Research Article

Journal of Environmental Nanotechnology

A Comparative Study on the Seismic Performance of the Different Types of Bamboo Stilt Houses of North-East India

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Received: 18.03.2017 Accepted: 09.05.2017 Published: 30-06-2017
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ABSTRACT

The north-eastern part of India which includes the seven sister states and Sikkim is very prone to seismic activities. Over the years, a number of earthquakes have caused large disturbances to public life and property in this region. The population in this region mainly consists of indigenous tribes, who inhabit the forests and rural areas. Hence the predominant housing in this area is the traditional vernacular type. Although, there are numerous types of vernacular housing typical to each tribe inhabiting the region; they can be broadly classified into mainly four types: Kutchha houses, Assam/Ikra type houses, Bamboo houses on stilts and High pitched roof kutchha houses, characterized with some spatial variations. Keeping in mind the difficult conditions prevalent here, the traditional houses are built with features to combat the various natural calamities, without loss of life and property. This is evident from the past records of the earthquakes, where the traditional houses were least affected. Although qualitative records of the seismic resilience of these houses are available, the same have not been backed by quantitative studies. This paper seeks to address this gap, by quantitatively analysing the seismic performance. For this purpose, the Bamboo house typology on stilts built on a slope is selected and a comparative study is conducted on the different types of prevalent stilt systems to understand which one provides for the maximum seismic resistance. From the preliminary investigations, it has been found out that the cross bamboo stilts provides the maximum resistance, the details of which are presented in the paper.

Keywords: Bamboo; Stilt House; North-East India.

1. INTRODUCTION

The north eastern part of India includes the eight states of Sikkim, Assam, Arunachal Pradesh, Manipur, Mizoram, Tripura, Nagaland and Meghalaya, which is connected to the mainland through Siliguri corridor of West Bengal. The region can be divided into various regions according to the difference in geographic characteristics and climatic variations. Geographically, north-east India consists of hilly terrains interspersed with valleys, with altitude ranging up to 7000m. The region is subjected to many natural calamities periodically. It records the heaviest rainfall in the world as a result of which the Brahmaputra River floods every year. In addition to this, the region falls under Zone V of the seismic map of India according to IS1893:2002, and had been subjected to continuous seismic activities over the centuries.

Untouched by development, this region hardly houses any major city and the population here mainly consists of indigenous tribes, who live in forest dwellings and rural areas. These locales hence, have devised their own methods to protect themselves from the wrath of nature, where vernacular architecture plays a major part. The paper briefly describes the prevalent housing in the region in different bioclimatic zone, as gathered from literature. Henceforth, an attempt to quantify the structural soundness of one of the major prevalent architecture is made, which has been described in the following sections.

2. PREVALENT VERNACULAR ARCHITECTURE

Vernacular architecture in north-east India attributes its characteristics to a number of factors, namely the climate, terrain and population geography. Each of these factors contributes majorly in the spatial variations of vernacular architecture. The region can be divided into three major bioclimatic zones: warm and humid, cool and humid, cold and cloudy (Singh *et al.* 2007) as shown in Fig. 1. The details of each of each of these zones are tabulated in Table 1.

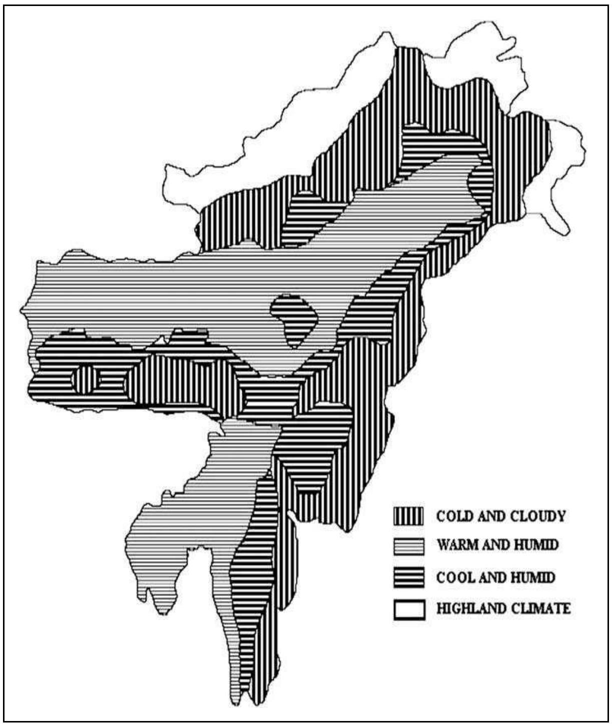


Fig 1: Bio climatic zones of North-east India.

