Low Cost Earthquake Resilient Housing

An analysis of the design process.

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Executive Summary

Nepal is a country that experiences frequent seismic movements which causes significant damage to buildings. This report introduces a design for a low-cost earthquake resilient house for the victims of the Nepal earthquake. The design incorporates four main features which allow it to be earthquake proof:

- The walls of the house are made of compressed stabilised earth bricks (CSEB), these are made from local materials (i.e. soil, gravel, slit, cement).
- The walls are reinforced using iron bars which will be inserted inside the CSEB walls to strengthen the structure of the house.
- Bambusa Balcooa bamboos are attached in between the walls to resist any horizontal seismic movements, this feature can withstand 445603.5N when being compressed.
- The house is built on top of a rigid flat foundation made of stone. This aids the stability of the house during seismic movements.

To maintain a comfortable temperature inside the house when the outdoor temperature fluctuates between -10℃ and 30℃, we used materials with high thermal mass (low heat absorption) such as thatched roofing and earth bricks.

This low-cost earthquake resilient house meets all the requests from the clients, the simple design structure allows uneducated labours to be able to build it. Moreover, all materials are found locally which means no further cost will be needed for transportation and this keeps the price under the budget of 5000 NZD. Thus, this earthquake resilient house is highly recommended to be built in the mountainous area of Nepal.

The final recommended design is the shell of a house with a single common area, this report assumes the use of communal kitchens and bathrooms in the village it will be situated in. This corresponds with the lack of amenities included in the design.

1.0 Introduction

The Earth's crust is made up of large tectonic plates which are constantly in motion. An earthquake is a result of the seismic waves produced when various plates collide with each other (Endsley, 2018).

The effects of an earthquake are largely felt by developing countries, where the lack of knowledge and education around civil engineering leads to very few buildings exhibiting earthquake resilience.

Nepal is still feeling the effects of the devastating magnitude 7.8 earthquake that hit in 2015, killing nearly 9000 people and injuring 22,000 (Rafferty, 2018). Due to major collapsing of poorly designed buildings which were unable to withstand the tremors, Nepal still has a substantial demand for low cost and earthquake proof housing. It is estimated that only 5% of the homes are rebuilt till now (Adhikari, 2017), this leaves approximately 570,000 houses still needing reconstruction.

The aim of this report is to examine possible solutions for the current housing crisis in Nepal following the recent disastrous earthquakes. This report looks at the design process followed to come up with the final recommended design for a low-cost earthquake resilient house. The data in this report was largely sourced from contact with Build Up Nepal which is an emergency earthquake relief organisation. The main conclusion drawn from this report were that it was vital to follow the design process thoroughly to obtain an effective design at the end. It was central to the development of the final design as it provided the framework and steps required to complete a design that met the product design specifications such as cost-effectiveness and earthquake-resistance. The scope of this report covers the design process that was undertaken to come up with a final, cost effective, earthquake resilient design.

2.0 Project Objectives

The objective is to design a low-cost earthquake resilient house located in remote parts of mountainous Nepal. The design must be constructed within the budget of $5000 NZD (373889 NPR). The use of local materials is encouraged due to the isolated nature of mountainous Nepal which has no vehicular access hence transportation of materials not found locally will greatly consume time and money. The single floor house must have sufficient space for a family of four (2 adults, 2 children), be livable between the temperatures of -10°C to 30°C and have enough strength to withstand a ground acceleration of 0.4g.

3.0 Model Development

3.1 How was the problem modelled/analyzed?

The first stage of the design process comprised of defining the problem at hand by creating a needs assessment and stakeholder analysis. The stakeholders were found to be the people who would be living in the proposed houses, they need structurally sound housing which will be able to resist the damaging effects of an earthquake and provide an adequate living space. The Nepali government was another stakeholder, they required the proposed design to be cost effective and abide by local building code and safety standards. The final group of stakeholders were the contractors and laborer's who require a simple design with easy-to-source materials. This assessment of stakeholders and their needs led to the production of the Product Design Specifications (PDS). **See Appendix One.**

The next stage was concept generation and brainstorming. With the stakeholder's interests and the design specifications in mind, possible solutions were proposed. This allowed the development of key components of the house.

A morphological analysis (**See Appendix Six**) was then carried out to compile options for the main features of the house, this included the foundation, roof, roof shape, etc. After researching the suitability of each option, decisions were made on the final features.

After deciding upon the fundamental elements of the house, concept designs were produced by each group member (See Appendix Seven)

3.1.1 Justification of Body of House

Materials of the house

CSEB is a high-density mixture of Soil, Sand and Cement stabilized with iron bars through the center of each brick. The composition of the soil is 20% clay, 15% gravel and 15% silt. The cement makes up 10% of each brick. (Build Up Nepal, n.d.). After emailing Andreas Kolling, the Deputy Managing Director of Build Up Nepal (an organisation which specialises in rebuilding earthquake stricken villages in Nepal) a response was given outlining the benefits and physical properties of CSEB. These include:

- A **higher thermal mass** than fired bricks, translating into warmer indoor climate in winter and cooler during the warm summer months i.e. the earth bricks themselves can act as a form of insulation. (Kolling, "Earth Brick Cost and Earthquake Proof House Design", 2018)

- Cheaper alternative to standard fired bricks costing **294795 NRS ($3933). See Appendix Two** to build the entire house including skilled labour (assuming unskilled labour is also provided voluntarily by the village).

Bambusa Balcooa bamboo will also be attached horizontally in between CSEB brick walls allowing the house to be able to resist earthquakes in all directions. With a tensile strength of 164 N/mm^2 and compressive strength of 39.4 N/mm^2 (Schroder, 2011), it can withstand 445603.5N (see Appendix Two B-ii) when being compressed and 1854790.8N when being stretched (see Appendix Two C-ii) in between CSEB walls at a height of 2.4m. This has proven that with bambusa balcooa bamboo as a horizontal supporting beam for the house, an applied moment of 9662.46Nm from a 0.4G earthquake can be counteracted. **See Appendix Four D-I for calculations and Appendix Eight for corresponding Diagram)**

Dimensions of the house

A floor area of 36m^2 was decided since 64% of cities in Asia have an average floor area of 5-14m^2 per person. Each person in the family of four was given 9m^2 of space (the median value of the average floor space per person for most Asian cities). This will translate into a total area of 36m^2 for the house. (United Nations Centre for Human Settlements, "Charting the Progress of Population", n.d.)

