GUIDELINES FOR BUILDING BAMBOO-REINFORCED MASONRY IN
EARTHQUAKE-PRONE AREAS IN INDIA

by

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Sreemathi Iyer

Dedication

This thesis is dedicated to my family in India who made my dream a reality.

Sreemathi Iyer

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Hypothesis

In response to the devastating Earthquake of January 26, 2001 in Bhuj, India, it is assumed a low-cost alternative with better seismic performance can be developed and tested, using bamboo-reinforced masonry, similar to the traditional technology prevalent in the region.

Abstract

The objective of this thesis is to provide a set of guidelines to help the average house-builder in India construct seismically safe, reinforced bearing masonry.

Research in the past proposed bamboo to be a competent alternative to steel as reinforcing material. Tests on bamboo, performed as a part of this thesis, confirmed its tensile strength and bond strength in mortar, the test values were used to compute shear wall lengths and rebar spacing to be provided to the user in the guidelines.

Test results proved bamboo to be a worthy alternative to steel and cost-effective material to be used as reinforcing in bearing masonry for seismically safe houses.

Key words: Bamboo rebars, bamboo-reinforced masonry, earthquake safety, Indian housing, low-cost housing, seismic design, vernacular housing.

1. Introduction

The recent earthquake in India, that literally shook peoples lives on January 26, 2001, was an event of catastrophic proportions. It caused widespread damage to life and property, both of which if not avoided could have been minimized. The count of human life losses rose above 25,000. Over 370,000 houses were completely destroyed and over 922,000 partially destroyed, total damages exceeding 5 billion US Dollars. Around 50% of this damage, upto 2.5 billion US Dollars, were incurred due to household property damage.

It is obvious that a lot of these losses could have been minimized if the houses were better engineered. However, an expectation of this sort is quite difficult to fulfill. In a developing country like India, a person from the lower economic strata is incapable of building engineered houses. Most "lower-income" group houses are built by just hiring a mason or a contractor, neither qualified to engineer the building. Also the chief building system preferred by these people is bearing masonry using brick, clay block or cement block. These systems, if not reinforced, are most susceptible to complete collapse during seismic activity.

The objective of this thesis is to provide a comprehensive set of guidelines for the benefit of the average house-builder to construct seismically safe, reinforced bearing masonry using bamboo as alternative reinforcing material. Researches in the past have proved bamboo to be the fastest renewable natural building material and a worthy alternative to steel. However, the merits of bamboo have been continuously overlooked with the advent of "modernity" in building construction.

2. Seismicity in India

Seismicity of a place can be defined as the distribution of earthquakes in space, time and magnitude in that area. India, being a large landmass, experiencing the constant "continental drift" northward, has definitely had a large number of earthquakes. A list of significant ones in the last 180 years is as below *(Earthquakes of magnitude 8 or greater have been highlighted):*

DATE	EPICENTRE		LOCATION	MAGNITUDE
	Lat(Deg N)	Long(Deg E)		
1819 JUN 16	23.6	68.6	KUTCH,GUJARAT	8.0
1869 JAN 10	25	93	NEAR CACHAR, ASSAM	7.5
1885 MAY 30	34.1	74.6	SOPOR, J&K	7.0
1897 JUN 12	26	91	SHILLONGPLATEAU	8.7
1905 APR 04	32.3	76.3	KANGRA, H.P	8.0
1918 JUL 08	24.5	91.0	SRIMANGAL, ASSAM	7.6
1930 JUL 02	25.8	90.2	DHUBRI, ASSAM	7.1
1934JAN 15	26.6	86.8	BIHAR-NEPALBORDER	8.3
1941 JUN 26	12.4	92.5	ANDAMAN ISLANDS	8.1
1943 OCT 23	26.8	94.0	ASSAM	7.2
1950 AUG 15	28.5	96.7	ARUNACHAL PRADESH -CHINA BORDER	8.5
1956 JUL 21	23.3	70.0	ANJAR, GUJARAT	7.0
1967 DEC 10	17.37	73.75	KOYNA, MAHARASHTRA	6.5
1975 JAN 19	32.38	78.49	KINNAUR, HP	6.2
1988 AUG 06	25.13	95.15	MANIPUR-MYANMAR BORDER	6.6
1988 AUG 21	26.72	86.63	BIHAR-NEPAL BORDER	6.4
1991 OCT 20	30.75	78.86	UTTARKASHI, UP HILLS	6.6
1993 SEP 30	18.07	76.62	LATUR-OSMANABAD, MAHARASHTRA	6.3
1997 MAY 22	23.08	80.06	JABALPUR,MP	6.0
1999 MAR 29	30.41	79.42	CHAMOLI DIST, UP	6.8
2001 JAN 26	23.6	69.8	BHUJ, GUJARAT	7.6

Table 2.1: History of Earthquakes in India (IMD website, 2002)

The following map will help to get a better understanding of the seismicity of South-East Asia. The concentration of earthquake occurrences almost along the border of India can be explained by continental drift of the Indian Peninsula northward into Asia (earlier Eurasia).
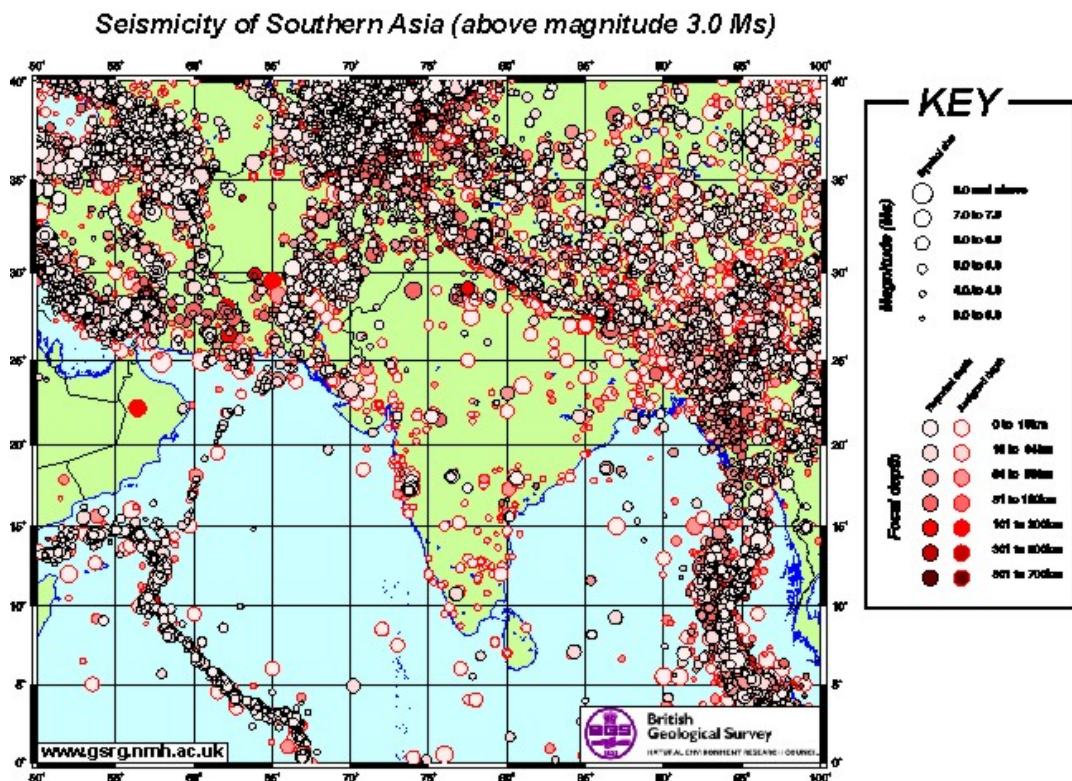
Fig 2.1: Seismicity Map of South-East Asia (British Geological Survey, 2001)

The seismicity in the country can be better understood by tectonic plate map of India, which is as below:
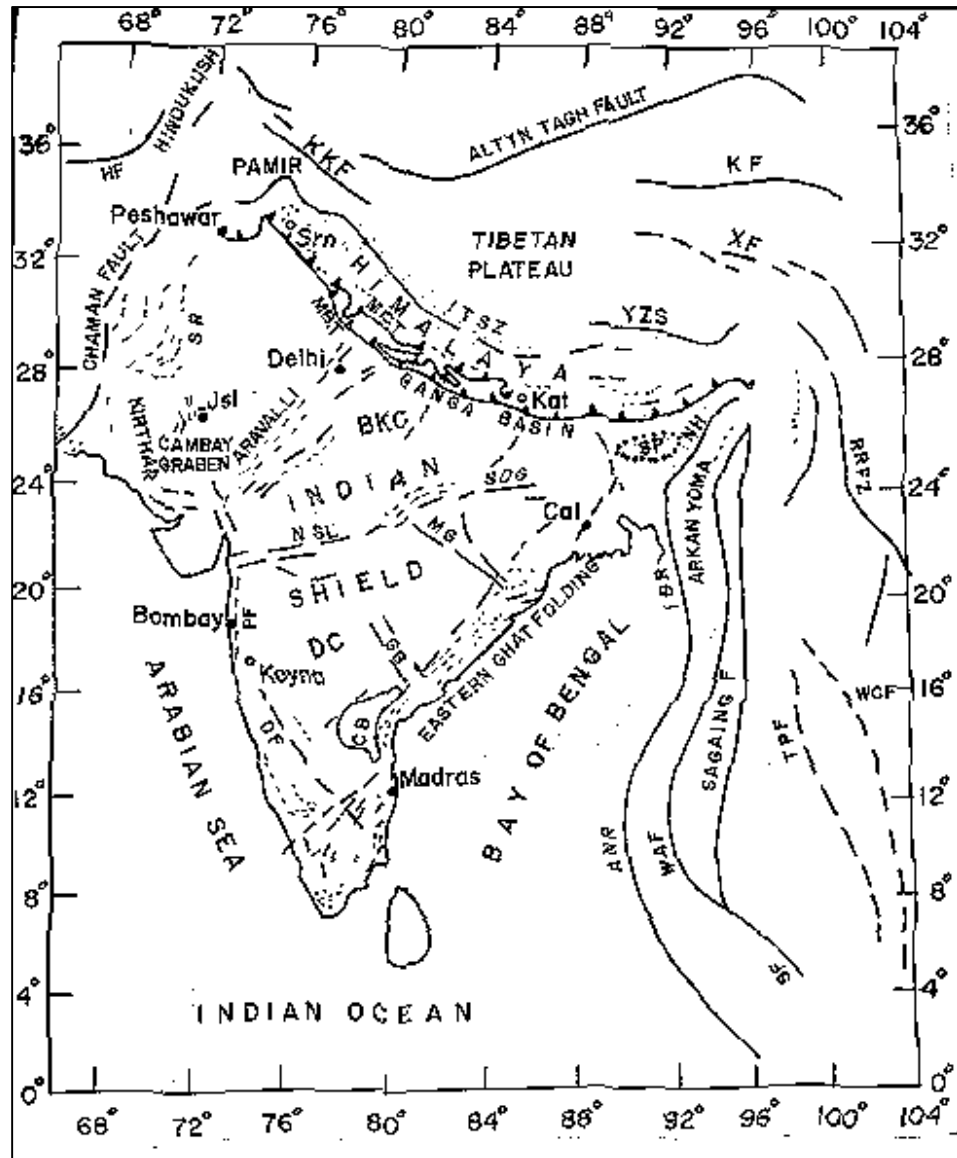
Fig 2.2: Tectonic Map of India (National Geophysical Research Institute – India, 2001)

The tectonic plate studies and seismological studies are being advanced by setting up multiple observatories and using advanced instruments.

The India Meteorological Department (IMD) with its Headquarters in New Delhi is the nodal agency of the Government of India for dealing with seismological studies in the country. The Seismology Division of IMD has the following responsibilities:

- Monitoring earthquakes in and around India:

For effective monitoring of earthquakes, the IMD maintains the following:-

1. 45 national seismological observatories, 9 for special studies in North India and 3 mobile observatories in and around Delhi.

2. A National Seismological Database Center (NSDC) along with a Central Receiving Station (CRS) in New Delhi to receive and archive seismic data. Both digital and analog data are received here in near real time mode.
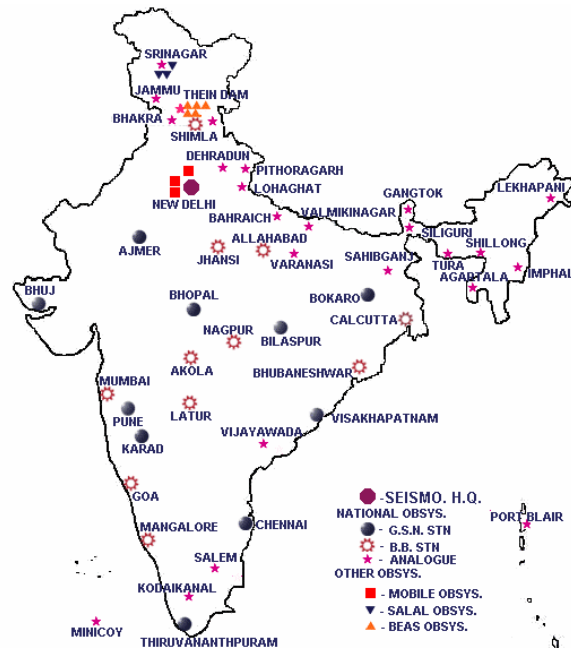
Fig 2.3: Map of seismological observatories in India by IMD (IMD website, 2001)

3. Upgrading observatories with the latest seismographs available.

- Research in Pure and Applied Seismology

- Responding to queries relating to earthquakes

- Manufacture of seismological instruments

- Micro-earthquake surveys

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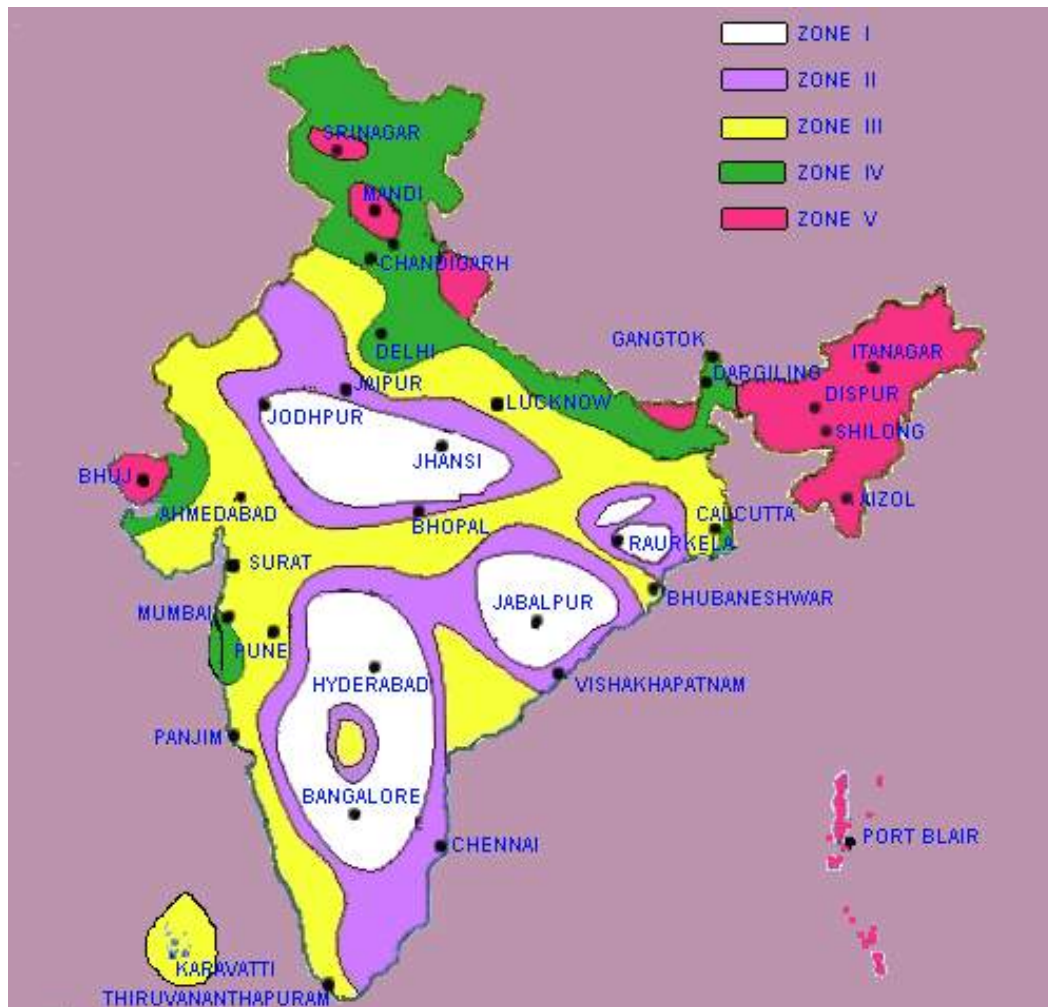
Fig 2.4: Seismic Zoning Map of India

The Seismic Zoning Map shown above divides the sub-continent into zones based on the intensity of earthquakes in the area. Zone I has the lowest and Zone V has the highest magnitude or probability of earthquakes.