A survey of the different vernacular architecture has been conducted in the three regions (Singh et al 2009). As it is evident, locally available materials like bamboo, cane, cane leaves, mud, lime, stone chips, rock slabs and wood are mostly used in the construction. In the warm and humid climatic zone residential houses are generally traditional wooden framed structures with mud blocks and baked bricks in rural areas.

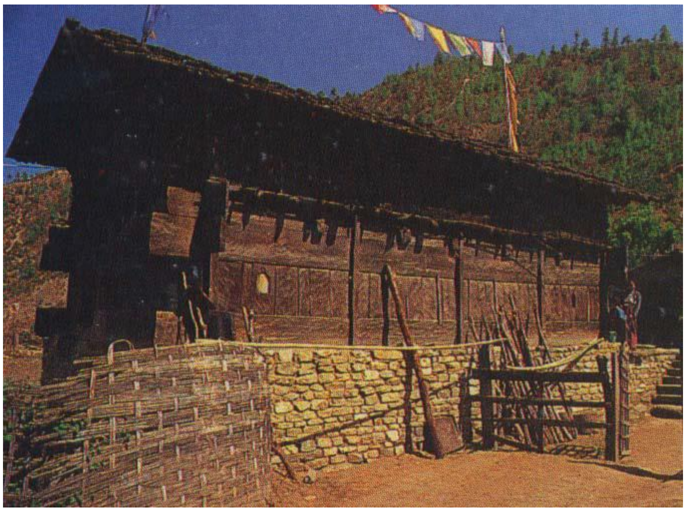
Bamboo is the main constituent material in the cool humid climate, where it is sandwiched between double layers of processed mud for walls, locally known as *Ikra* walling. Roofs are made of thatched grass and asbestos sheets. In the cold and cloudy climate, stone blocks are used in walls, with elevated wooden floors and roofs of cane leaves. All the residential units are built in a fashion, which not only makes the units energy efficient, but are also resistant to seismic and fluvial activities, wherever applicable. The vernacular architecture of the north-eastern region of India has been further enriched with the tribal architecture. The states are abode to numerous tribes, each characterized with a distinct dwelling. Some of these dwelling units, with typical characters have been tabulated below in Table 2.

Table 1. Specifications of reclassified bioclimatic zones of north-east India.

			Bioclimatic zones		
			Warm and Humid	**Cool and Humid**	**Cold and cloudy**
Temp (°C)	Summer	Max	30-35	25-30	20-25
		Min	22-27	20-24	14-19
	Winter	Max	25-30	20-25	15-20
		Min	10-15	10-15	5-10
Relative Humidity (%)			75-90	75-95	80-90
Rainfall (mm)			1700-2100	1500-2000	>2000
Sky Conditions			Generally clear sky but overcast during monsoon	Generally clear sky but heavy overcast during monsoon	Occasionally clear sky but overcast for the rest of the year
Wind directions			Low wind during summer and from NE, N, SE directions	High wind during summer and from E, SW, W directions	Medium wind from NE, SW and W direction
Vegetation			Heavy	Heavy	Heavy

Table 2. Prominent vernacular architecture of tribes of North-east India.

