovetail connector

The set of specimen tested was : a set of Beams connected with a dovetail

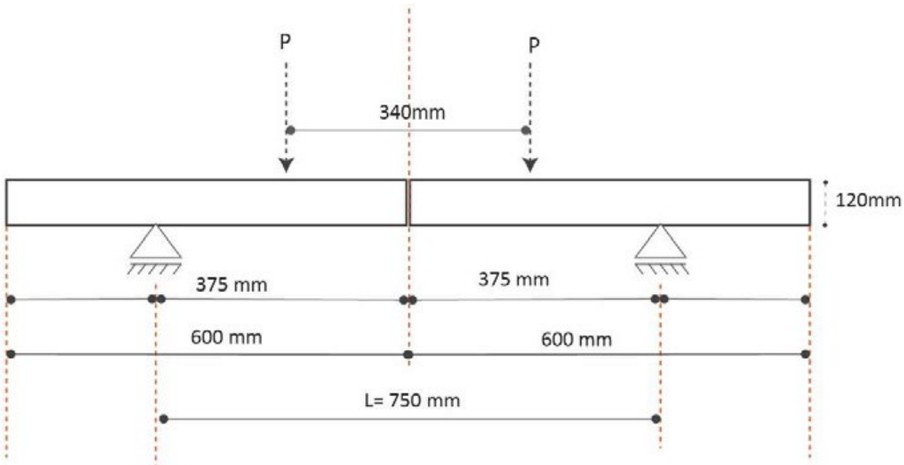


Figure86: Schematic Diagram for the four from bending test setup

Figure 87: Figure showing the test setup for Four point Bending using Zwick/ Z100

Results and discussion:

The primary mode of failure was associated with the fabrication technique where the bamboo strands are laid out in longitudinal layers. A closer inspection of the prototype shows the splitting occurred at the edge of the dovetail.

The figure 90 shows the graph with maximum load of 12 KN achieved by the prototype.Figure 89 shows an image of the final deformation of the prototype.It can be seen that all the components were intact.Cracks were observed on the underside on the beam. It is also observed that the splitting occurs close to the adhesion layer. There was no damage observed on the dovetail connector. With no damage, the connector was very important to the beam intact even after maximum loading. The slipping of the dovetail from the joinery can be because of the loose-fitting of the dovetail connector in the slot and High tolerances.

In conclusion, the strength of the joinery was dependent on the connections reworking on the tolerance in the further experiment may fetch higher results. Dovetail connection can be very effective when used in Tensile direction of the material. Additionally the test shows the maximum stress that can be taken by the joinery in terms of deformation.With a safe deformation limit of 1/240 of the span the beam can take a safe load of 6 KN and maximum load of 10KN for this particular geometry.

Further, in this case, the dovetail was inserted throughout the Beam and no fiber is continuous with a continuation of fiber by inserting the dovetail 1/ 2 the depth the Beam will be able to take higher load,For further research the total limits will be reevaluated on the above test.

Figure 88: Images from four Point bending test

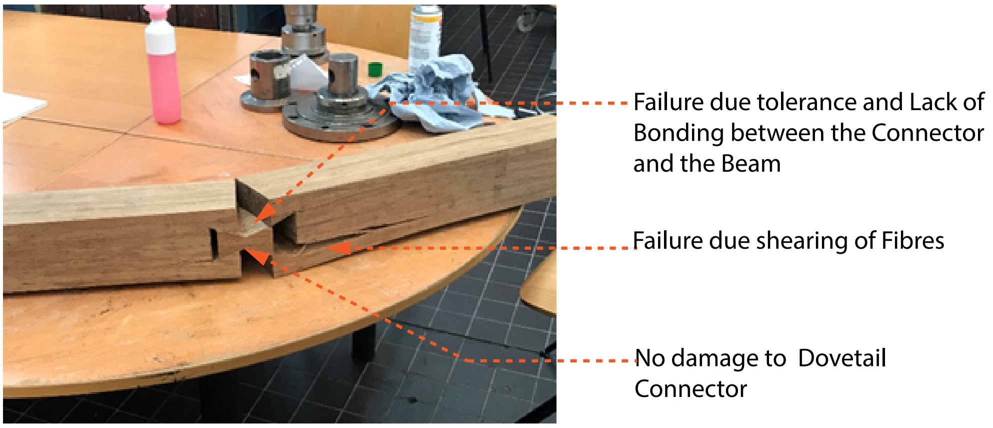


Figure 89: Analysis of the result of the test

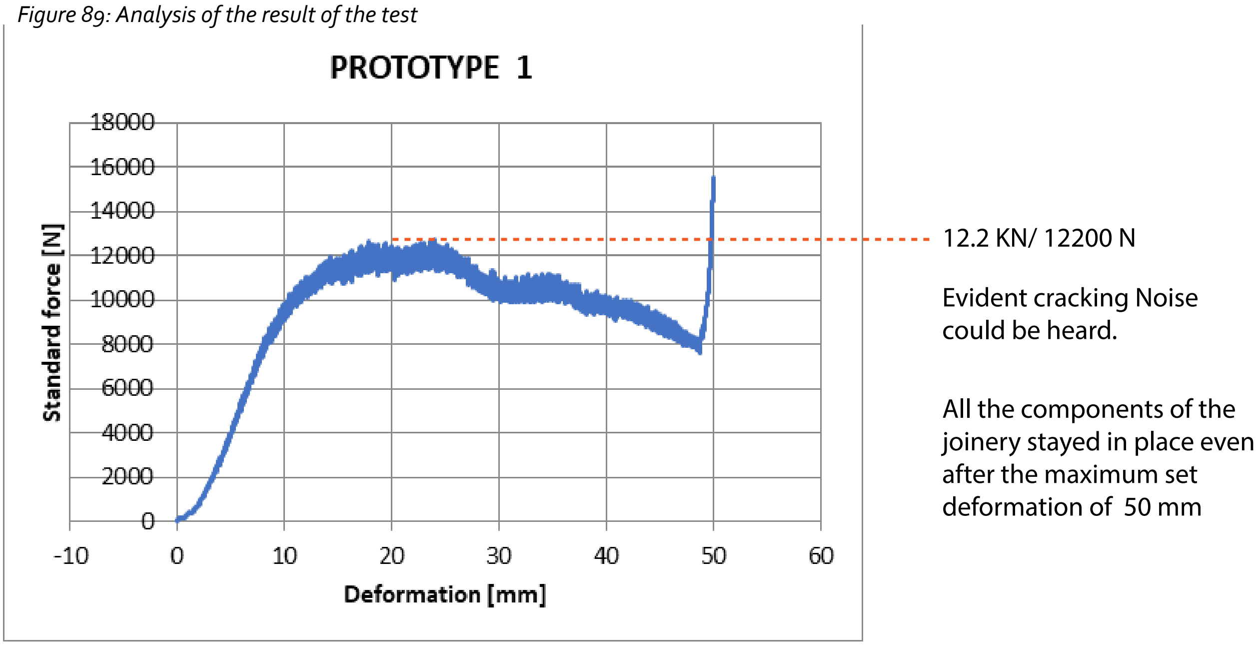


Figure 90: Result of the test. Graph showing the tensile force and the

The above analysis helped us understand the behavior of the material in design configurations and methods of the joinery.it should also be noted that when designing joints for the entire structure and when more members are supported by an individual member there is not definite joint which can be repeated or used in the same way. As the above research helped understand the advantages of each joinery in each type of essential and elaborate connection, further research will focus on the elaboration on these connection systems.

After analyzing the behavior of the joinery, further, the development will include designing with all the assembly members. How the structural components are assembled has to be figured into joinery. Some pieces of the frame have to be slid together; others must be dropped into place and secured with pegs. A well-designed frame doesn't depend on the dovetail inserts for stability, though the inserts do add strength and provide a wedging action for stiffness.

After having an understanding of the behavior of the joinery, a further design exploration was done to understand the joinery of multiple members together keeping in mind also the assembly sequence. The most important aspect of workable joinery along with its strength is also the sequence of assembling the joinery and also minimizing the extra supports required until the structure is assembled.

The relative fibers direction and the strength of the joinery in different configuration will also be analyzed., There is no limit to the range of possible configurations of joinery for the frame, thus some design elaboration was done based on the above understanding, before proposing the final design.

Final structural Sizing and Design proportion.

The final structural size is based on the safe load calculation from chapter 6 and also on the design proportions understanding from the traditional timber joinery system. Additionally, the proportions are also based on the number of structural components coming together at the same point. The more structural components attaching to the member, the larger the size of the member.

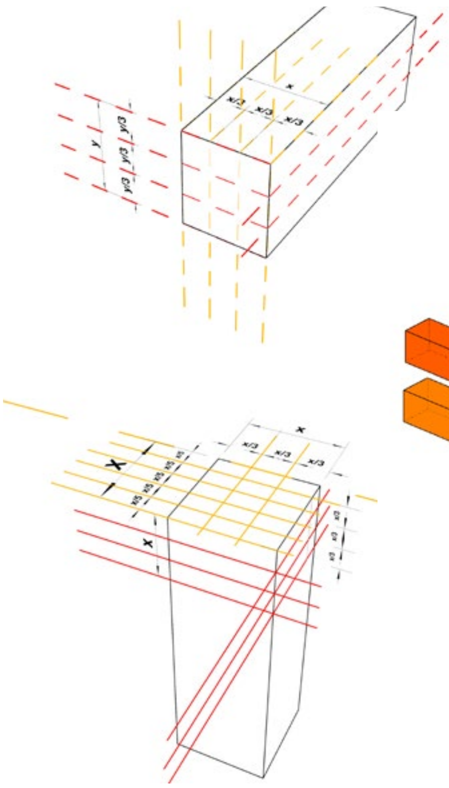


Figure 91: Figure showing the design proportions generally followed for further development of the joinery configurations.