The house has dimensions of 6m x 6m with a height of 2.4m, this creates symmetry. When a symmetrical house experiences an earthquake, the forces acting on it will be divided equally among the house. This will help stabilize the structure during the earthquake.

Reinforcement

The CSEB brick walls will be reinforced with iron bars to strengthen the structure. Iron is a suitable material for earthquake resistant houses as it has a high ductility. This means that it can resist a large force until deformation (Abbott, 2017) ,therefore, the addition of the iron reinforcement will allow the house to resist a greater amount of force for earthquakes.

Foundation

A strong, flat foundation is essential for the house's stability. The destruction caused by the recent earthquakes has left rubble from demolished houses still lying around. The stone from these remains will be utilised for the **foundation** for the house. This will not be at an added cost to the budget as it is already found locally and is widely available. Laying the stone rubble will provide a strong, flat foundation for the house to be built on.

3.1.2 Roof - Bamboo trusses and thatched roofing

Material of roof

Bamboo has become a very popular material for building houses in Nepal post-earthquake because of its many earthquake resilient properties. Bamboo, such as Bambusa Balcooa is indigenous to Nepal (Schroder, 2011), this limits costs attributed to transportation and the use of heavy crane machinery. Bamboo has very high tensile and compressive strength which helps the house resist ground movement during earthquakes (SpacesNepal, 2016). Bamboo is also a lightweight material which means that in the event of a collapse, the residents of the house are less prone to major injuries. The only drawback to bamboo is that it is susceptible to moisture and insects which results in bamboo having to get treated with a solution before use. The treatment solution strengthens the bamboo and gives it a longer lifespan. The solution is quite expensive however the budget allows for this expenditure as it is vital for the bamboo to be treated before being used to construct the house. (**See Appendix Two**).

In addition to the bamboo trusses, thatched roofing is being used as the cover. Thatching is a cost-effective form of roofing and acts as a good insulator (Historic England, "Energy Efficiency and Historic Buildings", 2012). This allows the house to retain a warm or cold environment, depending on the environment preferred by the resident.

Shape of the roof

The roof is made up of bamboo trusses. There have been multiple trusses used to add redundancy. Redundancy in a truss allows it to maintain equilibrium when larger forces are applied to it. If a force is applied at any position on the truss, it is directed sideways instead of down, hence, it does not bend (Palladino, n.d.).

The intermediate members of the trusses are embedded into the walls of the house. This provides a horizontal force that pushes against the wall and prevents it from falling inwards. (**See Appendix Three, C**)

4.0 Recommended Design

The final recommended design satisfies all the needs of the stakeholders and meets the product design specifications. Earthquake resistance was a vital feature required for the design due to the large importance placed on the safety of the locals. The use of materials (CSEB and bamboo) and the shape of the house were key to the houses earthquake resistance. The CSEBs were reinforced with iron bars to strengthen the walls of the house. To further increase the house's resistance to external forces, the intermediate members of the bamboo trusses were embedded into the wall. This feature can withstand 445603.5N when being compressed (**See Appendix 4.C**). The symmetrical nature of the house (6m x 6m) helps stabilise the house during an earthquake as the forces will be equally distributed. All these factors allowed the house to withstand ground acceleration of 0.4g. Another important specification was the budget allocated to the house. The house was built within the constraints of the budget, coming to a total of **294795** NRS, which is just below $4000 NZD. Temperature control was also extremely important as temperature can range from -10^{o}C to +30^{o}C in mountainous Nepal. CSEB as mentioned in the report has a high thermal mass and can control the temperature within the house, the straw thatching is also an excellent insulator. The total area of the house is 36m^2 this corresponds with the average area required per person in Asia.

See Appendix Nine for Final Design Sketch -- See Appendix Five for Detailed Orthographic Representations of the Final Design -- See Appendix 10 for 3D CAD Representations of the final design.

5.0 Conclusions

After producing a recommended design which fulfils all the project objectives, the following conclusions were made:

- To produce an effective design, an iterative design process had to be followed. This process began with analysing the given problem and defining it with a Product Design Specification (PDS) **See Appendix One**. After defining the problem, a morphological analysis was carried out with features of the house and possible outcomes for those features. The outcome of this analysis can be seen on **Appendix 6.**
- This analysis led to three concept designs (one from each group member) which incorporated all aspects of the decided features.
- Making use of materials found locally such as bamboo, stone, soil and gravel was crucial as the location of the house was extremely isolated and it also helped keep the house within budget.
- Through calculations, extensive research on best practice for the decided features and contact with Build Up Nepal, an emergency earthquake housing organisation, a final recommended design was produced that lied within all the given constraints and met all the project objectives. This final design included some aspects from all three of the initial concept designs.

6.0 References

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7.1 Appendix One

PRODUCT DESIGN SPECIFICATION

Product Identification

- Low cost earthquake resilient house
- structurally sound housing for a family of four in a mountainous area of Nepal.
- Has sufficient space for up to 2 adults and 2 children.
- Able to resist peak ground acceleration levels of 0.4 g
- must be liveable within temperatures ranging from -10°C to +30°C.

Stakeholders

- victims of the earthquake in Nepal want safe housing
- The Nepal government wants to ensure low cost housing
- Labourers and contractors want utilise local materials

Physical Description

- Floor space of $36m^2$ (justified in report)
- Consists of a single room or larger
- Accommodates at least a family of four: two adults and two children

Manufacturing Specifications

- The materials of the resilient house should be found locally or preferably supplied from nature sources in Nepal due to poor transportation
- The design of the house will not be too complicated allowing the uneducated labours/builders to be able to construct the resilient house.
- The size and mass of the materials should not exceed certain amount (approximately 15kg and no larger than 1m2) this allows labours to carry around for over 3 hours.