3. Bhuj Earthquake: January 26, 2001 disaster

In the early hours of the Republic day of India, January 26 2001, people of India experienced violent tremors. The day the Constitution of Independent India had been written, 54 years ago, the residents of Bhuj and the neighboring areas experienced a powerful earthquake, with a magnitude of 6.9 on Richter scale.

Fig 3.1: Map showing the Bhuj Earthquake (www.mapsofindia.com)

Bhuj was earlier believed to be the epicenter as is noted in the map above. The epicenter of the earthquake was, however, 13 kilometers North-West of a town called Bhachau (Kutch, Gujarat). The quake was felt all over India and even in parts of Bangladesh, Nepal, and Pakistan.

Fig 3.2: Map of showing affected areas around Bhuj (www.mapsofindia.com)

This map takes a closer look at Bhuj and the neighbors marking out areas on the basis of the amount of damage due to Bhuj.

A general overview of the damage provides the following numbers (Survey, 2001):

- 1.59 m of 3.78m population affected

- Villages damaged   -   7,900

- Deaths   -   20,000

- Injured   - 166,000

   Critically Injured   -   20,700

- Livestock (cattle) loss   -   20,700

Comparison of property damages during the Bhuj Earthquake

	Household	Public Utilities	Infrastructure	Industrial	Commercial
Series1	2500	125	225	1000	625

Loss value in US Dollars (100,000 $)
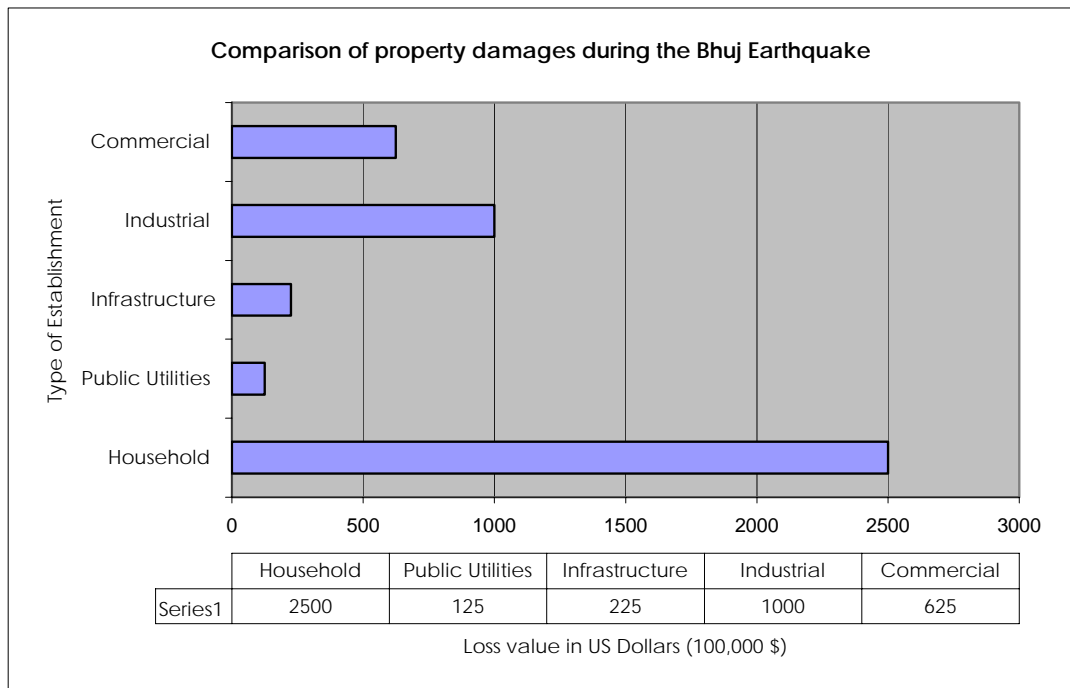
Graph 3.1: Comparison of different types of property damages

Studies estimate the total monetary loss to be close to 5 billion US Dollars. The graph above compares the losses to different types of establishments in US Dollars highlighting the extensive damage to households, which has far exceeded that of any other kind of establishment.

The losses to life and residential property alike have been phenomenal. This brings forth a need to study them in greater detail and provide adequate retrofit and mitigation methods for this section of construction. This shall be the focus of the chapters hereafter.

4. General Construction Practices in Bhuj:

In the wake of the disastrous earthquake, several research projects were carried out to study in detail the various construction practices carried out in and around Bhuj. This would help architects and engineers to expedite the mitigation and redesign for the earthquake-hit areas.

"Earthquake Disaster Mitigation Research Center (EdM), Hyogo, Japan" and *"Department of Civil Engineering, Indian Institute of Technology, Mumbai, India"* conducted a combined research and established the following broad categories for residential construction:

a) Traditional Kutchchi houses (Bhonga)

b) Unreinforced burnt brick/ Stone masonry & cement concrete block masonry

c) Reinforced Cement Concrete

d) Precast Concrete

All these construction types have been thoroughly studied and each type presented with its basic properties, seismic strengths and weaknesses.

a. <u>Traditional Kutchchi houses (Bhonga)</u>

This traditional type of housing is typically circular in plan with a conical roof. The inner diameter varies between 3 to 6 meters. A *bhonga* typically has walls of sun-dried mud (adobe) blocks and a bamboo-framed roof covered with thatch. In some cases, use of lintel bands at the top of the walls and bamboo framing in the walls is possible.

Fig 4.1: View of a *Bhonga* – exterior & interior

<u>Seismic Performance</u>

Some examples of this ancient building tradition have performed surprisingly well in the Bhuj earthquake. An analysis of the structures shows the following strengths and weaknesses.

<u>Strengths</u>

- Circular shape, hence excellent resistance to lateral forces
- Thick adobe walls - high in-plane stiffness
- Light-weight roofing with ductile materials

Fig 4.2: *Bhongas* that survived the earthquake

- Use of lintel bands and collar bands in some cases as reinforcing members

Weaknesses

- Poor quality of materials used for construction

- Use of one single post to support the roof at the center

Fig 4.3: *Bhongas* that collapsed in the calamity

b. Unreinforced Burnt Brick Masonry & Cement Block Masonry

These structures are typically single–storied brick masonry structures, have an exterior wall thickness of 300 – 350 mm (11.8″ – 13.7″) and interior walls are about 230 mm (9″). In case of cement block masonry structures the wall thickness is uniform 200 mm (7.8″) for exterior

Fig 4.4: Typical masonry house plan

and interior walls. Both types have roofs consisting of bamboo/ wood purlins covered with clay tiles. In some cases, a concrete slab of about 100 mm (4″) thickness may also be used.

Fig 4.5: Typical brick masonry house

Fig 4.6: Typical cement block masonry house

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Seismic Performance

Though these are relatively stronger when compared with the *bhongas*, but they have their own problems in case of seismic activity. Their seismic strengths and weaknesses are as below:

Strengths

- Use of lintel bands and collar bands in some cases as reinforcing members

Fig 4.7: Collapsed Unreinforced brick house

Weaknesses

- Improper connections
- Openings very close to corners
- Inadequate shear resistance near openings
- Damage to light-weight roofs
- Asymmetrical plan

Fig 4.8: Collapsed Cement Block masonry structure

c. <u>Reinforced Concrete</u>

Reinforced Concrete structures are normally multi-storied structures. The structural system consists of moment-resisting frames resting on shallow isolated footings. The structures have infill wall panels of brick, cut-stone or cement block.
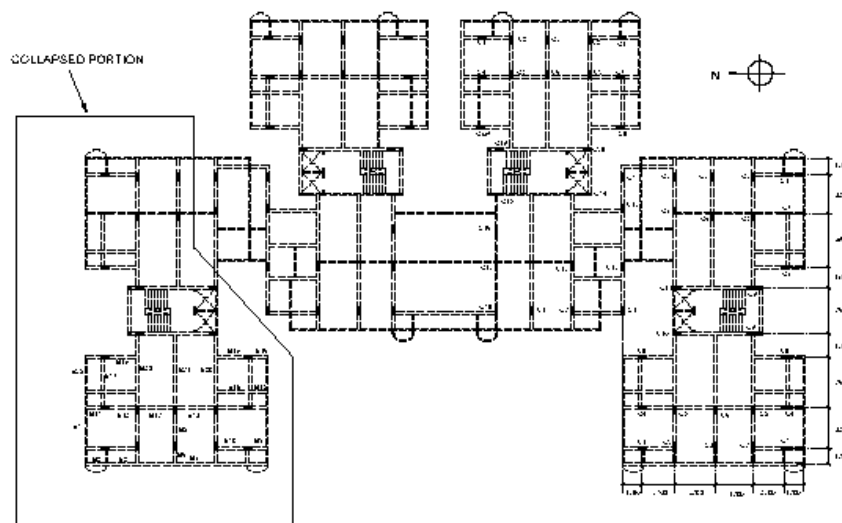
Fig 4.9: Plan of a typical RC apartment complex

Initially RC structures built for office or commercial purposes and residential dwellings were more of the single-family independent house type. However, shortage of land and high land values necessitated the building of multi-storied residential complexes. RC is a better solution with respect to seismic activity and is a labor-intensive type of construction, advantageous for India with a large labor force.

The seismic strengths of RC structures are:

- RC moment-resisting frame with brick infill most effective in areas prone to seismic activity.

- Rectangular plans, symmetric framing system without horizontal or vertical discontinuities quite effective.

- Symmetrical lift cores act like shear walls.

- Closely-place stirrups with ends bent add to the ductility factor.

In order to understand the seismic weakness of RC construction, it is necessary to look into the typical structural systems used in RC construction for initial construction and retrofitting structures.
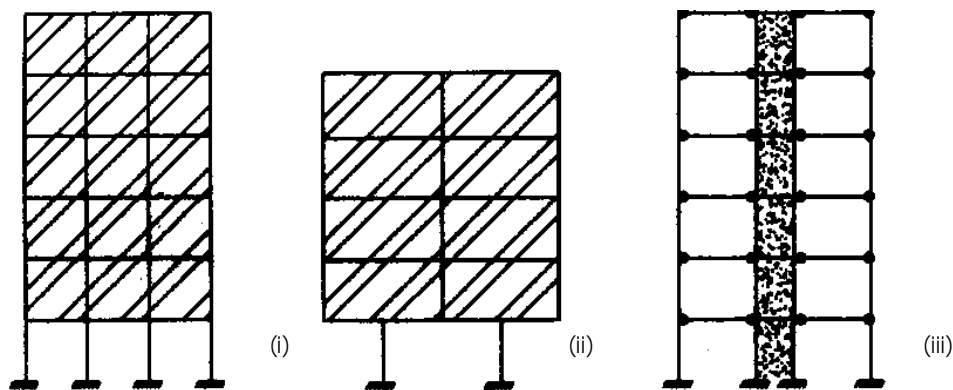
Fig 4.11: Typical Structural systems used in initial construction

Type (i) – Framed structure with soft story.

Type (ii) – Framed structure with upper floors cantilevered beyond the soft story.

Type (iii) – Framed structures with a concrete shear core.
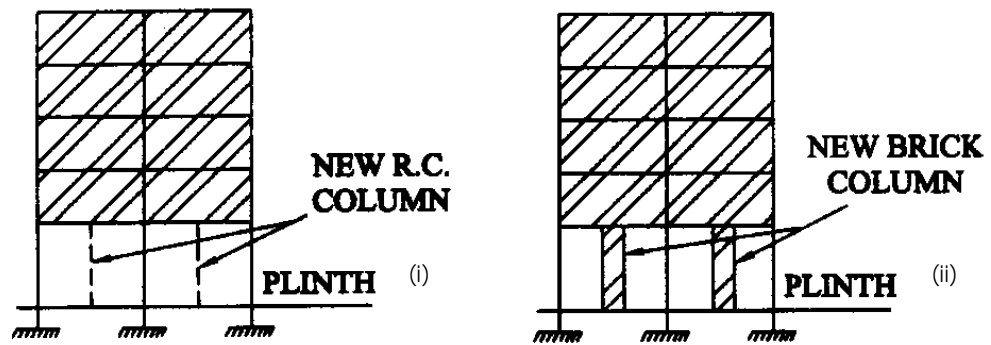
Fig 4.12: Typical methods used in retrofit construction

Type (i)   – This system is used to retrofit the Type (a) of initial construction. In this system, new RC columns without foundation are added to strengthen the soft story.

Type (ii) – This system is also used to retrofit the Type (a) of initial construction. This system uses new brick columns without foundation to strengthen the soft story.

In both of the above types of retrofit, the common mistake is that of not providing foundations for the new columns (both RC and brick). This might appear to support the slab above, but don't actually help seismically strengthening the structure. It is these types of retrofitting schemes and later additions to the RC structure that are responsible for the collapse of a great number of RC structures. A detailed study of the seismic weaknesses of RC structures highlights the issues above together with other issues that have been overlooked or disregarded during construction.

Seismic Weaknesses

- Configuration problem – building wings must be separated by seismic joints

- Inadequate soil tests for foundation design

- No plinth beams for reducing slenderness of ground floor columns

- Discontinuous horizontal and vertical members

- Inadequate transfer mechanism of lateral loads from other areas to lift cores

- Inadequate support to water tanks on roof

- Inadequately strengthened soft stories for parking

- Poor quality of concrete

Fig 4.13: Absence of plinth beams

Fig 4.15: Inadequate transfer mechanism

Fig 4.16: No Support for rooftop water tanks

Fig 4.14: Discontinuous members

Fig 4.17: Collapsed soft stories

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5. Proposed Rehabilitation technique for RC structures

This rehabilitation/redesign technique has been proposed by a civil engineer Abhijeet Mukherjee of Indian Institute of Technology, Mumbai. The observations made by this engineer are shown below:

- RC structures failed due to lack of ductility.

- Joints of RC structures are most susceptible

- There was a lack of confinement in joints which leads to crushing of concrete

- Long, unsupported lengths of reinforcement caused it to buckle
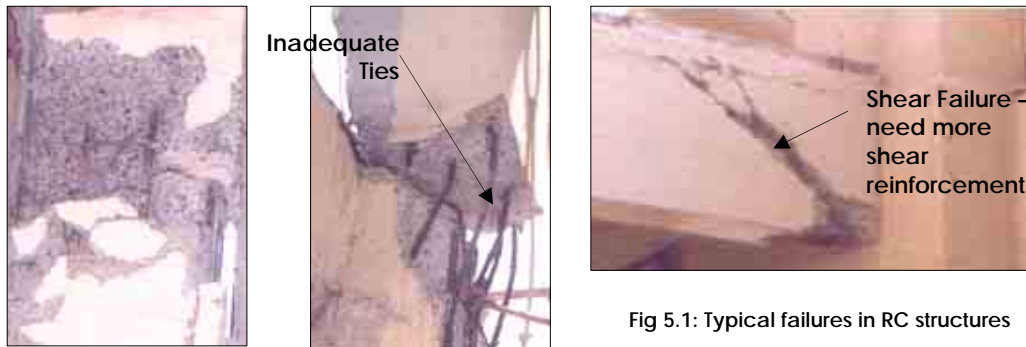
Fig 5.1: Typical failures in RC structures

Mr. Mukherjee has proposed the use of "Glass Fiber Reinforced Plastic" as reinforcement for RC structures instead of steel rebars. The propertis of GFRP are as follows:

- The material has high strength of 1700 – 3000 Mpa (240 – 430 ksi) and high ultimate strain (3-5%)

- The material can be strengthened to desired level.
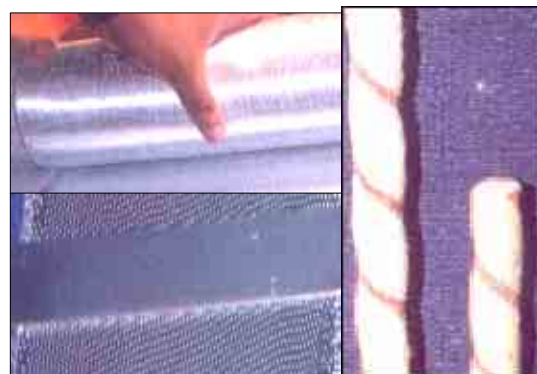
Fig 5.2: Glass fiber roll, Precured GFRP plate, rebar

- It is light, easy to handle and resistant to corrosion, hence durable.