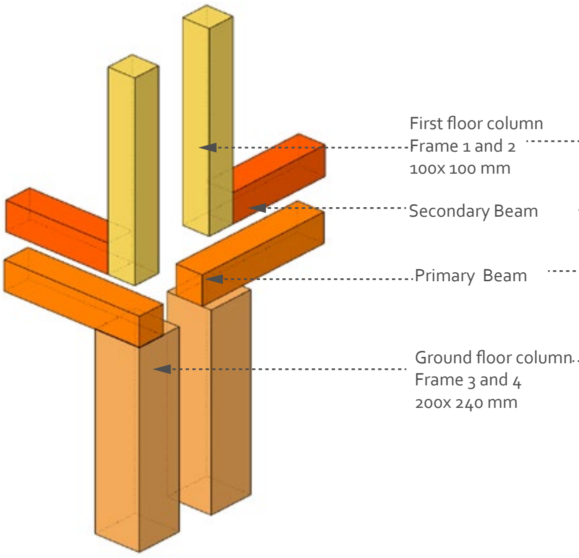


Figure 92: *Images Showing the essential components for Perpendicular connection of frame elements*

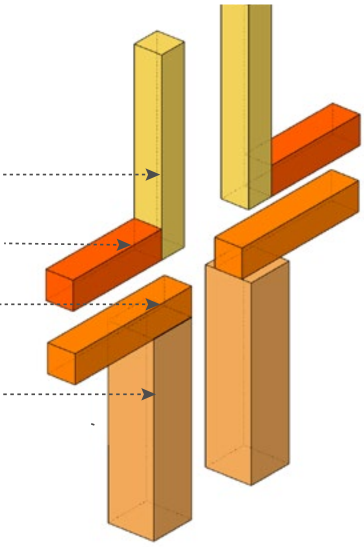


Figure 93: *Showing the essential components for parallel connection of frame elements*

Column design :

In the case of an upper floor the load from the to be floor transferred to the subfloor from here is transferred to the primary beam and floor beam is transferred to the column easy load which is connected to the column. Thus with an idea of a column supporting the beam and in order to reduce lateral displacement of the beam (due to other forces and stresses like wind), the column dimension is considered larger than the beam. Additionally, the column also is connected to the lateral support member and the façade.

The column needs to be strong enough even after these connections to the members. The final column size considered for further designing is = 200 mm 200mm and square-shaped column eases the connections in corner junctions and is also aesthetically pleasing.

The ground floor column needs to support a number of structural members than the first floor.

Beam Design :

The beam transfers the load on the column and thus and needs to be connected to the column for easy load with minimal stresses induced. For lateral support and to avoid lateral displacement of the beam either needs be well connected, or needs fit in the column, thus it is ideal to have beam small in dimension than the column width.

Additionally as discussed in the chapter above the for flexural strength and shear strength the beam depth needs to be accommodated the shear stress-induced due to bending and load transfer from first floor. The beam is shaped rectangular in order to achieve higher depth and also to stay within permissible stress limits, even after the design of notched and cutout from the beam depth. The final beam size is 120 x 140 mm in depth.

Dovetail insert design and Sizing

Too larger or too small an insert can take a lot of material away from the member it is inserted in. also a very acute or obtuse flare angle for the dovetail can cause the design to fail and make it difficult in terms of carpentry and productional standard dovetail angle followed based on the tools available in 21 to 22 deg or based on 1/ 3 of beam width/depth rule..

Proportions: As a thumb rule, adopted for the timber ½, 1/3 or 1/5 of the beam/column depth or width is followed for the further design process. The diagrams also showed an elaboration of the number of members coming together for connection.

Further design exploration :

A design is proposed based on the above understanding of the joinery, in order to connect the upper floor, the dovetail is used in Z direction connecting all the frame components together. Further, this configuration is explored and analyses to understand the possible arrangements to accommodate members from the first floor.

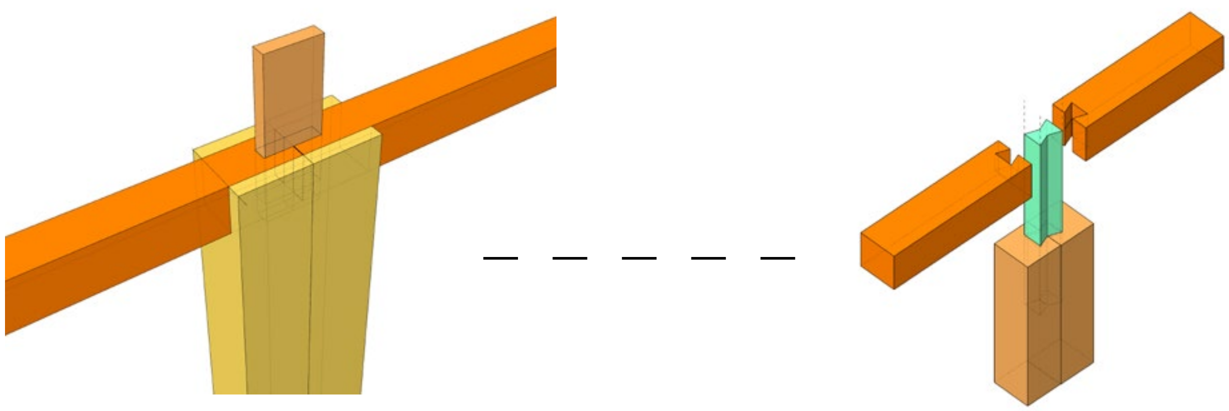


Figure 94: Figure showing the design configuration explored.

Design for strength

The designs are reworked worked upon further with an understanding of the strength of the joinery. An advantage of this joinery is that the one dovetail member can connect multiple structural members together, but it's also important to analyze if the dovetail takes any load/stresses and if so, are those stresses within permissible limits. For any joinery design, it is crucial to understand the strength and performance of the joinery and the kind of stresses induced in the joinery after loading. Design for strength is a design that understands the structural behavior of the design and components, predicting high-stress areas. The type of connections and direction of the fibers also affects the strength of the connection.Even the smallest member in the joinery is capable of taking load if designed well, thus the whole capacity of the joinery based on efficiency, design precision and members sizing. Majorly the strength of the joinery is evaluated based on the loading, and the type of stresses acting on the joinery.

The maximum load and stress-induced in the frames are due to the loading from self-weight and load from the floor above. Plus additional weight acting from live load, wind and snow load. In the case of the first floor built above the ground floor, the total vertical load needs to be carried from the roof -to the first floor- to beam- to column and to the foundation. Additionally, the forces acting on the structure are from lateral wind load acting on facade, seismic loads. the understanding of theses forces is taken into account analytically in design process but, no structural calculations are carried out.

To understand the stresses acting on the joinery, a structural validation supported by predictive analysis and analytical analysis is made. Based on this analysis, the designs are optimized from predictions of stress and validation it, using static structural analysis in ANSYS.

For structural validation, a small scale prototype of each joinery configuration is analyzed. All the contacts between the members are input as bonded and the joinery is loaded for maximum UDL load of 8000 N, which is 1/2 times the actual load acting on top surface of the structure. Fixed support is provided only on the bottom face of the Column, in ideal scenario the column will be well connected to the foundation.

Assumptions: The validation is done in order to compare the performance of each of the joinery configuration and help select the best for further optimization and not for final structural validation and loading. In reality, there many more forces acting on the beam including torsion and rotational moment in the joinery, but are not considered is structural validation of the research Thus the main idea of the following structural validation to understand the behavior of the joinery than to validate based the final load taken. The final global analyses are carried out in a later chapter.

Design Optimization

For parallel frame connection, the design is optimized to reduce the total deflection and stresses.

As shown in figure 96, In the first design the beam simply rests on the column and is connected to column only with the support of the Dovetail members, In case of any lateral displacement of the beam the total load will be taken by the dovetail. The goal of the optimizations is to reduce the stresses acting on the dovetails, as the main purpose of the dovetails is to connect the components and not take the load. The dovetail will be inserted in up to one-third of the column length for the ground and first-floor columns.

As shown in fig 98, In Second design optimization the entire beam is inserted in the column supported by the dovetail. In this case, the lateral displacement of the beam is prevented.

As shown in fig 101, In the third alteration the beam is notched and 2/3 part is inserted in the column, supported by the dovetail. The notch helps prevent the upward pulling of the beam component.

Both the design configuration were analyzed for a load of 8 kN.

Optimization result: Evaluation and inference

It can be seen from the analysis that inserting the beam in the dovetail in the second will prevent lateral load but total deformation remains the same. But in the second case with an addition of the notch, the total deformation almost reduce by 50 %. Additionally, the shear stress acting on the dovetail is reduced in the optimization. In the third prototype design the dovetail connection takes the least shear stress. The graph 104 shows a comparison of the total deformation of the three design configurations discussed above and the third design configuration with the lowest deformation value is chosen as a final design.

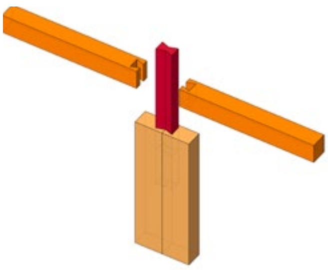


Figure 95: Prototype design configuration 1 for optimization.

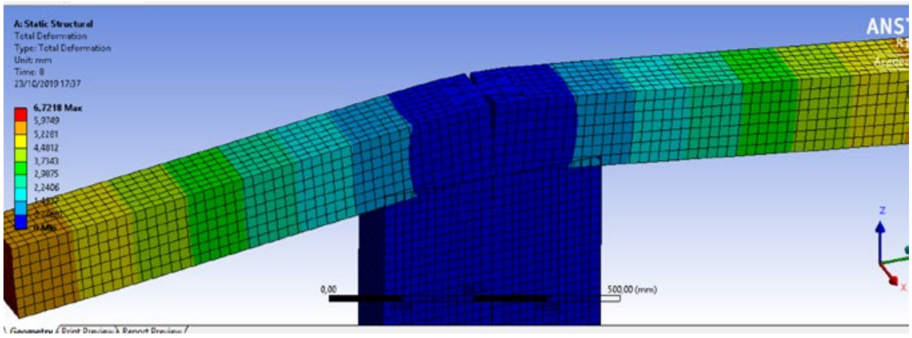


Figure 96: Image showing results for Total Deformation for prototype 1 in ANSYS structural analysis

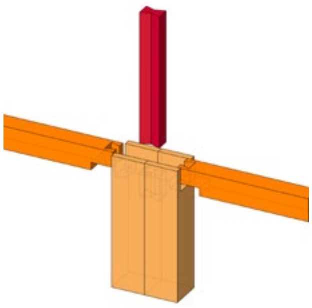


Figure 97: Prototype design configuration 2 for optimization.