Life cycle and Maintenance

- The house should last more than 50 years
- The straw thatching should be replaced every 10-15 years provided proper installation

Legal and Social Requirements

- The average area per person in Asia is $9m^2$.
- The house must comply with the building code as well as safety requirements in Nepal

Financial Requirements

- Total construction cost should not exceed $5000 NZD ($380334.46 Nepalese Rupees). This budget is labour inclusive.

Key Project Deadlines

- Deadline to produce a completed design is 9:00am 7th May 2018.

7.2 Appendix Two

Budget Calculation (Kolling, "Earth Brick Cost and Earthquake Proof House Design", 2018)

Material	Units / Type	Cost per unit	Total (Nepalese rupees)
CSEB Bricks (30cm x 15cm x 10cm)	1872	45	84240
Iron reinforcement for the bricks.	12 mm iron bars — 7mm iron bars		44015 12253
Cement			75 508
Binding wire			2099
Bamboo (10m)	22	70	1840
Bamboo Treating solution (Abari, n.d.)	22	300	6600
Thatched roofing (Tonnes) (PW Reporters, 2018). Also **See Appendix Three**	1		13540
Skilled Labour			54700
TOTAL			**294795 NRS**

7.3 Appendix Three

Area	Barley straw	Wheat straw
North East	110 (=)	100 (=)
East Yorkshire	100 (=)	93 (=)
North Midlands	87 (=)	79 (=)
East Midlands	100 (=)	90 (=)
Central Midlands	85 (-10)	75 (-10)
Eastern Counties	95 (=)	88 (=)
South-east	85 (=)	75 (=)
South	115 (=)	105 (=)
South-west	150 (=)	130 (=)
South Wales	110 (=)	100 (=)
SE Scotland	90 (=)	85 (=)

Cost of straw needed for roof thatching

$$\sum Wheat\ Straw\ Prices\ Per\ Tonne \div Number\ of\ Regions$$

$$100 + 93 + 79 + 90 + 75 + 88 + 75 + 105 + 130 + 100 + 85) \div 11 = 93\ GBP = \mathbf{13450\ NRS}$$

7.4 Appendix Four

A. Force from earthquake

CSEB density = 1700-2200 kg/m3, will be using **1900 kg/m3 for calculation.**

A horizontal supporting bamboo supports half length of the wall (0.15m x 2.4m x 3m)

i. Mass of the wall

$$1900kg/m1900\frac{kg}{m^3} \times 0.15m \times 2.4m \times 3m = \mathbf{2052kg}$$

ii. Force due to 0.4g earthquake on the wall

$$2052kg \times 0.4 \times 9.81ms^{-2} = 8052.05N$$

iii. Force needed from the bamboo to resist 0.4g earthquake

$$Mclockwise = Manticlockwise$$

$$8092.5N \times 1.2m = (2.4 - 0.06) \times F$$

$$\boldsymbol{F = 4129.5N}$$

B. Compressive strength of bamboo

Compressive strength of Bambusa balcooa = **39.4 N/mm²**
Diameter of the bamboo = 60mm to 150mm, will be using **60mm** for calculation.

i. Area of the bamboo

$$60mm \times 60mm \times \pi = \mathbf{11309.7mm^2}$$

ii. Amount of force that can be resisted by the bamboo when being compressed.

$$39.4\frac{N}{mm2} \times 11309.7mm^2 = \mathbf{445603.5N}$$

The maximum force that the bamboo can resist (**B.ii**) is larger than the force needed to resist the 0.4g earthquake, therefore, this structure is able to withstand small seismic movement.

C. Tensile strength of bamboo

Tensile strength of Bambusa balcooa = **164N/mm²**
Diameter of the bamboo = 60mm to 150mm, will be using 60mm for calculation.

i. Area of the bamboo

$$60mm \times 60mm \times \pi = \mathbf{11309.7mm^2}$$

ii. Amount of force that can be resisted by the bamboo when being stretched.

$$164\frac{N}{mm^2} \times 11309.7 = \mathbf{1894790.8N}$$

D. Moment due to two forces

<u>**Compression**</u> (this is the case when the force from the earthquake is acting towards the house, and the bamboo is being compressed)

i. Clockwise moment due to earthquake

$$1.2m \times 8052.05N = \mathbf{9662.46Nm}$$

ii. Max anticlockwise moment can be resisted by the bamboo

Distance from the bottom of the wall to the centre of bamboo = 2.4 - 0.06 = **2.34m**

$$2.34m \times 445603.5N = \mathbf{1042712.2Nm}$$

<u>**Tension**</u> (this is the case when the force from the earthquake is acting away from the house and the bamboo is being stretched)