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6. Good Performances in the Bhuj Earthquake

Though there was widespread damage that seemed to be the most common feature of the landscape after the seismic disaster, there were examples of structures that surprisingly held their own. Some of these were located quite close to the epicenter. These structures were analyzed to learn the reasons for the good performance. They are as below:

- These structures were mostly industrial facilities.

- This could mean that they were built to higher standards of construction and better quality materials.

- Often times the construction companies that are commissioned to build industrial facilities in India are international – like American or German companies. This highlights the possibility of greater quality control.

Fig 6.1: Examples of Good Performances during the Bhuj Earthquake

7. Uniform Building Code (UBC) Equivalent Static Force Method of Seismic Design

Seismic base shear is based on Newton's law:

f = m a (Force = Mass x Acceleration)

The UBC Static Method defines base shear using the following acceleration:

Base Shear,   V = Dead Load x Seismic Acceleration

Base Shear, $V = W\dfrac{ZIC}{R_W}$

Where,   W= Building dead load (DL) + 25% live load (LL) of warehouses only

   Z = Seismic Zone factor

   I = Seismic Importance factor

   C= Ground Motion Amplification Coefficient

   R_w= Lateral-force-resisting system Coefficient (min 4 to a max 12)

- Seismic Zone Factor (Z):

  The *seismic zone factor,* **Z,** corresponds to the expected peak ground acceleration as defined by the Seismic Zone map for the United States (UBC Figure 16-2).

  Z-factors are defined as:

Zones:	Zone 0	Zone 1	Zone2A	Zone 2B	Zone 3	Zone 4
Z-factors	0	0.075	0.15	0.2	0.3	0.4

Table 7.1: Z-factors according to seismic zones in the United States

- <u>Seismic Importance Factor (I):</u>

The *seismic importance factor*, **I = 1.25**, for essential or hazardous facilities (hospitals, police and fire stations) and **I = 1** for all other occupancies. Increasing the importance factor can be looked at increasing the seismic forces expected to act on the structure.

- <u>Ground Motion Amplification Coefficient (C):</u>

The *ground motion amplification coefficient*, **C**, is a coefficient that accounts for the effect of periodic modes of vibration, damping, and soil quality on a building's response to typical seismic ground motion.

$$C = 1.25 \, S \, / \, T^{2/3}$$

Where,

    S = Site Coefficient

    S_1 **=** 1.0 rock-like and stiff dense soil < 200' deep

    S_2 = 1.2, medium-dense or stiff soil > 200' deep

    S_3 = 1.5 (default), soft to medium stiff soil > 20' deep

    S_4 = 2.0, soft clay > 40' deep

    T = Period of Vibration of the structure

    T = $C_t \, h^{3/4}$

    C_t = 0.035 for steel moment frames

    C_t = 0.03 for concrete moment frames and eccentrically braced frames

    C_t = 0.02 for all other structures

    h = height of the structure above the ground

- <u>Lateral- Force-resisting system Coefficient (R_w)</u>

  The *lateral-force-resisting system coefficient,* R_w, relates the building's structural system (specifically, the part of the structural system that resists horizontal forces) to its performance under seismic loads. In particular, the structure's ability to absorb energy (ductility) is rewarded in assigning values to Rw. These values range from 12 for steel or concrete "special moment-resisting frames" down to 4 for various bearing wall systems including concrete and heavy timber braced frames resisting both gravity and lateral loads.

The structure is assumed to behave like a vertical cantilever rigidly attached to the ground. Hence lateral forces at higher stories will be greater.
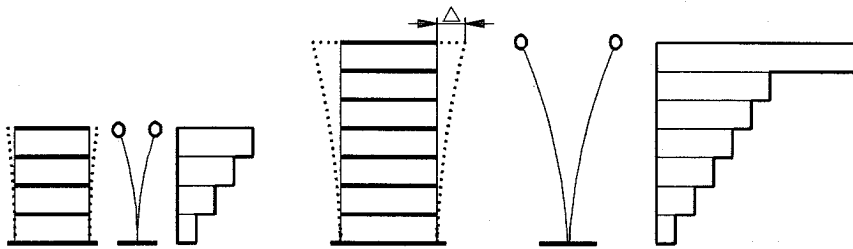
Fig 7.1: Lateral forces increase with height due to increasing acceleration (Schierle, 1996)

Lateral forces per level are computed as:

$F_x = (V - F_t)\, w_x h_x\, /\, \sum w_i h_i$

Where F_x = Lateral force at each story

W= total dead weight of story

h = height of story above ground

n = number of stories

F_t = whip force on top of the building in addition to F_n

F_t is computed as:

$F_t = 0.07\, T\, V\ <= 0.25\, V$ for T > 0.7 seconds

Shear distribution:

Shear increases from top to bottom since each floor resists its own force plus all forces above.

Overturning moment distribution:

The overturn moment at each level is the sum of all forces above that level multiplied by their respective lever-arm to the level considered.

8. Conclusions & further research

It can be concluded from the previous chapters that extensive work has been done for the redesign and retrofit of RC structures. However, surveys prove that the prevalent type of construction, housing a majority of the population falls under the category of "Non-engineered" structures, as can be observed from the pie charts below.
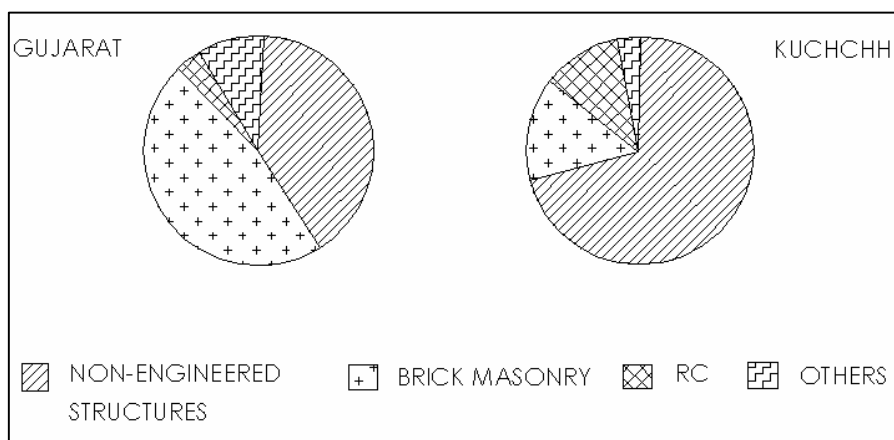
Fig 8.1: Comparison of popular building techniques in Gujarat and Bhuj

This brings forth the following points for consideration:

- Research in the field of block masonry structures is found to be seriously lacking.

- Masonry is the more common building type for the lower class of people.

- A cost-effective measure to rehabilitate/redesign the masonry structures is essential to satisfy the larger masses.

- A lot can be learned from the traditional (bhonga) house construction.

Further Research

It has been proved in previous researches that the best way to seismically strengthen masonry structures is to reinforce them. Steel rebars are commonly used for this purpose. However, steel is an expensive material for a third world country like India and most people living in unreinforced masonry structures do so because of insufficient money for better houses. Steel is practically unaffordable to this kind of people. It is therefore necessary to propose an alternative material to be used as rebars. In my further research, I propose to study the use of bamboo as a rebar for masonry construction.

Why Bamboo?

- It is the fastest-growing renewable natural building material.

- It is much less expensive than steel.

- The material is very familiar to the people of Bhuj.

- Tests have proven that bamboo is a viable (if not better!) alternative for steel, concrete and masonry as an independent building material.

9. Introduction to Bamboo

Bamboo is primarily a type of giant grass with woody stems. The stems are called "shoots" when the plant is young and "culms" when the plant is mature.

2.5"-3"

Fig 9.1: Various types of Bamboo

Each bamboo plant consists of two parts – the "culm"/stem that grows above the ground and the underground "rhizome" that bears the roots of the plant.

Bamboo grows in either clumps or like runners. Bamboo growing in a clump adds a new shoot around one central culm thereby increasing the clump size radially. As for runners, they just literally "run" around, growing in a haphazard manner. "A single bamboo clump can produce up to 15 kilometers of usable pole (up to 30 cm in diameter) in its lifetime."

Bamboos can grow in tropical and sub-tropical regions (from 46°N to 47°S) and at elevations upto 4000m like in the Himalayas. Till date, there is a consensus on the recognition of about 60 – 90 genera with about 1100 to 1500 species. The general properties of the plant are:

- The plant matures very quickly, new shoot grows to its full height in 2-3 months.

- Once it has matured, the culm size remains the same for the rest of its life.

- It is a very flexible plant that sways in the wind, but rarely snaps. This can be attributed to its hollow stem and nodes.

Fig 9.2: Bamboo clumps

- With an exception of a couple, the bamboos generally fall under the category of evergreen plants.

- Though the life span of a single bamboo is only about 20 years, the grove stands forever because bamboo regenerates itself eternally.

- Bamboo rarely flowers; some plants only do so once in 120 years.

Known as a plant of "a thousand uses" in India, there are literally about 1500 documented uses for bamboo in the small-scale industry apart from other uses like cooking, paper industry, construction, vegetation cover, soil erosion check, transportation, fisheries, etc.

Fig 9.3: Bamboo Building by J. Morán U., Guayaquil, Ecuador

10. Bamboo Properties

The primary focus of this study is the use of bamboo in the field of construction. Hence this chapter shall concentrate on the properties of bamboo that are useful for building.

Researches in the past have yielded knowledge of over 27 species of timber bamboo, having varying resistance to cold, sunlight, diameter, height. Bamboo used in construction maybe used as a full culm or splits (3/8″ – 1/2″ wide).

Fig 10.1: Full culms & splints

Studies carried out to test the structural properties of bamboo by the "Kerala State Bamboo Corporation Ltd." show the following results (converted to psi):

Tensile strength test

a) Tensile strength parallel to the grain direction of cross band	6450
b) Tensile strength perpendicular to the grain direction of cross band	1590

Flexural strength test

a) Flexural strength parallel to the grain direction of cross band	12,200
b) Flexural strength perpendicular to the grain direction of cross band	6060

Compressive strength test

a) Compressive strength parallel to the grain direction of cross band	5435
b) Flexural strength perpendicular to the grain direction of cross band	3265

Table 10.1: Strength of bamboo acc. to "Kerala State Bamboo Corpn. Ltd." tests

Francis E. Brink and Paul J. Rush did a study and calculations way back in February 1966 incorporating bamboo as rebar in RC beams and columns. This project was carried out at the U.S. Naval Civil Engineering Laboratory, Port Hueneme, California. This study assumes the following values for the mechanical properties of the material:

Mechanical Property	Symbol	Value (psi)
Ultimate compressive strength		8,000
Allowable compressive stress	σ	4,000
Ultimate tensile strength		18,000
Allowable tensile stress	σ	4,000
Allowable bond stress	u	50
Modulus of elasticity	E	2.5×10^6

Table 10.2: Strength of bamboo according to Francis E. Brink & Paul J. Rush

Since bamboo is a natural material, different species perform differently for the same set of tests. The above-mentioned values are only ballpark figures to use in calculations. To be more accurate, the right kind of bamboo to be used for construction might have to be subjected to the standard tests to be able to determine a value for calculation purposes.

The following species of bamboo are commonly found in India (listed alphabetically by botanical names):

1.	*Bambusa longispiculata*	Common Name: "Mitenga" Bengal) &"Thaikwa"(Burma), Origin: Bangladesh/India., Specification: 18m x 10cm to +5 deg C.,	Forms beautiful open clumps with well-spaced straight ivory-striped greyish-green culms. Large decorative leaves and structurally good. Spectacular light blue/green edible shoots are striped cream, have a scattering of strong, dark contrasting hairs on the culm leaf and a wrinkled, hairless fairly flat broad blade.

Table 10.3: Species of bamboo commonly available in India

2.	*Bambusa oliveriana*	Common Name: "Wapgusan". Origin: Burma and India., Specification: 10m x 5cm to 0 deg C.	A very pretty moderate sized dense clumping bamboo with thick-walled strong, straight, glossy, green culms. Smallish, very pointed delicate leaves. Edible shoots are purple tinged green sporting black hairy stripes on the blades. Very good for fishing poles.
3.	*Bambusa tulda*	Common Name: Bengal Bamboo. Origin: India, where it is a major source of paper pulp., Specification: 25m x 8cm to -2 deg C.	A fast growing often deciduous superior structural bamboo (tensile strength tested at 52,000 psi). It has large leaves on upper branches and fewer smaller leaves lower down. Fairly straight very smooth dark green culms. Edible slightly bitter shoots (often pickled) have spectacular bulging pale blue powder covered sheaths with wide green blades that flair out almost horizontal to the shoots' surface. Used extensively for furniture, basket making and a wide range of household utensils and as concrete reinforcing. The sacred flute called "Eloo" used by the priests of Arunachal Pradesh is made from B tulda.
4.	*Dendrocalamus brandisii*	Common Name: Sweet Dragon, Origin: India., Specification: 36m x 20cm to -4 deg C.	The tallest bamboo in the world, this vigorous giant produces thick-walled strong green culms covered with a velvet bloom of pale hairs imparting a slightly milky appearance. Strong aerial root growth on the lower nodes. Lower culms branchless for many meters then masses of very large light green rough textured leaves. Huge delicious edible shoots are dark bronze and hair covered with purple blades. Extensively used for house construction, furniture making and paper production but becoming hard to find in Asia.
5.	*Dendrocalamus strictus*	Common Name: "Male Bamboo". Syn Bambusa stricta., Origin: India., Specification: 18m x 8cm to -7 deg C.	A drought-resistant bamboo with small light green furry leaves. Its strong lower erect grey-green slightly rough culms are often without hole for about half their length and are without lower branches or leaves displaying the extremely tightly clumped culms. The pendulous upper culms and their fine leafed display are very graceful. An added feature is the visible retained paper-like lower culm leaves. The shoots light green and lightly powdered are edible. A major paper pulp and structural bamboo of India.

Table 10.3: Species of bamboo commonly available in India (contd.)

Of the species mentioned in Table 10.3, all except the *Bambusa oliveriana* could be used for construction purposes. Apart from these species, the *Bambusa tuldoides*, originating in China also has a very high tensile strength and is recommended for use in construction.

11. Bamboo in Construction

Bamboo is the fastest growing, renewable natural resource known to us. It is a small wonder, therefore, that this material was used for building extensively by our ancestors. Bamboo being a natural material has its disadvantages like infection by insects and fungi, poor fire-resistance. Bamboo used in the construction industry can be either in the form of full culms or splits. Boards and mats are also made from bamboo for building. Bamboo is maybe used as any one of the following building components:

- Foundations
- Framing
- Scaffolding
- Flooring
- Walls
- Roof
- Trusses

Fig 11.1: Example of Bamboo house

Foundations

For use as foundation, the bamboo poles are directly driven into the ground. They have to, however, be pre-treated for protection from rot and fungi. This prolongs the life of the foundation beyond that of an untreated bamboo pole.

Framing

Many rural and semi-urban areas, hardwoods are preferred to bamboo as framing of a building. This is because hardwoods provide better rigidity, which is interpreted as better strength and most hardwoods are better resistant to rot and fungi than untreated bamboo. There is also a certain amount of prestige associated with using hardwoods as they are more expensive and hence a potential symbol of wealth. However, in earthquake prone areas, bamboo is given higher preference because of higher resilience.

Scaffolding

Since ancient times, bamboo poles have been tied together and used as scaffolding. The properties of bamboo such as resilience, shape and strength make it an ideal mterial for the purpose. The working platforms for masons can also be built of bamboo.