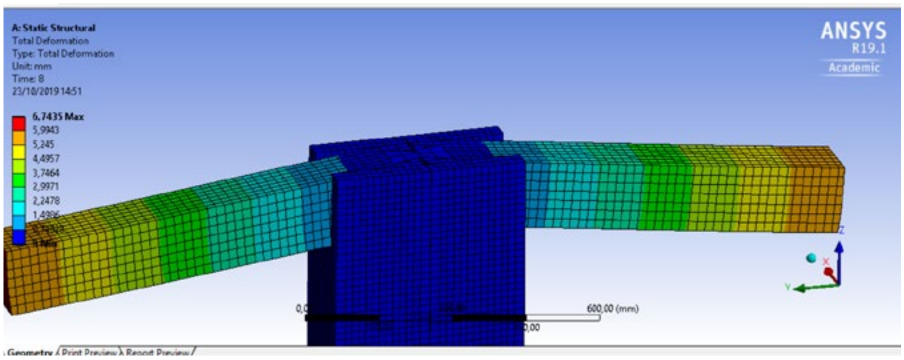


Figure 98: Image showing results for Total Deformation for prototype 2 in ANSYS structural analysis

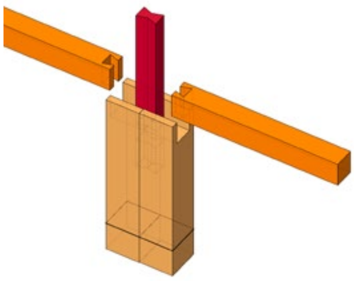


Figure 99: Prototype design configuration 3 for optimization

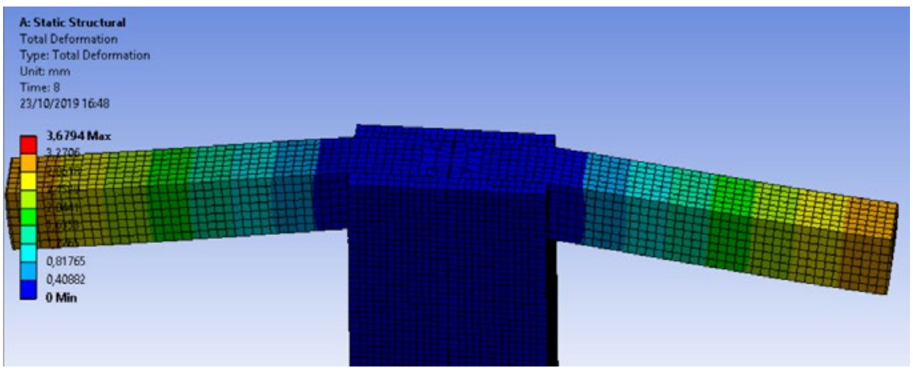
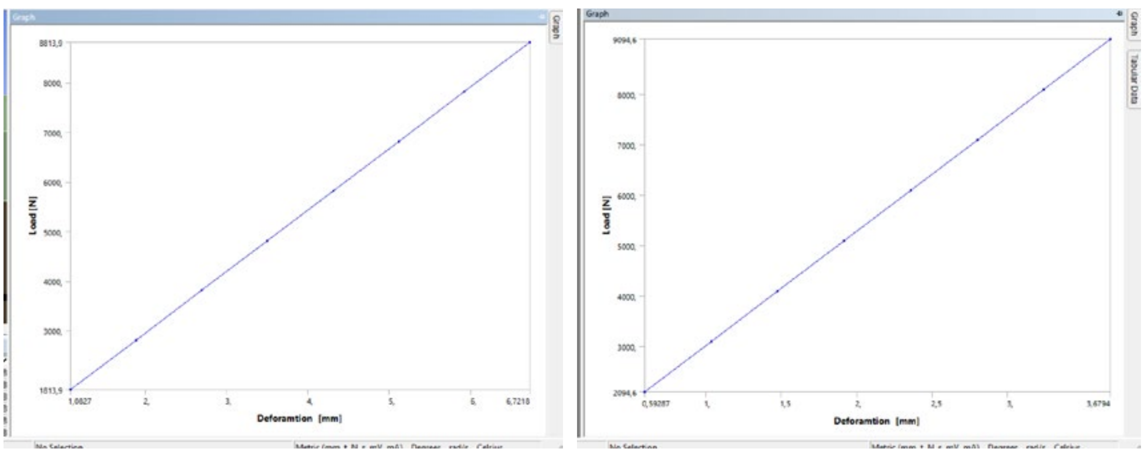


Figure 100: Image showing results for Total Deformation for prototype 3 in ANSYS structural analysis



.Figure 101: Image showing results for Maximum Shear stress areas for Prototype 3 ANSYS structural analysis

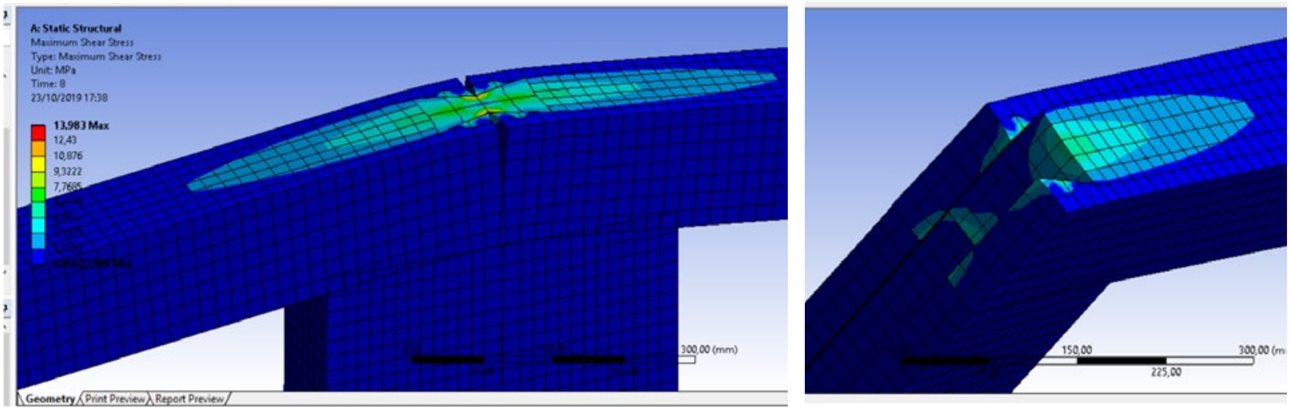


Figure 102: Image showing graph for comparative analysis of total deformation for a maximum load of 8 KN for Prototype 1 and 2 and 3.

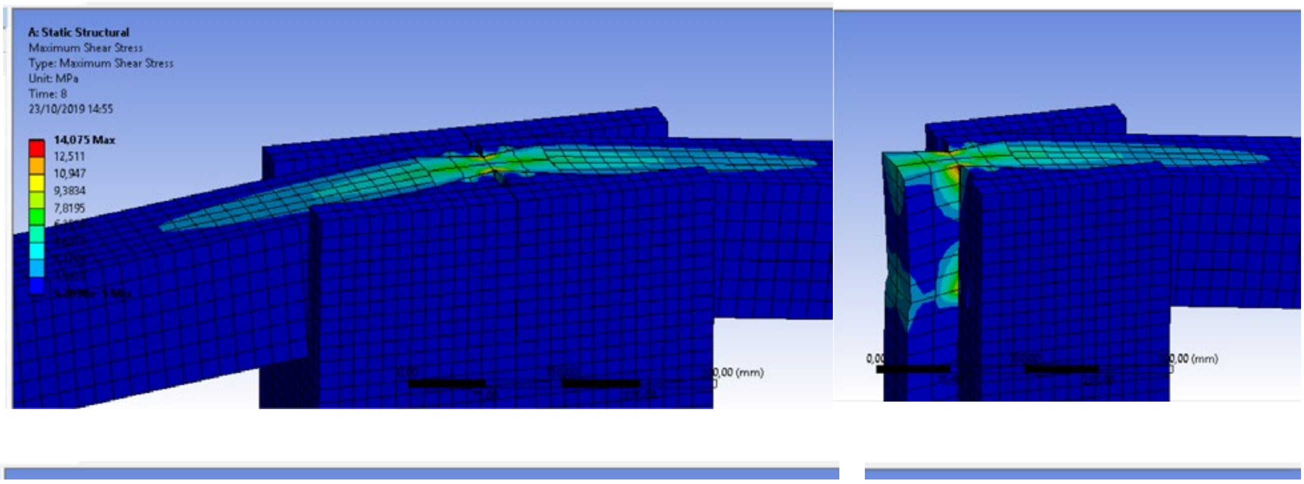


Figure 103: Image showing results for Maximum Shear stress areas for Prototype 1 ANSYS structural analysis

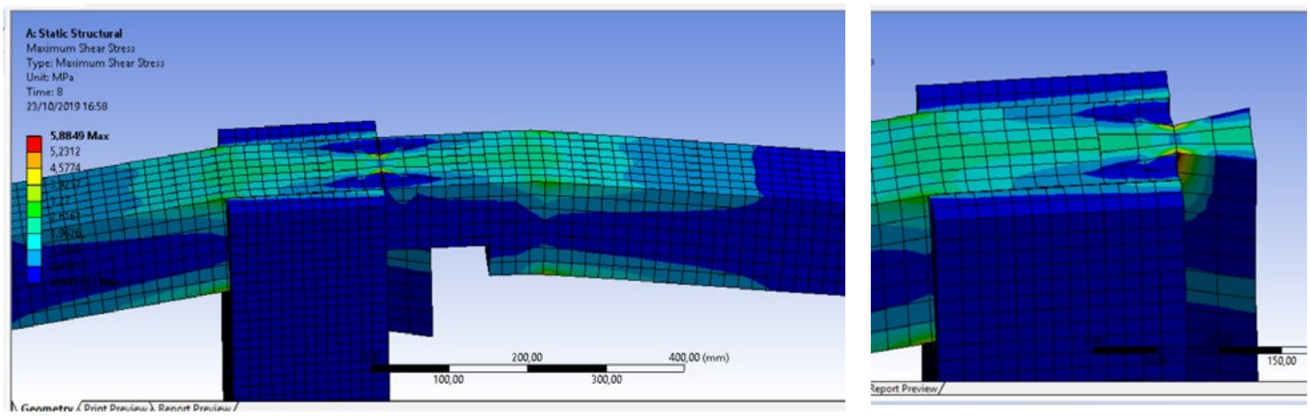


Figure 104: Image showing results for Maximum Shear stress areas for Prototype 2 ANSYS structural analysis

Design for assembly :

Efficient joinery is the one that can be assembled easily and will also need minimum support until the complete joinery is assembled. An effective connection in terms of assembly is the one where the maximum components can be connected before the erection of the frame structure, thus reducing the dependency on extra support. Additionally, the joinery which requires minimum labor effort, tooling and equipment.