State	Tribe	Dwelling Unit	Characteristics
Arunachal Pradesh	Nyishi	Dafla house	• The traditional Dafla house is a long hall erected on poles. (3) • The width is usually 18 to 20 feet ; the length varies depending upon the number of hearths • The walls are made of twilled mats, and the floor of flattened bamboo. • The thatches used are dried plantain, cane leaves and millet or paddy straw, or the thatching grasses. • Lifespan of over three years. • Flexible and lightweight, resistant to earthquakes 
	Apatanis & Adis	Wooden stilt house /Adi Gallong Houses	• Apatanis live in simple bamboo huts perched on top of vertical wooden stilts forming dense settlements called *Bastis* [4] • Apatani Houses are built of cane, bamboo, wood, leaves etc with no use of metal in the construction. • Wooden stilts and wooden floors are distinctive features. [5] • The Adi tribae generally build their homes on sloping land so that floods can be avoided; also provides protection against landslides.  Source: http://www.global-gallivanting.com/meeting-the-apatani-tribe-of-ziro-valley/

	Monpa & Sherdukpen	Stone and Timber Houses	• High Altitude houses found in West Kameng and Tawang. • Basement made of stone masonary and main structure is wooden with bamboo matting.[6]  Source: A+D magazine, Oct 95 [24]
Manipur	**Meitei & Loi**	Meitei Yumjao / Loi House	• A "Meitei Yumjao" is built with locally available material like bamboo of different strength and size, cane, mud, straw and thatch • Locally developed technique and style used for fixing and joining various parts of the structure [7]. • The "Meitei *Yumjao*" has two types by its mode of wall construction: ---(1)Complete straw reinforced mud thick wall up to the roof height embedding the main load bearing post bamboos with *Pungjei* in different heights as reinforcement. ---(2) Thick straw reinforced mud half wall up to a height of 4 to 5 feet and above that with split bamboo (*Wachet*) with uniformly distributed and binded *Shinghoot* by bamboo strips (*chepsi Paya*) and straw reinforced and cow dung mix mud plastering in different coats. • Thick mud wall gives required thermal insulation for a comfortable living space. • The Loi House is similar to Meiti House except for the direction of the entrance, which faces south, whereas the Meitei house faces east. [8]

			 Source: [7]
	Mao	Onymosoch, Ochiyaho, kosomychi and Uripi koyhiinmchi	• A common house or dormitory is common in most of tribal societies of North Eastern India. These dormitories have different names. [3] • The Kabuis call it *khangchang* or *khangchu*, the Tangkhuls *yellong* or *yaranlong*, the Marams *rangki*, the Maos *khrechiyeku* or *ekhrochi*, the Thangals *khalang* etc. • In Senapati, Tamenglong and Ukhrul districts tribes do not construct a mud foundation or a raised platform for a house. They use piling method for construction of a house. • The pillars of the pile system are made of varieties of wood and bamboo. The walls are made of plaited bamboo. • They have a veranda of various sizes. • Roofs of most of the houses are made of thatch. Roof skeleton is made of bamboo sticks or rods and are tied with bamboo strips or creepers. • Pattern of the roof is like an inverted "V". The rear portion of the roof has a low inclined angle. Most of the gable ends reach an approximation of the floor. • In some places the pillars and walls are also made of wood. The wall planks are made of one solid timber hewed with axe. Planks are tied to the wall with strong creepers or vines.
	Tangkhul	Khunchon, Kharuk And Sheikhui	
	Kabui / Rongmei	Pumchan kai, Lakpui kai, Sianlongpui kai, Hoi kai, Thingpu kai, uche kai, and Khong kai	
Nagaland	16 major tribes, namely, Ao, Angami, Chang, Konyak, Lotha, Sumi, Chakhesang, Khiamniungam, Kachari, Phom, Rengma,Sangtam, Yimchungrü, Kuki, Zeliang and Pochury along with a	Traditional Naga House [9]	• These buildings are typically found in flat, sloped and hilly terrain. • Buildings are rectangular in shape; a few tribes build in circular shapes as well. • This housing type has very limited openings. A typical house has about 2-5% openings in the surface area of its walls. • The vertical load-resisting system is timber frame providing a continuous load path. • Load is transferred through wooden/bamboo beams and columns/ posts embedded into the ground. • Long wooden pieces / bamboo are used as beams and compression members. They are tied well with the help of bamboo rope/cane. • Each side the roofs almost touch the ground, to secure the roof from the stormy winds. [3]

