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Evaluation of Engineered Bamboo Alternative Technologies for Low Rise Housing Construction in Northeast India

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Abstract:* (FAO, 2010) Food and Agriculture Organization reported that bamboo is an increasingly important economic asset in poverty eradication and economic and environmental development. Centuries of sustenance of bamboo structures developed by traditional Indian communities has proven bamboo to be a lightweight construction material ideal for withstanding seismic loads. With the new goals set to meet housing demand by the Government of India, the surplus availability of bamboo as a construction material and strengthening of the rules for seismic safe buildings, the development of accredited engineered bamboo construction systems may aid in mitigating the gap between housing demand and supply in the country.

Keywords: *Engineered bamboo, GluBam®, prefabrication, dwelling unit, seismic safety, durable joints*

1. INTRODUCTION

Under the Pradhan Mantri Awas Yojana formulated by the Ministry of Housing and Urban Affairs, the government of India aims to provide ‘housing for all’ by 2022. However, the growing effects of global warming induces an immense responsibility on the construction industry to reduce the energies associated with a building. These issues can be addressed through development of prefabricated modules using energy efficient vernacular materials and technologies.

Lying in the tropical and sub-tropical zone, Asia contributes to 65% of world bamboo resources covering an area of 24 million hectares (FAO, 2010). Bamboo reserve area in India sums up to 14 million hectare, out of which 5.6 million hectares lie in the north eastern belt of the country (ISRF, 2017). With rich resources in terms of material availability and traditional construction systems, bamboo exhibits a deep potential for development in the construction industry of north-eastern Himalayan range.

Despite its immense experience in traditional bamboo construction, the construction industry in India still falls back on conventional methods of construction due to shortage of expertise, poor availability of quality material and lack of right codes and standards of practice. (Bhowmick, 2017) “The full development of codes and standards is still necessary to utilize bamboo as a structural material internationally”.

Agencies such as National Mission for Bamboo Application, National Bamboo Mission, IPIRTI, BMPTC, TRADA, etc. have boosted the usage of bamboo in construction industry through the development of engineered bamboo technologies. The challenge now, is to develop prefabricated modules using the recent accredited bamboo technologies for the fast construction of high quality, durable low rise affordable housing in earthquake prone north eastern belt of India.

1.1. Bamboo as a Construction Material

Bamboo is an endogenous tree available in 91 genera and about 1200 species spread across the world. They are available in two groups – herbaceous and woody. Woody species are strong and can be used for construction. The diameters of these species vary from 50mm to 200mm, with a width of up to 25mm and generally mature in three to five years. Some of the common species of structural bamboo available worldwide are listed in *Table 1*.

The structure of a bamboo stem consists of two main parts – culm and nodes. While the culm forms the main body of the stem with an outer skin and an inner skin, the nodes act as diaphragm at almost equal distance preventing the stem from buckling. The body between two nodes is termed as the internodes, where the cellulose fibers and vascular bundles run parallel to the stem.

Table 1: Common Species of Structural Bamboo

Scientific Name	Areas Found	Diameter (in mm)
Guadua angustifolia Kunth	South America	120 - 160
Dendrocalamus strictus (Calcutta)	Asia	25 - 80
Bambusa vulgaris	Africa, Asia, South America	80 - 150
Phyllostachys edulis (Moso)	Asia	120 - 180
Dendrocalamus asper (Petung)	Asia, South America	80 - 200
Bambusa blumeana (Spiny/Thorny Bamboo)	Asia, Asia-Pacific	60 - 150
Gigantochloa apus	Asia	40 - 100

Bamboo exhibit very high structural properties parallel to the fiber, but is weak when loading is done perpendicular to the fiber. The hollow nature of bamboo may result in splitting of the fibers leading to failure of the structural system, specifically at the joints. High susceptibility to insect attack and poor fire resistance are among other drawbacks of the material. However, due to its low density and high strength to weight ratio, it demonstrates extremely good seismic performance in earthquake prone areas; and due to its high energy to cost ratio, it is considered as an alternative emerging technology for energy efficient construction.

1.2. Engineered Bamboo Technologies

Engineered bamboo products are formed by processing raw bamboo culm into laminate composite lumbers suitable for different forms of construction. The main process involves drawing of strips from the bamboo culm of a species suitable for construction (such as Guadua, Moso,etc.), treating and netting bamboo mats, gluing and hot pressing the strips to a suitable thickness and finally conditioning in controlled environment to produce treated bamboo composite lumbers.