Fig 11.2: Bamboo scaffolding

Flooring

Earlier most houses had a floor of rammed earth raised above the ground a little with filling to prevent flooding due to drainage. Later houses had raised floors. This was more hygienic and had a serviceable area underneath that could be put to good use. Bamboo was used for this purpose. The higher resilience of bamboo culms made them better than conventional timber for floor beams. These would then be covered by either small whole culms, strips or bamboo boards made by opening and flattening out culms attached to the beams by wire lashings or small nails.

Walls

There are several ways in which bamboo can be used in wall-building. They are:

- *Bajareque* wall

  This wall-building technique is very well-known in Latin America. Bamboo strips or slender culms are nailed or tied on either side of timber, or in some cases bamboo, posts. The intermediate space is then filled with mortar or mortar and stone.

- Bamboo Board wall

  This is a common method of construction in Indonesia. Horizontal bamboo poles are nailed/tied to the mortices in vertical supporting bamboo poles. The bamboo board panels are then nailed to the horizontals. These walls maybe finished with stucco. For better adhesion, barbed wire reinforcing is used under the stucco.

Fig 11.3: Bamboo board

- Wattle wall

  These walls consist primarily of bamboo or reed lath used as a base for application of a mud plaster to one or both sides. A mixture of clay and organic fiber is used as plaster.

- Mat wall

  Mat walls are constructed by nailing a thin bamboo mat to either sides of a braced timber frame. These walls may then be plastered with cowdung, mud, sand or lime.

Fig 11.4: Bamboo mat wall

- Solid wall

  This wall uses full or split sections of bamboo side by side vertically in a frame. The wall may be made water-tight by cladding with closely woven mats.

Roof

Bamboo is used commonly as both framing and roofing. The following are the three most common types of bamboo roofing:

- Bamboo tile roofing

  This is the simplest form of bamboo roofing. The culms are split into halves, the diaphragms scooped out and these run full length from eave to ridge. The first layer of bamboo splits are layed

Fig 11.5: Bamboo tile roofing

  concave side up and the second layer interlocks over the first with convex side up. Though a very simple method, it can be completely watertight. The minimum pitch of the roof should be 30°.

- Bamboo shingle roofing

  Shingles are made from mature bamboo culms, typically 3-4 cm wide, and air-dried. These are attached to bamboo battens atleast 4 cm wide. The battens are tied or nailed to bamboo purlins not less than 7 cm in diameter. The minimum pitch of the roof should be 30°.

Fig 11.6: Bamboo shingles

- Thatch roofing

  The roof is framed using bamboo purlins and rafters. The thatch is tied to this framing. Split bamboo is used to pin down the thatch at valleys and ridges.

<u>Trusses</u>

For the spanning larger distances in public utility buildings like schools, storage areas, commercial buildings, bamboo is utilized as a truss member. Bamboo has a high strength/weight ratio and hence is a good alternativve for roof framing.

Fig 11.7: Bamboo truss

An award-wining example of bamboo being used in modern day construction is the pavilion designed by Simon Velez, architect-artist-engineer in Manizales, Colombia. It was an exact replica of the EXPO2002 paviliion desined by him in Hannover, Germany. He designed the pavilion with bamboo to take 7 feet plus of overhangs.

He filled the joints with concrete to increase the traction strength of bamboo making it stronger than steel. He married organic and inorganic materials for a second time when he used bamboo fiber reinforced cement board for the roofing. The bamboo was

Fig 11.8: Simon Velez pavilion of bamboo.

protected from insects and pests by an age-old Japanese technique of "smoking bamboo".

Besides the use of bamboo as a building material, there have been proposals in the past to use bamboo as reinfocement in RC columns, beams and slabs. One of the examples is a silo made of bamboo-reinforced concrete. This is the avenue for

Fig 11.9: Bamboo-reinforced concrete silo

further research in the process of combining the ancient of bamboo building with modern materials like concrete.

Fig 11.10: Bamboo reinforcement

12. Initial Assumptions and Calculations

Based on data available from previous research by Francis E. Brink and Paul J. Rush (Feb 1966) certain calculations were made to estimate the required shear wall length, rebar spacing and bond length.

The following values were assumed for calculations:

Assumed values	Steel	Bamboo
Allowable tensile stress	24,000	4,000
Unit bond stress (given)	150	50
Area of reinforcing, A_v	#4 bar = 0.19	0.216
Wall thickness, t	12″	12″

The following table compares the results from the calculations performed using the above values for steel and bamboo

Results	Steel	Bamboo
Required spacing, s	16″	1¾″
Required shear wall length in each direction, d	20′-4″	15′-8″
Required bond length	22″	16″

In the calculation of the required bond length for bamboo splints and additional Factor of Safety of 1.5 was assumed. This is to account for the fact that bamboo is non-uniform and hence will bond differently in the areas with and without nodes.

13. Testing Needs

The results from the previous chapter of "required bamboo rebar spacing", cast doubts over the validity of the value of shear strength assumed. Also due to the non-homogeneity of bamboo, it was considered advisable to the results to verify the values. For this purpose the following tests were proposed to be carried out:

1. Tensile tests – to determine the ultimate and allowable values for bamboo culms or splints.
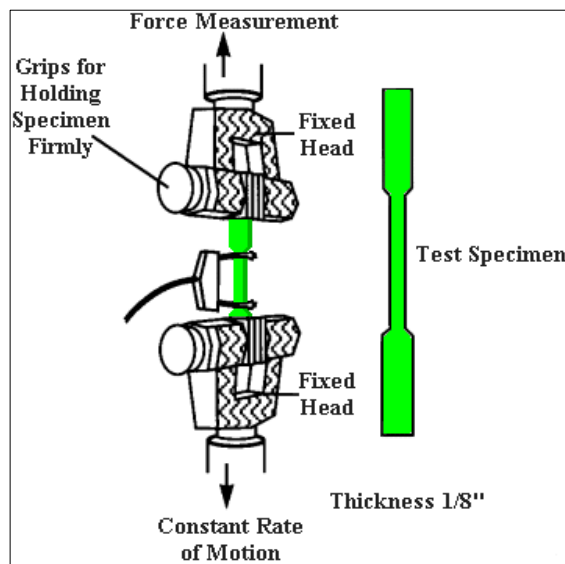

Fig 13.1: Tensile test principle

2. Bond tests – to determine the strength of bonding between bamboo, mortar and brick.

    A testing mechanism similar to the one above can be used for performing a "pull test" on a sample. In this case a bamboo splint embedded in mortar to test the bond strength.

14. Test Protocol

This chapter describes in brief the test protocol adopted for performing the tensile and bond tests on bamboo.

Tensile Test 1: Bamboo specimen with wooden supports

According to the manual for Laboratory testing of bamboo, a bamboo specimen tested without supports is bound to slip out of the testing machine. It is, therefore, advised to make wooden supports for the bamboo specimen to provide better grip.

Fig 14.1: Wooden support for specimen

The supports were prepared according to the specifications in the Figure 14.1 from the manual.

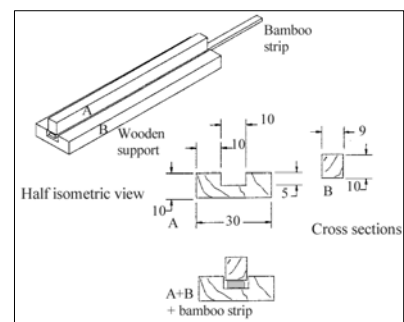Figure 14.2 shows the specimen loaded in the tester ready for testing.

Fig 14.2: Specimen loaded in tester

Tensile Test 2: Bamboo specimen fixed to wood supports

The objective of Test 2 was to study the behavior of the bamboo specimen in tension if fixed to the wooden supports. The three methods used to fix the supports to the specimen:

a. Using wood glue: The specimen was glued to the wood supports using "carpenter's" wood glue. This test failed too because of slippage and inadequate adhesion of the glue.

Fig 14.3: Glued specimen loaded for testing

b. Using epoxy: The supports were glued with the specimen using epoxy and allowed to set for 24 hours before testing.

Fig 14.4: Epoxy glued support end

c. Using wooden dowels: Dowels were also used instead of glue to bind the specimen with the wood support as shown in the Figure 14.5.

Fig 14.5: Doweled support end

Tensile Test 3: Bamboo specimen with no supports

Test 3 aimed to test the bamboo specimen by itself, without any supports. Before starting the test, the bamboo specimen was just held in place in the machine without applying too much pressure on the grip jaws. As the load was applied, the jaws "bit" into the specimen, automatically tightening the grip on the specimen with increase in load.

Fig 14.6: Specimen with no supports loaded in tester

Tensile Test 4&5: Bamboo specimen with single node

Earlier tensile tests used a bamboo specimen with two nodes. Tests 4 & 5 were conducted to compare the difference in results between a specimen having two nodes v/s a specimen having a single node in the test length. Two tests were conducted with two such bamboo specimens.

Fig 14.7: Single Node Test specimen

Bond Test 1: Bamboo specimen embedded in mortar

In order to test the bond strength between the mortar and a bamboo splint, a sample of mortar block with an embedded splint was prepared. For this purpose, a mortar mix of 1:3 (cement: sand) proportion was used. 72 milliliters of water was added for 1lb of mortar mix. After mixing the mortar, it was filled in a plastic mold of 5-inch diameter. The height of the sample was maintained at 5-inches. A bamboo splint was embedded in this mortar-filled mold, taking care to ram the mortar compactly around the splint. Mortar achieves 85-90% of its strength in the first 24 hours.

The sample was allowed to set for 36 hours before testing. Upon starting the test, the splint developed a longitudinal crack and the test was stopped mid-way to inspect the damage. The test was later continued with the same sample and the specimen resisted load higher than estimated by calculation before slipping from the mortar block.

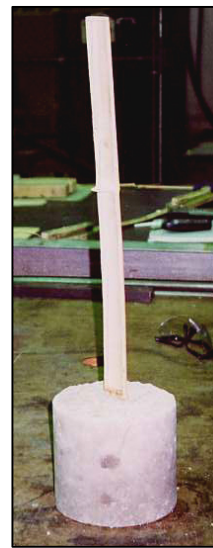Fig 14.8: Mortar sample loaded in tester   Fig 14.9: Mortar sample

Bond Test 2: Bamboo specimen embedded in brick pier

In order to validate the values obtained from the earlier bond test and to simulate a condition similar to real-life masonry construction, the next specimen for the bond test was prepared by embedding the bamboo splint in a brick pier.

The brick pier was prepared using standard red bricks used in masonry construction with the same mortar mix as the previous test (1:3 mix of cement to sand). The pier was allowed to set for 7 days before testing. The mortar was cured regularly during this period.

Fig 14.11: Brick with embedded splint

Fig 14.10: Brick sample loaded in tester

Bond test 3: Bamboo specimen embedded in mortar block

In order to compare the results obtained from the previous test (bamboo embedded in brick pier) with bamboo embedded in only a mortar block, a mortar block test sample of diameter 4″ and height 8″ (same as the brick pier) was prepared. A plastic mold of the same size was used for casting the mortar block. The mortar proportion was 1:3 of cement to sand and 72 milliliters of water per lb of dry mortar. A bamboo specimen of the same size as the one in the brick pier was inserted in the mortar block was inserted. This sample was let to set for 1 week before testing.

Fig 14.12: Mortar block For Comparative test

Bond test 4,5, 6: Comparative bond tests

For tests 4,5 and 6, similar mortar samples like test 3 were prepared. The objective of these three tests was to compare various parameters affecting bond strength. Test 4 sample was prepared with no node in the mortar block, to compare the strength with and without node. Test 5 sample was prepared by embedding a wider bamboo splint (3/4″ thick) in the mortar block. Test 6 sample was similar to Test 5 but with a 1″ wide bamboo splint. All mortar blocks were allowed to set for the same period of 1 week before testing.

15. Test Apparatus

In order to test the modulus of rupture and bond strength of bamboo, the 5590 HVL series Universal Hydraulic Tester (for compression and tension) by SATEC Instron was used. The Civil Engineering Lab of University of Southern California provided this facility. The salient features of the tester are as under:

- Load capacities range from 67,000 lb through 600,000 lb

- Frame design features dual test space which eliminates the need to change fixing when performing both tensile and compression testing

- Variety of crosshead styles permit easy loading of specimens

- Variety of grip actuation options include: crank and pinion, lever arm, or hydraulic grip

- Superior load cell technology increases accuracy and reliability of test result

Fig 15.1: 5590 HVL series Universal tester and computer for operation

Frame Design

A typical 5590-HVL frame includes a tension crosshead, adjustable crosshead, compression table, screw columns, notched columns, a protective piston boot, a load cell or nest of load cells, a cylinder and a piston.
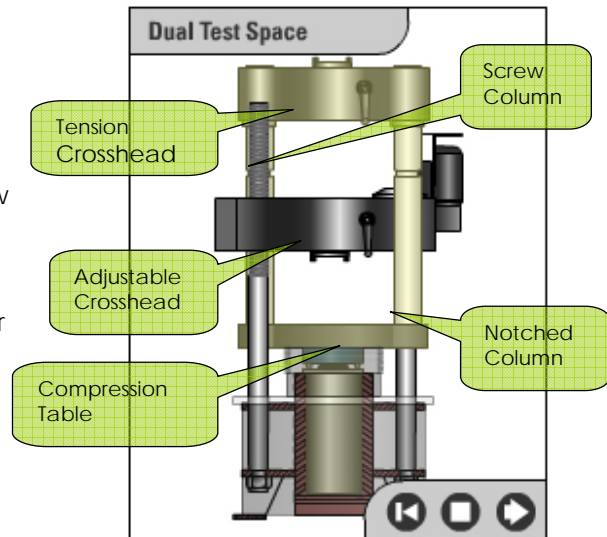

Fig 15.2: Parts of Universal tester 5590 HVL series

The dual test space design of a 5590-HVL system provides the capability of performing both tension and compression testing without changing fixtures. Tension tests are performed in the upper test space between the tension crosshead and the adjustable crosshead. Compression tests are performed in the lower test space between the adjustable crosshead and the compression table.
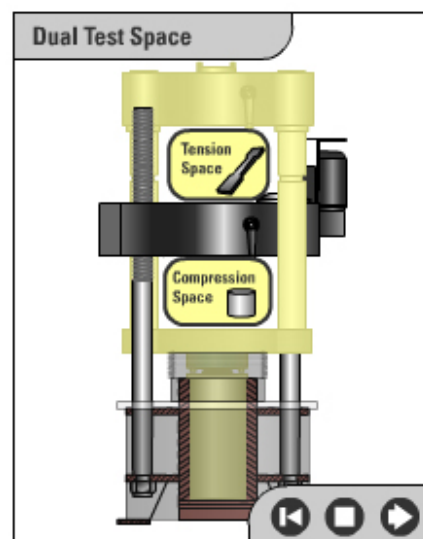
Fig 15.3: Dual test space in Universal tester

Hydraulic Operation

The machine uses hydraulic fluid for lifting the actuator assembly. This facilitates supply of compression force in the lower portion and tension force in the upper portion of the tester.

Crosshead styles

The 5590 HVL systems allow the user three kinds crosshead styles for different loading and gripping requirements:

Fig 15.5: In-head grip options

1. Closed front open crossheads

2. Semi-open crossheads to reduce insertion time of specimen into the tester

3. Fully open crossheads for easy insertion of long or bulky specimens.

Grip Actuation options

The 5590 HVL systems also allow three kind of in-head grip actuation assemblies:

1. Crank and pinion grip for manual lowering or raising of grip jaws

2. Hydraulic lever helps the operator to adjust grip jaws with pushbutton operation

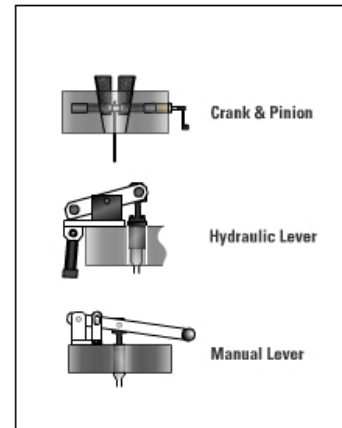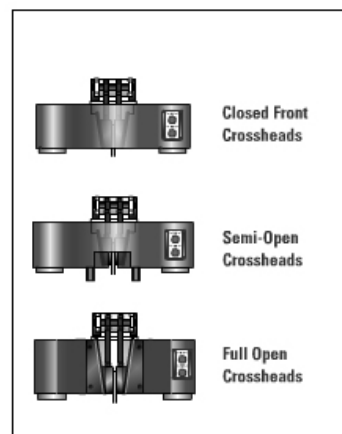3. Manual lever grip is also available in lieu with the grip and pinion option

Fig 15.4: Crosshead styles

Along with these features the Universal Tester is also supported by 5500 Series Control Electronics and Partner software

5500 Series Control Electronics

Instron's 5500 electronics allows accurate and advanced real-time control. These control the frame using any combination of load, strain, or speed rates. They also have automatic recognition and calibration of transducers to ensure safe and proper testing. The salient features of the Controller are 40,000 Hz data sampling, 500 Hz selectable data capture, 32-bit DSP technology, 19-bit resolution.