The design studied above satisfies the requirements for the assembly process as each of the members can slide in and one dovetail member connected to multiple members, with no extra support required while the erection of remaining frame structures.

The tolerances in the joinery also depend on the assembly sequence, too tight-fitting members would need high strength to be fitted in. The design for assembly is governed by the shape of the members. As a consideration of both aspects, The design for assembly and design for strength go hand in hand.

Design for Interlocking :

With absolute, no use of cross pegs or nuts and bolts to keep the members on place the preventing from pulling out forces becomes of prime importance. The whole design strength is dependent on the Interlocking strength of the members. The lower the allowances for movement within the joinery higher the strength. Thus tolerances need to be within 1 mm for the design to work in terms of strength. However 1 mm tolerance for member can need extra precision in terms of production, limiting the possible options for production. Additionally, low or minimum tolerances within the joints would need extra force for the member to be fit into each other.

Thus the designing for interlocking is perfect sizing for low tolerance and to be able to be assembled without extra force or without the force required which can damage the components while assembling.

10.11FINAL DESIGN :

With an understanding of the analysis above a final design is proposed in order to build a G+ 1 story structure. The most important frame connections are designed and the structure is validated based on the final connection.

The diagram below shows the final structural system proposed and the location of the final joinery design in the structure.

Certain assumptions are made for other connections in Joinery. For foundation, the dovetail connecting the column will be inserted and the concrete foundation. The material of the dovetail connecting the foundation and the column is not pre-determined. After a compatibility analysis, any other material can be used instead.

The direction of the fibers in Structural members :

As discussed above in chapter --- in material analysis, the use of the material in the right structural direction can help reduce the stresses and will also save a lot of material in terms of not oversizing in order to get the stress in permissible limits. The following diagram analysis shows the direction of fibers for each of the design component in the joinery

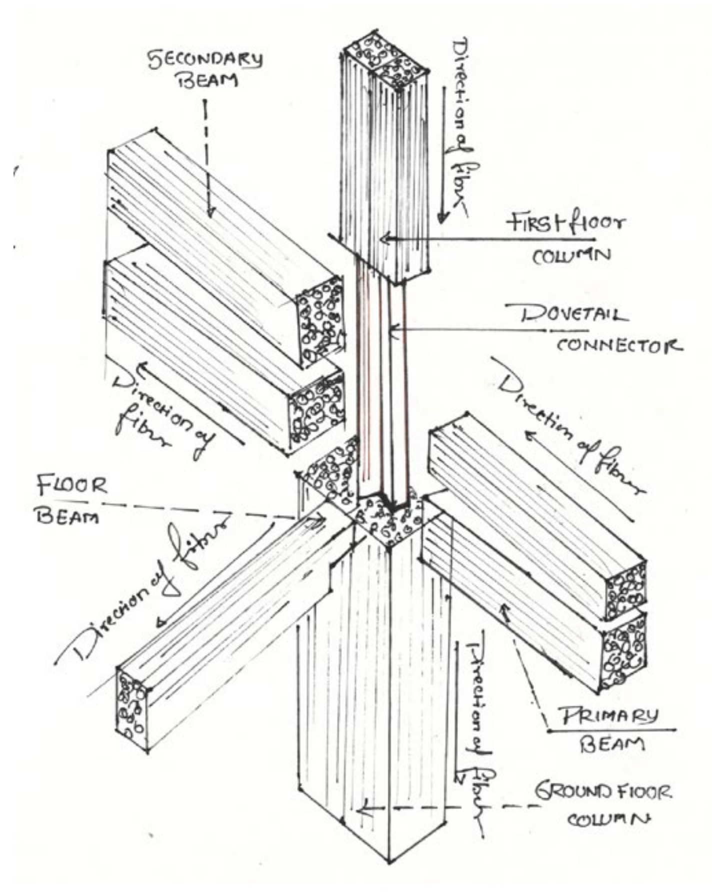


Figure 105: Image showing the direction of fibers and the components for final structural system

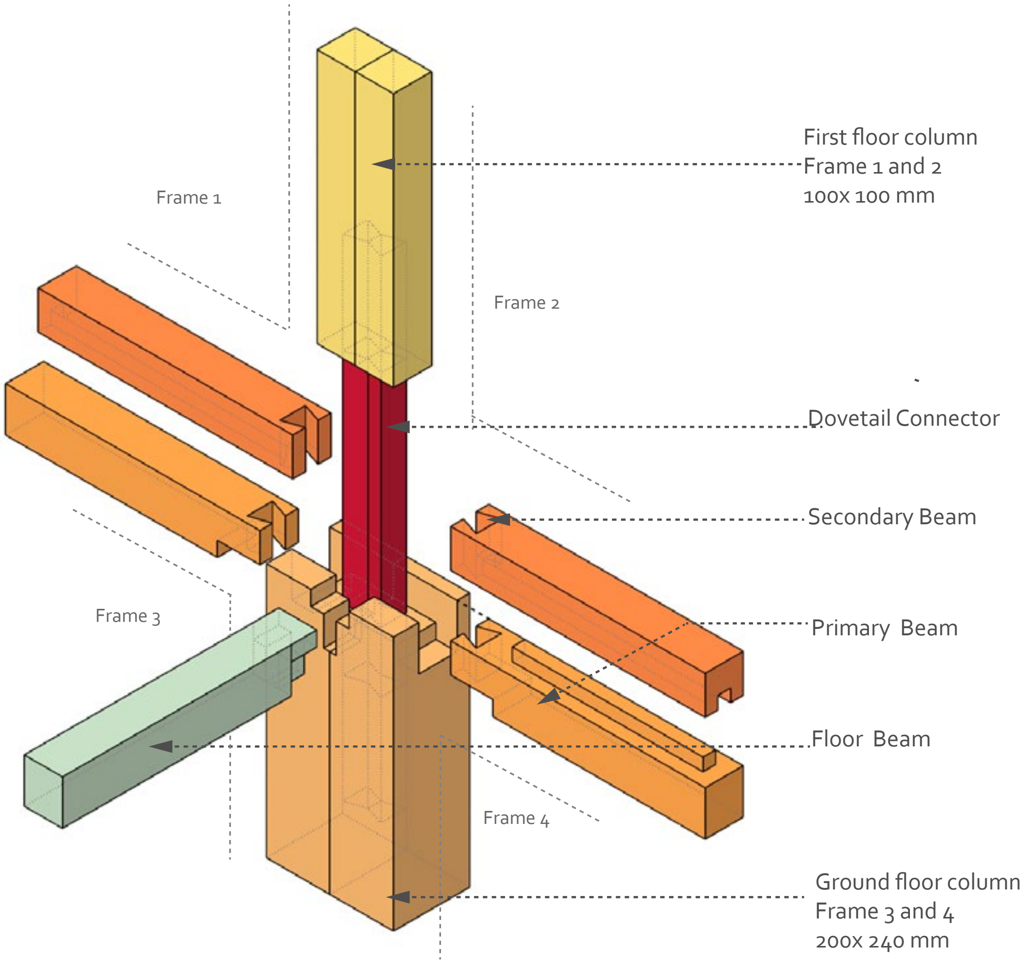


Figure 106: a .Final design configuration for a parallel frame connection. .b assembly sequence for connecting the frame components.

Connection design configuration for connecting frames in parallel.

As shown in figure 106 the main connecting member is a dovetail shaped component vertically inserted in the column after the place of the column beam in place. The most important function of the dovetail is to establish a connection between the ground floor and upper floor column. A can dovetail connection can be avoided if the upper story is not built.

The secondary beam of the frame component acts as a sacrificial beam which helps connect and keep all the floor beams in place in which the Primary beam remains intact with not the discontinuation of fibers to function at its full strength capacity. The Primary floor beams can be of timber or Bamboo.

Assembly sequence for connecting the members

Placement of column - placement of Primary(where the notch will avoid displacement) -Placement of secondary beam and floor beam, Dovetail insert- Frist floor column.

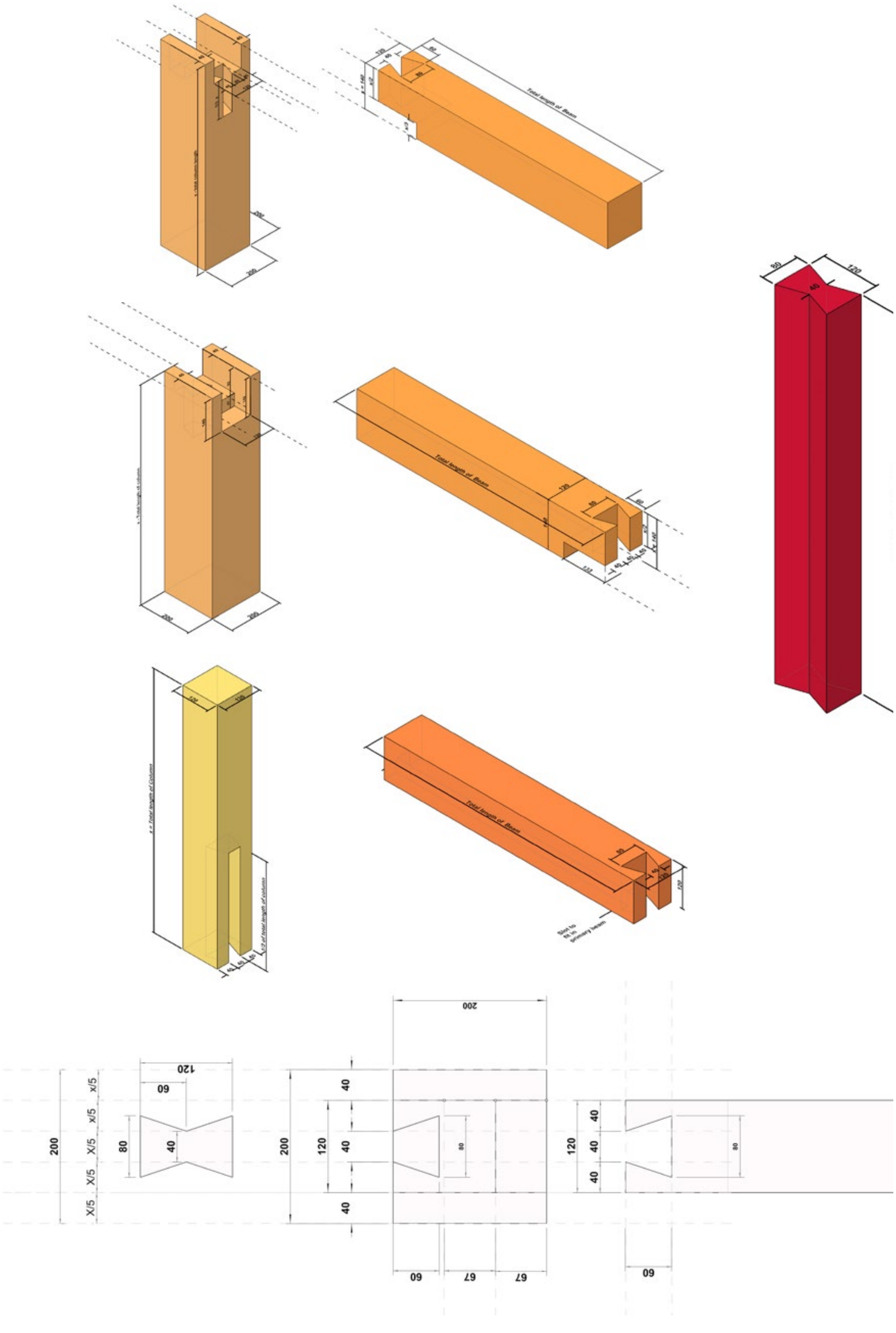


Figure 107: Individual frame component sizes for joinery in Figure 106.