Table 2: IS codes for engineered bamboo products

IS Code	Areas Found
IS 14588: 1994	Specification of Bamboo Mat Veneer Composite for General Purpose
IS 13958: 1999	Specification of Bamboo Mat Board for General Purpose
IS 15476: 2004	Specification of Bamboo Mat Corrugated Sheets
IS 15972: 2012	Specification for bamboo jute composite corrugated and semi-corrugated sheets

In India Building Materials and Technology Promotion Council (BMTPC) under the Ministry of Urban Development & Poverty Alleviation and the Indian Plywood Industries Research and Training Institute (IPIRTI) have developed engineered bamboo products for walls, floors, doors etc. both for structural and non-structural applications in housing and buildings construction. Specifications of these products are provided in IS codes enlisted in Table 2. These materials are however, used for cladding purpose with bamboo poles, timber studs of steel sections used as the load bearing members. ICBR has constructed several prefabricated engineered bamboo houses using this system in China.

1.3. Glued Laminated Bamboo

Structural properties exhibited by Glued Laminated Bamboo beams or Glubam® makes it an alternative to conventional load bearing systems. The process of manufacturing GluBam involves finger jointing laminated bamboo veneer sheet and cold pressing the section produce. The section is further strengthened by applying two layers of 0.22mm thick carbon fiber strips bonded by epoxy at the bottom. Tested and experimented in the Institute of Modern Bamboo, Timber and Composite Structures (IBTCS) at the Hunan University, this beam resulted in a carbon fiber reinforced polymer (CFRP) and laminated bamboo composite beam.

In his research, (Kariuki , 2014) Kariuki concludes that laminated bamboo beams are recommended to be used as structural beams or truss members; they have superior strength properties compared to timber. Bolts and Steel plates are recommended for connections.

Since GluBam is a comparatively recent technology, very few data is available related to the mechanical properties of the material. In their respective research, Correal (Correal & Lopez , 2008) and Xiao (Xiao , Shan , Yang, Li , & Chen , 2014) have published the mechanical properties of glued laminated bamboo girders. *Table 3* gives a comparison of the mechanical properties.

Table 3: Mechanical properties of GluBam

SN	Description	Location of testing	Ultimate compressive stress (MPa)	Density (kg/cum)
1	Glued laminated guadua	Columbia	5.4	800-900
2	GluBam	China	4.6	800-900

2. METHODOLOGY

Despite the strong merits of engineered bamboo composite lumbers, the demerits take a higher position due to shortage of expertise, poor availability of quality material and lack of right codes and standards of practice. Moving towards prefabrication will integrate all the engineered bamboo products available in the market. This cannot only help in meeting the demand for mass production, but also produce high quality, treated, weather resistant and durable bamboo products to the construction industry.

However essential it may seem to use the engineered bamboo products, the system may render a complete failure if it does not fulfil the space requirements of the users. The north eastern belt of India consists of eight states – Arunachal Pradesh, Assam, Manipur, Meghalaya, Mizoram, Nagaland, Sikkim and Tripura. These states have rich traditional lifestyles. The starting challenge thus, becomes the analysis of the dwelling units of the people living in traditional societies of the north eastern belt of India. After determining the spatial requirements of the dwelling unit, the best solutions for durable prefabricated units can be generated through detailed analysis of the available engineered bamboo products.

2.1. Dwelling units of traditional societies of North East India

Due to the harsh terrains and poor road networking, availability of contemporary construction materials become a problem in the remote towns and villages of the North eastern states. As a result, most of the traditional societies fall back on vernacular architecture reinforced by locally available materials and technology for the construction of their dwelling units. The use of these techniques make the dwelling units thermally comfortable and help the built form sustain in natural calamities such as inundation, landslides, earthquake, etc. **Error! Reference source not found.** highlights the variation in vernacular architecture of dwelling units in the different states of North east India.