User Control Panel

Universal hydraulic testers include a modern user panel. Operators can perform important test control functions such as start, stop and return conveniently at the load frame.
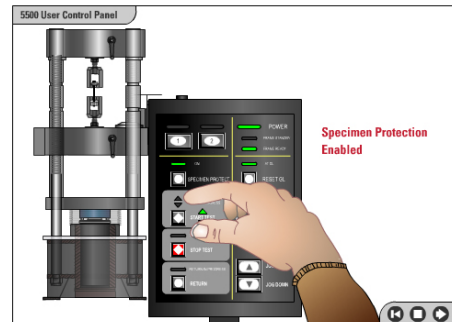

Fig 15.6: User control panel

Partner software

It is designed and written for the Windows® platform, Partner software allows easy multitasking of materials testing capability with the Microsoft® Office suite. Partner manages and automates the entire testing process from entering pretest parameters through report generation and distribution. Application-specific modules allow test technicians to quickly perform tensile, compression, shear, bend, or torsion

testing. Partner has networking capability, database structure, and built-in E-mailing capability allows users to share test results with other.

Other tools used for the preparation of the test specimen are as shown below:

- Bamboo Splitter

  The 6-way splitter is made of cast iron and used to split the full bamboo culm into splints. These splints were used as specimen for tensile strength tests or for embedding in mortar for bond tests.

Fig 15.7: Bamboo Splitting method

Fig 15.8: Splitter

- Rubber mallet

  This hammer is used in conjunction with the splitter to split the bamboo culms. A rubber/wooden mallet must be used in place of a regular metal hammer to prevent damage to the cast-iron splitter.
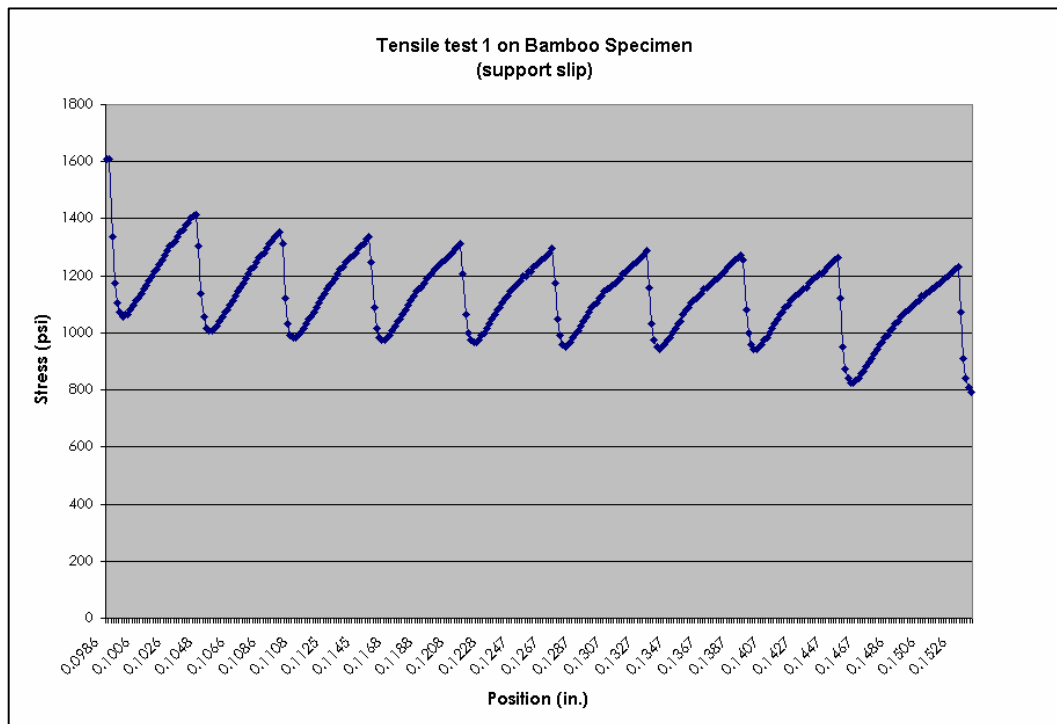

Fig 15.9: Rubber Mallet

16. Test results

Tensile Test 1: Bamboo specimen with wooden supports

Test 1 yielded in slippage of the wooden supports and hence the bamboo splint could not be stressed to its limit. The graph below shows the slipping of the support clearly.
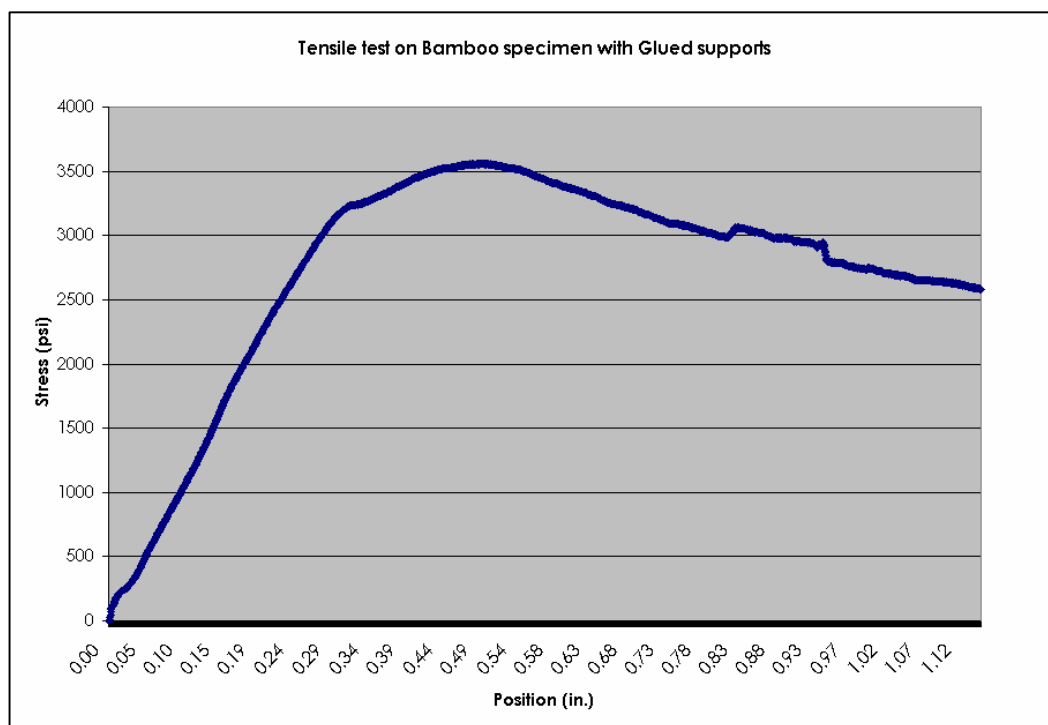

Graph 16.1: Failure due to support slippage

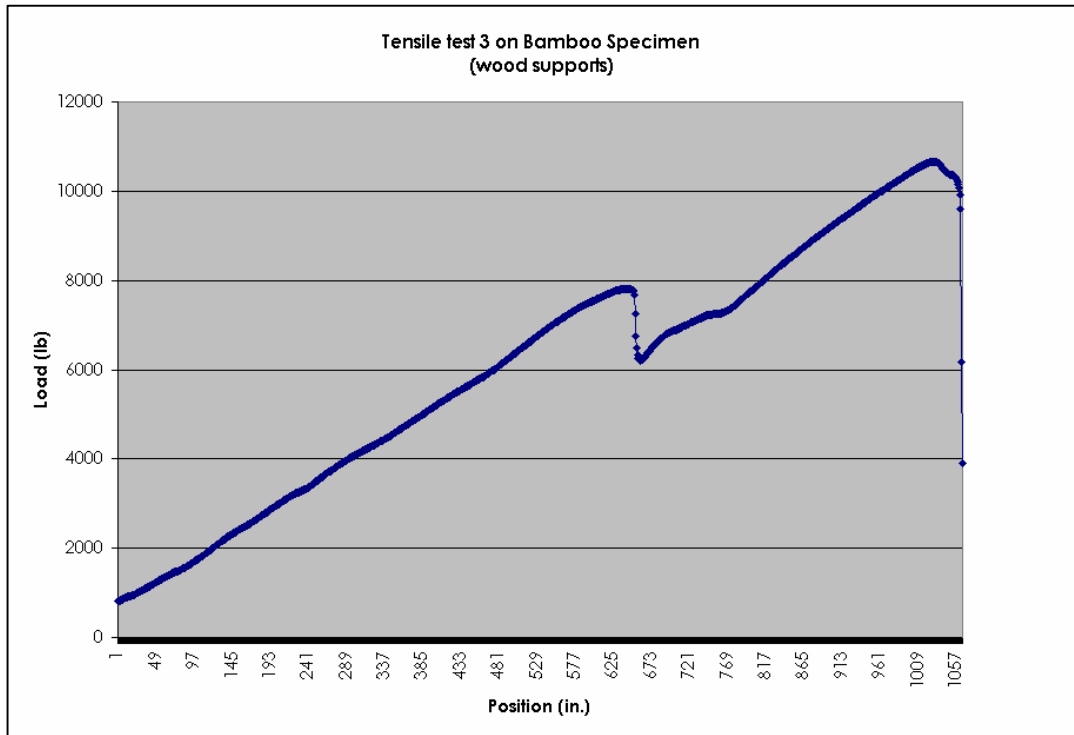**Tensile Test 2: Bamboo specimen fixed to wood supports**

Test 2a had the wooden supports glued to the bamboo specimen with an epoxy. The test failed due to cracking of the wooden supports and not the specimen.

Fig 16.1: Failed support

Tensile test on Bamboo specimen with Glued supports

Stress (psi)

Position (in.)

Graph 16.2: Failure due to cracking of glued wooden supports

Graph 16.3: Tensile test with doweled supports

Tensile Test 3&4: Bamboo specimen with no supports

The second set of tests was conducted with no supports for the bamboo specimen and using double node specimen and single node specimen. These were successful in both cases.

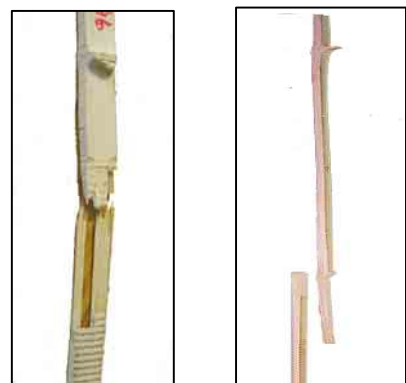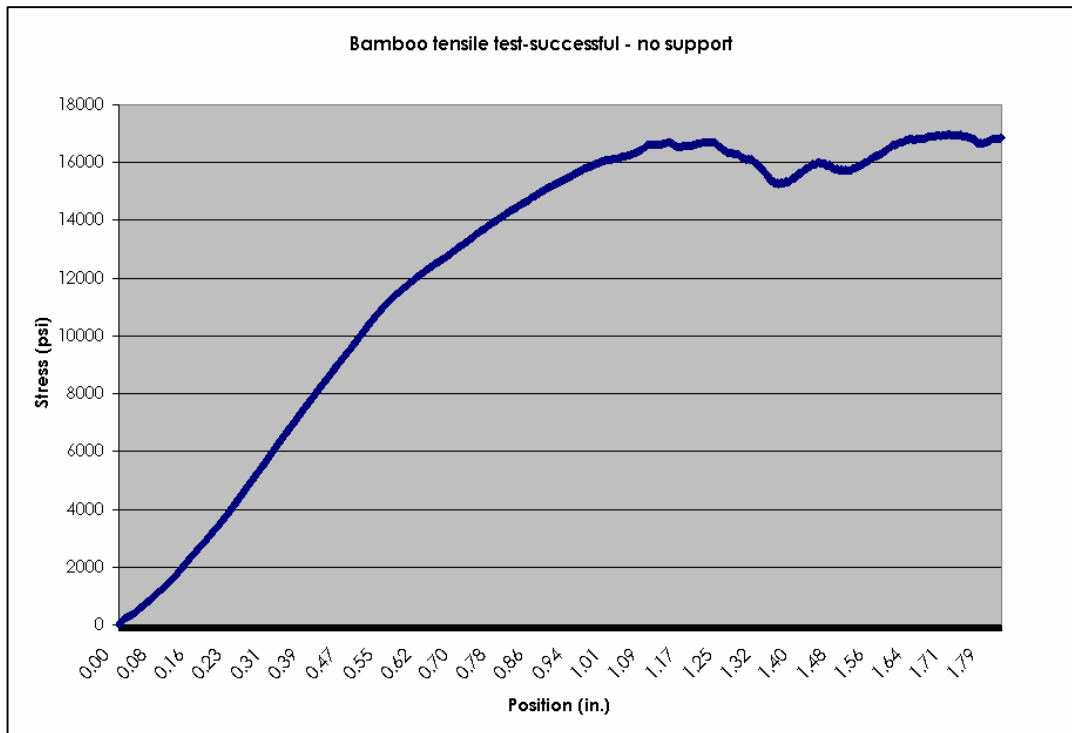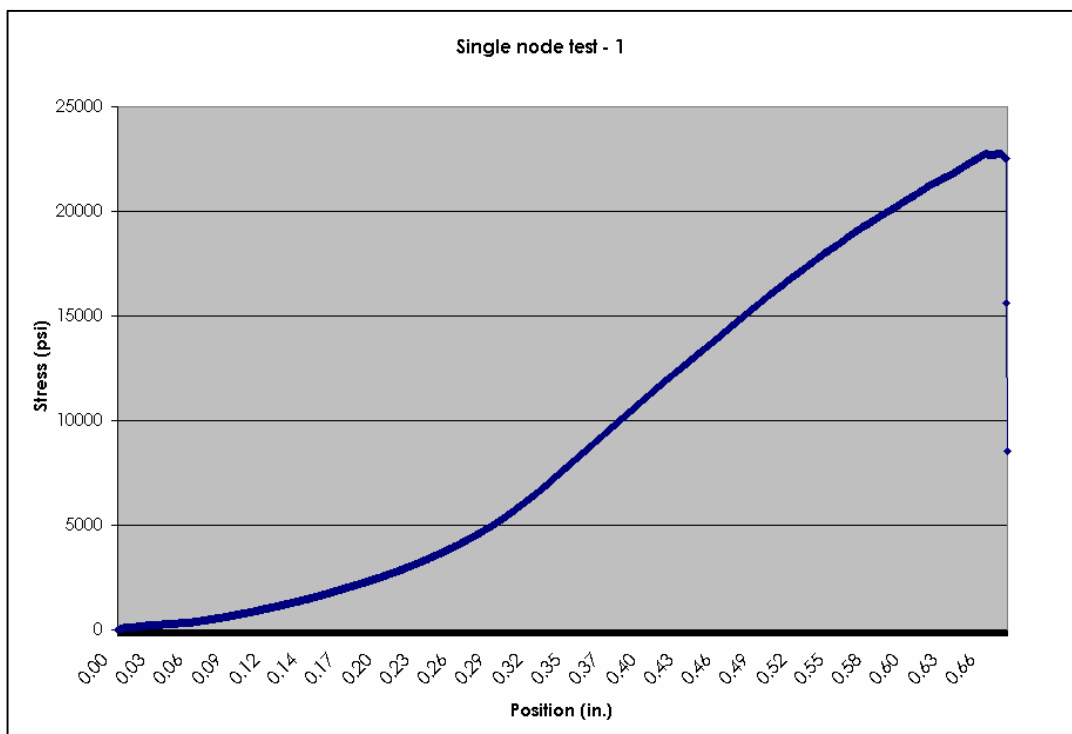The values were however, higher with the single node test as compared with the double node test.