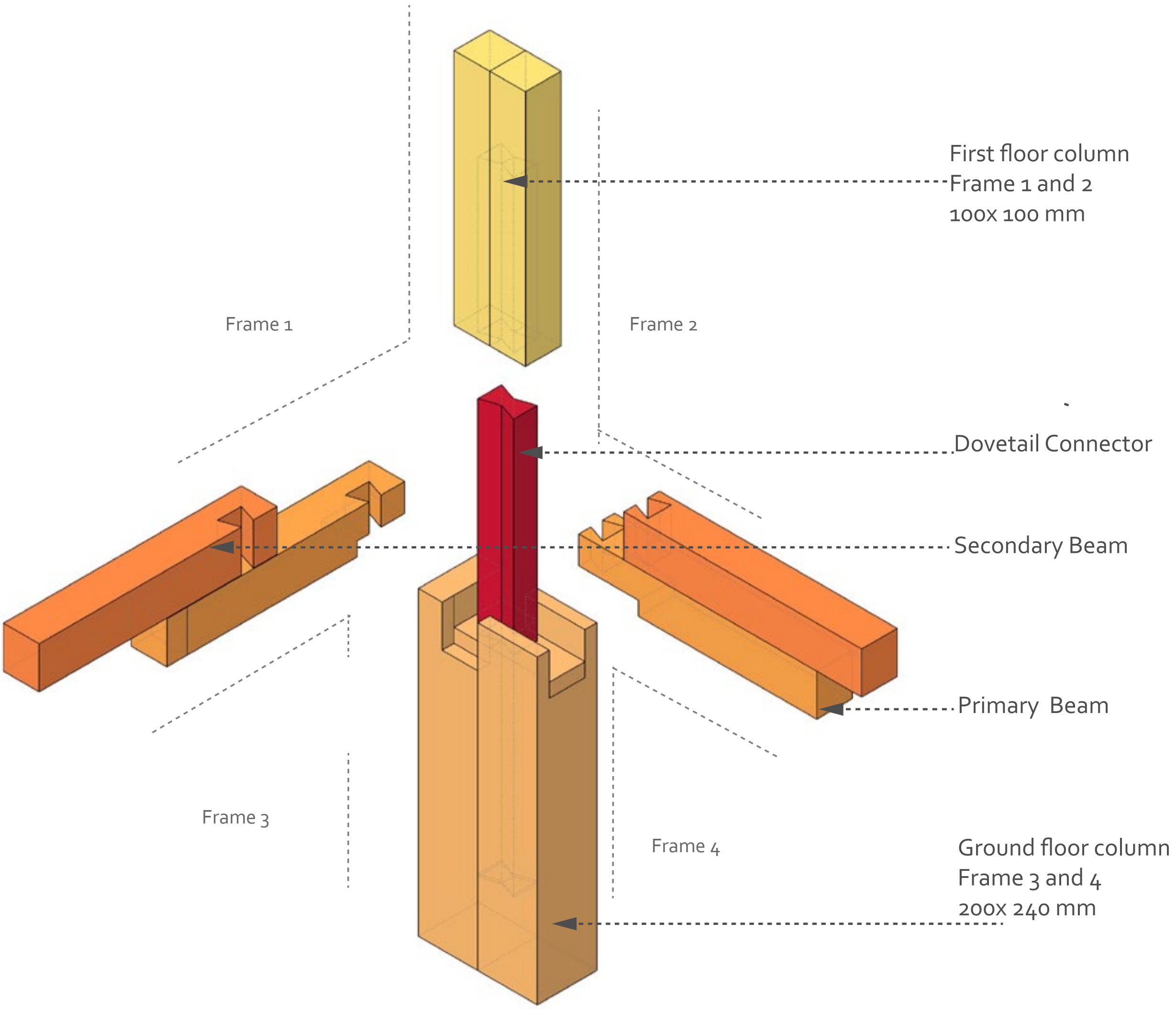


Figure 107: a .Final design configuration for a perpendicular frame connection. .b assembly sequence for connecting the frame components.

Connection design configuration for connecting frames in parallel.

As in the case of parallel frame connections the Perpendicular connections are also designed based on the main dovetail shaped connector. For the perpendicular beam, rests on the column below and is connected to dovetail in sideways. The floor beam will only rest on the secondary beam, in this case, thus column in corners are sized smaller than the main parallel connection column.

Assembly sequence for connecting the members

Placement of column - placement of Primary(where the notch will avoid displacement) -Placement of secondary beam, Dovetail insert- Frist floor column.

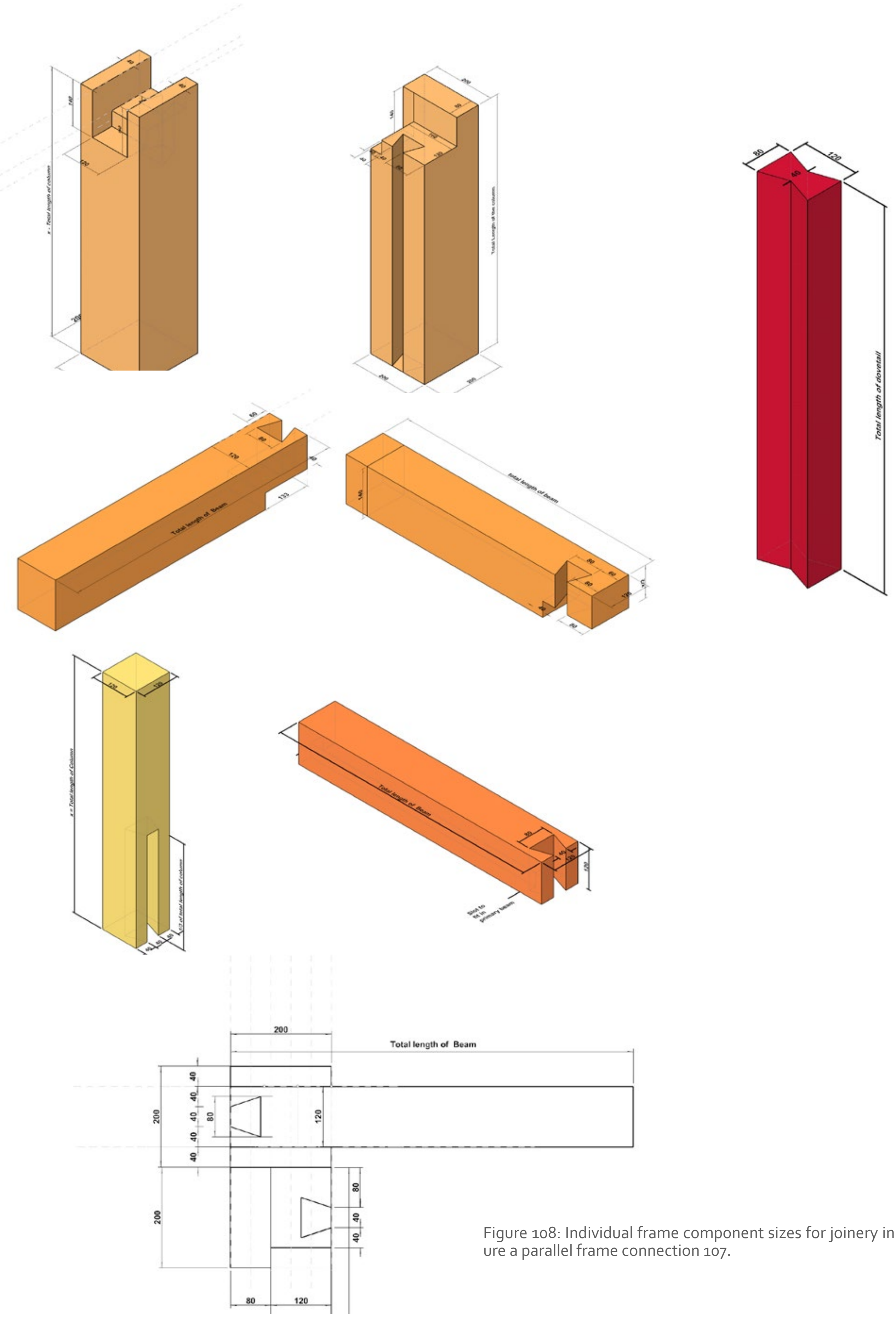


Figure 108: Individual frame component sizes for joinery in Figure a parallel frame connection 107.

10.12 STRUCTURAL VALIDATION

The proposed final joineries come together as an entire structural system. A structural analysis to understand the behavior of the joinery was done in section Design of Strength, based on the analysis, a final design was proposed , in this section a global structural analysis will be carried out to evaluate the stresses involved in joinery components at their true scale and compare these stresses values with the permissible stress limit values.

For the structural analysis, static structural analysis was run in ANSYS software to calculate the flexural strength, deflection, and shear in the tension members and for compressive strength in compressive members.

The structural system as a whole needs to perform for the total load and forces acting on the structure. For simplification of the calculation, the roof is not modeled and only the load acting on a flat surface is considered for the final validation model. Final loading is considered from Chapter 07.