iii. Anticlockwise moment due to earthquake

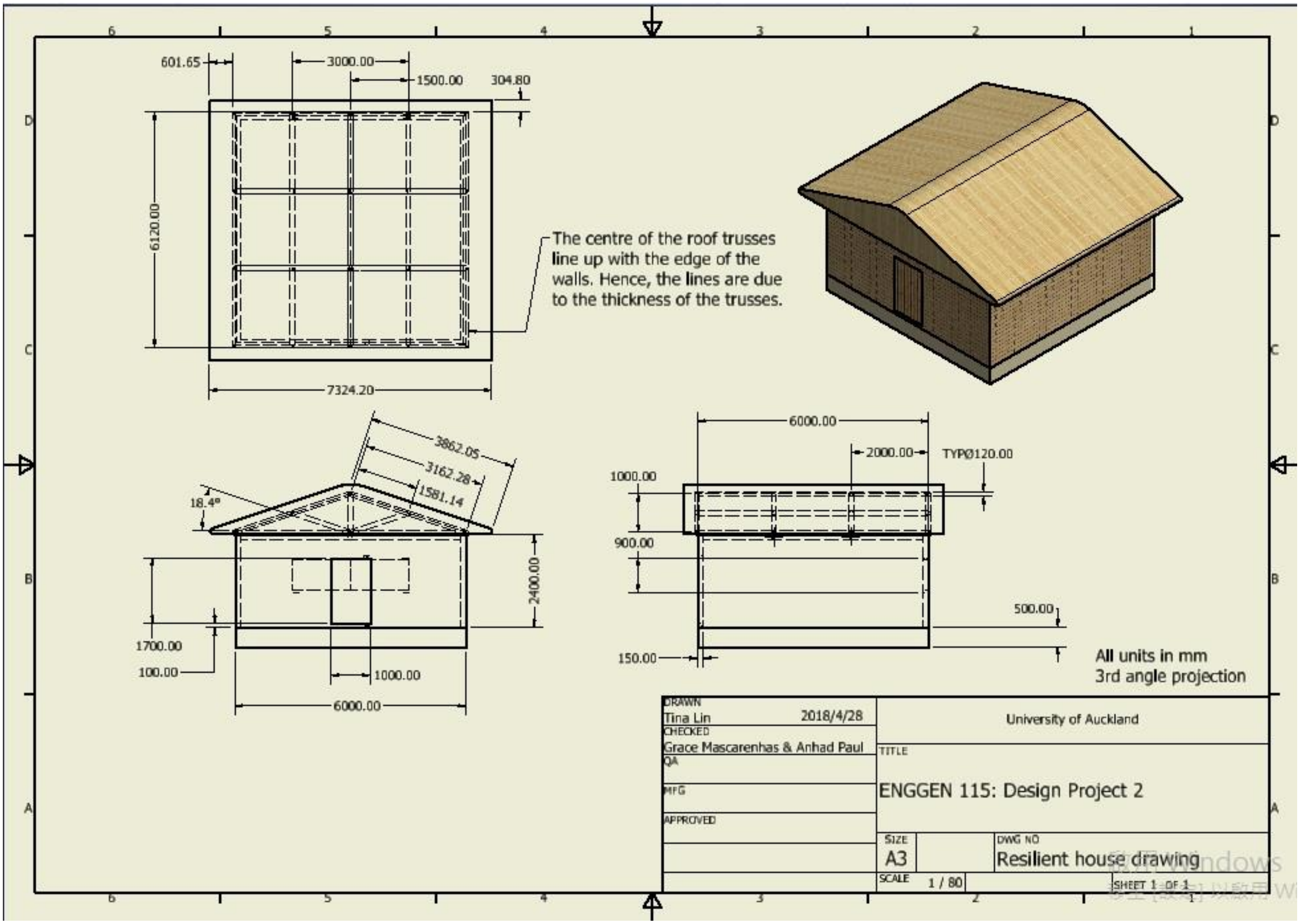
$$1.2m \times 8052.5N = \mathbf{9662.46Nm}$$

iv. Max clockwise moment can be resisted by the bamboo

$$2.34m \times 1854790.8N = \mathbf{4340210.5Nm}$$

The calculation has proven that with bambusa balcooa bamboo as a horizontal supporting beam of the resilient house, a moment of 9662.46Nm (**See Appendix Four Di**) due to 0.4g earthquake can be withstood.

7.5 Appendix Five



Detailed Drawing of Recommended House Design

7.6 Appendix Six

MORPHOLOGICAL ANALYSIS

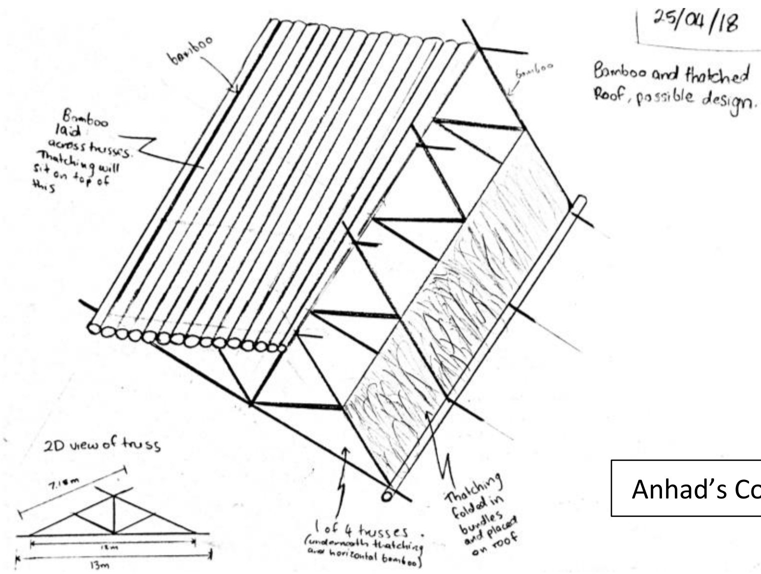
Feature	**Solution**				
Roof	Wooden Trusses	Thatched Straw	Bamboo Trusses	Corrugated Iron	
Roof Shape	Flat	Circular	Triangular		
Temperature Control	Bricks	Straw Thatching	Utilising high thermal mass of CSEB		
Body of House	Bricks (CSEB)	Bamboo	Sandbags	Reinforced Concrete	
Base Support	Base Isolation (rubber material)	Concrete Base	Sits directly on to ground	Rubble of old houses	Structural Steel
Window	Glass	Bamboo (can slide open)	Cut directly out of wall		