	number of sub-tribes.		• The lateral load-resisting system is timber frame, Roof truss/bracing. • Lateral forces are resisted by cantilever action of the embedded posts and the bracing effect of diagonal bracing members where they are provided. • The typical plan dimensions of these buildings are: length 10 - 15 meters, widths 4 - 5 meters. The building is 1 storey high. • There is no suspended flooring. Ground floor is simple earthen floor with mud plaster in some cases. At times the floor of the house is raised slightly. This safeguard against flooding and dampness during the rainy season. • Bamboo matting is used to cover the mud floors. • Bamboo posts are inserted for foundation action into the ground upto a depth of 1 meter. • Different Naga tribes have developed this projecting profile of roofs in their own ways. Some project just the ridge piece while others create a stepped profile along the gable end, up to the free end of the projecting ridge beam [10].  Source: [24]
		Morung	• Morungs were community structures for youths present in almost every village of different tribes in Nagaland except for Angami tribes [11][12].

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Source: http://uratours.blogspot.in/</td>
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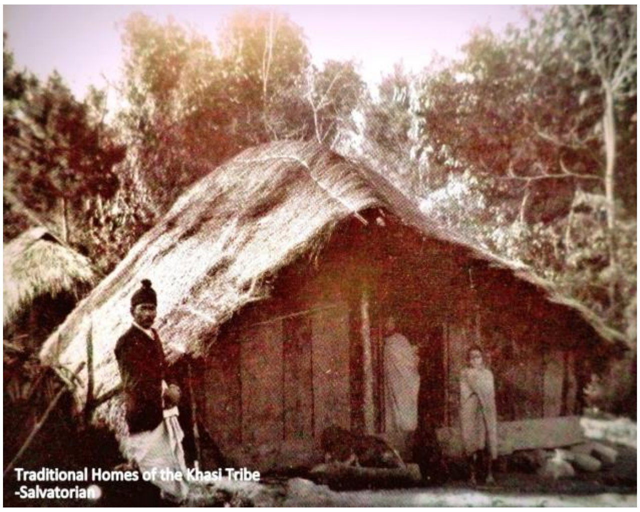
<tr>
<td rowspan="2">Meghalaya</td>
<td>Khasi & Jaintia/ Pnar</td>
<td>Thatched raised cottages with stone/mud walls</td>
<td>

- It is raised on a plinth some two to three feet from the ground and is built on post and beam principle.
- The beams are so low that it is impossible for a person of ordinary stature to stand erect within.
- The roof is independent of the exterior walls and rests on additional beams and stone columns.
- In the event of an earthquake the roof may remain intact even if the exterior walls collapse owing to this.[13]
- The Khasi houses are oval shaped, and is divided into three rooms, a porch a centre room, and a retiring room.[3]
- Nails not used and tongue and groove system used which allows dissipation of earthquake forces.[14]
- The Pnar house roofs are made of palm leaves [15]



Source: [15]
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<td>Garo</td>
<td>Garo long house/ Nokmong</td>
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- Traditional Garo houses are earthquake resistant. They build their house on horizontal wooden beams upon which the posts are raised.[3]
- The houses in average are about 80 feet in length.
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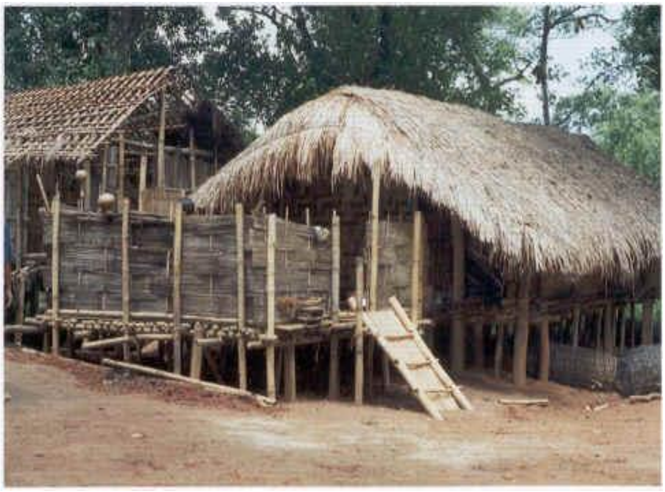
			• More than half of the house is open from end to end forming one long apartment for general use in which are the earthen hearths for cooking. • The house of the Garo chief is a large structure about 260 feet in length and 40 feet in breath, raised on piles varying in height according to the inequalities of the ground, and supported by substantial posts of timbers placed with the broad ends uppermost as more convenient to support the beams.  Source: http://guyshachar.com/en/2016/garo-hills-traditional-tribal-architecture-meghalaya-india/
Assam	Tiwas, Boro, Mishing, Karbi	Kutchcha bamboo stilt houses	• They construct their houses on plinths. [3] • Thatch is used for roofing. • Generally bamboo posts are used in their houses but the well-to-do sections use wooden posts. • Walls are made of reeds and bamboo and mud plaster. [16]  Source:[16]