Table 4: Prominent vernacular architecture of dwelling units in North East India

State	Dwelling Unit	Size of the unit	Common characteristic features					Architectural features	
			Stilt	Stone Plinth	Sloping roof	Entry verandah	Window openings	Structural	Non-structural
Arunachal Pradesh	Dafla House, Adi Galong House	Length: 12m-15m Width: 5m-6m	✓	×	✓	✓	×	*Column*: Bamboo posts *Floor*: Bamboo beams *Roof*: Bamboo truss, purlins	*Wall*: Twilled mats *Floor*: Flattened bamboo *Roof*: Cane leaves, thatch
	Stone and Timber house	Length: 12m-15m Width: 5m-6m	×	✓	✓	✓	×	*Column*: Bamboo posts *Foundation and Floor*: Stone *Roof*: Bamboo truss, purlins	*Wall*: Bamboo mats *Floor*: Flattened bamboo *Roof*: Flattened bamboo
Manipur	Loi house	Length: 10m-12m Width: 4m-5m	×	✓	✓	✓	×	*Column*: Bamboo posts *Foundation and Floor*: Stone *Roof*: Bamboo truss, purlins	*Wall*: Straw reinforced mud with cow dung mix mud plaster *Floor*: Mud plaster *Roof*: Thatch
Nagaland	Naga house	Length: 10m Width: 4m-5m	×	✓	✓	✓	2-5% of wall area	*Column*: Timber frame *Foundation and Floor*: Stone *Roof*: Bamboo truss with bracing, purlins	*Wall*: Bamboo mats *Floor*: Mud plaster with bamboo mat *Roof*: Thatch
Meghalaya	Garo house	Length: 12m-50m Width: 5m-6m	✓	×	✓	✓	×	*Column*: Timber/ Bamboo posts *Floor*: Timber/ Bamboo beams *Roof*: Bamboo truss, purlins	*Wall*: Flattened bamboo with mats *Floor*: Flattened bamboo *Roof*: Palm leaves, thatch
Assam	Boro and Karbi house	Length: 10m Width: 10m	✓	×	✓	✓	×	*Column*: Bamboo posts *Floor*: Bamboo beams *Roof*: Bamboo truss, purlins	*Wall*: Twilled mats *Floor*: Flattened bamboo *Roof*: Cane leaves, thatch
Mizoram	Lushai house	Length: 10m-12m Width: 4m-5m	✓	×	✓	✓	2-5% of wall area	*Column*: Bamboo posts *Floor*: Bamboo beams *Roof*: Bamboo truss, purlins	*Wall*: Bamboo mats *Floor*: Bamboo mats *Roof*: Thatch
Tripura	Riang house	Length: 10m-12m Width: 4m-5m	✓	×	✓	✓	×	*Column*: Bamboo posts *Floor*: Bamboo beams *Roof*: Bamboo truss, purlins	*Wall*: Bamboo mats *Floor*: Bamboo mats *Roof*: Thatch

State	Dwelling Unit	Size of the unit	Common characteristic features					Architectural features	
			Stilt	Stone Plinth	Sloping roof	Entry verandah	Window openings	Structural	Non-structural
Sikkim	Lepcha house	Length: 10m-12m Width: 10m-12m	✓	×	✓	✓	×	*Column*: Series of solid tree base *Floor*: Timber beams *Roof*: Timber truss, purlins	*Wall*: Woven split bamboo plastered with rammed earth mixed with cow dung and straw *Floor*: Timber planks *Roof*: Thatch

2.2. Evaluation of Engineered Bamboo Product

INBAR recognizes more than 28 varieties of Bamboo composite lumber products in the form of bamboo scrimber, bamboo laminated lumber, bamboo flooring, bamboo plywood, corrugated roof board, bamboo veneer, bamboo composite Table 5 enlists the different products of engineered bamboo that will be considered for the design of the prefabricated dwelling unit.

pipe, bamboo particle board and innovative bamboo composite pipes, etc. These products, used for non-structural interventions, are weather resistant, insect resistant and structurally more durable than raw bamboo materials.

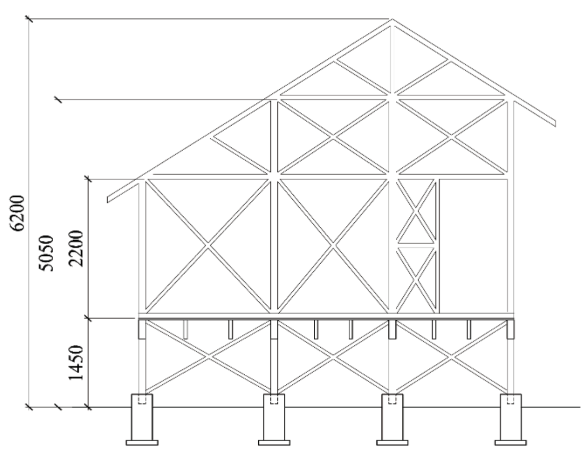
For structural interventions, GluBam, Glued laminated Guadua, Composite bamboo I-beam may be used.