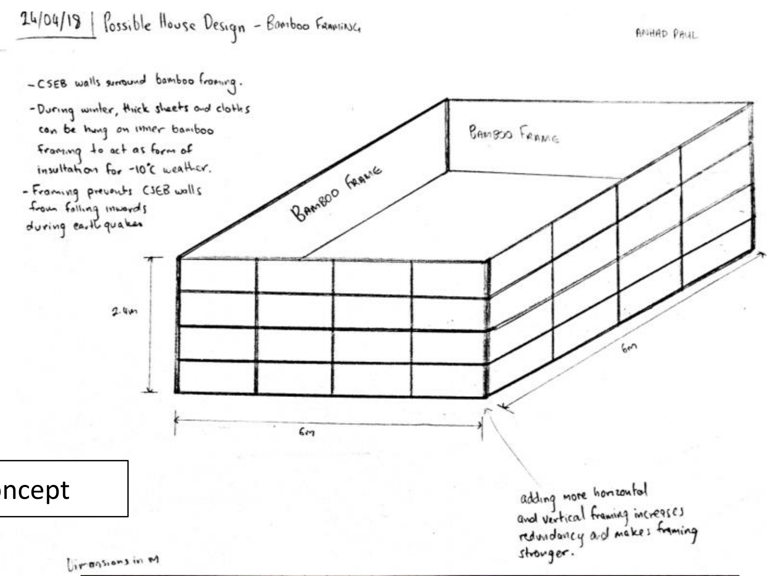
ANALYSIS OUTCOME

Feature	Roof	Roof Shape	Temperature Control	Body of House	Base Support	Window
Overall Solution	**Thatched Straw**	**Triangular**	**Utilising High thermal mass of CSEB**	**Bricks (CSEB)**	**Rubble of Old Houses**	**Cut Directly out of wall.**