<table>
<tr><td>Mizoram</td><td>Lushai</td><td>Sttilted bamboo/ wooden houses on slopes</td><td>• Most of the houses are built on the slopes and are supported by wooden posts of varied lengths, so that the house is horizontal with the level of the road.[17]
• Cross beams are tied against these posts and over the beams long solid bamboos are laid.
• Bamboo matting forms the floor and walls of the house.
• The roof consists of solid as well as split bamboo frames covered with thick thatch and some other kind of leaves.
• Cane is generally used for keeping the joints together and in some cases, iron nails are also used.
• It may be noted that in some cases the floor, doors and windows are made of wooden planks, while in others split bamboos are used instead.
• In case where the floor of the house is much above the ground, a ladder made entirely of a piece of log is placed across the intervening space between the floor of the house and the ground.

Source:http://www.mizostory.org/mizopix/mizpixpages/Mizo_House.html</td></tr>
<tr><td rowspan="2">Trip ura</td><td>Halam</td><td>Tong Ghar</td><td rowspan="2">• Similar in nature, these houses are built with bamboo and Chan grass as the primary materials for construction. [18]
• These houses are typical hill dwellings, constructed on bamboo slits to create a large horizontal platform, the floor of the house.
• Bamboo posts are arranged on a square grid and inclined whole bamboo members strengthen these.
• A required number of posts extend above the surface of the floor platform to support the roof structure.[19]</td></tr>
<tr><td>Riang</td><td>Riang House</td></tr>
</table>

			 Source:[26]
Sikkim	Lepchas	Kaa Den-Mo-Lee/ Raised bamboo-stone-mud house on timber and stone foundation	• The main structure of the Lepcha house is made completely of wood. • The house is constructed square in shape and the size cannot be tampered with addition or subtraction of rooms after the completion. • The base of the house has a huge centre pillar made of one solid tree. • Accordingly eight additional centre pillars are placed surrounding it in three rows with equal spacing in between; these nine pillars are each made from the entire tree length. • There are other additional supporting pillars. • The front part of the house rests on alleviated land. • All of the pillars are placed on top of a round stone. This elevated pillar structure prevents the house from sliding when hit by natural calamities such as floods or landslides, as the flood soil passes away through the open spaces in between the huge pillars without damaging the house. • Notches are made on all four sides of these nine huge tree size pillars and long cross beams are inserted through these notches, thereby holding the pillars together and preventing them from falling down; wooden pegs or wooden wedges are nailed in the notches. • The flooring planks, beams, joist beams, cross beams, rafters, battens used in the house are all very thick and roughly smoothed and dressed with axe and knife. • In between the wooden pillars and the joist beams a frame work of split bamboos is woven; this frame work is plastered with rammed earth well mixed with cow dung and straw. • The roof is round and slanting in shape so that rain, snow and hailstones may slide off easily. Further the thatched grass reeds absorb the direct heat from the sun.[20]

			 Source:[20]
	Bhutia, Limbu, Sherpa	Raised house on timber and stone foundation	• A house made of mud or bamboo with a straw roof.[21] • Similar to the lepcha houses.[22]  Source : http://sikkimarchives.gov.in/bhutia-house/#prettyPhoto[pp_gal]/0/