The first step of final validation is to analyze the total and directional deformation in the member

A complete frame model connection model Is used for the analysis. The symmetry region option is used for the total frame and structural component.

Setup: All the contacts between the members are input as bonded and the joinery is loaded for maximum UDL load of 16800 N, which the actual load acting the structure. Fixed support is provided only on the bottom face of the column, in an ideal scenario the column will be well connected to the foundation with a side casing and strength of the dovetail needs to be evaluated.

Validation Setup image: Image 109 shows the boundary condition setup in ANSYS for simplification of the analysis. The model is validated for Directional deformation in Z direction, for equivalent bending stress, and for shear stress.

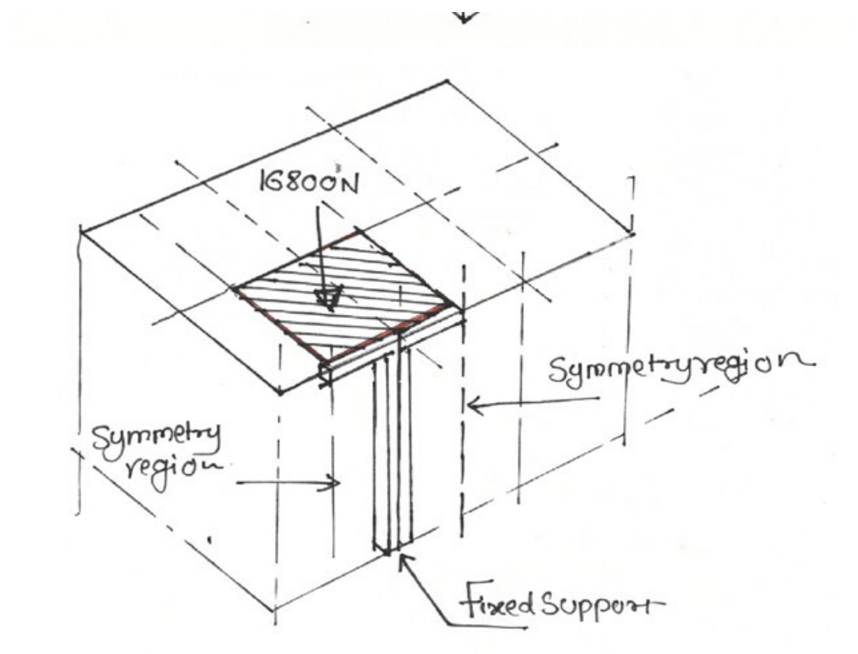


Figure 109: Image showing the applied boundary condition in ANSYS for simplification of the analysis

Results :

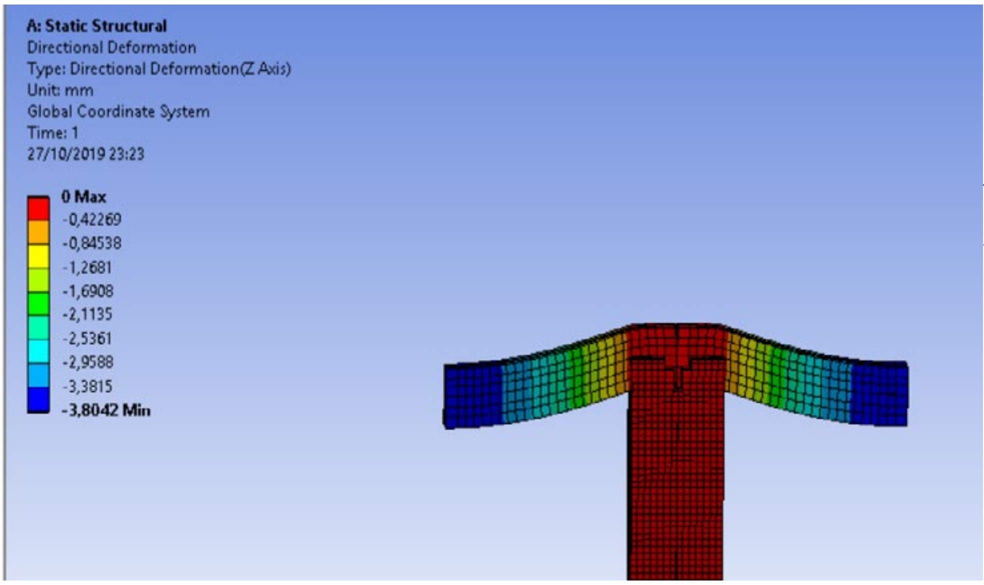


Figure 110: Image showing results for z directional Deformation for Final parallel frame connection in ANSYS structural analysis

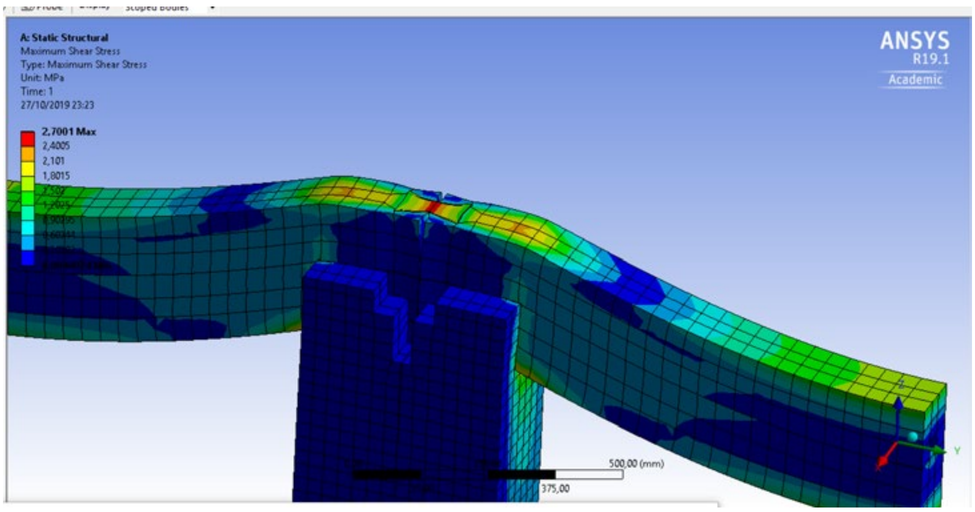


Figure 111: Image showing results for maximum Shear stress for final parallel frame connection in ANSYS structural analysis

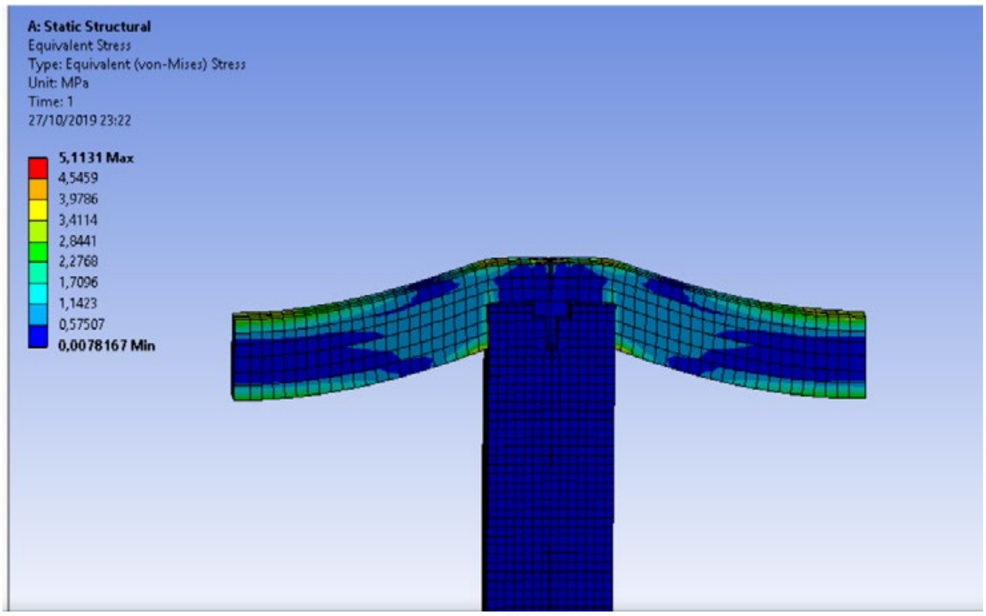


Figure 112: Image showing results for equivalent bending stress for final parallel frame connection in ANSYS structural analysis

The maximums equivalent values for total deformation, bending stress and shear stress are summarized in the table below.

Type	Permissible Limits (based on results from (Trujillo & López, 2016)	Results from Manual structural calculation	Results from ANSYS analysis
Horizontal Shear stress	7.5 N/mm2	5.547 N/mm^2	*2.7 Mpa*
Total deformation	From standard 1/240 of span rule =8.3Mm Based on testing of the prototype :	2.68 mm	*3.8 mm*
Flexural Strength : Maximum bending	39.66 n/mm2	10.7 N/mm^2	*5.1 Mpa*
Equivalent stress	25N/mm2		

Table 113: Showing the comparative analysis of final values for deformation, shear and bending with the safe permissible value data from (Trujillo & López, 2016) and manual calculation done in chapter 9

Assumption :

For permissible limits based on the research by (Trujillo & López, 2016) as shown in the table are taken as ½ of the actual values for permissible limits.

Total deformation values are based on the manual calculations and on prototype testing. The testing setup and type can affect the deformation values but are considered in this case for a better understanding based on the comparison

Thus comparing the values, it can be concluded that even after analyzing the structure with joinery, the stress values for the structure are within permissible safe limits. In further advanced calculation, a global FEM analysis needs to be carried out.

10.13 PRODUCTION TO ASSEMBLY OF THE STRUCTURE AND COMPONENTS :

The first phase of design for assembly is the production and fabrication of the joinery. Which includes sourcing the right type of bamboo material locally, defined within local transport distances.(which may differ according to the region) and producing it using locally available materials and equipment. A business proposal is to have a small scale factory set up to allow local production of the elements. An alternative is to ship the material from the companies producing it currently. It must be kept in mind that shipping the material can increase the cost of the structure, as well as the environmental impacts due to transportation, which will increase.

After the production of the component which needs to be designed for assembly, the assembly sequence needs to be decided. Understanding of the design for assembly of individual joinery in seen in the chapter ----- in sections. This part will show the overall assembly sequence of the structure, and determine the members which need to be assembled off-site and which needs to be assembled onsite. Based on the components to be assembled on-site, the no of labors, tooling, and equipment required for assembly is determined. An ideal design would reduce the dependency on all the above thus simplify the process. Also this section evaluates the assembly based on the transport requirement in terms of parts that need to assembled off-site and transported. For example a component would need a large transport truck thus increase the cost of the projects and dependency on advanced equipment to install a larger prototype on site.