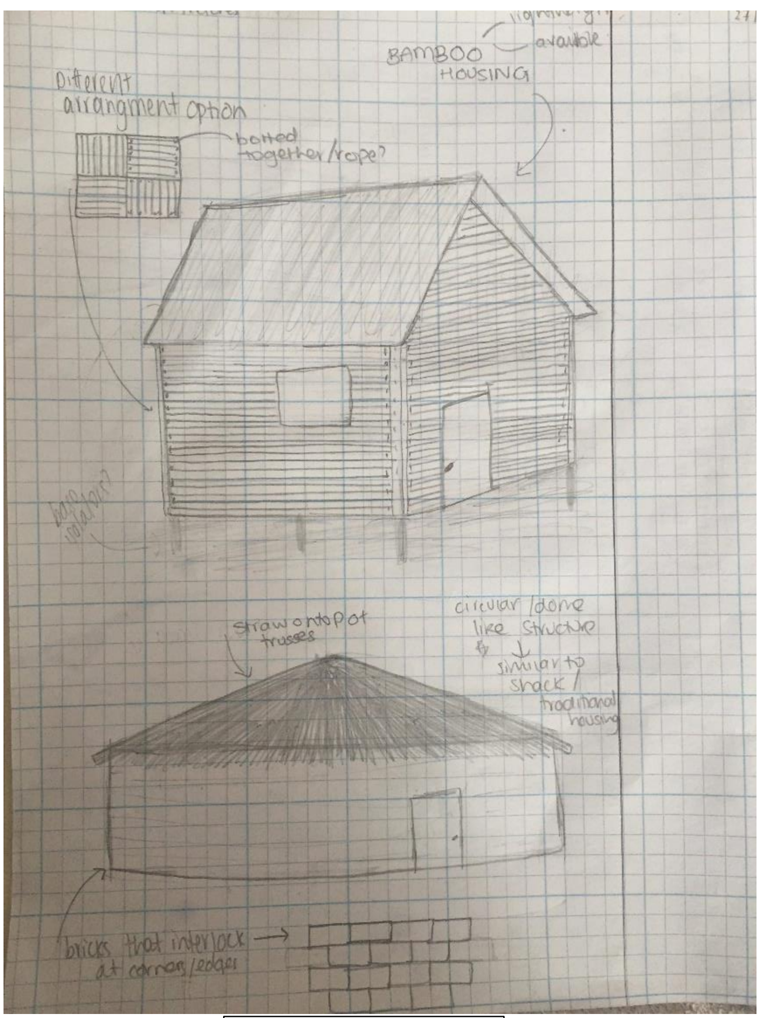
7.7 Appendix Seven

CONCEPT DESIGNS

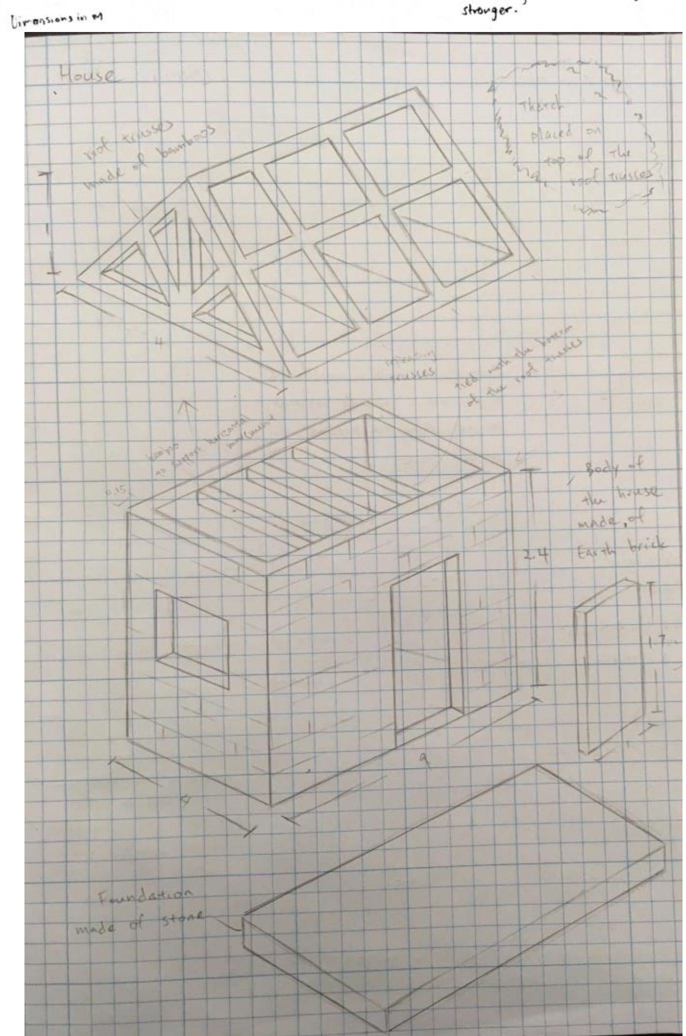




Anhad's Concept



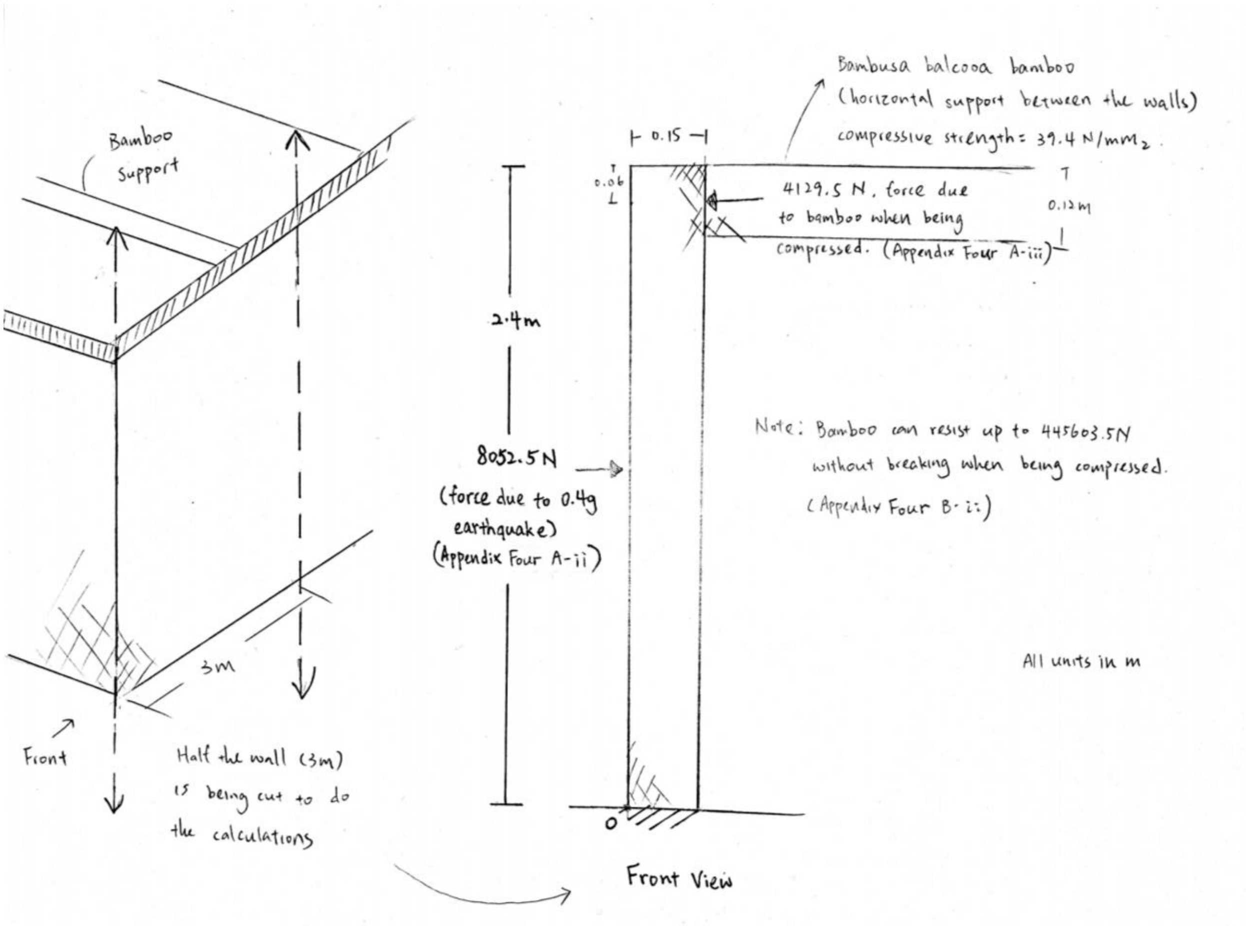
Grace's Concept



Tina's Concept

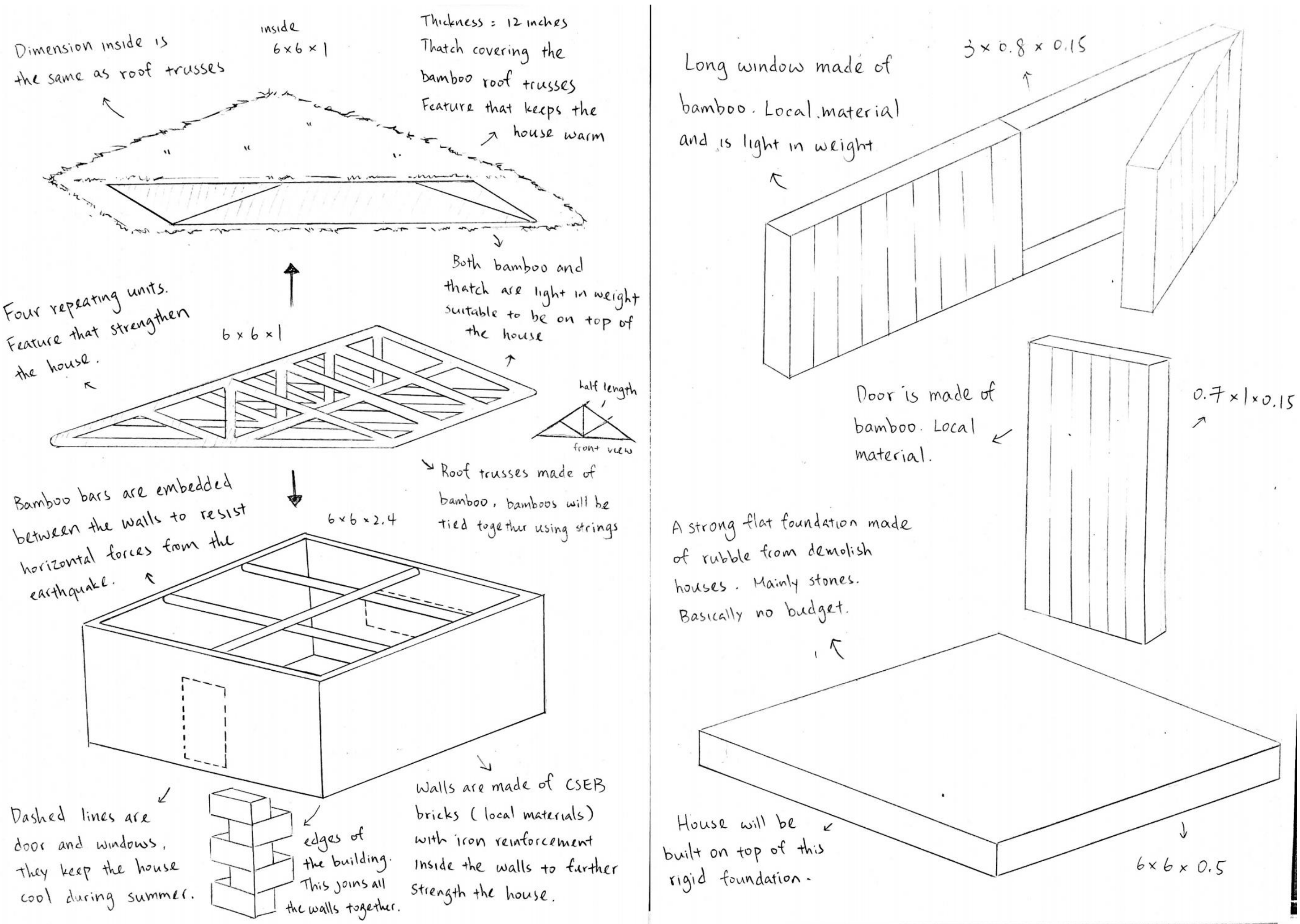
7.8 Appendix Eight