**Fig 16.2: Failed Bamboo splint – single node and double node**

**Graph 16.4: Successful tensile test with double node specimen**

Graph 16.5: Tensile test with single node specimen

Bond Tests 1st set: Bamboo specimen embedded in mortar block and brick pier

These were performed to check the bond strength of bamboo embedded in mortar. The values were higher when the bamboo splint was embedded in a brick pier, as compared with bamboo embedded in a mortar block. But the sizes of both the splints and the area of mortar in which the bamboo splint was embedded were different so there was actually no ground for comparison.
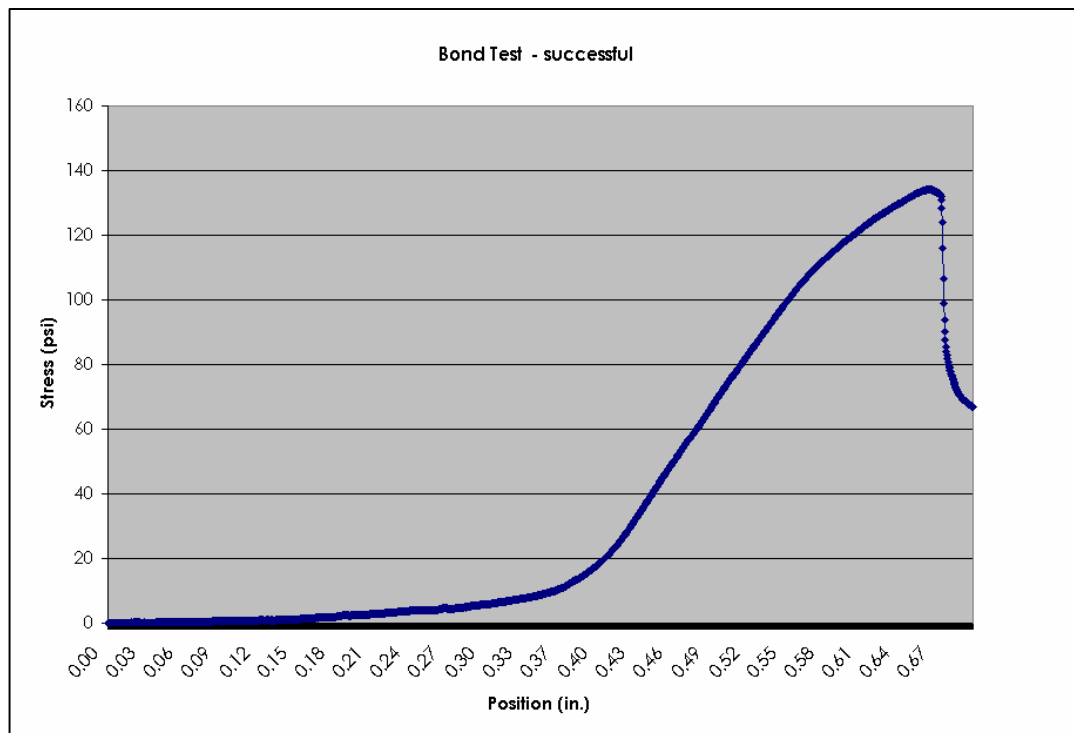
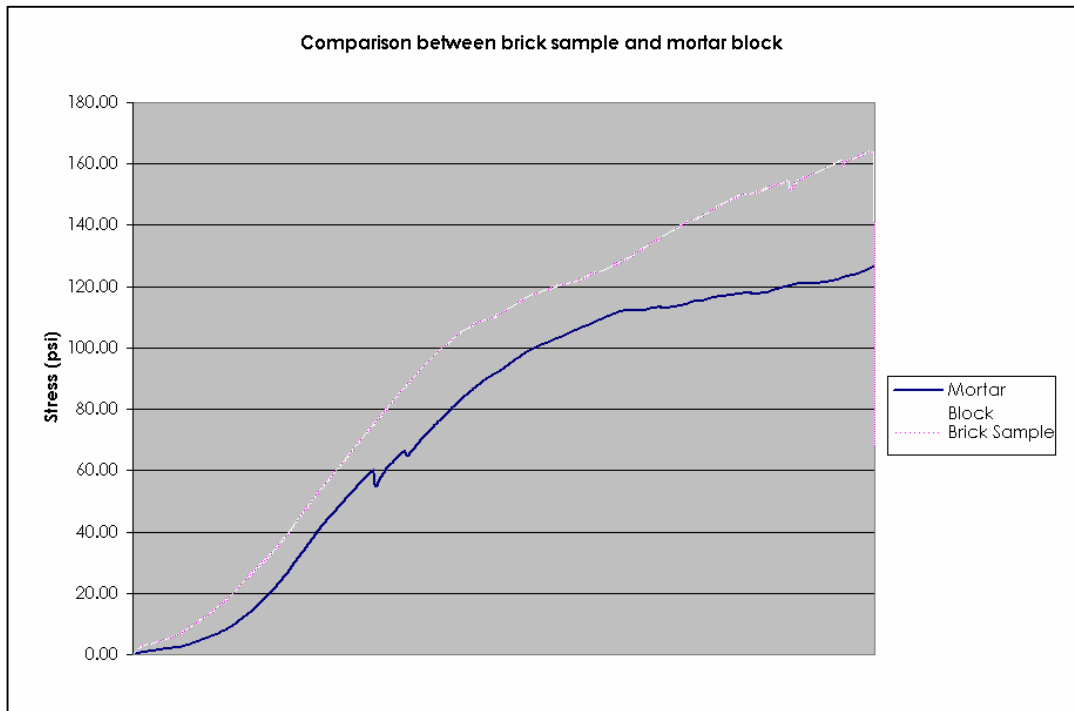Graph 16.6: Bond test with specimen embedded in mortar block
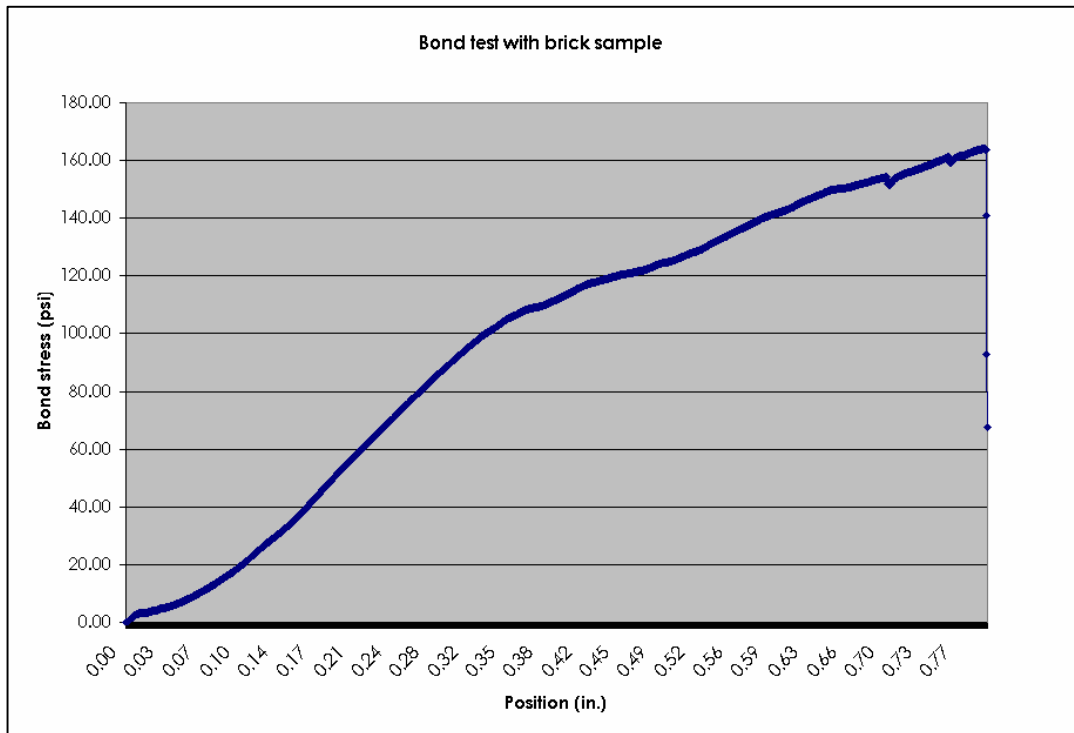
Graph 16.7: Bond test with specimen embedded in brick pier

Bond tests – 2nd set: Comparative tests

These were performed to compare all the parameters that affect the bond strength of bamboo in mortar.

The first test was performed on bamboo specimen in equivalent mortar block to compare the results with bamboo in brick pier. This test yielded lower values than bamboo in brick pier.

Graph 16.8: Comparative Bond test with specimen embedded in equivalent area mortar block
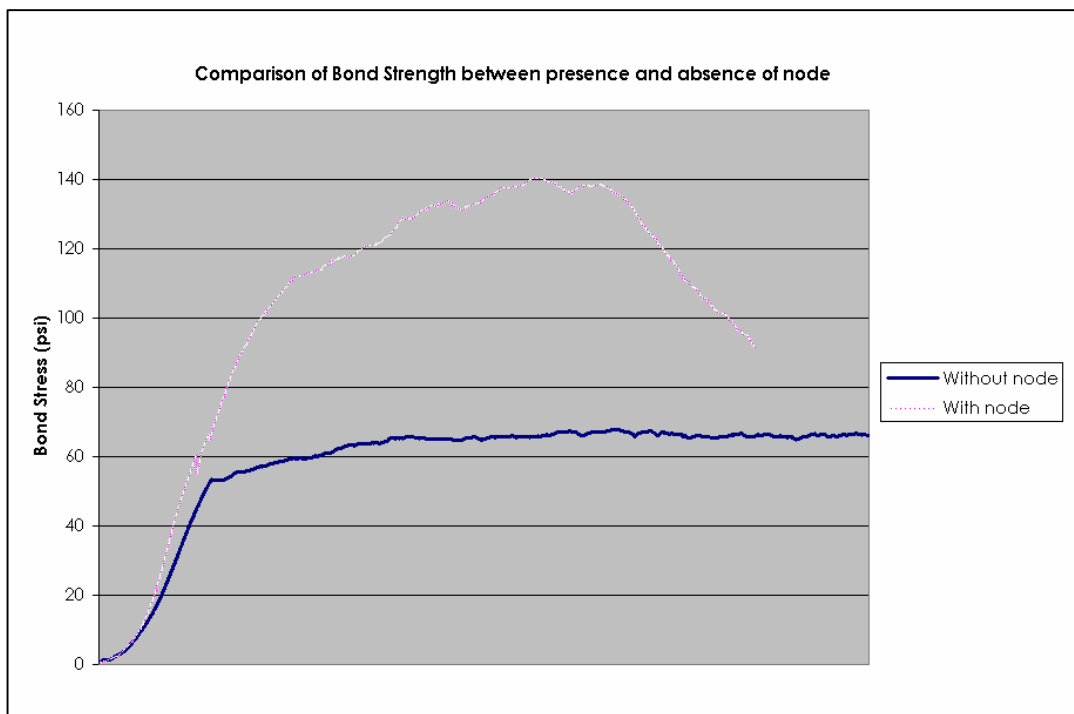
Graph 16.9: Comparison of Bond Strength between presence & absence of node in mortar block

The second test was performed on a specimen with no node in mortar block to compare the results with earlier tests. The results of this test were much lower.

The last two tests used progressively increasing sizes of bamboo splints to compare the results between varying sizes of bamboo splints in mortar.
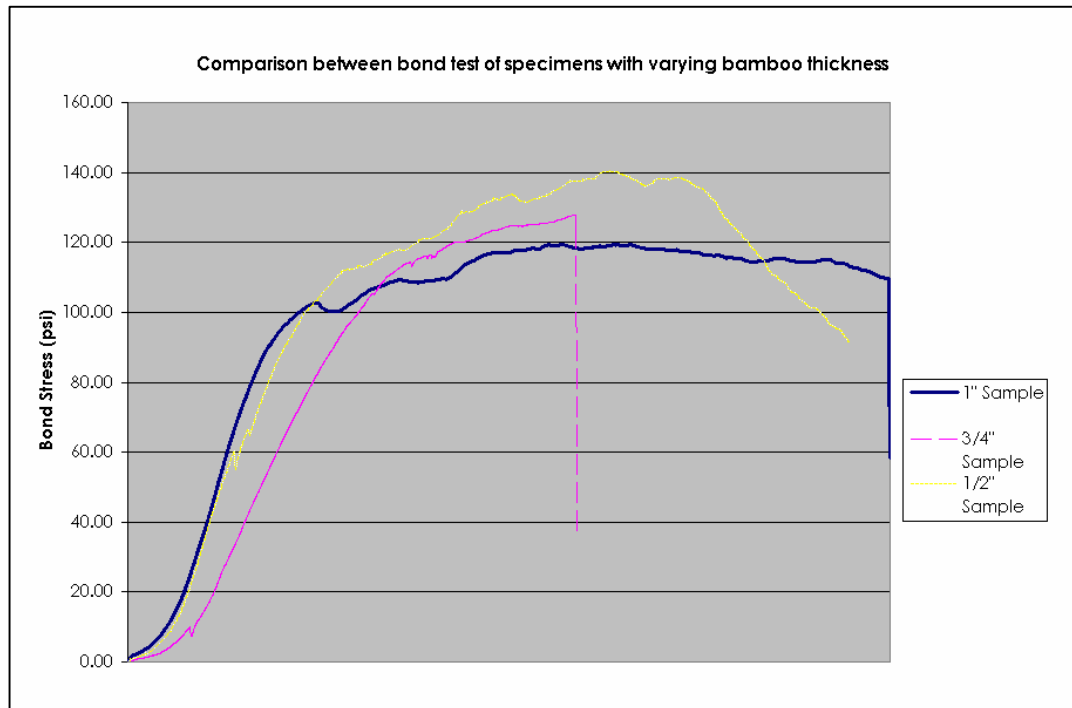
Graph 16.10: Comparison of Bond Strength between varying size of bamboo splints

17. Computations

For the purpose of guiding the layman about the step-by-step construction of bamboo-reinforced masonry, some basic calculations are required to estimate the amount of material required, bond strength etc. Unlike steel rebars, allowable tensile stress for bamboo reinforcement cannot be used to the maximum because the bamboo "splint" will fail long before in shear. Hence modulus of rupture is assumed as yield stress for calculation purposes. The following calculations are based on the values taken from the United Nations publication jointly prepared by D. Narayanmurthy and Dinesh Mohan of India (Narayanmurthy 1972). Test results conducted for this thesis also yielded similar results (see chapter 16).

Available Data:

Bamboo:

* Average modulus of rupture $f_y' = 18,460$ psi → use	$f_y' = 18,000$ psi
Allowable tensile stress, $F_a = 0.4 \, f_y = 0.4 \times 18,000$ psi	$F_a = 7,200$ psi
Allowable compressive stress $F_a = 0.4 \times 18,000$	$F_a = 7,200$ psi
Modulus of Elasticity	$E_b = 2.2 \times 10^6$ psi

Masonry:

Masonry modulus of elasticity (per 1988 UBC)	$E_m = 750 \, f'_m$
Asssumed specified compressive strength	$f'_m = 1500$ psi
For $f'_m = 1500$ psi → $E_m = 750 \times 1500$	$E_m = 1.125 \times 10^6$ psi
Bond strength	$u_{ult} = 140$ psi
Allowable bond strength= $u_{ult}/3$	$u = 47$ psi

Assumptions:

One story residence

$Z = 0.4$, $I = 1$, $S = 1.5$, $R_w = 6$

Roof DL (concrete)	150 pcf
Roof DL (pitched roof)	
Purlins	25 psf
Roof tiles	15 psf
Masonry DL	120 pcf
Floor area	A = 1000 sqft
Exterior wall length	L = 2x(25′+40′) −10′ (for window/door openings)
	= 120′
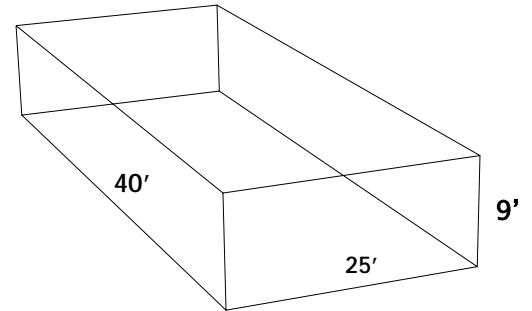
Fig 17.1: Assumed one-story residence

Loads:

Exterior Walls (120'x9'x12"/12")(120/1000)	= 130 psf
Partitions (UBC)	= 20 psf
Roof (12" slab) + Roofing [CONCRETE]	=150+8 psf
Roof (Purlins + tiles) [PITCHED ROOF]	= 25+15 psf
Σ DL [CONCRETE]	**= 308 psf**
Σ DL [PITCHED]	**= 190 psf**
LL	= 20 psf
Σ DL + LL [CONCRETE]	**= 328 psf**
Σ DL + LL [PITCHED]	**= 210 psf**

PART I: CONCRETE SLAB

Total dead load

W = 308 psf (1000 ft²)/1000   **W = 308 k**

Base shear (to be multiplied by 1.5 per UBC, section 1628)

$$V = 1.5\left[\frac{ZIC}{R_W}\right]W$$

$$\therefore V = 1.5\left[\frac{0.4 \times 2.75}{6}\right]308 = 0.275 \times 308$$ **V = 85 k**

Calculations:

Thickness of wall   = 12″

Specified compressive strength of masonry, f'$_m$ = 1500 psi
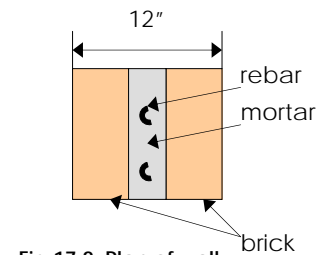

12″

rebar

mortar

brick

Fig 17.2: Plan of wall

Case 1: Rebars resisting all shear.

