ANALYSIS AND DESIGN OF LOW COST ENGINEERED BAMBOO STRUCTURES

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(2018CES2181)

DEPARTMENT OF CIVIL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY (IIT) DELHI

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Submitted by

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(2018CES2181)

Under the guidance of

Prof. SURESH BHALLA and Dr. S. K. DHAWAN

In fulfilment of the requirement of the degree of

Master of Technology in Structural Engineering

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CERTIFICATE

This is to certify that the work which is being presented in this report entitled, "**ANALYSIS AND DESIGN OF LOW COST ENGINEERED BAMBOO STRUCTURES**" which is being submitted by **RAHUL MEENA** (**ENTRY NO: 2018CES2181**) in the fulfilment the requirements for the award of degree of Master of Technology in "**STRUCTURAL ENGINEERING**" is a record of the student's own work carried out at **Indian Institute of Technology Delhi (IIT) ,India** under my supervision and guidance.

The matter embodied in this thesis has not been submitted elsewhere for the award of any other degree or diploma.

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July 2020,
New Delhi

CERTIFICATE

I certify that the work which is being presented in this report entitled, "**ANALYSIS AND DESIGN OF LOW COST ENGINEERED BAMBOO STRUCTURES**" in the fulfilment the requirements for the award of degree of Master of Technology in "**STRUCTURAL ENGINEERING**" is a record of the my own work carried out under the supervision of **Prof. Suresh Bhalla** and **Dr. S. K. Dhawan**, Department of Civil Engineering at **Indian Institute of Technology (IIT) Delhi, India.**

I have not submitted the record embodied in this report for the award of by other degree or diploma.

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ABSTRACT

India has worlds' 17.71% population it thereby holds second position among countries on population count. As India is a developing country, such a large population needs high infrastructure development on account of which construction works are continuously going on. Also, Indian government has initiated many new projects under scheme **"Housing for all 2022"**, in order to especially provide houses to underprivileged society of the country. Unfortunately, production of every ton of cement and steel releases at least one ton of CO_2. To fulfil the requirement of this scheme, a sustainable and economical construction is preferable. Also, as we can see in current scenario of environment, Air Quality Index (AQI) continues to go more and more worse day by day due to pollution created by construction industries involving building of structure by concrete and steel. This project incorporates bamboo as eco-friendly, economical and easily available structural material because its environmental edge over conventional material such a high strength and low density. Also being a species of grass, it can be harnessed multiple times, consequently, may have given an economical and sustainable construction practice.

This M. Tech. project is a part of **Impacting Research, Innovation and Technology (IMPRINT)** Project which has attempted to fabricate structural elements like beams, column and roof from bamboo. In this thesis, focus has given to two types of designs (i) "Fabricated Reinforced Bamboo Composites (FRBC)", and (ii) "Light Battened Bamboo Sections (LBBS)". FRBC is suitable for carrying heavy load like multi-storey structures. FRBC involves bamboo culms and propylene fibres glued with the help of high strength adhesive like epoxy. The technology was developed at IIT Delhi in 2013. Computational analysis has been done for a single storey hexagonal house designed using FRBC elements. Based on this analysis, a single story 1BHK model house shall be constructed in part II of the project. LBBS is considered good for light weight and temporary structures. initial tests have been done as part of this thesis necessary a modification is being done made by battening the bamboos using steel plates or fixtures. This thesis focused on tests on LBBS beams in laboratory to achieve the desired structural behaviour and finds its application in structures.

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LIST OF ACRYNOMS

3D	Three Dimensional
FRBC	Fibre Reinforced Bamboo Composite
LBBS	Light Battened Bamboo Composite
BHK	Bedroom Hall Kitchen
TCD	Trinity College Dublin
IS	Indian Standard
NBC	National Building Code
DG	Dendraucalamus Gigantus
BP	Bamboo Pallida
DS	Dendraucalamus Strictus
ESG	Electrical Strain Gauge
TPI	Threads per inch

LIST OF SYMBOLS

CO_2	Carbon-dioxide
E	Young's modulus
μ	Poisons ratio
G	Shear modulus
σ_c	Calculated direct stress
σ_{bcb}	Allowable bending stress under compression
σ_{bct}	Allowable bending stress under tension
σ_u	Ultimate failure stress
σ_{cbx}	Calculated bending stress under M_y moment
σ_{cby}	Calculated bending stress under M_x moment
σ_{bc}	Allowable direct stress
C	Compression force over section
T	Tension force over section
k	Neutral axis coefficient
D	Depth
b	Width
M_r	Moment of resistance
$M_{r\text{-}act}$	Actual moment of resistance
γ_m	Additional partial factor of safety
γ_o	Bonding material quality reliability
F_s	Factor of safety
P	Applied load
P_u	Ultimate axial load capacity
M_y	Applied moment about y axis
M_x	Applied moment about x axis
Z_y	Section modulus about y axis
Z_x	Section modulus about x axis
A_{be}	Effective area
A_{bg}	Gross area

R_a	Ratio of actual area to gross area
p	No. of bamboo in width
q	No. of bamboo in depth
$Ø_o$	Outer diameter
$Ø_i$	Inner diameter
m	Modulus ratio
ε	Strain
S_g	Strain gauge constant
R_1	Initial resistance of ESG
R_o	Final resistance of ESG
V_b	Maximum wind speed
V_z	Design wind speed
P_d	Design wind pressure
C_f	Force coefficient
A_e	Effective frontal area
V_b	Design lateral force
A_h	Horizontal seismic coefficient
W	Seismic weight
σ_{min}	Minimum generated soil stress
σ_{max}	Maximum generated soil stress
$q_{all,net}$	Allowable net bearing pressure
$q_{all,gross}$	Allowable gross bearing pressure
γ_{soil}	Soil bearing capacity
z	Section modulus
e	eccentricity
$A_{st,req}$	Required area of steel
V_u	Ultimate shear force
τ_v	Design shear stress
τ_c	Concrete shear stress acapacity
H	Horizontal force

LIST OF FIGURES

CHAPTER – 1

INTRODUCTION

1.1 BACKGROUND

There has been a phenomenal rise in the field of civil engineering during recent years, reflecting increased demand of housing. All these activity demand building more structure, which will invariably cast an adverse impact globally, as carbon-dioxide (CO_2) is one of the undesirable effluents of steel and cement industry. Production of both concrete and steel cause considerable deterioration of the environment. Cement, the main constituent of concrete, requires heating of limestone and other ingredients to over 1,400^{O}C by burning fossil fuels. Producing every ton of cement result in the emission of one ton of carbon dioxide (CO_2). Roughly 5 to 10 percent of global CO_2 emissions are related to the manufacture and transportation of cement. Similarly, production of every ton of steel is accompanied with the release of over two tons of CO_2 in the atmosphere (Bhagat, 2017).

On the other hand, Bamboo is biologically a grass and it consumes CO_2 from the atmosphere based on this we can referred it to be "green gold or miracle plant", is very economical for construction (www.financialexpress.com). By using bamboo in construction industry, we can maintain healthy environment. Its growth shall ensure an effective reconstruction of damaged ecosystem as bamboo generates 35% more oxygen than trees. some bamboo species absorb up to 12 tons of carbon dioxide per hectare per annum, which makes it an efficient replenisher of fresh air, while at the same time serving as a highly renewable (with 3 years life cycle) and everlasting construction material, available to mankind. If engineers start specifying bamboo for housing, its commercial value will increase compared to the present situation. When the demand increase, millions of small farmers can safely select to invest in bamboo plantation due to improve of prospects of financial benefits.

From structural point of view, bamboo has competitive strength characteristics. Typically, species like Dendrocalamus gigantus have tensile strength of about 120 MPa, compressive strength of 55 MPa, and young's modulus of 14 GPa. Concrete has much lower strength than bamboo in comparison. In addition, the low density of bamboo, which is 700 kg/m^3 results much higher strength to weight ratio as compared to steel which has density of 7800 kg/m^3 and concrete density of 2350 kg/m^3 (Bhalla et al., 2008).

India with huge population, is expected to witness substantial economic growth in the next decades. The government of India has coined a slogan **“housing for all by 2022”** (www.pmindia.gov.in, declared it a national mission for urban housing on 17th June 2015, union cabinet chaired by PM Narender Modi), to meet the housing and permanent infrastructure need of this country (Bhagat, 2017).

This thesis come with the use of bamboo as element of structural elements.

1.2 OBJECTIVES AND SCOPE

The main objective of this project to develop and demonstrate a low-cost construction technique with eco-friendly bamboo as construction material for 1BHK rural house. Requirement of healthy material can be fulfilled by bamboo. So, the design based on bamboo fabricated and used as structural elements is initiated. Using the previously researched FRBC (Bhagat, 2017), this project is extended the work done on FRBC, in an applied sense by designing a single storey house structure that would be analysed using STAAD Pro software. One more design of fabricated bamboo like LBBS is proposed in this project thesis for taking lighter loads. laboratory tests will be done on LBBS and in this project, work has been planned to construct house with both type design accordingly.

1.3 ORGANIZATION OF THESIS

This thesis has a total of six chapters. After list of contents, the list of figures, table, symbols, and abbreviation are specified. The notations have been well defined as the place where they first appear. The content of each chapter is briefed below

Chapter 1

This chapter covers the brief introduction of construction issues and highlights various reasons to find another low-cost material and technique followed by objective and scope.

Chapter 2

This chapter presented the literature review of bamboo as structural element and the work done so far on bamboo structures. Identification of research gaps. Objectives and scope are specified in detail

Chapter 3

This chapter covers the analysis and design of 1 BHK house using fibre reinforced bamboo composite (FRBC).

Chapter 4

This chapter covers the methods involving fabrication and various laboratory tests results of light battened bamboo sections (LBBS).

Chapter 5

This chapter covers utility and applications

Chapter 6

This chapter contains the conclusions of work done so far and future work

Finally, work schedule and references have been provided.