Table 5: Major bamboo products available in market

SN	Product	Bamboo species	Available size (l x w x d)	Application
1	GluBam®	Moso	9600mm x 110mm x 600mm	• Beam • Truss
2	Glued laminated Guadua	Guadua	50mm x 50mm x 3000mm	• Column
3	Composite bamboo I-beam	Guadua	2440mm x 200mm x 300mm	• Column • Beam
4	Bamboo Scrimber	Any species	2440mm x 1220mm x 19mm thick	• Floor boards
5	Bamboo mat boards	Any species	2400mm x 1200 mm 2100mm/1800mm x 1200mm/ 900mm	• Walls panels • Floor board
6	Bamboo mat veneer composites	Any species	2440mm x 1220 mm 2140mm/1840mm x 1220mm/ 920mm	• Floor boards
7	Bamboo mat corrugated sheets	Any species	2440mm/ 2140mm/ 1800mm x 1050 mm	• Roofing sheet

2.3. Design and Fabrication

Error! Reference source not found. concludes that a basic dwelling unit typology of the north east India is a rectangular (12mx5m) or a square plan form (10mx10m), with height varying from 3m to 5m (Figure 1). The houses are built on stilts made of bamboo post or possess a high plinth with stone foundation to avoid damages during floods. Each house is marked by an entrance verandah and have openings not more than 10% of the wall area. Pitched roof is a characteristic feature for sustenance during peak monsoon season (Figure 2).



Bamboo or timber posts are the load bearing member of the structure, mounted bamboo or timber truss. Depending on the climate conditions, the walls are covered with bamboo mats in humid climate or straw reinforced rammed earth with mud plaster in cold regions. While the floor constitutes of layers of floor boards or mud plaster, the roof is covered with thatch and palm leave. Some new houses use materials such as processed timber or bamboo for frame and corrugated sheets for roofing.