Allowable masonry shear stress

$$F_{v(max)} = 1.5\sqrt{f'_m}$$

In case of shear walls with reinforcement designed to resist all the shear force,

$$F_v = 1.5\sqrt{f'_m} = 1.5\sqrt{1500}$$

$$F_v = 58.09 \text{psi}$$

According to UBC section 1603.5, the stresses can be increased by 33%.

Therefore F_v=1.33 x 58.09 = 77.26 psi.

In case of non-inspected masonry, the maximum allowable shear stress is 50% of

$F_{v(max)}$ = 38.6 psi

Rebar size (assume 12 bamboo splints from a pole of $\varnothing \approx 3''$ and wall thickness $\approx \frac{1}{4}''$)

$$A_v = \frac{1}{12}\left[\frac{\left[\pi(3)^2 - \pi(2.5)^2\right]}{4}\right]$$

$$A_v = \frac{1}{12}[2.16] = 0.18\ \text{sq.in}$$
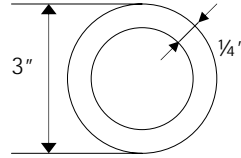

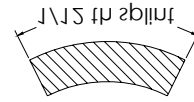**Fig 17.3: Full culm**   **Fig 17.4: 1/12th "splint"**

Rebar spacing

$$S = \frac{(A_v \times F_s)}{(F_v \times b)}$$

$$= \frac{0.18 \times 7200}{38.6 \times 12} = 2.79'' = 3''$$

Required effective wall length

d= V/(F$_v$xb) = 85x1000/[38.6x12]   **d ≈ 184″**

Use 2 walls in each direction (one for each exterior wall)

L = d/2 + 4″ (4″ reinforcing cover on one side)

Fig 17.5: Shear wall cover

L = 184″/2 + 4″ = 96″ → 96″/12 = 8′   **Use L= 8′**
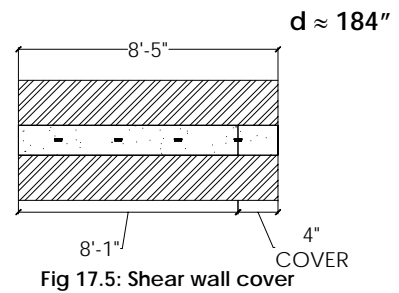
Case 2: Masonry resists all shear

Allowable masonry shear stress,

$$F_v = 1.0\sqrt{f'm} = 1.0\sqrt{1500}$$

$$F_v = 38.7\text{psi}$$

According to UBC section 1603.5, the stresses have to be increased by 33%.

Therefore F$_v$=1.33 x 38.7 = 51.47 psi.

In case of non-inspected masonry, the maximum allowable shear stress is 50% of

$F_{v(max)}$ = 26 psi

Rebar area, A_v=0.18 sq.in……………………. Case-1

Rebar spacing

$$S = \frac{(A_v \times F_s)}{(F_v \times b)}$$

$$= \frac{0.18 \times 7200}{26 \times 12} = 4.15" = 4"$$

Required effective wall length

d= V/($F_v$xb) = 85x1000/[26x12]   **d ≈ 272.45″**

Use two walls in each direction (one for each exterior

wall)

L = d/2 + 4″ (4″ reinforcing cover on one side)

Fig 17.6: Shear wall cover

L = 272.45/2 + 4 = 140.25 → 140″/12 = 11.67′   **Use L = 11′-8″**
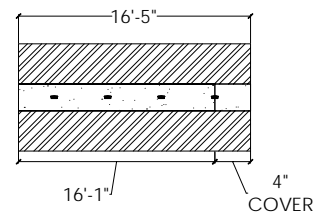
The bond stress developed on the surface area of the bamboo splint embedded in

the mortar can be given by,

$$\text{Bond Stress}, u = \frac{\text{Tensile force}}{\text{Total surface area of embedded splint}}$$

$$= \frac{f_s \times A_v}{\text{Perimeter} \times \text{Bond Length}}$$

Therefore,

$$\text{Bond Length}, l = \frac{f_s \times A_v}{\text{Perimeter} \times u} = \frac{7200 \times 0.18}{1.93 \times 47} \approx 15"$$

This means that each bamboo splint has to be embedded in atleast 15″ of mortar at

its free end.

PART II: PITCHED ROOF

Total dead load

W = 190 psf (1000 ft²)/1000   **W = 190 kip**

Base shear (to be multiplied by 1.5 per UBC)

$$V = 1.5\left[\frac{ZIC}{R_W}\right]W$$

$$\therefore V = 1.5\left[\frac{0.4 \times 2.75}{6}\right]190 = 0.275 \times 190$$

V=53 kips

Calculations:

12" nominal wall, effective thickness   = 12″

Specified compressive strength of masonry, f'$_m$ = 1500 psi

Case 1: Rebars resisting all shear.

$$F_{v(max)} = 1.5\sqrt{f'_m}$$

In case of shear walls with reinforcement designed to resist all the shear force,

$$F_v = 1.5\sqrt{f'_m} = 1.5\sqrt{1500}$$

$$F_v = 58.09\text{psi}$$

According to UBC section 1603.5, the stresses have to be increased by 33%.

Therefore F$_v$=1.33 x 58.09 = 77.26 psi.

In case of non-inspected masonry, the maximum allowable shear stress is 50% of

F$_{v(max)}$ = 38.6 psi

Rebar size (assuming 12 nos. of bamboo splints from a pole of $\varnothing \approx 3''$ and wall thickness $\approx \frac{1}{4}''$)

$$A_v = \frac{1}{12}\left[\frac{\left[\pi(3)^2 - \pi(2.5)^2\right]}{4}\right]$$

$$A_v = \frac{1}{12}\left[2.16\right] = 0.18 \, sq.in$$

Rebar spacing

$$S = \frac{(A_v \times F_s)}{(F_v \times b)}$$

$$= \frac{0.18 \times 7200}{38.6 \times 12} = 2.79'' = 3''$$

Required effective wall length

d= V/(F$_v$xb) = 53x1000/[38.6x12]   **d = 114.4"**

Fig 17.7: Shear wall cover

Use 2 walls in each direction (one for each exterior wall)

L = d/2 + 4″ (4″ reinforcing cover on one side)
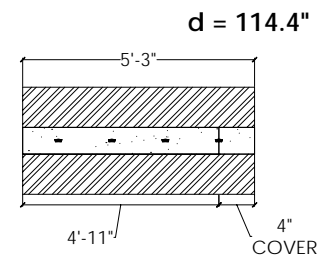
L = 115″/2 + 4″ = 61.5″ → 61.5″/12 = 5.125′   **Use L= 5′-2″**

Case 2: Masonry resists all shear

In case of shear walls with masonry designed to resist all the shear force,

$$F_v = 1.0\sqrt{f'_m} = 1.0\sqrt{1500}$$
$$F_v = 38.7psi$$

According to UBC section 1603.5, the stresses have to be increased by 33%.

Therefore F$_v$=1.33 x 38.7 = 51.47 psi.

In case of non-inspected masonry, the maximum allowable shear stress is 50% of

$F_{v(max)}$ = 26 psi

Rebar area, A_v=0.18 sq.in……………………. Case-1

Rebar spacing

$$S = \frac{(A_v \times F_s)}{(F_v \times b)}$$

$$= \frac{0.18 \times 7200}{26 \times 12} = 4.15" = 4"$$

Required effective wall length

d= $V/(F_v \times b)$ = 53x1000/[26x12]   **d= 170"**

Fig 17.8: Shear wall cover

Use 2 walls in each direction (one for each exterior wall)

L = d/2 + 4″ (4″ reinforcing cover on one side)

L = 170″/2 + 4″ = 89″ → 89″/12 = 7.42′   **Use L= 7′-5″**

The bond stress developed on the surface area of the bamboo splint embedded in

the mortar can be given by,

$$\text{Bond Stress, } u = \frac{\text{Tensile force}}{\text{Total surface area of embedded splint}}$$

$$= \frac{f_s \times A_v}{\text{Perimeter} \times \text{Bond Length}}$$

Therefore,

$$\text{Bond Length, } l = \frac{f_s \times A_v}{\text{Perimeter} \times u} = \frac{7200 \times 0.18}{1.93 \times 47} = 14.28 \approx 15"$$

This means that each bamboo splint has to be embedded in atleast 15″ of mortar at

its free end.

18. Guidelines for building bamboo-reinforced masonry homes

The guidelines for building will be divided into five main categories:

1. Calculation of required bamboo poles.

2. Purchase, transportation and storage tips (from earlier research by others).

3. Splitting & sizing techniques (standards previously established).

4. Treatment for water-resistance and insect/fungi resistance.

5. Building guidelines for:

    (a) Foundation

    (b) Walls

    (c) Windows & doors

    (d) Roof – pitched & flat slab

6. Precautions & forewarnings.

1. Calculation of required bamboo poles

To begin the process of building a bamboo-reinforced brick/cement block house, some basic calculations are needed to estimate the number of poles to be purchased for the purpose. Calculations for the spacing between bamboo "splints" (part of a whole bamboo pole/"culm"), with the strength of masonry (brick and cement block) taken into consideration, yield the following results,

For a house of total floor area = 1000 sq. ft.

Reqd. effective length of shear wall in each direction		Min. required spacing betn. splints
Conc. Slab (L_c)	Pitched roof (L_p)	Conc. Slab/ Pitched roof
35'-0"	22'-4"	6"

Using the above, one can calculate the length of shear wall required for one's house by,

$$\left(\begin{array}{l}\text{Reqd. Length of}\\ \text{Shear Wall in}\\ \text{each direction}\end{array}\right) = \frac{\text{Own house area (sq.ft.)}}{1000} \times \left(L_c \text{ or } L_p\right)$$

The shear wall length maybe subdivided into smaller lengths to suit the elevation but should not be made smaller than 4'.
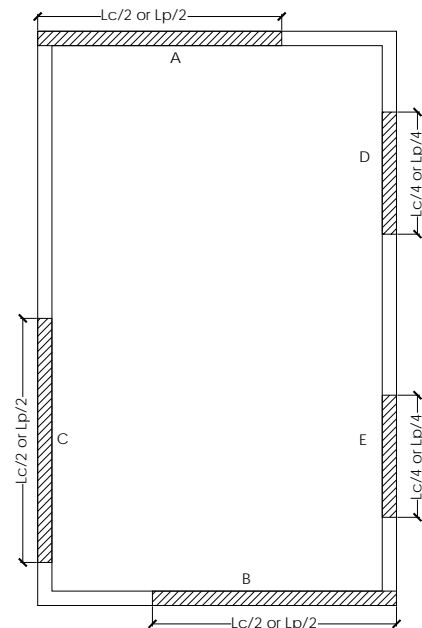

Fig 18.1 –Shear wall placement

Min. Shear wall in each direction = L_c or L_p

Wall **A** + **B** = L_c or L_p

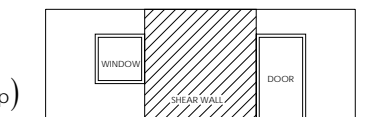Wall **C** + **D** + **E** = L_c or L_p

Fig 18.2 –Shear wall in elevation

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Upon calculating the length of TOTAL shear wall length required (A+B+C+D), an approximate number of splits required can

$$\begin{pmatrix} \text{Reqd. No.} \\ \text{of Splints} \\ \text{for walls} \end{pmatrix} = \frac{\text{TOTAL shear wall length} \times 12}{(\text{Reqd. spacing for splint})}$$

$$\begin{pmatrix} \text{Reqd. No.} \\ \text{of Splints} \\ \text{for walls} \end{pmatrix} = \frac{(A + B + C + D) \times 12}{6"} \ldots\ldots\ldots(1)$$

be determined as follows,

Note: The multiplication by 12 is to convert the wall length dimension from 'feet' to 'inches'.

Also horizontal splints should be provided @ 2' distance. Therefore for a 9' high wall, 4 horizontal splints will be required.

In case of foundation for the walls, at least **2** splints must be provided along the length of the concrete the footing. The total length of splints required for the foundation of a single-story house can be roughly estimated from the adjoining figure,

$$\begin{pmatrix} \text{Total Length of} \\ \text{splints for Foundn.} \end{pmatrix} = 2(X + Y) \ldots\ldots\ldots(2)$$
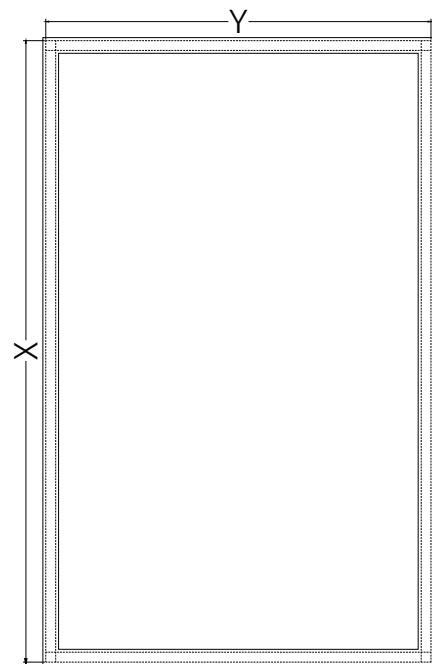

Fig 18.3 –Foundation rebars

The **Total** number of bamboo splints required (for the walls, foundation, floors and collar beams) may be provided with a contingency of 2% to arrive at the final figure for required number of splints.

Bamboo culms available in India are roughly of 3 different sizes – 3″, 4″, 8″ϕ.

The adjoining table gives the number of the number of splints of ¾″ width that each of the culms can yield:

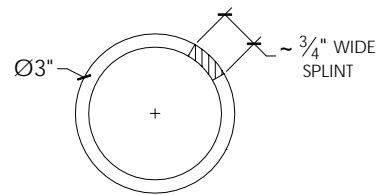| Common Species of Bamboo used in bldg.	ϕ of culm	No. of splints
Bambusa tulda & Dendrocalamus Stricta	3″	12
Bambusa Longispiculata	4″	16
Dendrocalamus brandisii	8″	33

Fig 18.4 –Full culm and splint

Upon deciding the species of bamboo to be used, the number of poles to be purchased can be determined by

$$\text{No. of poles} = \frac{\text{Total no. of splints reqd}}{\text{No. of splints for species selected}}$$

Based on this calculation, one can buy the number of poles required for the project.

2. Purchase, Transportation & Storage of bamboo poles

The following tips on purchase, transportation and storage of bamboo poles are taken from earlier investigations. Since these are tried and tested methods, they are enlisted here for the benefit of the homebuilder.

a. Purchase:

The common practice in the purchase of bamboo poles is to opt for culms of ages around 6 to 9 years. It is believed that the culm has achieved maximum maturity in that time. The most preferred way of curing the culms is air-seasoning and only such culms should be bought. Kiln-dried culms should be avoided as far as possible.

b. Transportation:

The culms are usually tied into bundles with rope or wire and may be transported in bullock/horse-drawn

carts. There is no need for any special precautions during the transportation.

c. Storage:

The poles are usually stored in a vertical position on a vertical platform atleast 30 cm above the ground. The storage area should be thoroughly checked and cleaned prior to storing. Protecting from rain and contact with soil can prevent decay of the poles. Good ventilation and frequent inspection are important.