CHAPTER 2

LITERATURE REVIEW AND GAP IDENTIFICATION

2.1 LITERATURE REVIEW

Now a day's bamboo is not used for load taking element instead used as decorative material. For low cost and eco-friendly structure, Bamboo can be used as the main load taking element. In this regard, study of the strength of structural bamboo elements is necessary. In bamboo, fibres are arranged longitudinally so taking an advantage of this alignment maximum strength can be achieved by cutting the bamboo laterally. Other basic properties like young's modulus, tensile strength, compressive strength of bamboo should be known before it is used as structural element.

In India over 100 species found but 20 bamboo species that have been systematically tested so far, resulting 16 species are recommended for structure use. Mechanical properties of the 16 key species are summarised for air dry and green condition respectively from National Building Code (NBC) 2005. In this regard, work done so far has been reviewed and summarised below

Bhalla et al. (2008) this paper discussed about designing of a shed, 5 m in height and 10 m of span length by using environment friendly material "Bamcrete", In which DG bamboo was used as the straight member and the ferrocement was used as the batten element as seen in Fig. 2.1. Different type cross-sections used for designing different members like column, bamboo bow beam for supporting roof, purlins. The frame is analysed for different loads combinations.

Figure 2.1 Bamcrete column (Bhalla et al., 2008)

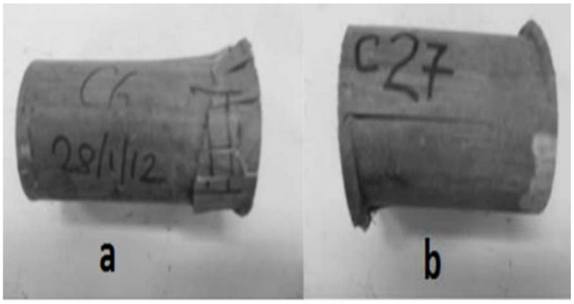
Chauhan (2012) reported focused on designing of the bamboo shed and its various component like base plate and foundation. Also, to validate experimental results, Analysis in STAAD Pro was conducted. Design and fabrication battened column, shown in Fig. 2.2 had been fabricated in IIT Delhi laboratory by using 4 bamboo culms and battened them with the help of the split bamboos.

Kajjam et al. (2012) reported the shear and compressive strength of two species of bamboo Dendraucalamus Strictus (DS) and Bamboo Pallida (BP). Compressive strength of DS is higher than the BP. The shear strength was tested for use of bamboo half splits used as batten and it was done on two types of sample, single hole and double hole, in split bamboo piece then found the average strength. For double hole strength found was 14.376 MPa which is much higher than single hole. The fabrication of a single column using two columns of two different species DS and BP had been done using four bamboo integrating them with help of clamps and half split bamboo pieces had been used as batten. Finally, compressive load test was carried out on built up column at Trinity College Dublin (TCD), as shown in Fig. 2.3. Stress-strain relationship was studied for the columns and concluded that the load capacity of BP column was 17.5kN that of by DS column was 21kN.

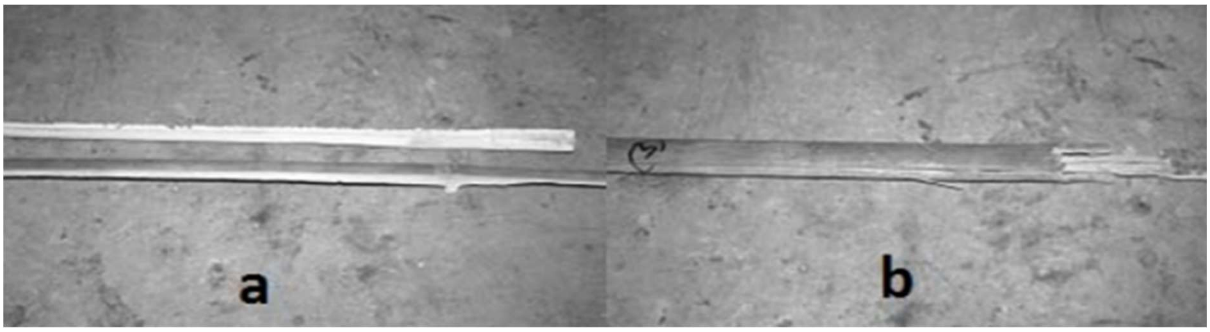
Figure 2.2 Battened column (Chauhan, 2012)

Figure 2.3 Battened column compression test (Kajjam et al., 2012)

Bhalla and Shaw et al. (2013) reported that the tests had been done on two types, one is of black colour and other is red, of Dendraucalamus Strictus (Giant Bamboo or Dragon Bamboo) bamboo species origin in Assam, for tensile and compressive strength, as shown in Fig. 2.4. Compressive strength of black one found as 64 MPa and for red one it was 45 MPa and the tensile strength of black was reported as 76MPa and for red it was 62 MPa. In this paper, focus on the moisture content relation with the bamboo strength had given and concluded that higher the moisture content lowers the strength.



(a)



(b)

Figure 2.4 (a) Bamboo sample after compression test

(b) Split bamboo sample after tension test (Bhalla and Shaw, 2013)

Gupta (2013) this thesis presented the work done for fabrication and the roof of the frame was constructed as discussed in the Rahul Bargania's thesis, roof was fabricated by using the steel fixtures and the bamboo battened section. For long span, fixtures used were tested to find relation between torque and the compressive load which is taken by the fixtures in different conditions like with or without bamboos upper layer, water dipped and dry conditions and has concluded that when we increase the torque the load taking capacity increases, but maximum load i.e. 40kN was found at 20 N-m torque. The maximum load was achieved by removing upper layer and water dipped bamboo. Fixtures tightening and testing shown in Fig. 2.5.

Bargania (2013) in this thesis work has been presented on bamboo frame and fabrication of the bamboo column by using the battens incorporated bamboo splits. End plate were also attached at the end of the columns, stiffeners were also provided in the end plates, as shown in Fig. 2.6. He also reported Roof frame which was fabricated by using bamboo and for joining the bamboos for the long span, steel fixtures were used. For the Bamboo frame structure, concrete foundation was provided and designed the base plats for connect column and foundation and then frame was tested for different end conditions.

(a)

(b)

Figure 2.5 (a) Tightening of fixture up to suitable torque.

(b) Compression test of fixture (Gupta 2013)

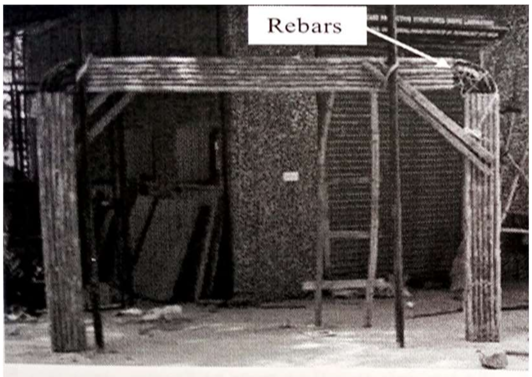
(a)

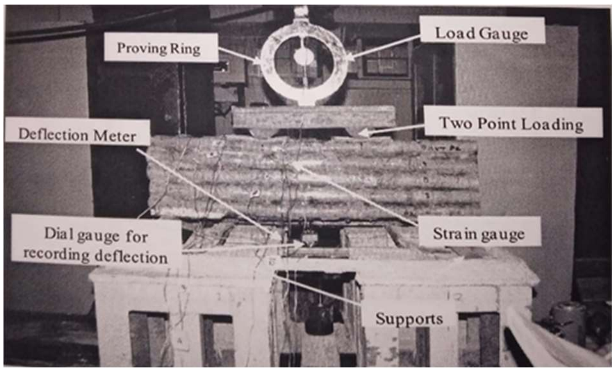
(b)

Figure 2.6 (a) Connecting base plate at one side of built up column

(b) Roof plan for shed (Bargania, 2013)

Bhagat (2017) in this thesis a different type design of bamboo was introduced fibre reinforced bamboo composite (FRBC). Different elements of a structure like column, beam, portal frame and joints which is fabricated by using FRBC, was tested under various loads and concluded that they had shown appropriate behaviour and load taking capacity. The design philosophy bamboo elements have been also discussed in this thesis which proved that bamboo elements can withstand heavy load if fabricated using FRBC.





(a) (b)

Figure 2.7 (a) Portal frame fabricated by using FRBC
(B) Bending test of beam (Bhagat, 2017)

2.2 IDENTIFICATION OF RESEARCH GAPS

From the literature review one can see that only bamboo-based battened column section has been fabricated and tested in the laboratory, giving good results to use them as structure element. However battened bamboo-based beam sections have not yet fabricated and tested. Also, designs using FRBC has been fabricated and tested in the laboratory and showed appropriate results to withstand heavy loads. However computational analysis of such design, using FRBC properties, has not been done yet to purpose a form 3D structure. FRBC has also not been used for fabricating bamboo real 3D Structures till date.

2.3 AIMS AND SCOPE OF THE PROJECT

The major aims and scope of this project is given below

1. To Perform different tests on the structural element made with light battened bamboo section (LBBS), to achieve the desired behaviour.

2. Computational analysis of 1 BHK hexagonal shape house 3D frame shall be carried out in STAAD.Pro using properties of Fibre reinforced bamboo composites (FRBC) as structural members.

3. Fabrication of a model house based on results obtained from computational analysis using FRBC shall be done accordingly. Since the tenure of IMPRINT project is more than a year hence fabrication will start in coming year.

CHAPTER 3

DESIGN AND ANALYSIS OF FIBRE REINFORCED BAMBOO COMPOSITE (FRBC) RURAL HOUSE

3.1 INTRODUCTION OF FRBC

Fibre reinforced bamboo composite (FRBC) is come out as a solution to increase the bamboo's load carrying capacity as the structural element developed by Bhagat (2017) in IIT Delhi. Using FRBC, it would be possible to fabricate structural element possessing higher axial and flexure capacity. Also, FRBC is considered of great utility to achieve a regular unified rectangular/circular (prismatic) member which shows composite behaviour by being a single unit, under all condition of load i.e. moment and shear stresses. Fabrication procedure is described in detail in Bhagat (2017).