Figure 1: Typical Dwelling Unit: Plan
Source: Author

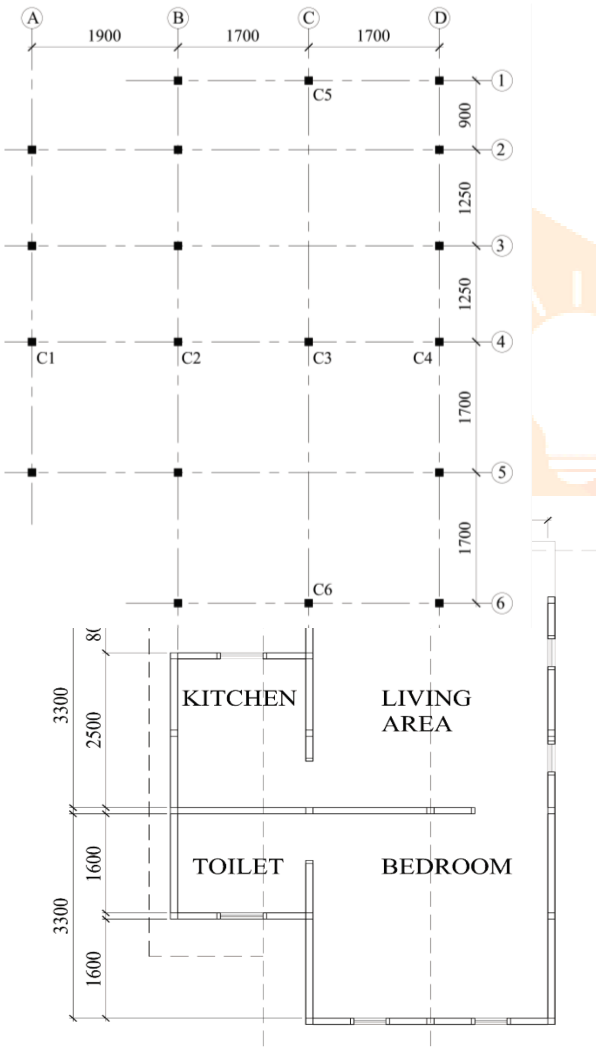


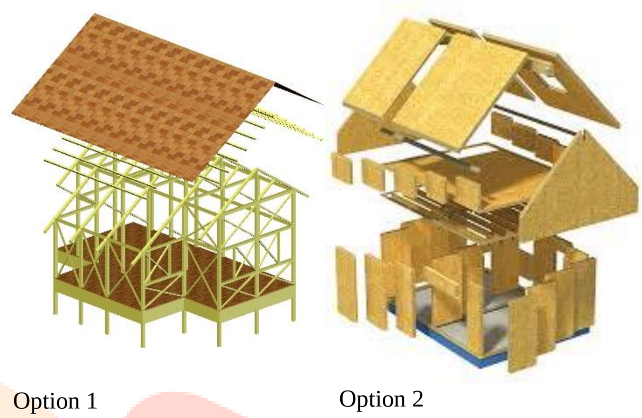
Figure 2: Typical Dwelling Unit: Plan
Source: Author

(Figure 3) Two fabrication techniques are analyzed for the generation of the prefabricated dwelling unit module.

1. In the first case, the GluBam shall be bolted to concrete foundations using stainless steel joints. All beams, bracing and truss shall be fixed using stainless steel jointing plates. Prefabricated wall, floor and roof shall then be fixed to the structural frame installed.

Figure 3: Comparison of fabrication techniques

2. In the second case, stone masonry foundation shall be made on site. Prefabricated modules of structurally insulated bamboo wall, floor and roof panels shall then be installed using stainless steel



connectors. SIPs consist of expanded polystyrene insulation compressed between OSB sheathing, providing both structural support and insulation (Hairstans, 2010). The popularity of SIPs is a result of their high thermal performance and air tightness and low embodied energy.

2.4. Structural stability

Falling under the Garo Khasi range and Purvachachal range, the eight states fall under Zone 5 of the India Seismic Zone. The developed module of the dwelling shall thus, be tested for structural stability in compliance with the Indian Standard codes for attaining seismic safe building design. For the design of this dwelling unit, column sizes of 150mm x 150mm are considered (Figure 4).

Figure 4: Plan
Source: Author

Dead load of roof DL_R = 2.60 kN/m^2
Dead load of ground floor DL_{GF} = 1.55 kN/m^2
Dead load of wall DL_W = 2.45 kN/m^2
Imposed occupancy load IL_O = 2.00 kN/m^2
Live load on roof IL_R = 0.69 kN/m^2
(considering reduction for sloped roof)

Figure 5: Frame along Grid 4
Source: Author

DL + LL, roof level $TL_R = (2.60+0.69)$
$= 3.29\ kN/m^2$

DL + LL, GF level $TL_{GF} = (1.55+ 2.45+2.00)$
$= 6.00\ kN/m^2$

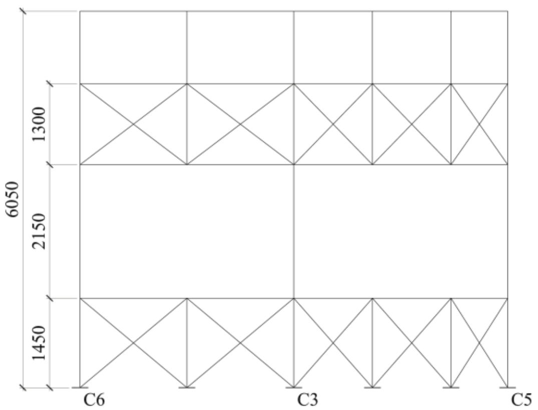


Figure 6: Frame along Grid C
Source: Author

For checking the structural stability, two frames which have maximum load, that is, frame along grid 4 and frame along grid C, are examined.

2.4.1.Column load calculations

Table 6: Load on column due to Dead load and Live Load

SN	Column description	Influence Area (m^2)	Load on column (kN) $F_{C1} = TL_R \times IA + TL_{GF} \times IA$
1	C1	1.40	13.00
2	C2	2.66	24.71
3	C3	5.78	53.69
4	C4	1.254	11.65
5	C5	2.125	19.74
6	C6	2.89	26.85

The load on each column is calculated by multiplying the total load of roof and total load of floor multiplied by the respective influence areas (*Table 6*).

2.4.2.Static Analysis

All frames are braced frames and all column beam joints act as hinged joints as they are bolted. Therefore, column members will have vertical force only.