CORRESPONDING DIAGRAM FOR CALCULATION OF MOMENTS APPLIED DURING EARTHQUAKE (Appendix Four D-i)



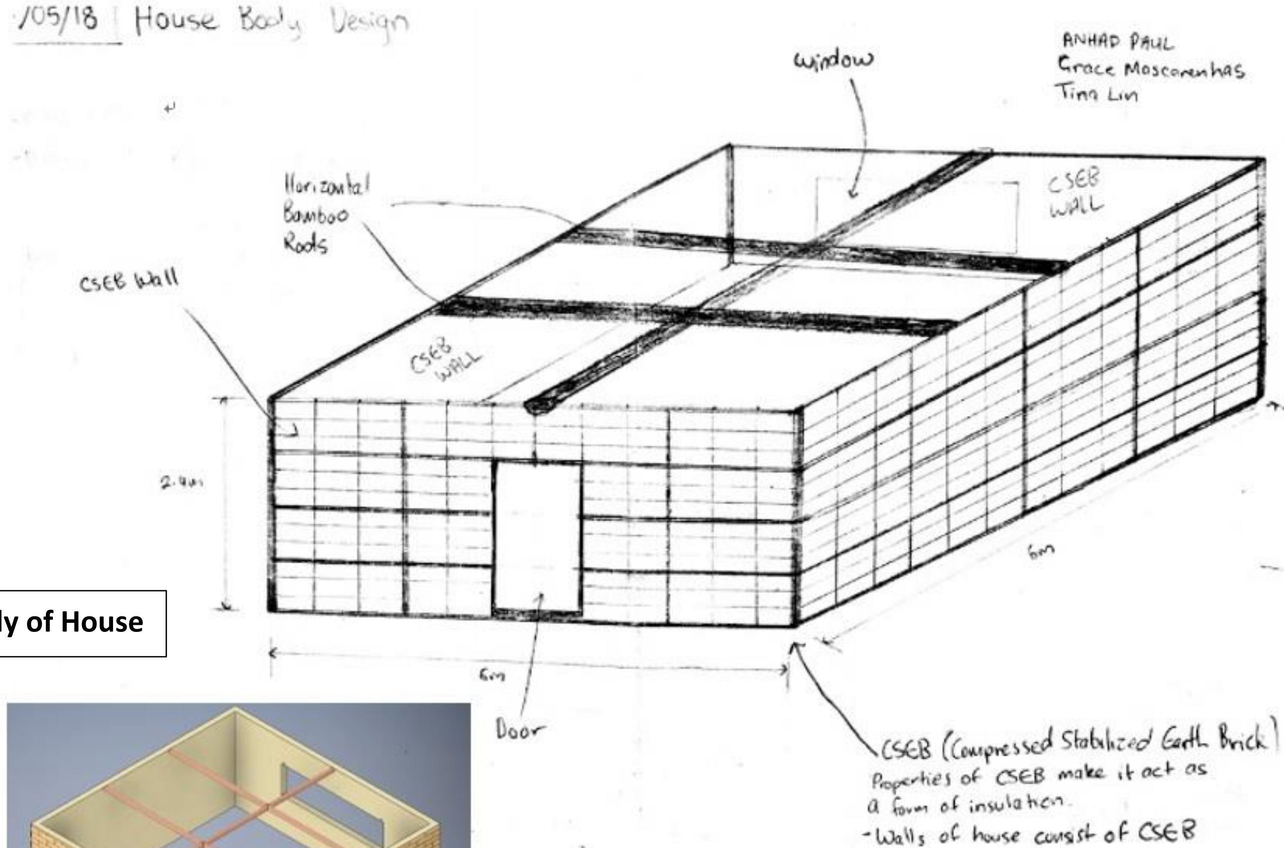
7.9 Appendix Nine

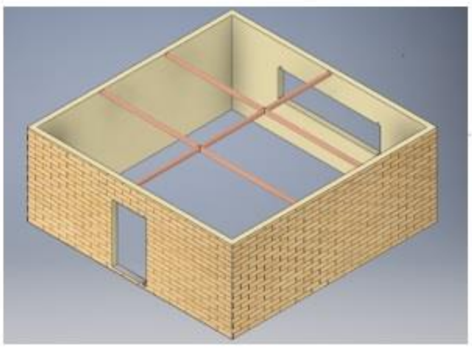
FINAL DESIGN SKETCHES



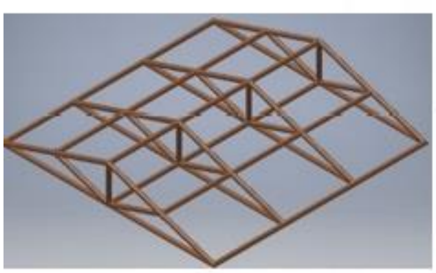
More sketches of recommended design on following page