Figure 3.1 Cross section of the FRBC (Bhagat, 2017)

3.2 HEXAGON SHAPED 1BHK HOUSE BASED ON FRBC

For requirement of a low cost and environment friendly house under scheme "housing for all 2022", Indian government planned for a 1 BHK house to provide housing to underprivileged section of society specially in north eastern regions. It is shaped as hexagon inspired by "honeycomb", as shown in Fig. 3.2(a). In future more rooms or a full 1 BHK house of hexagon shape can be co-constructed, as shown in Fig. 3.2(b). To Plan this hexagonal house, elements were fabricated as FRBC, which can take heavy loads and take the prismatic shape.

The research gapes also fulfilled by use of FRBC in such structures and the computational analysis has also done for the house by using FRBC properties in STAAD Pro software.

(a) (b)

Figure 3.2 (a) Honeycomb cells fit together

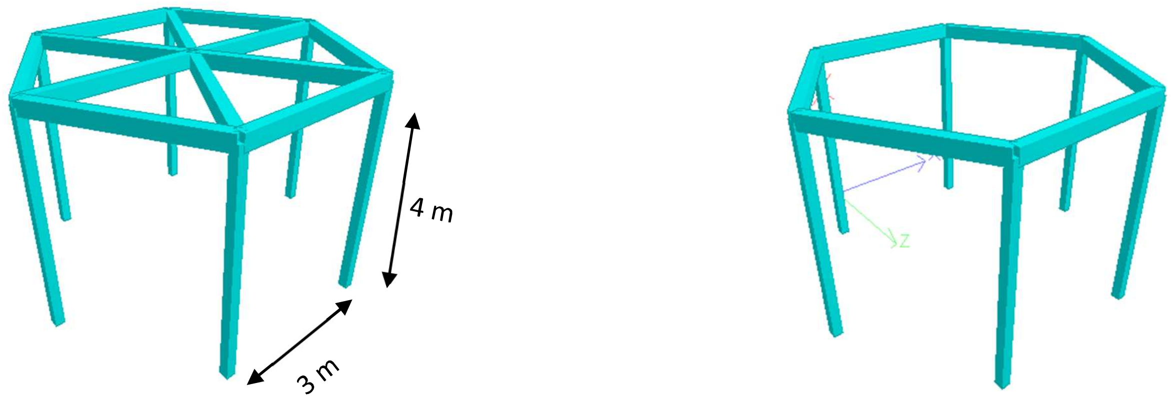
(b) Final hexagon unit (en.wikipedia.org)

3.3 ANALYSIS OF 1 BHK FRBC HOUSE

The computational analysis has also done for the house by using FRBC properties in STAAD Pro software. The version of software used is Bentley's STAAD Pro 22.02.00.26. The loads have been calculated manually and has been applied to the structure. codes used for loads calculation are IS 875 (Part 3): 2015, for wind load calculation and IS 1893: 2016, for earthquake load calculation. The wall and roof properties are unknown yet and it is not decided that which type material is to be used for their fabrication. So, the wall and roof are taken as dead load in the analysis by taking in combination with other dead loads.

3.3.1 Geometry of The Structure

The roof frame constructed of hexagonal shape, which supported over six columns at six corners. The area required for the 1 BHK is around 250 sq. foot (1 room , bathroom , kitchen and required passage) hence to cover the required size of the house, each side of the hexagon has taken 3 m. Height of the structure is assumed to be 3 m but for the analysis to overcome the fixity of the column the height is taken as 4 m. There are two type of frame which has to be analysed, one including cross beams included and other without crossbeam.



(a) (b)

Figure 3.3 (a) FRBC hexagon frame with cross beam

(b) FRBC hexagon frame without cross beam

3.3.2 Properties

The properties used has taken from the previous research work (Bhagat, 2017). Size of the column and the size of the beam is being adopted according the previously fabricated members those were tested in the laboratory previously i.e. the size of the column is 160×160 mm and the size of the beam is 180×255 mm.

3.3.3 Material

Material choose for the structure analysis is the FRBC properties adopt from previous work (Bhagat, 2017).

Table 3.1 FRBC material properties

Sr. no.	Material property	Value for analysis
1.	Young's modulus (E)	3.48×10^{09} N/m^2
2.	Density	1000 kg/m^3
3.	Poisson's ratio (μ)	0.25
4.	Shear modulus (G)	1.329×10^{09} N/m^2
5.	Allowable bending stress under compression (σ_{bcb})	12 MPa
6.	Allowable bending stress under tension (σ_{bct})	15 MPa

3.3.4 Supports

At the bottom support of all the column is considered as fixed. To analyse the concrete foundation and the bottom connection plate, the column length is increased by 1 m so total column length at the time of analysis is taken as 4 m.

3.3.5 Load Calculation

Loads are manually calculated and applied at the suitable location. Walls and roof members have not provided but the load effect of the roof or wall on the frame applied as additional dead load to find the real load or reaction for the design.

3.3.5.1 Dead load and live load

Dead loads are calculated according to the weight of the members, which is dependent on the material density. Material density has defined, in the material section, as FRBC density 1000 kg/m^3 and the density of the roof and the wall material is 1200 kg/ m^3 and the dead acting towards ground. The dead load is self-calculated to be applied on software. The roof is considered as inaccessible roof, so the live load is considered over the roof is .75 kN/m$^{2.}$

3.3.5.2 Wind and earthquake load

To find the earthquake and wind load, the different Indian standard codes have considered i.e. for wind load calculation use code IS 875 (part 3): 2015 and for the earthquake load use is 1893: 2016.

Total wind load was found to 16.329 kN and earthquake load 26.520 kN. Hence earthquake analysis has done.

Detailed calculations are covered in Appendix A.

3.3.5.3 Load combinations

Analyse structure under different load combinations.

1. (Dead load + live load)
2. (Dead load +earthquake load)
3. (Dead load + live load + earthquake load)
4. (.9×Dead load + earthquake load)

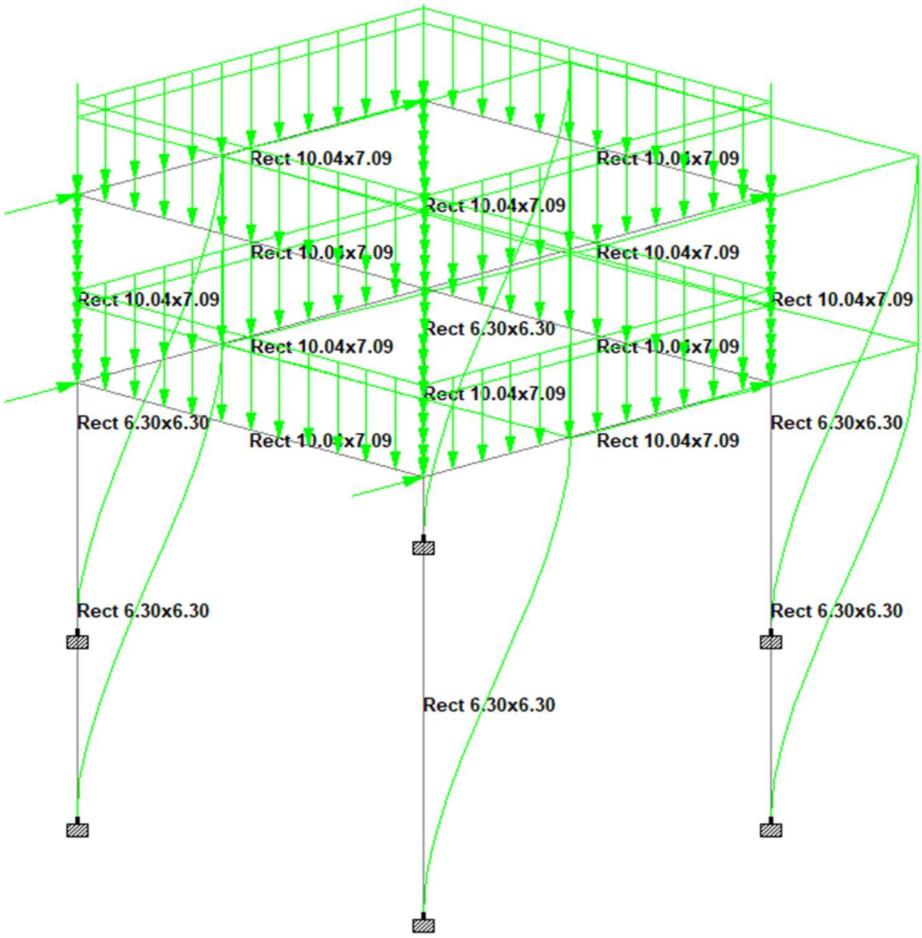


Figure 3.4 under load deflected hexagon frame

3.3.6 Analysis

After Running the software for analysis of structure, post processing results obtain is shown below:

3.3.6.1 For structure with cross beams

1. Maximum axial load in the column	27 kN
2. Maximum moments in the column (about local z axis)	9.169 kN-m
3. Maximum moment in the column (about local y axis)	0.382 kN-m
4. Maximum bending moment in the beam	8.189 kN-m
5. Maximum shear force in the beam	8.34 kN
6. Maximum load on foundation transfer by column	26.99 kN
7. Maximum moment act on the foundation	9.058 kN-m
8. Maximum horizontal force act on the foundation	4.55 kN

3.3.6.2 For structure without cross beam

1. Maximum axial load in the column	21.02 kN
2. Maximum moments in the column (about local z axis)	8.573 kN-m
3. Maximum moment in the column (about local y axis)	1.422 kN-m
4. Maximum bending moment in the beam	8.287 kN-m
5. Maximum shear force in the beam	8.903 kN
6. Maximum load on foundation transfer by column	21.020 kN
7. Maximum moment act on the foundation	8.573 kN-m
8. Maximum horizontal force act on the foundation	4.22 kN

3.4 MANUAL DESIGN OF THE CROSS SECTIONS

For designing safe structure, section force taking capacity should be more than the force generate in the section from given by results of analysis of structure. The procedure of Bhagat, (2017) was adopted.