3. <u>Splitting and sizing techniques for the bamboo poles</u>

Bamboo to be used for the purposes of reinforcement is most effective in the form of bamboo splints due to increased surface area for bonding. The common tools used for splitting and sizing bamboo poles are:
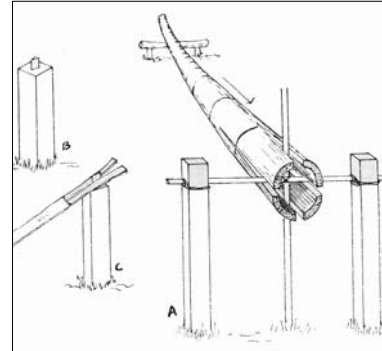

Fig 18.5 –Crossbar splitter

a. <u>Cross-bars</u>

In this technique, crossbars of iron/wood (about 1″ thick) are supported by posts set firmly in the ground. Some initial splits are opened into the edge of the culm with an axe. These are held apart by wedges and the culm is placed in position on the crossbars. The culm is then manually pushed/pulled to split it.
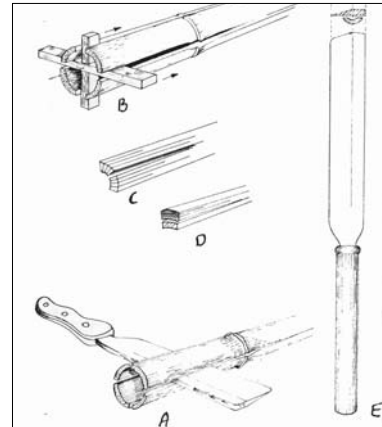

Fig 18.6 –Other tools for splitting

b. <u>Steel Wedges</u>

These are used for splitting quartered culms.

c. <u>Mechanical splitters</u>

Mechanical devices can also be used for splitting the culms. These are more expensive but also more precise.

Fig 18.7 –Mechanical splitter

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4. <u>Treatment for water-resistance and insect/fungi infection</u>

The recommended preservation technique for bamboo poles/splints used in construction is "hot-dipping" of air-dried culms. The cheapest and most-effective preservative is a mixture of coal tar creosote and fuel oil (50:50 by weight). 1% of dieldrin can be added to this mixture in termite-infested areas and 1% of pentachlorophenol can be added in areas of high decay.

In this process, splints are immersed in a tank of preservative, which is heated either directly over a fire or through steam coils. The tank can be easily made by and cutting the cylinders into half and welding them together along the length.

An alternative process is that "pressure treatment". This process is found suitable for dry culms. The same preservative as mentioned above may also be used for the pressure process.

There are certain other prescribed chemical preservatives like

- Copper-chrome-arsenic composition
- Acid-cupric-chromate composition
- Copper-chrome-boric composition
- Chromated Zonc chloride

These may also be used for treating the splints.

Apart from these the splints should also be treated for water-resistance. Asphalt or coal tar emulsion is considered the best option to provide adequate water-resistance to the splints. However an excess of asphalt might reduce the bonding between the splint and the mortar.

5. <u>Building guidelines</u>

This section is aimed at providing the homebuilder with basic information about using bamboo splints as reinforcement in masonry construction. It is divided into 4 parts:

a. <u>Foundation</u>

The foundation for a bearing masonry structure should be a continuous bed of at least 1:2:4 mix of concrete (cement: sand: aggregate). The width of the concrete bed required can be calculated as under:

- One story residence – (Wall thickness + 4")
- Two story residence – (Wall thickness x 2)

The depth of the footing from the top of soil/ground should be kept at a minimum of 2' to get adequate anchorage into the soil.

The minimum thickness of the concrete bed is given by

$$\text{Min.thickness} = \begin{bmatrix} \text{reqd. bond length for bamboo} \\ + 3" \text{ cover} \end{bmatrix}$$

$$= 15" + 3" = 18"$$

In case of inadequate thickness of the bed, additional reinforcing may have to be tied in at 90°.
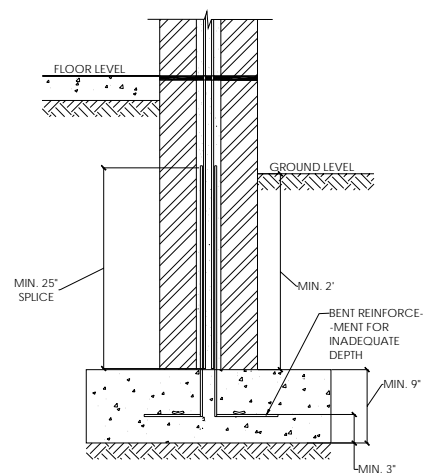

Fig 18.8 –Section thru' foundation

It is advisable to have atleast 2 splints in the longitudinal direction of the concrete bed as reinforcement. The splints should have a cover of atleast 3″. The dowel bars should have an overlap of atleast 25″ with the wall reinforcement splints.

b. <u>Wall:</u>

After pouring the concrete bed and curing it for the requisite period of time, one can start with construction of the wall.

For wall building, it is advisable to use a mortar mix of 1:6 (cement: sand). Appropriate grade of cement should be used to get desired strength of bonding. Wall construction may be of two main types- solid wall and cavity wall construction.

i) <u>Solid wall construction</u>

This is the most common wall type for the unreinforced type of masonry construction. It is, however, highly difficult to adapt this kind of wall construction for reinforced masonry because of the likelihood of high wastage of bricks.

ii) Cavity wall construction:

This is a more feasible option for reinforced masonry. The adjoining figure shows the "stretcher bond" which is the typical brick bond used for cavity wall construction, as there is minimal wastage of brick.
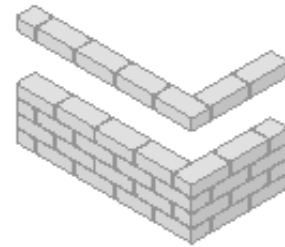

Fig 18.9 –Stretcher bond

During the construction of a cavity wall, care should be taken to ensure that the width of the cavity is **atleast 3″** to ensure proper embedding of bamboo splints in the mortar.
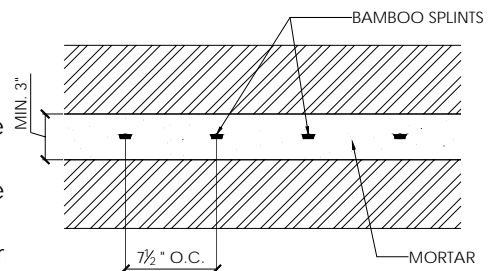

Fig 18.10 –Plan of cavity wall

According to calculations, the maximum spacing between the splints required to get the optimum performance out of the bamboo splints is **6″ on center** in both the horizontal and vertical direction. The adjoining isometric gives a good idea of the construction of a cavity wall and spacing of splints.
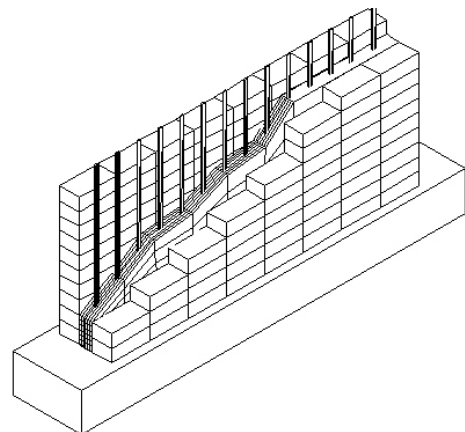

Fig 18.11 –Isometric view of cavity wall

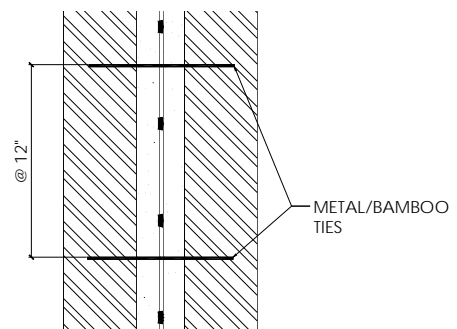The two sides of the cavity wall should also be connected to each other by using metal or bamboo ties.

Fig 18.12 –Section thru' the wall

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b. Windows and doors

During wall construction, certain special precautions are to be taken into consideration are required to be made about providing reinforcing around the window and door openings.

The UBC code requires that a reinforcing bar is provided on top of doors and windows have a bearing of atleast 24″ into the adjoining masonry. Vertical reinforcing bars must also be provided on either side of the openings.

c. Collar beam & roof

For better seismic safety of reinforced masonry structures, it is advisable to provide a collar beam of concrete at the top of the wall before the roof is constructed. The collar beam binds the entire masonry wall into a frame and makes it better resistant to seismic forces. It is advisable to use a 1:3:6 mix of concrete for the collar beam. The required depth of the collar beam can be calculated as under

$$\begin{bmatrix} \text{Reqd. depth} \\ \text{of collar beam} \end{bmatrix} = \text{Min. bond length of splint} + 1"$$
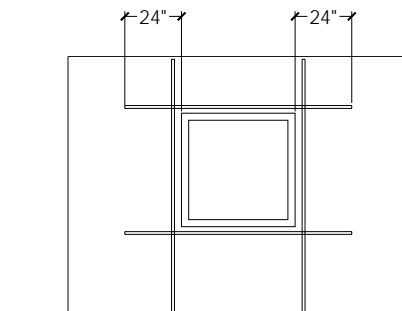
$$= 15" + 1" = 16"$$

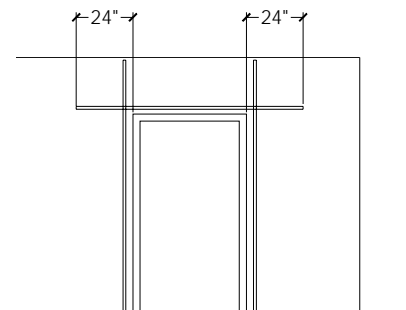**Fig 18.13 –Reinforcing around window**

Fig 18.14 –Reinforcing around door

The collar beam can be provided in two ways as is illustrated in the adjoining figures:

i) The first option tops the brick wall with a concrete collar. This option is easy to cast, but not very aesthetically appealing to the eye as an elevation feature.

ii) The second option involves casting the collar in the cavity of the wall. The process of casting this collar is more cumbersome but it is more aesthetically appealing.

Fig 18.15 –Collar beam above wall

The roof may be pitched roof with timber/bamboo purlins and tiles or concrete slab. Depending on the type of roof, the spacing of the reinforcement splints and length of shear wall required will change.

It is also advisable to use timber or bamboo trusses for supporting the pitched roof to provide additional stability.
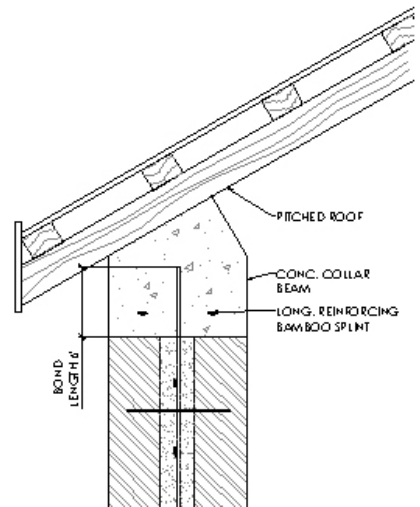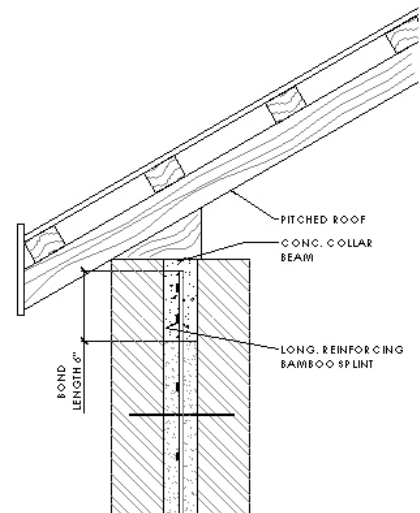
Fig 18.16 –Collar beam in cavity

Cost comparison

Assuming the current rates of steel rebars and bamboo splints, a comparison between the cost of using steel rebars v/s using bamboo splints yielded the following results fro a 1000 sq.ft of house.
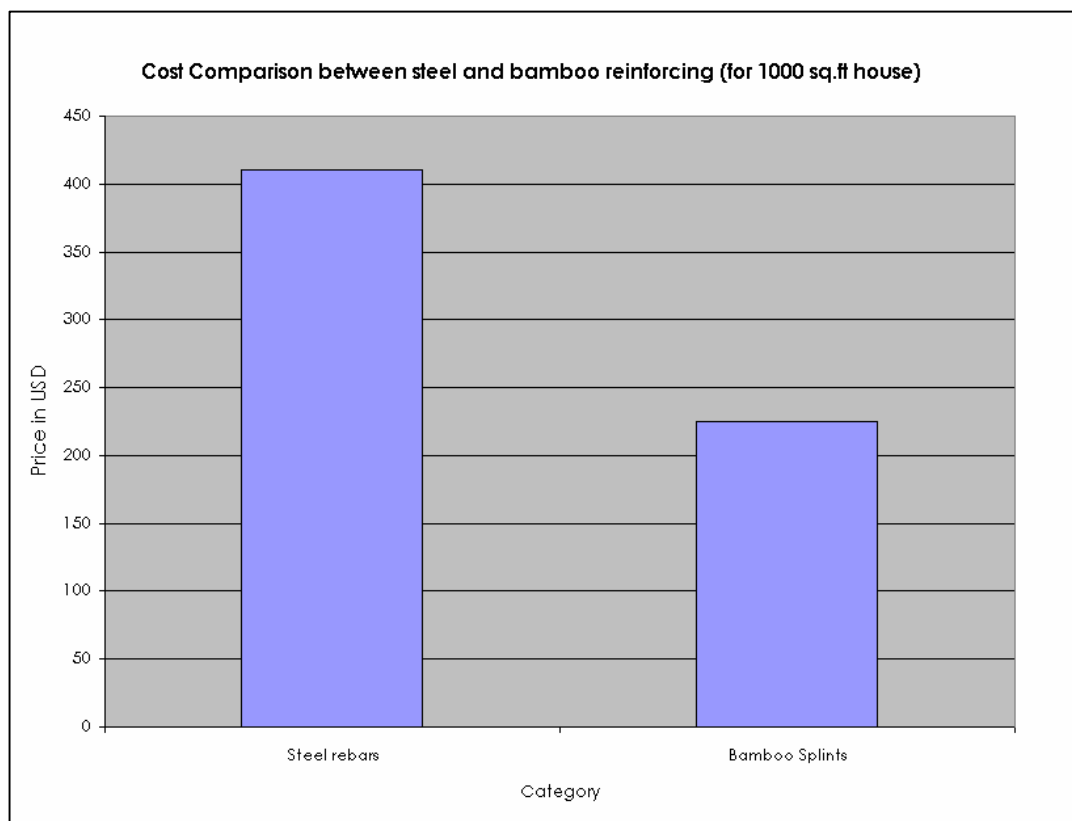

Fig 19.1: Graph comparing the cost of steel rebars v/s bamboo splints

The graph clearly highlights the cost advantage of using bamboo as reinforcing in bearing masonry. Though, bamboo might not be a good alternative for high-rise structures, for single or double story structures, commonly built by lower-income communities in India, it is a worthy alternative.

III Conclusions & Further Recommendations

The tests conducted for shear and bond stresses during this thesis show contrasting results. For better shear resistance, larger area of bamboo splint is preferred and for better bonding, lesser splint area is advisable. In order to strike a balance, a set of possible results has been provided for the benefit of the user. Depending on the available labor expertise, a suitable result can be chosen and used in the building.

This thesis concludes that it is possible to use bamboo splints as reinforcing for masonry structures. Thought the tensile strength of bamboo is about 1/3rd that of steel, this is sufficient for masonry structures and provides a more economical and environment-friendly alternative that is accessible to every section of the society. However, there is still ample scope for research on the subject.

Further research may be conducted to determine the following:

- Splicing length for bamboo splints.

- Factor of Safety to calculate allowable stresses of bamboo to be used in calculation.

- Adaptation of calculations and guidelines to the Indian Standard Code.

- Economical and mechanical splitting methods for bamboo culms.

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