Assembly Sequence:

Foundations dovetail connectors are cast in the concrete foundation in advance. The dovetail connectors can be replaced by Steel or wood connectors. The columns are inserted in the dovetail. As shown in figure the column and beam can be inserted together as a frame component. Additionally, it is also possible to Pre-assemble the frame with facade components with lateral support.

10.14 PRODUCTION

The individual design components can be produced in multiple ways :

10.14.1 By Mould -pressing to shape :

The production process of the bamboo scrimber beam was studied in chapter 04 Undset the section production process. Based on the analysis and understanding of the production process it is possible to press the components in the desired shape using a mold - casted press.

This method is very useful in terms of large quantities of modular housing in which repetitive components need to be produced. Another advantage of the mold pressing the components of the desired joinery is to avoid defects and increase precision in the fabrication of the components. As seen and discusses above the strength of the joinery is dependent on the tolerances and precision in the joinery fabrication. Mold pressing the joinery will eliminate all these issues dependent on manual skills of carpentry and also the tooling.Additionally, while designing the components are designed in such a way that there are no undercuts and are suitable for the primary press process.

1.1.2 By using advanced cutting tools like CNC cutting machine.

A recent development in the production of the timber joinery system is producing the joinery used CNC cutting tools, thus reducing the dependency on skilled labor. CNC routing can be utilized for more or less any wood-like product including composites included. Currently, common CNC machines have the ability to cut in 5 or 6 directions, or axes. Consequently, complex forms - ones that are curved and angled in varying configurations - are possible. Automated drill heads move above and around a stationary wooden piece, cutting away at it where necessary. Drill bit movement is dictated through CAD/CAM software in 3D coordinates (x,y,z). A typical CNC machine is shown in Figure ----CNC technology is comparatively a new technology and can be a bit expensive in terms of large scale and quant*ity* production.

Image showing Wood CNC engraving and cutting machine close up processing

1.1.3 Manually used simple carpentry or using advanced timber cutting machinery

The production of the joinery elements will require skilled carpentry expertise requirement

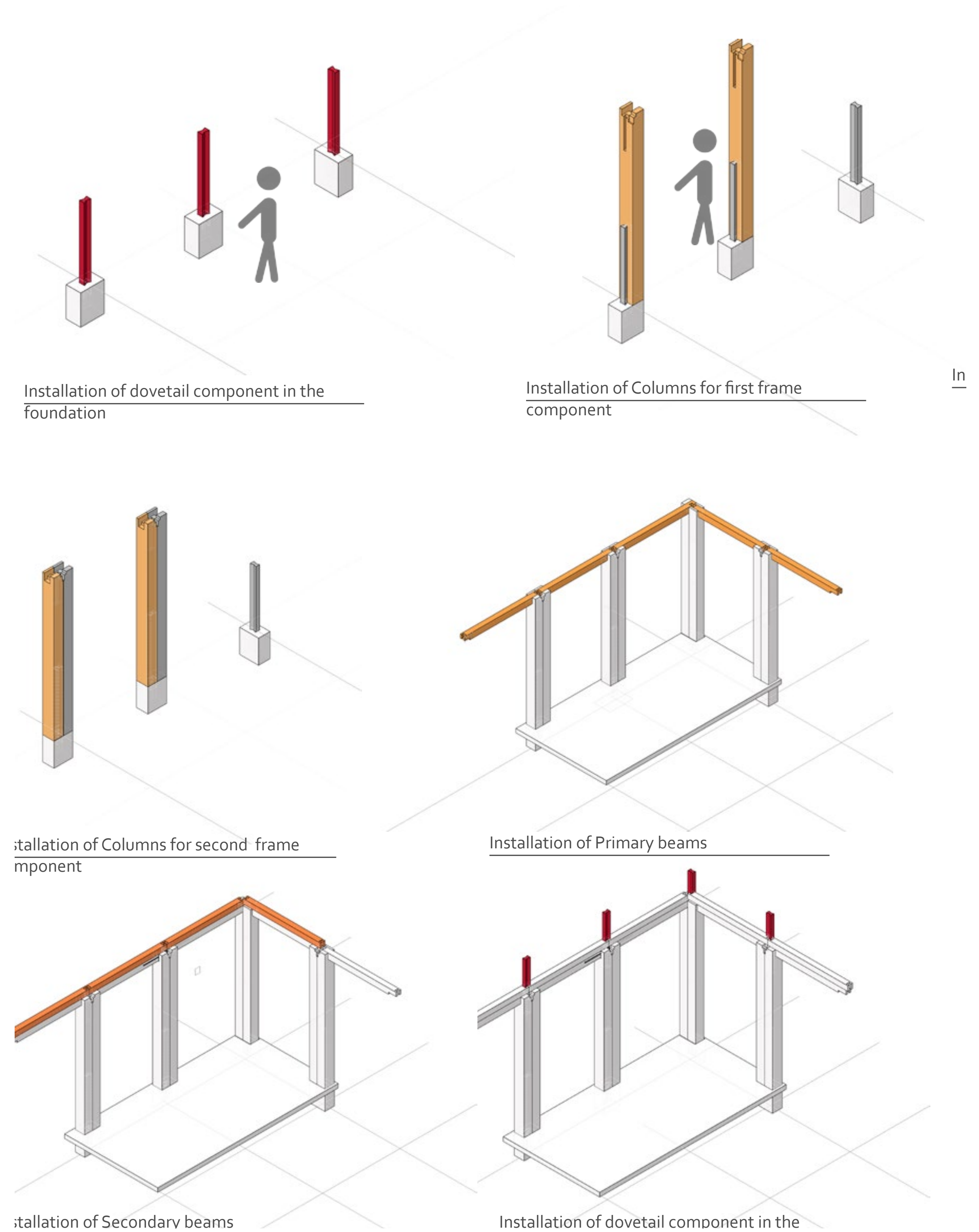
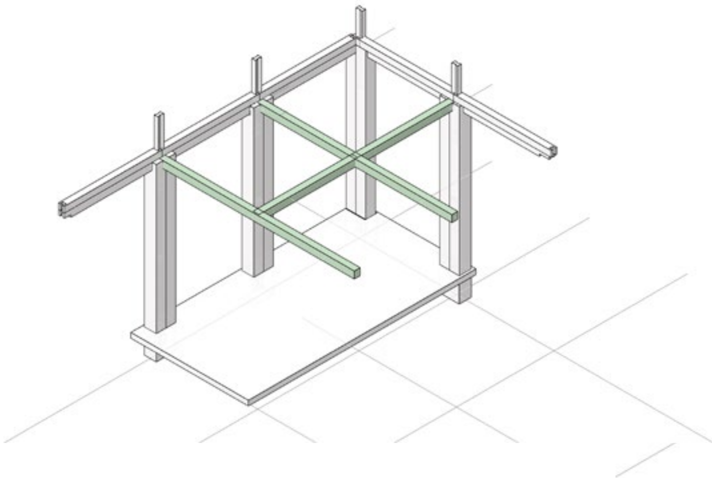
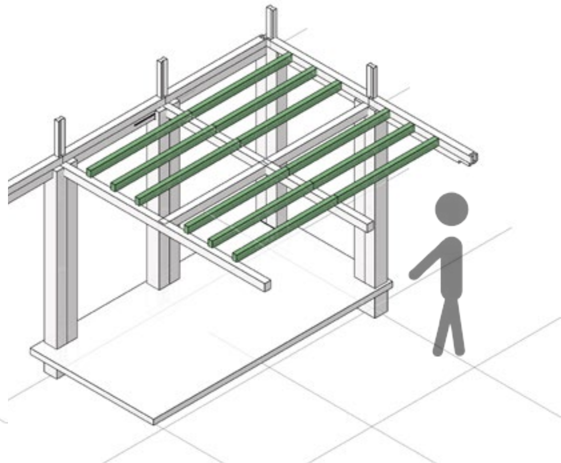


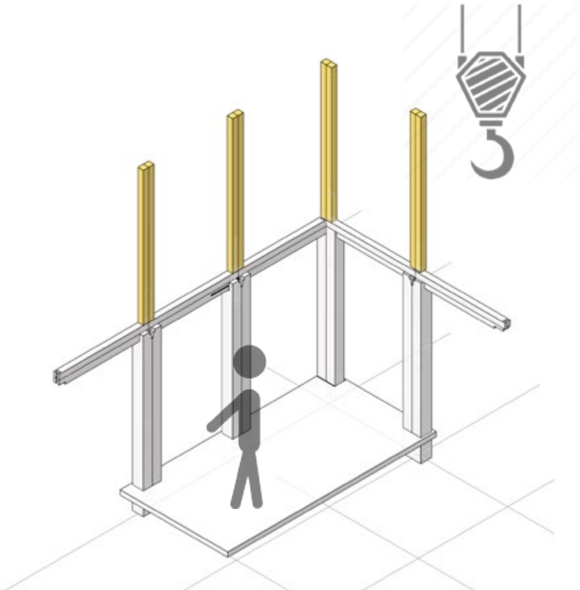
Figure 115: Image showing assembly sequence for construction process of structural system using final joinery