Maximum column load (on C3), F = 53.69 kN
say 55 kN

(from *Table 3*) Compressive strength of GluBam
= 5.4MPa

Permissible compressive stress,

$$S_C = \frac{5.4}{FS} = \frac{5.4}{2} = 2.7\ N/mm^2$$

Area of cross section of column =

$$\frac{F}{S_C} = \frac{55 \times 1000}{2.7} = 20370\ mm^2$$

Provided area = 150 x 150 = 22500 mm^2

2.4.3.Seismic Analysis

As per IS 1893-1 (2002), design horizontal seismic coefficient for a structure,

$$A_h = \frac{Z \times I \times Sa}{2 \times R \times G}$$

For zone 5,
Zone factor, Z = 0.36
Importance factor, I = 1.0
Response reduction factor, R = 4.0
Avg. response acceleration coefficient, $\frac{Sa}{G} = 2.5$

Therefore, $A_h = 0.1125$

For seismic shear calculations, 50% of the wall panel load has been considered at roof level and 50% at the floor level. Live load on roof need not be considered for seismic analysis.

i. Frame along Grid 4 (Figure 5)

Total load on roof, W1 =
$(DL_R + 0.5xDL_w) \times (IA_{C1}+IA_{C2}+IA_{C3}+IA_{C4})$
= 42.43 kN = 43kN (say)

Total load on roof, W2 =
$(DL_{GF}+0.5xDL_w+IL_O) \times (IA_{C1}+IA_{C2}+IA_{C3}+IA_{C4})$
= 52.97 kN = 53kN (say)

Seismic base Shear, $V_{bx} = (W1+W2) \times A_h$
= 10.80 kN

As per clause 7.7.1 of IS 1893 (part 1):2002,
Design lateral force,

$$Q_i = V_{bx} \times \frac{W_i h_i^2}{\sum W_j h_j^2}, \quad h_R = 3.6m, \quad h_F = 1.45m$$

$\sum W_j h_j^2 = 43x3.6^2 + 53x1.45^2 = 668.71\ kNm^2$

Design lateral force at roof level =

$$Q_{Rx} = 10.80 \times \frac{43 \times 3.6^2}{669} = 8.99kN$$

Design lateral force at floor level =

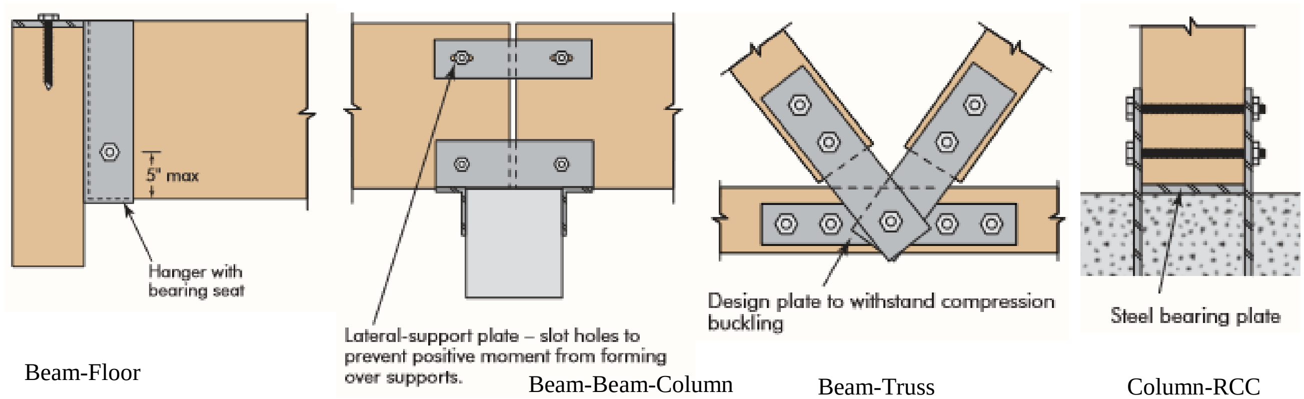
$$Q_{Fx} = 10.80 \times \frac{53 \times 1.45^2}{669} = 1.80kN$$

Moment at base, $M_{baseX} = (Q_{Rx} \times h_R)+(Q_{Fx} \times h_F)$
= 34.97 kN-m

ii. Frame along Grid C (Figure 6)

Total load on roof, W1 =
$(DL_R+0.5xDL_w) \times (IA_{C3}+IA_{C5}+IA_{C6})$
= 41.29 kN = 42 kN (say)