3.4.1 Beam Section Capacity

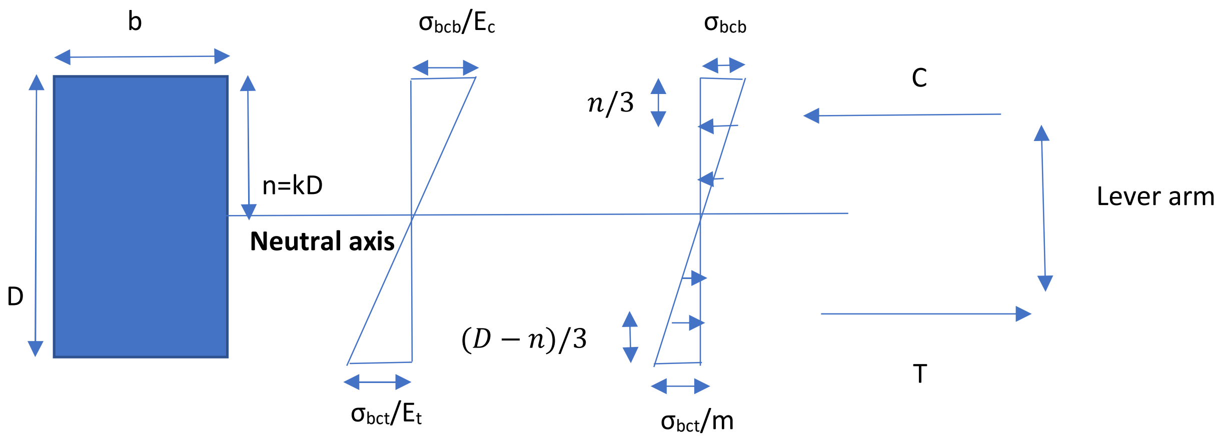


Figure 3.5 stress and strain diagram of FRBC beam (Bhagat, 2017)

σ_{bcb} = 12 MPa allowable bending stress in compression side

σ_{bct} = 15MPa allowable bending stress in the tension side

m = 1.29 modular ratio (from previous data)

$$C = T \tag{3.1}$$

$$k = \frac{m\sigma_{bcb}}{m\sigma_{bcb}+\sigma_{bct}} = .47 \tag{3.2}$$

By geometry

$$C = \frac{\sigma_{bcb}\times n\times b}{2} \tag{3.3}$$

Moment of resisting

$$M_r = C \times (total\ lever\ arm) \tag{3.4}$$

$$M_r = C \times 2 \times \frac{D}{3} \tag{3.5}$$

The moment of resistance (M_r) of any FRBC section would be directly proportional to its effective area, A_{be}

$$R_A = A_{BE}/A_{BG} \tag{3.6}$$

Actual moment of resisting

$$M_{R-act} = R_A \times \gamma_m \times \gamma_b \times M_R \tag{3.7}$$

γ_m = .9 additional partial factor of safety

γ_b = .9 bonding material quality reliability

R_a = ratio of the actual area to the gross area

$$A_{be} = bD - (p-1)(q-1)Ø_o{}^2\left(1-\frac{\pi}{4}\right) - (p-1)Ø_0{}^2\left(1-\frac{\pi}{4}\right) - (1-Q)Ø_o{}^2\left(1-\frac{\pi}{4}\right) - pq\pi \quad 3.8$$

p = number of bamboos in width (4)

q = number of bamboos in depth (5)

$Ø_o$= bamboo's outer diameter 40 mm

$Ø_i$= bamboo's internal diameter 20 mm

$$M_{R-act} = \frac{.567 \times 12 \times .47 \times 250 \times 188 \times 250}{3} = 12.5\ kNm$$

3.4.2 Column Section Capacity

For ignoring the contribution of epoxy and fibres (because of the possibility of discontinuity in the matrix), the ultimate axial force P_U can be determined as.

$$P_U = A_{be}\sigma_U \quad 3.9$$

σ_U = ultimate failure stress

Load carrying capacity of bamboo section for design

$$P = \frac{\sigma_U A_{be}}{F_S} \quad 3.10$$

F_s = 3 (factor of safety)

$$P = \frac{30.75 \times 15437.5}{3 \times 1000} = 158.23\ kN$$

Check for moment acting over column

$$\sigma_c = \frac{P}{A_{be}} = 1.74$$

$$\sigma_{cbx} = \frac{M_y}{Z_y} = 13.37$$

$$\sigma_{cby} = \frac{M_X}{Z_x} = .56$$

$$Z_y = \frac{Db^2}{6} \text{ or } Z_x = \frac{bD^2}{6}$$

For biaxial moment acting on column

$$\frac{\sigma_c}{\sigma_{bc}} + \frac{\sigma_{cbx}}{\sigma_{bcb}} + \frac{\sigma_{cby}}{\sigma_{bcb}} \leq 1.33 \; wind \; and \; eartquake \; load \; combiantions \qquad 3.11$$

$$\frac{1.74}{12} + \frac{13.37}{12} + \frac{.56}{12} = 1.3 < 1.33 \;\; (section \; safe)$$

3.5 FOUNDATION DESIGN

In frame there is six columns for these column rest over isolated footing. Which was designed according the maximum load and maximum moment which is calculated based on Staad.pro analysis of the frame with different load combination**.**

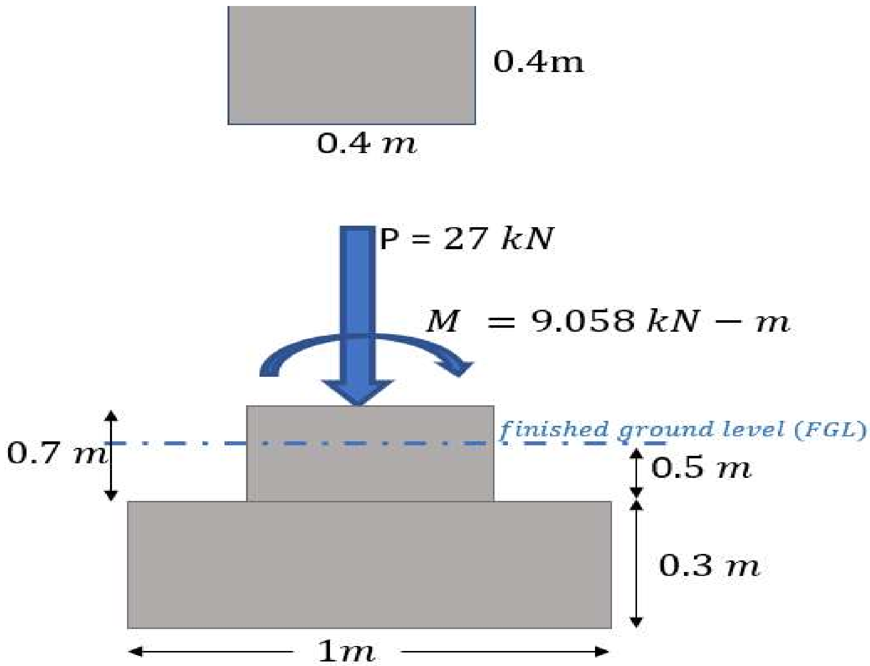


Figure 3.6 Max load applied on foundation

3.6 CONSTRUCTION OF HOUSE

After analysis of all proposed designs and loads on the structure, next step is to fabricate the member and construct a house. After fabricating desired members, suitable location and construction team, the construction will be started accordingly. This part is being outsourced to a contractor.

3.7 CONCLUDING REMARKS

All the forces calculated from computational analysis have been compared with the manual calculations for the section capacity and found satisfying to construct a house because all the sections coming out safe. The construction of house will start after testing the location. Some load or design may change according to the site.

CHAPTER 4

FABRICATION AND EXPERIMENTAL EVALUATION OF LIGHT BATTENED BAMBOO SECTIONS (LBBS)

4.1 INTRODUCTION

At present, Light battened bamboo structure (LBBS) is at developing phase in laboratory. LBBS was designed using bamboo to withstand load and the battened bamboo culms at a specific distance. Battening material was used for fabricating the bamboos in a prismatic shape, half split bamboo pieces were used for battening, which were tested for single hole or double hole and steel plates was also used as other battening material. Steel bars were used as a material for joining the bamboos and the battening material. The LBBS was designed as light weight elements for taking lighter loads. The structures constructed for temporarily settlement and the structure those are not designed for withstanding heavy loads, can be constructed with LBBS.

4.2 PREVIOUS FABRICATION OF LBBS (Bhagat, 2019)

The first LBBS beam fabricated in IIT Delhi, where beam made up of 4 bamboo culms those are fixed to a steel plates at both the ends to provide support. Steel bars of 6 mm diameter were used to tie these bamboos. To connect steel rings with the bamboos, steel sheets and the jubilee clamps were used as shown in Fig. 4.1. it was found that due to loosened connections, perfect shape of beam was not achieved.

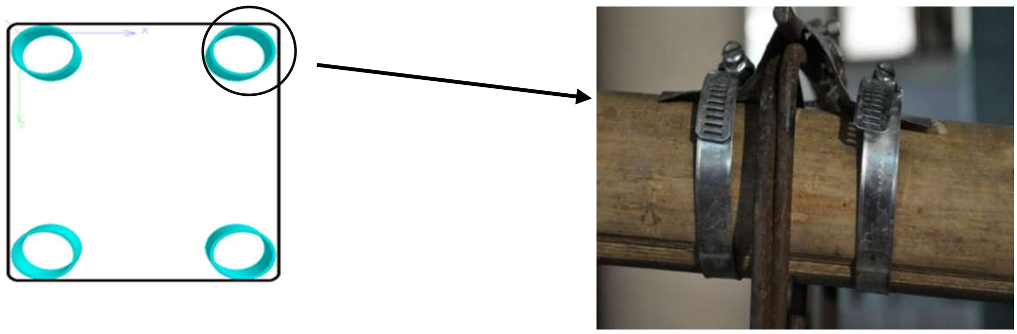


Figure 4.1 Previous LBBS cross section with loosed connection (Bhagat, 2019)

4.3 IMPROVED FABRICATION OF LBBS

To fabricate LBBS, the bamboo culms were used and to take the decisions on materials suitable for the battening and connections between the bamboo and the battens has also given importance while fabricating LBBS. Steps followed while fabrication are given below:

1. Firstly, choice has been made for the straight bamboo culms according to required size and cut them according to required span length.
2. Then the steel bars have been cut according to the size required then bend them to form rings according to the size and shape of the LBBS element.
3. The clamps were weld or fixed at the corners of the ring. One can also fix clamps at the location where bamboo culm was required to make element.
4. The clamps were fixed to the bamboo culms and clamps were tightened to give required rigidity to the element.