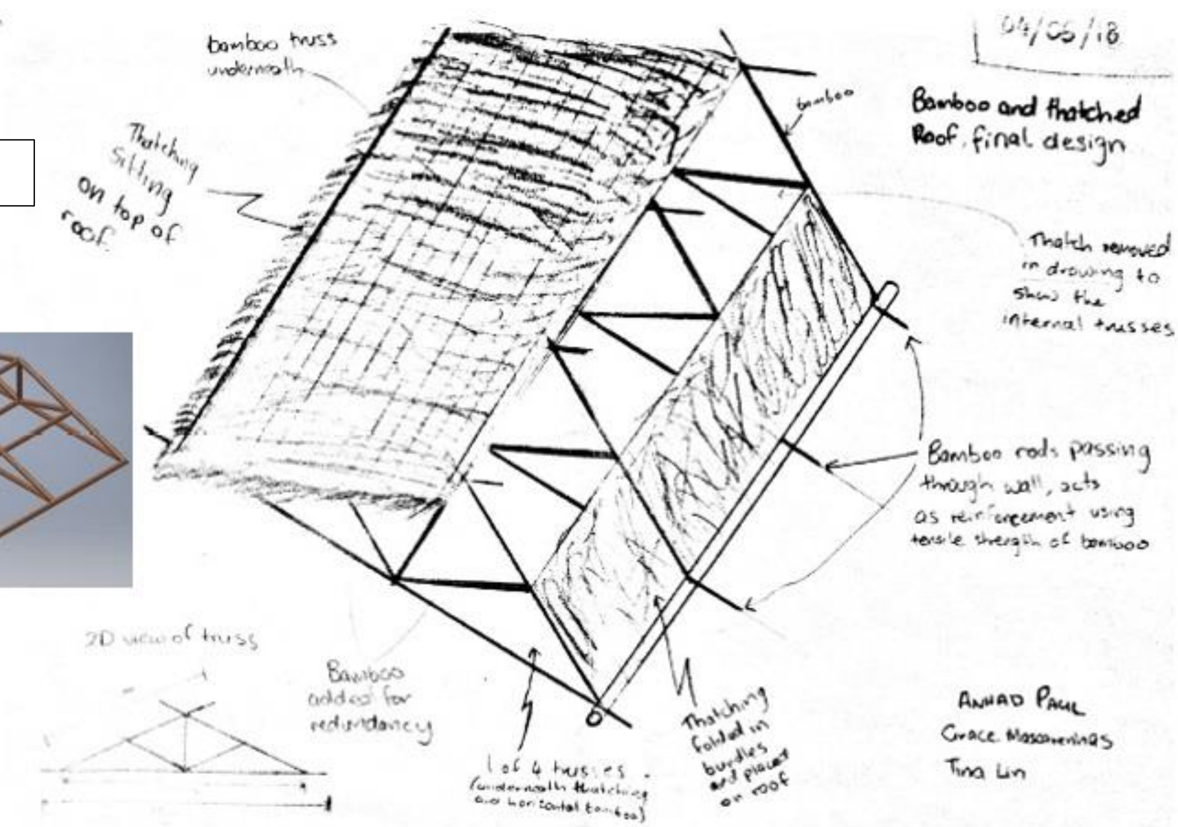
Body of House





Roof of House

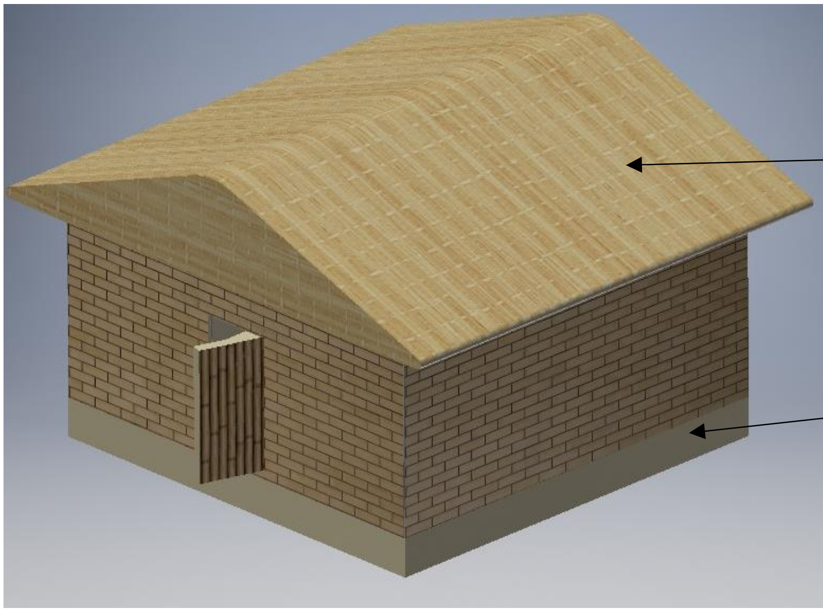




7.10 Appendix Ten

3D CAD REPRESENTATIONS OF FINAL DESIGN

See Appendix 5 for Detailed and Orthographic Representation of Final Design.



Thatched Roofing

Foundation made from rubble of destroyed buildings

Compressed Stabilized Earth Brick (CSEB) Walls Reinforced with Iron Bars.

Horizontal Support members providing added resistance against external horizontal forces.

Design of house without thatching to show internal truss members.