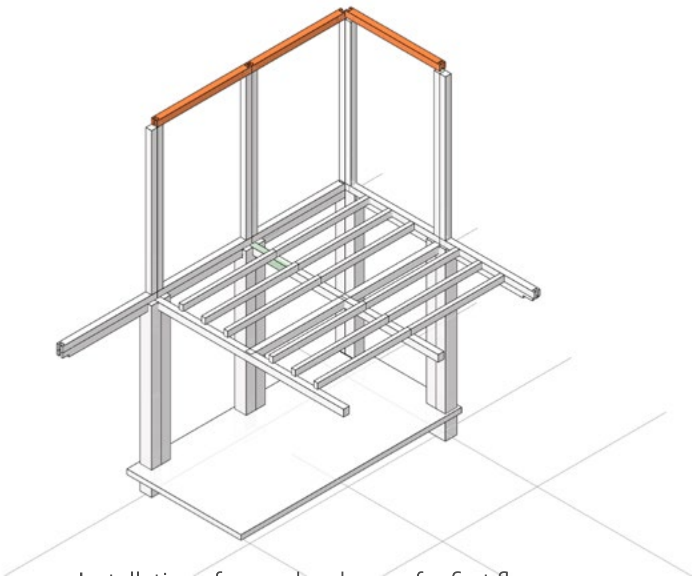
nstallation of primary floor beams



Installation of secondary floor beams

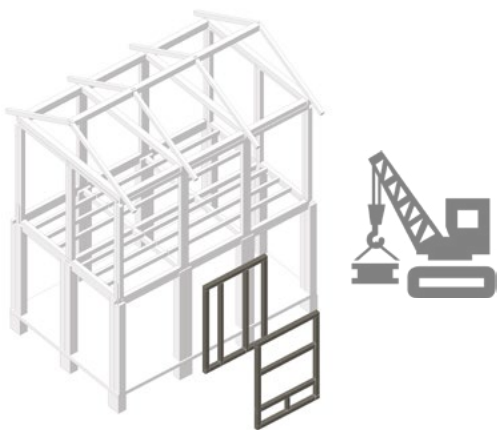


Installation of first floor columns



Installation of secondary beams for first floor

Installation of primary floor beams



Installation of facade components

Figure 115: Image showing assembly sequence for construction process of structural system using final joinery (continued)

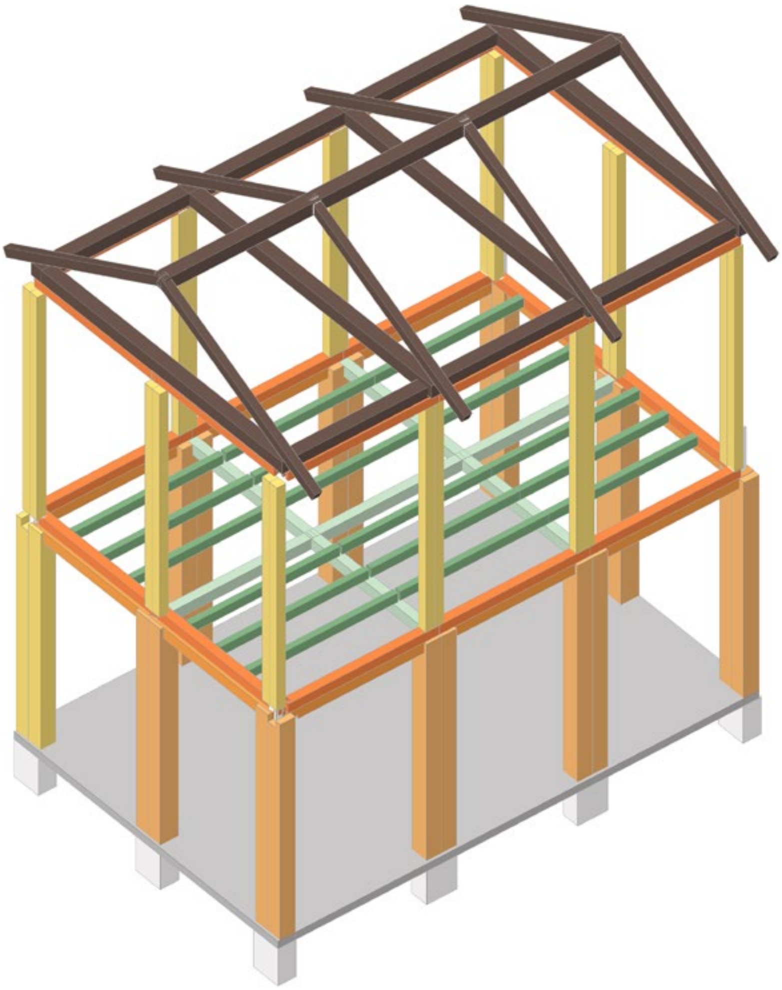


Figure 116: Image showing final assembled structural system

11. DISCUSSION AND CONCLUSION:

The findings of the research can be categorized with respect to the research done and posed research questions,

The initial analysis was intended to understand if there is a need for bamboo structures, if yes why are they still not built. Based on a set of questions it was understood that there is actually a need for more environmentally friendly material for construction today, and for energy-efficient housing based on the new rule coming up globally. With this understanding and an assumption for a need for housing, in order to change the perspective of using bamboo from poor man's timber, a basic housing system was developed catering to mass population. In order to facilitate the construction of the structure of the house, further understanding was done to explore and understand the material to be used to build the house.

The first step was to understand whether it is possible to build houses using the engineered forms of bamboo currently available, which led to **Explore the properties of the material in natural and engineered form. Understand if the physical and mechanical properties of material are suitable for construction purposes?**

The answer to this is given by summarizing the results for the literature review of Bamboo in natural and engineered form. From this research it was concluded that bamboo in natural and in engineered form display high structural strength. The properties of engineered form of bamboo are even further ahead, not only in terms of the strength but also in terms of long life, durability, and usability (based on standard section sizes) for structural purposes.

It can be seen from the analysis of the mechanical properties that the material displays very high strength but also comes with set mechanical failures like the issue of splitting, strength-based on fiber direction. Thus, with strong structural potential bamboo can be complicated to be used in construction and would require structured design rules.

Even after modifying the properties of Bamboo, up to 80 % of the material's behavior post-modification is similar to a natural bamboo pole. The modified bamboo shows higher strength and durability, but while designing one must not forget that the material still majorly behaves like natural form, thus most of the design consideration which is allowable to natural bamboo like avoiding direct contact with should be followed as they can affect the material strength in more ways than expected.

Additionally, it was analyzed that bamboo does not behave like wood and thus while adapting any design from timber construction and joinery, special care must be taken to understand and analyze the behavior of the joinery built using Bamboo.

Thus, it can be concluded that if designed with understanding and precision bamboo displays a very high potential to be used in construction and it is stronger than the majority of building construction material used today.

Understanding form timber construction techniques:

For the material analysis, it was concluded that Bamboo, similar to wood is a kind of heterogeneous and anisotropic material and therefore the physio-mechanical properties are extremely unstable, but in certain respects it is more unstable than wood. Also, from the research in timber joineries it was evaluated that it is possible to build timber structures without nails and external fasteners, a similar approach can be adapted in designing with bamboo by keeping in the limitations posed while developing with engineered bamboo***. Adaption from Japanese construction techniques designed with no external fastener.***

Understanding the prefabricated approach of construction and its relevance?

A basic understanding of the design using prefabricated techniques shows the engineered bamboo can facilitate prefabrication positively, ***showing a high potential for manufacturing and design for assembly***. Also, from understanding of the production process it is evident that the engineered bamboo production allows for more versatility in form and shape.

What methods suits the best in order to develop and design the connections?

Based on the understanding of the material a set of evaluation criteria were followed for further development. The joinery which follows highest number of aspects from the evaluation criteria table was also the most structurally stable joinery. Thus, the evaluation criteria can act as a design rule reference for future research on designing with bamboo as they are more generalized.

Evaluate Feasibility in terms of the strength of the connection?

Within the time and resources limitation, the strength and feasibility of bamboo were analyzed using ANSYS computational structural analysis software and based on intuitive analysis's results were positive and within the permissible limit assumed for use of bamboo for structural application.

It is safe to conclude that it is also possible to efficiently connect and use bamboo for structural application. Although these results can only give the understanding to project the possible behavior of the material. It is very crucial and important to prototype the designs and experimentally test for loading which would give the actual results for strength as well as the behavior of the material while loaded.

In conclusion, a house was designed based on several criteria and from an understanding of the timber construction system. In the initial design process of structural system certain assumptions were made and a system was proposed for further development of the connection.

How can the joinery components be produced in order to facilitate the process of connections efficiently?

With standard form and shape properties of engineered bamboo, it is possible to develop the joinery using more versatility of forming and shaping. Additionally, it is possible to produce prototypes using high precision machines like CNC, Water-Jet laser cutting, etc.

The project began with understanding the feasibility of building with bamboo and ended with a workable solution for using the material for structural purposed, with no sure data available to develop a concrete methodology.

Conclusion :

At present bamboo is evolving as a potential sustainable material with no standard of design rules for the material to be used in construction. Various researchers are working around the world to use engineered Bamboo for structural applications. During this Thesis, bamboo proved to be a very difficult material to understand and work with. Being so complicated, the beauty of the natural material is that it can also be worked on Intuitively.

Bamboo is a renewable material that has very high mechanical properties and thus also has the potential to be used much as engineered lumber. Presently, used or as a partial substitute for wood fiber in engineered wood products has a high potential for structural use not only in terms of strength but also in terms of design and construction workability. Thus, this Research will satisfactorily help designers with the process design and construction using engineered bamboo.

When to be used for the structural purpose each material has strengths and weaknesses, and it is up to the designer and the engineers than the apt ways possible for the benefit of contribution, design, and environment as a whole, and this thesis provides a base towards further work by assisting the users. The result is now in the hands of innovative architects, engineers, and builders to rediscover the use of Bamboo in construction for large, inner-city buildings that are architecturally exciting as well. Bamboo is not only a renewable resource, it comes from sustainably managed forests as an environmentally friendly material. Also, as a natural material its appearance and feel is aesthetically pleasing to the human soul.

12. LIMITATIONS AND FURTHER RECOMMENDATION:

12 LIMITATIONS AND FURTHER RECOMMENDATION:

This research was a basic feasibility analysis and understanding opening a lot more horizons for further research which were not possible to develop given the limitations of time and resources available at hand.

In terms of improvisation in material, further optimization of the joint details and adhesive should be considered in any future development, with particular emphasis on improving joint strength.

To improve the strength of the connection, considerations should be given to:

- Increasing the strength of the adhesive bonds while manufacturing of the material. (through curing at elevated temperatures or use of different chemical adhesives)
- Improvement in manufacturing techniques of the material (for example use of fibers in cross lamination) or an alternative method towards eliminating such joints entirely by developing a bamboo-adhesive composite from parallel/cross-laminated strands.
- Reinforcing the connections by bonding additional materials, such as carbon fiber or fiber-reinforced polymers while manufacturing. Or use of composite reinforcement.

In terms of design strength there no fixed safe permissible limits set for structural validation of the Material and can be researched further for practical applications. Additionally, with no building construction rules for the structural use of material, it may take time to be implemented as a main structural building material. But until then the research can be put to use for temporary installation and building in remote locations, where natural material is the only available source of building material.

A detailed understanding of design for assembly is required to improvise the design process.Further understanding of the production process for Press molding should be done and implemented in the design.

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Orange Bamboo Design

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