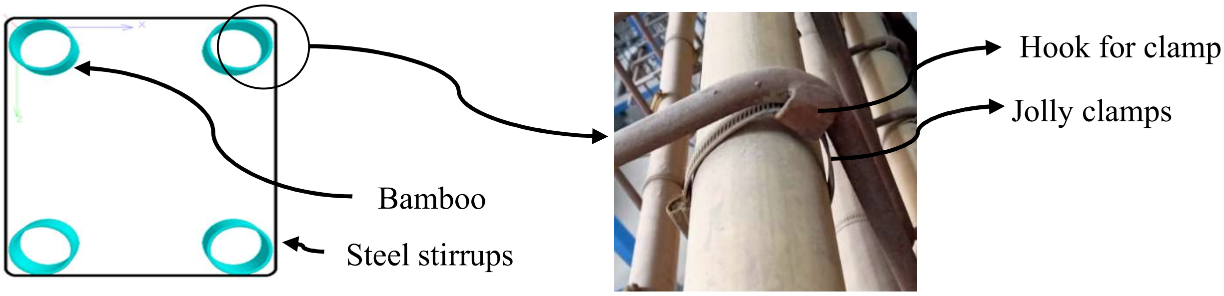


Figure 4.2 Improved LBBS beam's cross section

4.4 TEST IN LABORATORY

The previous work in the laboratory on the LBBS was related to column. In which we found the column fabrication and test results very satisfactory. It can be used for design and construction of the lightweight structure such as design of sheds. But beams made up of LBBS has not been tested yet for bending. To use the LBBS beam as the structural element the test results should give adequate capacity of the member otherwise it would fail in flexure or bending.

To find the capacity or behaviour of the section, test has been performed in the laboratory on LBBS beam. The bamboo culms have been used to fabricate the beam of length 3m. For battening the culms, steel bars of 12 mm have used, and the section size of the beam is 300×300 mm. Also, the steel jubilee clamps have been used to form connection between the bamboo and steel bars. The steel bars provided as stirrups at 200 mm distance to tightly hold the bamboo at the time of loading.

4.4.1 Trial Testing

The beam tested under two-point load test for bending. To established pure bending conditions on the beam, two-point loads apply at L/3 distance from both the supports hence the bending moment was created constant at centre up to L/3 distance to make calculation easier. To find the stress-strain behaviour of the section, four strain gauges (5mm, 120 ohm each) have been installed on the bamboo surfaces as shown in Fig. 4.3.

To calculate the strain from strain gauges, the resistance from the strain gauges was noted by using the Agilent digital multi meter and the for fast and easier connection for multiple strain gauges an Agilent multiplexer was used. For finding the applied load and the displacement curve the Micro Daq 10 datalogger was connected to the load cell and displacement meter.

Table 4.1 Location of the strain gauges

Sr. no.	Strain gauge no.	Location of the strain gauge	Strain
1.	Strain gauge no. 1	Top of the upper bamboo	ε_1
2.	Strain gauge no. 2	Bottom of the upper bamboo	ε_2
3.	Strain gauge no. 3	Top of the lower bamboo	ε_3
4.	Strain gauge no. 4	Bottom of the lower bamboo	ε_4

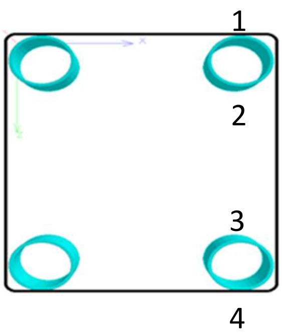


Figure 4.3 Location of strain gauges

Figure 4.4 Four-point load test setup

Calculation of strain from the resistance measured.

$$S_g \times \varepsilon = \frac{R_1 - R_0}{R_0} \tag{4.1}$$

Where

Ro is the Initial resistance of the strain gauge. R_1 is the Final resistance of the strain gauge and S_g is Strain gauge coefficient. ε is the calculated strain.

4.4.1.1 Trial test results

The load and displacement were recorded and the strain at different loads was also recorded as given in Table 4.2 and the strain pattern was studied for the behaviour of beam at the time of loading as shown in Fig. 4.5.

Table 4.2 test result (load and displacement)

Sr. no.	Displacement (mm)	Load (kN)
1.	0	0
2.	20	2
3.	36.95	4.8
4.	63.65	6.3
5.	83.55	8
6.	111.55	9.2
7.	144.25	10.6
8.	99	1.9
9.	74	0.6
10.	54.6	0

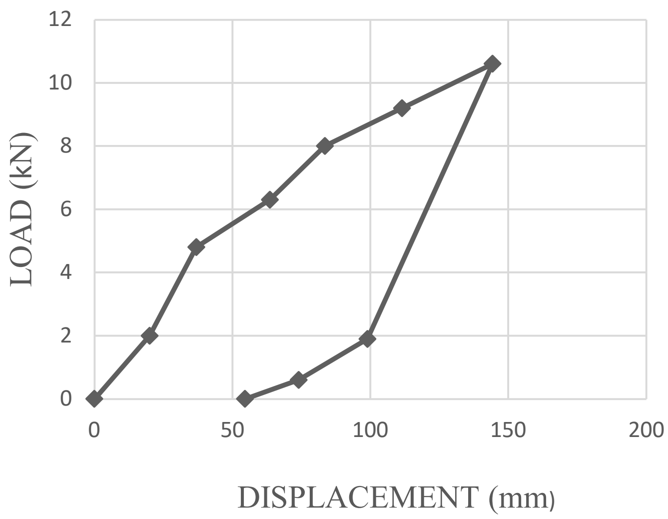


Figure 4.5 Load vs Dis. Graph for LBBS

After analysing load displacement data, capacity of the section came out as maximum bending moment 4.8 kN-m and the maximum load applied 10.6 kN.

Table 4.3 Strain gauge results

load (kN)	ε_1	ε_2	ε_3	ε_4
0	-0.00142	0.002574	0.002414	0.002577
2	-0.00083	0.003032	0.001765	0.002984
4.8	-0.00793	0.003497	0.001186	0.0034
6.3	-0.00696	0.004242	0.000251	0.004006
8	-0.00814	0.004768	-0.00066	0.004384
9.2	-0.00735	0.005382	-0.00175	0.004745
10.6	-0.00713	0.005917	-0.00091	0.004329

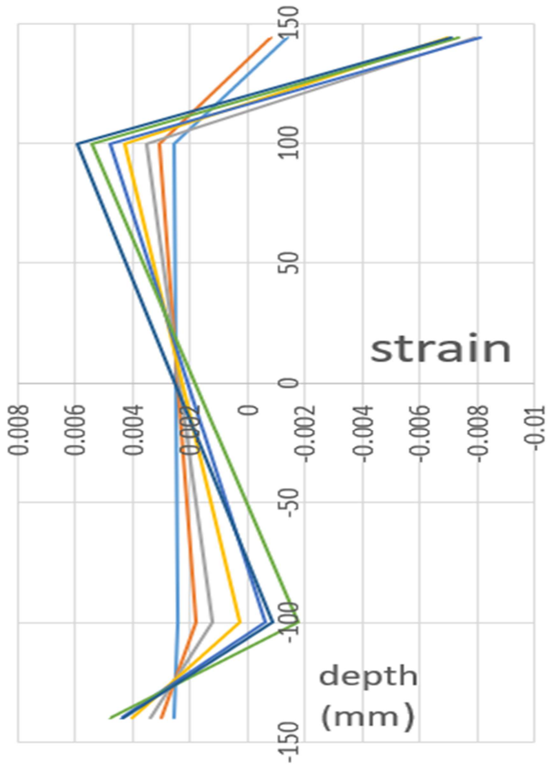


Figure 4.6 Strain diagram for LBBS beam

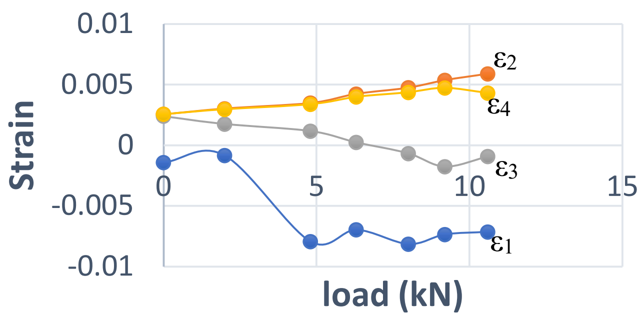


Figure 4.7 Strain vs load for LBBS beam

After studying the results obtained from the calculation of strain values, the behaviour of the beam has been found as, the upper part of bamboo was under compression and the bottom part was under tension. On concluding the behaviour while testing, all the bamboos behaved independently, and composite action was not shown by the beam. The assumption for the plain section remains plain after bending was also not fulfilled. The required behaviour was not achieved.

4.4.1.2 Trial test failure patterns

Failure pattern was observed as, bamboo's upper part fails under compression and lower part under tension. Cracks were seen in the upper part of bottom bamboo so, failure occurred on compression side was because of flexure.