Total load on roof, W2 =



Beam-Floor   Beam-Beam-Column   Beam-Truss   Column-RCC

$(DL_{GF}+0.5xDL_{w}+IL_{O})$ x $(IA_{C3}+IA_{C5}+IA_{C6})$

= 51.55 kN = 52kN (say)

Seismic base Shear, V_{by} = 10.58 kN

$\sum W_j h_j^2 = 42x3.6^2 + 52x1.45^2 = 653.65\ kNm^2$

Design lateral force at roof level =

$$Q_{Ry} = 10.58 \times \frac{42 \times 3.6^2}{654} = 8.81kN$$

Design lateral force at floor level =

$$Q_{Fy} = 10.58 \times \frac{52 \times 1.45^2}{654} = 1.77kN$$

Moment at base, M_{baseY} = 34.28 kN-m

iii. Column load calculations for frame along Grid 4 (Figure 5)

$$\text{Center of gravity, XX} = \frac{A \times (L_{ab} + L_{ac} + L_{ad})}{4 \times A}$$

= 2.65m from C1

Moment of inertia about CG, MI =

$A \times [XX^2 + (XX-L_{ab})^2 + (L_{ac}-XX)^2 + (L_{ad}-XX)^2]$

Say MI = A x T

T = 15.51 m^2

$$\text{Section modulus, Z} = \frac{MI}{\text{Distance from CG}} = \frac{A \times T}{L}$$

(*Table 7*) Force on column,

$$F = \frac{A \times M_{base}}{Z} = \frac{M_{base} \times L}{T}$$

Table 7: Load on column due to Seismic shear

SN	Column description	Distance from CG, L (m)	F = $\frac{M_{base} \times L}{T}$ (kN)
1	C1	2.65	5.99
2	C2	0.75	1.70
3	C3	0.95	2.15
4	C4	2.65	5.99

Under seismic condition, maximum compression in column (for C3) = 55+2.15 = 57.15kN

$$\text{Stress on column} = \frac{58x1000}{150x150} = 2.58N/mm^2$$

< S_c (2.7N/mm^2)

iv. Column load calculations for frame along Grid C

$$\text{Center of gravity, YY} = \frac{A \times (L_{14} + L_{16})}{3 \times A}$$

= 3.40m from C5 ()

T = 23.12 m^2

Table 8: Load on column due to Seismic shear

SN	Column description	Distance from CG, L (m)	F = $\frac{M_{base} \times L}{T}$ (kN)
1	C3	0	0
2	C5	3.40	5.35
3	C6	3.40	5.35

Figure 7: Stainless Steel Connection Details
Source: (The Engineered Wood Association, 2007)

Under seismic condition, maximum compression in column (for C6) = 26.85+5.35 ()

= 32.2 kN

< 57.15kN

Therefore, GluBam column measuring 150mm x 150mm is safe.

2.5. Durability

Past experience exhibit that raw bamboo is susceptible to insect attack. It is for this reason that IS codes specify that all engineered bamboo products shall be treated with preservatives such as boron, sodium pentachlorophenate, etc. before final processing of the product.

Though engineered bamboo possess higher mechanical properties than raw bamboo, the under extreme stresses, the joints undergo tearing failure. Structural connections thus, become essential for the longevity of the joints. The durability of stainless steel joints have been proven through their use in many contemporary timber construction. Thus, all joints between in the frames, between horizontal and vertical studs, bracing, ties, truss and roof shall be bolted with stainless steel connectors. Figure 7 shows some joints that can be used for the construction.

3. CONCLUSION

Numerous engineered bamboo products are available in the construction industry today. Since most of these products have risen through recent experimentation, not all the materials are compliant with codes. In India, the IS codes provide specifications for the manufacture of bamboo mat boards, bamboo mat corrugated sheets and bamboo mat veneer composites. However, no codes are published on the specifications and design of GluBam structures.

Xiao, Shan and Li (Xiao , Shan , Yang, Li , & Chen , 2014) have experimented in detail the use of GluBam® for structural application in footbridges and low rise residential units in China. The viability of prefabricated engineered bamboo technology in low rise dwelling unit is established through this paper.

However, this research has hurdled the question of non-availability of GluBam in the construction industry of India. The paper is restricted due to the unavailability of data related to GluBam in Indian market. To develop the prefabricated module ready for construction in India, it is important to process and manufacture GluBam using bamboo species available in India. Proper test results generating the mechanical properties of this material not only help in the construction of low rise houses, but also help in the publishing of codes for compliance.

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