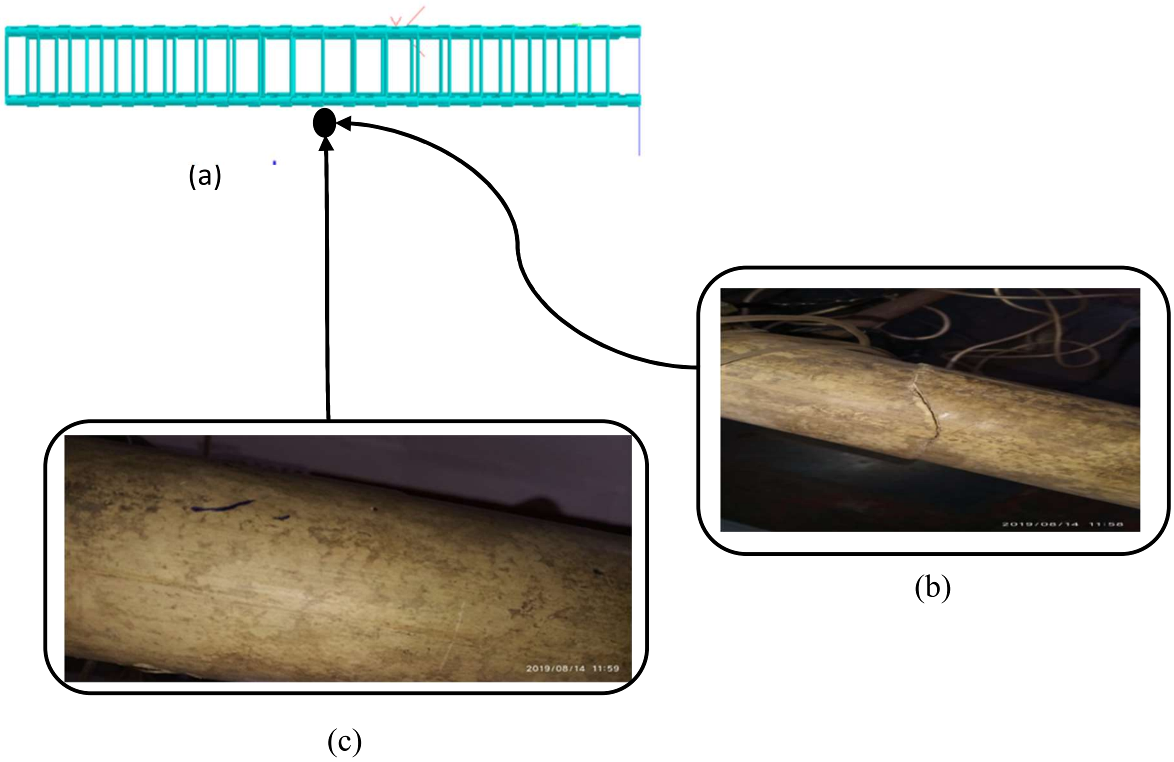


Figure 4.8 Failure pattern in bamboo

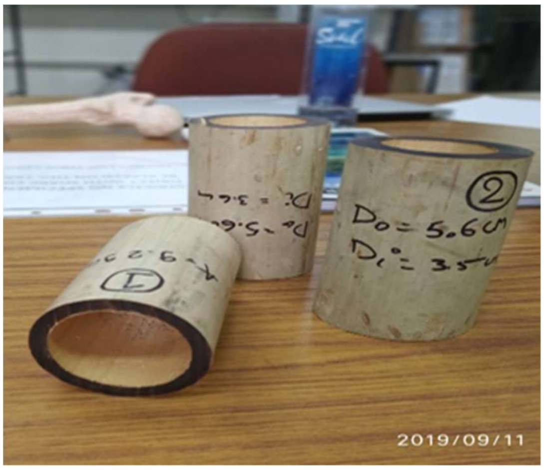
(a) LBBS showing failure location
(b) Top of the lower bamboo
(c) Bottom of lower bamboo

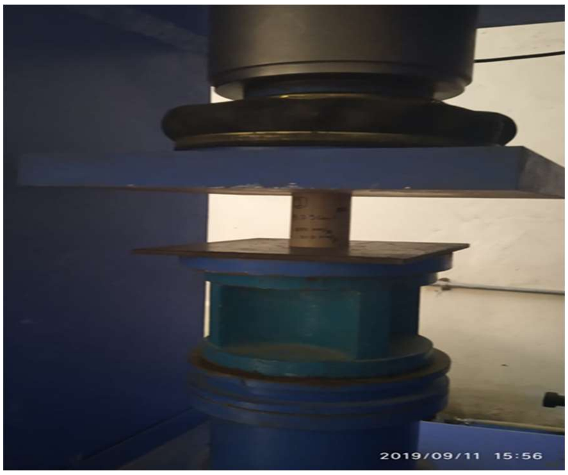
4.4.1.3 Compression test of individual bamboo culms

Specimen 1 was parted from that bamboo which was showing early cracks at the time of flexure test and tested under compression as shown in figure 4.9 and results are tabulated in Table 4.4

Table 4.4 Compression test result for 10 cm long bamboo

Outer dia. (mm)	Inner dia. (mm)	Area (mm^2)	Rate of loading (kN/s)	Peak load (kN)	Strength (MPa)
52	39	929.12	0.077	30.3	32.61
56	35	1500.8	0.102	79.6	53.03
56	36	1445.13	0.1	74.6	51.62





(a) (b)

Figure 4.9 (a) Test samples

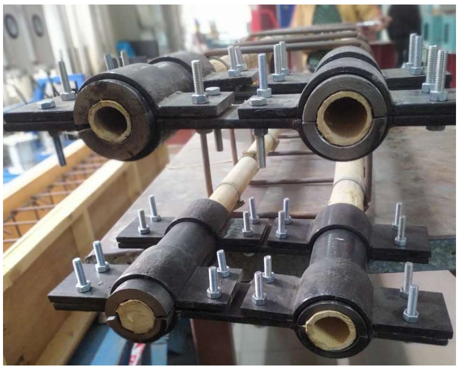
(b) Sample under compression test

4.4.2 Refinement (I) LBBS Configuration

For this setup, some changes were made based on the behaviour seen in the previous test. The testing procedure was kept like the previous testing pattern, the only changes made in the specimen for this test was removal of upper layer of bamboo and fixture was provided at the end of the bamboo. The fixtures consist of two half hollow cylinder in which inner side was threaded and the upper side tightened by the U shape clamps which were held tightly with the help of bolts. For achieving maximum capacity of the fixture, the torque has been applied on bolts up to an optimum value which is 20 N-m and the achieved fixture capacity is 40 kN, when upper layer of bamboo was removed. For connecting the bamboos, plates have welded at two sides with the fixture in view of getting combined behaviour of bamboo elements.

The rest of the setup was similar as the previous test and position of load applied was also kept same.

(a)



(b)

Figure 4.10 (a) Inner side threaded steel fixtures

(b) Tightened fixture plate assembly with LBBS beam

4.4.2.1 Refinement (I) LBBS test results

The test results were found in terms of strain in the bamboos are shown in figure 4.11 according to the values and pattern of strain it was found that the upper bamboo and bottom bamboo's upper part were under compression and the lower part was under tension which showed that bamboos were not behave in composite manner also in this test.

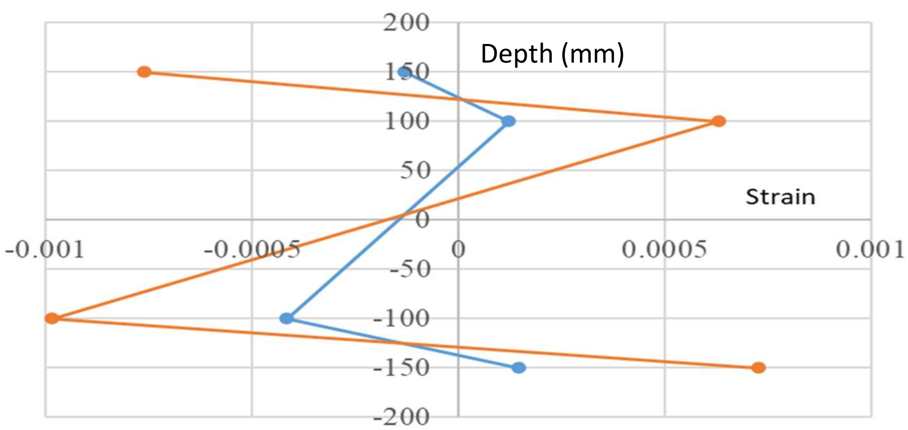


Figure 4.11 Strain diagram of LBBS after refinement (I)

4.4.3 Refinement (II) LBBS Configuration

There were some changes over specimen of 2nd test. the spacing between stirrups was reduces by 100 mm and the cross links welded over pair of three stirrups. The aim behind this set up was to strengthen the stirrups so that they could resist the moment in the bamboo and stirrup joints. Loading position kept according to four-point load test and were placed over upper side of stirrups.

(a)

(b)

Figure 4.12 (a) Three stirrups connected with cross links

(b) Full test setup

4.4.3.1 Refinement (II) LBBS test result results

One side of specimen beam showed proper bending behaviour but the actual strain pattern in the bamboos was found like the second test.

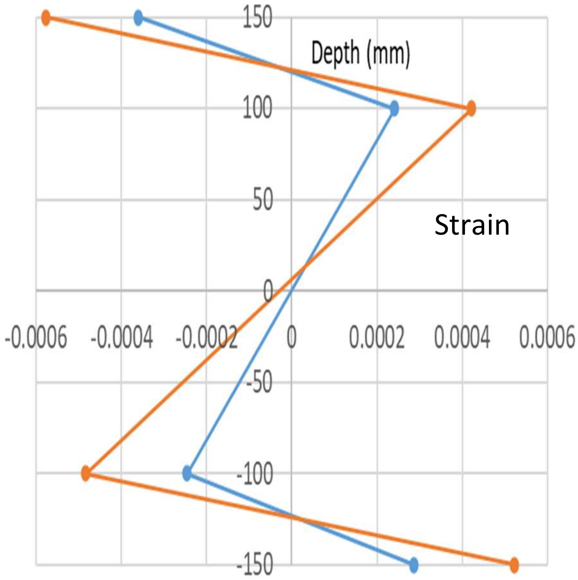


Figure 4.13 Strain diagram of LBBS after refinement (II)

4.4.4 Refinement (III) LBBS Configuration

The specimen was kept similar as previous test but the position of loads was changed in this test, the load was applied at the centre core of the beam so that it can transfer equally in the four bamboos at same time.

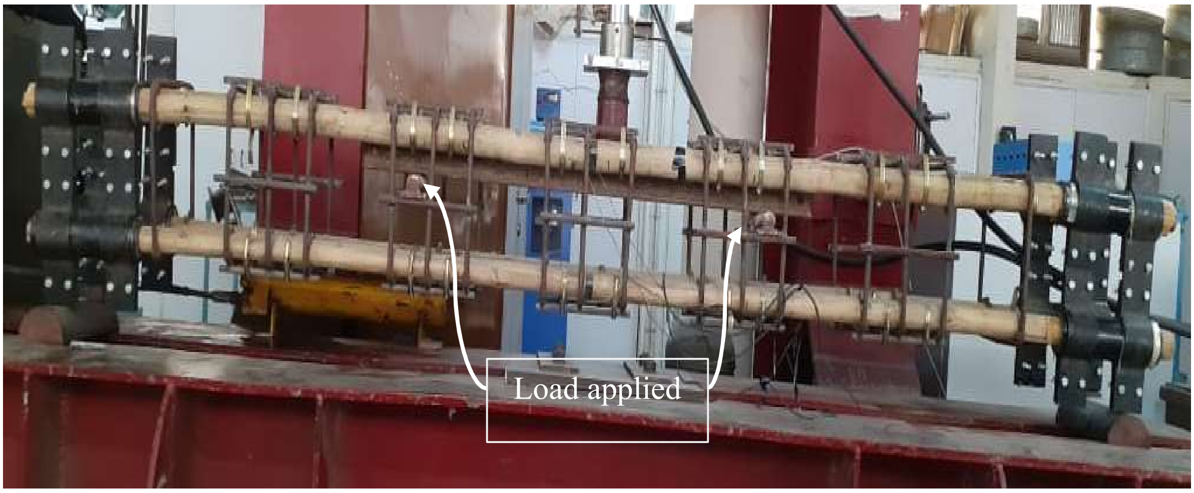


Figure 4.14 Full test setup with marking of load

4.4.4.1 Refinement (III) LBBS test result

One end which was tightened properly shows bending effect. However, the other end was not properly restrained with help of fixtures due to this bamboo were showed some movement within the fixtures. Hence the fabrication technique was successful.

Figure 4.15 Slip was found after applying load

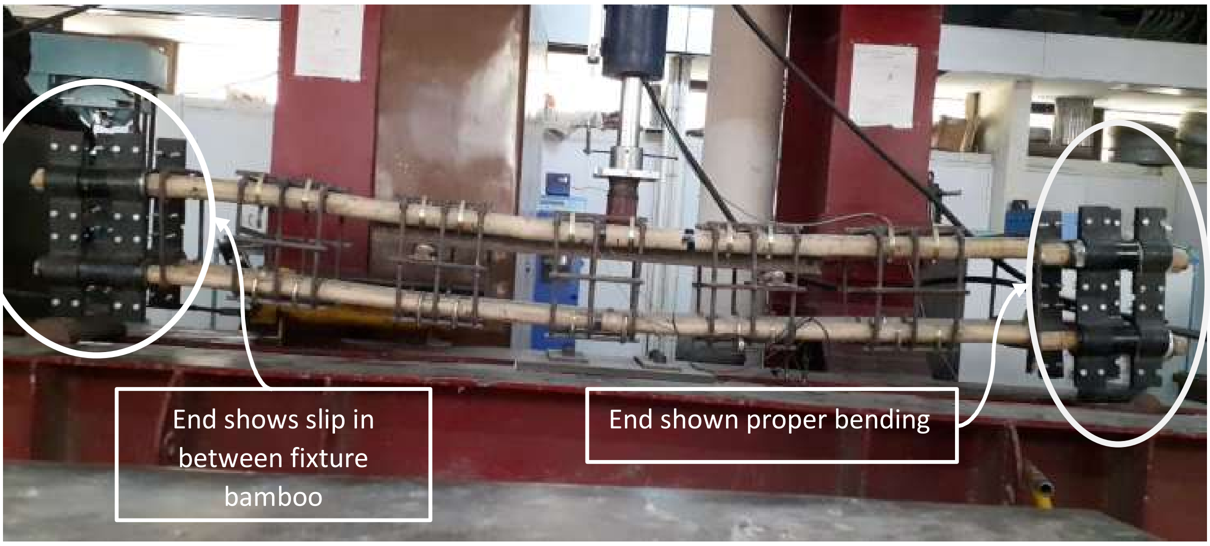


Figure 4.16 Properly tightened end shown bending

4.5 CONCLUDING REMARKS

LBBS was successfully achieved. To achieve the required behaviour, the bamboo should have held tightly at the ends. To hold bamboo at place, friction in the fixtures should be increased by tightening the bolts or by using the adhesive between the bamboo and the fixtures.

CHAPTER 5

UTILITIES AND APPLICATIONS

5.1 APPLICATION OF FRBC

1. Australia's tallest timber building makes a towering case for eco-friendly construction. FRBC can possibly use in place of timber.

Figure 5.1 Australia’s tallest timber building

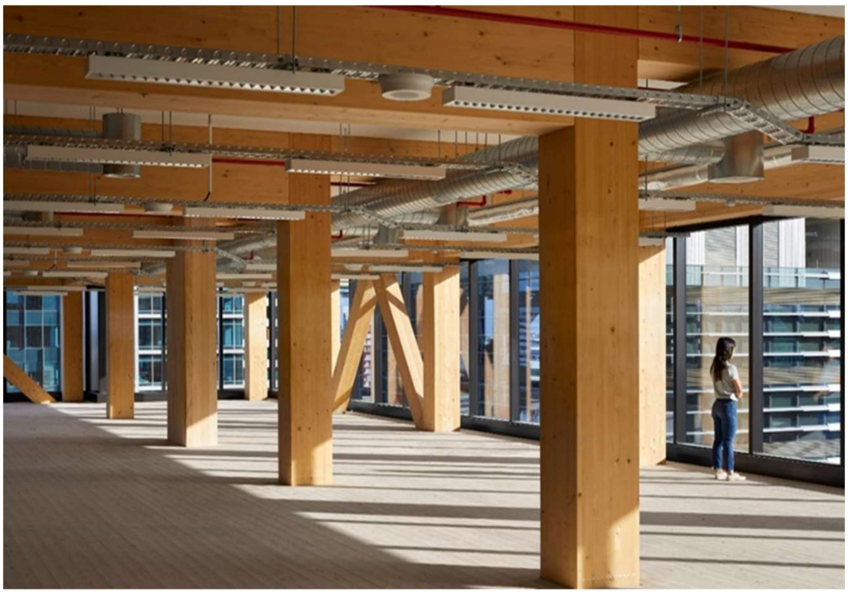


Figure 5.2 Timber beam and column used in timber building

5.2 APPLICATION OF LBBS

1. LBBS can be used as the structural element for structure which can take lighter loads.

Figure 5.3 Light battened bamboo structure for light load

2. Temporary structures which will experience lighter loads can be constructed safely by using LBBS.

Figure 5.4 Lightly loaded temporary bamboo

3.LBBS can replace heavy material used in construction of some structures like tents etc.

Figure 5.5 Steel's heavy temporary shed elements

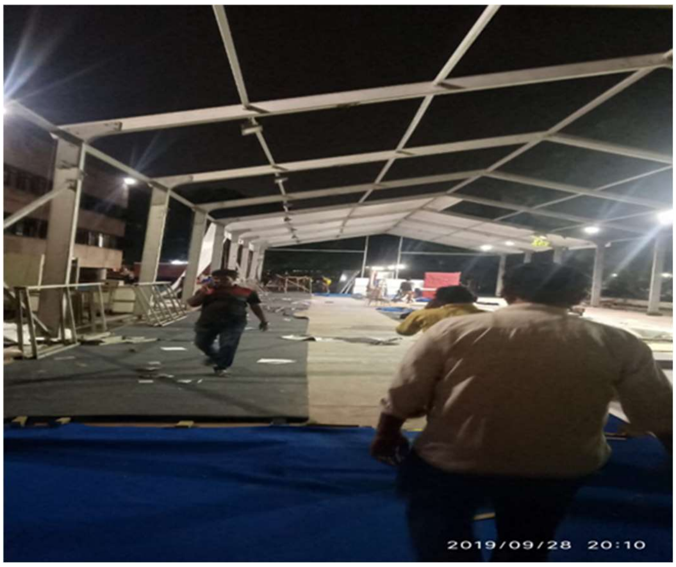


Figure 5.6 Temporary steel shed in IITD

5.3 FABRICATION AND ANALYSIS OF THE 3D PORTAL FRAME WITH LBBS

To fulfil the research objective of fabrication and analysis of structure like Light weight structure for example sheds and canopies which are used for temporary works, A 3D portal frame will be analysed by using STAAD Pro. And all the members are fabricated as LBBS. Length taken for the column is 3m and beam length is 3m and the section size is 300× 300 mm and battening material used is 12mm steel bars.

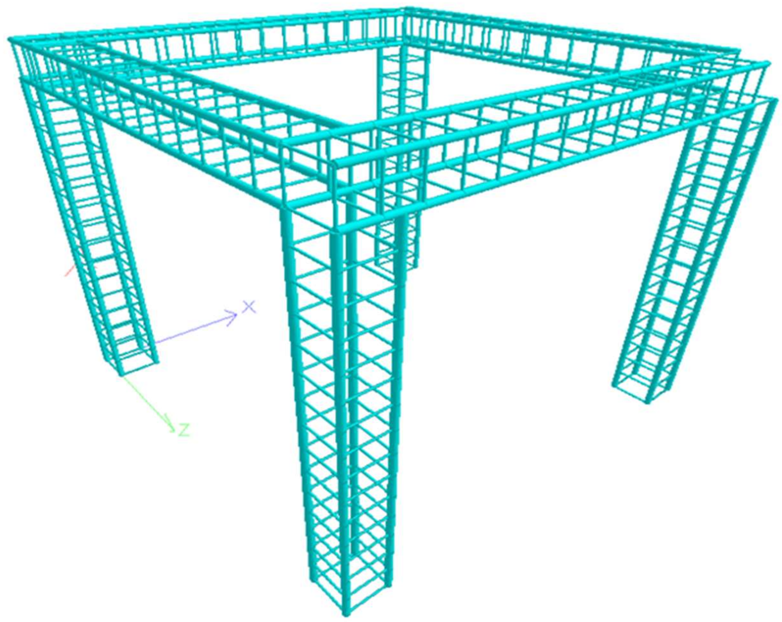


Figure 5.7 LBBS 3D portal frame

CHAPTER 6

CONCLUSIONS AND FUTURE WORK

6.1 CONCLUSIONS

Conclusions drawn from previous chapters can be briefed below:

1. The first part of project shown that bamboo can be used as economical and eco-friendly construction material because it gives desired results when tested in laboratories after fabricated in form of FRBC and LBBS. Analysis and design have been carried out using them as structural element, which is yet to be constructed.
2. A 1 BHK house has been conceived based on FRBC members. Analysis and design have been carried out based on loads as per IS codes.
3. LBBS configuration based, a beam has tested in laboratory and satisfactory results have obtained. They showed the required behaviour and can sustain suitable loads. Plain section remaining plain behaviour was not observed initially. After making some improvement in its fabrication, it may possible that these members can sustain loads if used in the structures after obtained desired behaviour. From the obtained load capacity and behaviour, LBBS can be used in some lightweight structures such as sheds. Using this it is also possible to analyse and fabricate a 3D portal frame.

6.2 FUTURE WORK

1) Tender is being processed to invite the contractors for fabrication of FRBC members for construction of a hexagonal house.
2) After construction, structure as whole will be tested for its load carrying capacity.
3) LBBS beam design will be changed using some improvement methods as stated above to obtain required behaviour.
4) Construction of a 3D portal frame using LBBS has also been planned and will be implemented accordingly.

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APPENDIX A

Wind load on structure

maximum wind speed (V_b) = 55 m/sec (maximum wind speed adopts to calculate maximum load under worst situation. area for maximum speed is Ladakh)

$$\text{Design wind speed } (V_z) = V_b \times K_1 \times K_2 \times K_3 \times K_4 \qquad 1$$

K_1= 1.1 for important building and structures such as hospital.

K_2= 1 open terrain with well scattered obstruction having height 1.5 to 10 m.

K_3= 1 based on the topography factor ($\theta<3^o$)

K_4= 1 importance factor for the cyclonic region (for all other type structure)

$$V_z = 60 \text{ m/sec}$$

$$\text{Wind pressure } (P_z) = .6 \times V_z^{\,2} = 2160 \text{ N/m}^2 \qquad 2$$

$$\text{Design wind pressure } (P_d) = K_d \times K_a \times K_c \times P_z \qquad 3$$

K_d = 1 may be used on design wind pressure for circular or near circular

K_a = 1 area averaging factor

K_c = 0.90 roof is subjected to pressure.

$$P_d = 1944 \text{ N/m}^2$$

$$\text{Wind force (F)} = C_f \times A_e \times P_d \qquad 4$$

C_f = .7 circular section force coefficient.

A_e = effective frontal area (4 m×6 m)

F = 32.659 kN

Wind Force at the roof level = 16.329 kN

Earthquake load calculation

Seismic weight of the structure with cross beams (W) = 58.935 kN

Seismic weight of the structure without cross beams (W) = 52.923 kN

Design lateral force $V_b = A_h \times W$ 5

Design horizontal seismic coefficient $A_h = \frac{Z}{2} \times \frac{I}{R} \times \frac{S_a}{g}$ 6

Z = .36 seismic zone factor (zone 5)

I = 1 importance factor

R = 1 response reduction factor

S_a/g = 2.5 design acceleration coefficient for different soil type

A_h = .45

Lateral force for the structure with cross beam (V) = 26.520 kN

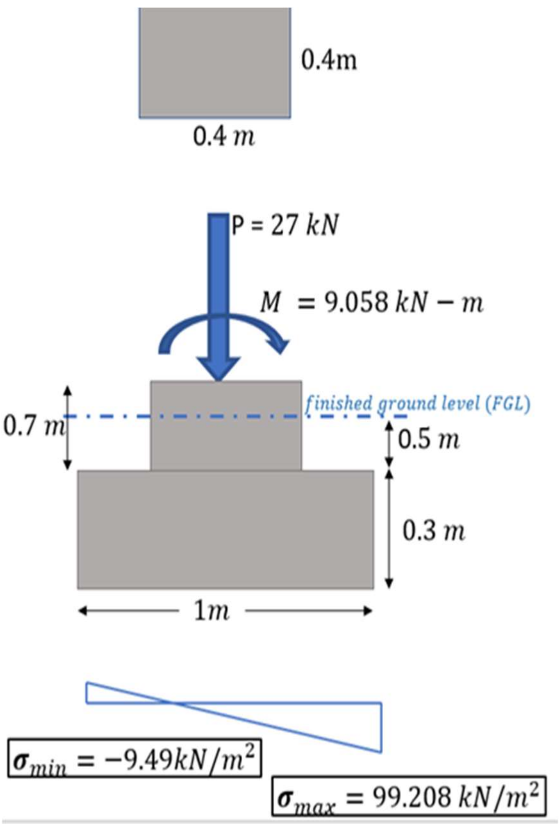
Lateral force for the structure without cross beam (V) = 23.815 kN

Wind force at roof level each node

With cross beam structure = 26.520/6 = 4.420 kN

Without cross beam structure = 3.96 kN

APPENDIX B



$$soil\ bearing\ pressure\ q_{all,net} = 150\ kN/m^2, \gamma_{soil} = 18kN/m^3$$

$$direct\ vertical\ load\ P = 27kN$$

$$moment\ M = 9.058\ kN - m$$

Under normal condition $q_{all,gross} = q_{all,net} + q = 159\frac{kN}{m^2}$ 1

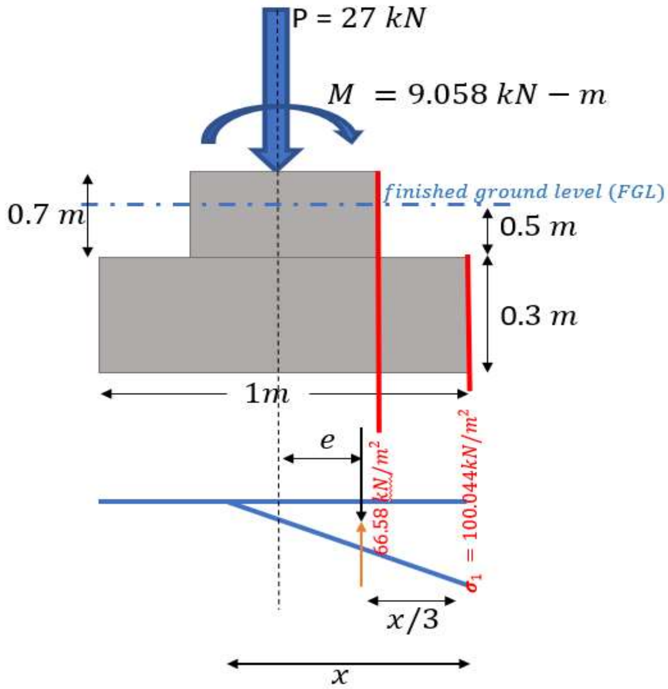
Under wind / earthquake $q_{all,gross} = 1.25q_{all,net} + q = 196.5\frac{\text{kN}}{m^2}$ 2

$P(total) = P_t = P + overburden = 44.86kN$ 3

Pressure at base $\boldsymbol{\sigma} = \frac{P}{A} \pm \frac{M}{Z}$ 4

Area $A = B^2 = 1m^2$

Section modulus $Z = {B^3}/{6} = \frac{1}{6}m^3$ 5



Pressure redistribution

$$e = \frac{M}{P_t} = .201m \quad (6)$$

$$\frac{B}{2} = \left(\frac{x}{3} + e\right) \quad (7)$$

$$x = 0.897\ m$$

$$\boldsymbol{\sigma}_1 = \frac{P_t}{.5xB} = 100.044\ kN/m^2 \quad (8)$$

Design of base of bending

$$M = 3.25\ kN - m/m$$

$$Mu = 1.5M = 4.88\ kN - m/m$$

$$A_{st,req} < (A_{st,min} = 0.12\%),\ A_{st,provide} = \frac{3\ cm^2}{m},\quad 8\text{Ø} @ 160\ mm\frac{c}{c} = 3.015\ cm^2/m$$

Check for one-way shear

$$V_u = 1.5V = \frac{6.06kN}{m} \quad (9)$$

$$\tau_v = 0.024\ N/mm^2$$

$$(\tau_c = 0.28\ for\ M20) > \tau_v \quad (10)$$

Safe

Check for two-way shear

$$V_u = 1.5V = \frac{22.90kN}{m} \quad 11$$

$$\tau_v = 0.054\, N/mm^2$$

$$K_s\tau_c = (.5 + B_c)(.25\sqrt{f_{ck}}) > \tau_v \quad 12$$

Safe

Check against overturning and sliding

Overturning

Restoring moment>1.4(moment due to .9 D.L.)+1.4(moment due to I.L.) 13

Safe

Sliding

Restoring force>1.4H 14

safe