Apart from the tribal housing, vernacular architecture also consists of non-engineered structures in the rural areas which have evolved with assimilated colonial characteristics. Villages have a variety of typologies which includes kutchcha to semi-pakka houses. Of these Kutchcha mud houses with thatched or corrugated roofing are widely prevalent. The houses are typically of length 5-10 metres, with widths 3-5 metres and floor height 1.6-2.5 metres. They are generally one to two storeys high [23].Another typical housing found in rural Assam is the Assam-type housing, which combines both traditional and colonial wisdom in the construction process. These houses have performed well during earthquakes owing to lightweight construction materials, sound framing and flexible joints. Built on an elevated plinth to keep out flood water, these single storey houses are C or L shaped with a long veranda running peripherally. The posts and roof truss is wooden with GI sheet covering the sloping roof. The walling is made traditionally with bamboo or reeds sandwiched between two mud layers, locally known as *Ikra* walling [24]. This type of walling has proved very efficient in resisting earthquakes. Bamboo-mud houses are also commonly found in the villages of Assam, Mizoram and Tripura. In some instances, the bamboo houses are built on stilts on hill slopes, similar to tribal houses, and in other cases they are built on elevated brick or RCC columns, where timber logs are used as beams and full bamboo culms as secondary members. The second types of structures are constructed by more affluent families, for storage of grains [25]. Single storey sloping roof house with tin walling, with or without raised brick plinth is another common typology found in the villages of Tripura [26]. As there is no clear demarcation between the rural and tribal demographics, modified tribal houses are also found to be strewn across the villages of North-east India, thus showcasing the true spirit of the potpourri culture of this region.

Taking into account the numerous types of houses present in North-east India, they can be broadly classified into four categories: Kutchha houses, Assam/Ikra type houses, Bamboo houses on stilts and High pitched roof kutchha houses with regional modifications. Of these, it can be envisaged that the Bamboo house on stilts or *Chang* house is the most widely used typology, found all though the plains, mountain slopes and river banks [25]. As noted from the records, these houses have performed remarkably in the past earthquakes, but few scientific studies have been conducted in order to quantify their performance. In the following sections, preliminary analysis of the same is presented.

Fig. 2: Kutchha House [24].

Fig. 3: Assam type house [29].

Fig. 4: Bamboo house on stilts [24].

Fig. 5: High pitched roof Kutchha House [24].

3. DESCRIPTION OF THE MODEL

Out of all the three regions in which *Chang* houses are found, the ones built on hill slopes are most vulnerable to seismic forces. Hence such a bamboo house with unequal stilts built on a slope has been chosen for the study. It has been considered that the entire house is made of bamboo, including the stilts, beams, roof truss, bamboo matted floors and walls. After surveying the typologies present all over the region, it has been found out that there are majorly five types of stilt systems prevalent in these houses, namely: (1) Simple vertical stilts (2) Cross bracing stilts (3) Diagonal stilts – I (4) Diagonal stilts – II (5) Branched stilts.

Simple models of the bamboo house with the above mentioned stilt systems have been built in the structural analysis software SAP2000. The house has dimensions 3.0 metres X 3.0 metres X 3.0 metres, with double sloping roof on either side. The house is assumed to be built on a slope of about 33.69°. There are six main stilts, three on each side, of sizes 1.5 m, 1.0 m and 0.5 m. The structure has been kept symmetrical in order to make the results independent of shape. Each of the five systems has been illustrated below:

4. MATERIAL & SECTION PROPERTIES

According to NBC 2005, Part 6, more than a 100 species of bamboo are native to India, out of which physical and mechanical properties are tested of 20 species in green and dry conditions [27]. For the purpose of our study, *Bambusa tulda* species is selected, which is widely distributed all through north-east India [28] and used for building structures [27]. According to Table 1, Part 6 NBC 2005, it has a density of 722 kg/m^3 in air dry conditions. For structural designing, modulus of elasticity (E) is given as 1.77 X10^3 N/mm^2, extreme bending stress as 12.8 N/mm^2 and allowable compressive stress as 11.6 N/mm^2, as per Table 2, Part 6, NBC 2005. As the structure is subjected to seismic load, which is a short term load in most cases, the permissible limits of stresses are multiplied with a factor of 1.5 as per Clause 5.4, Part 6. For defining the material in SAP2000, these properties are used, along with Poisson's ratio of 0.3 [29].

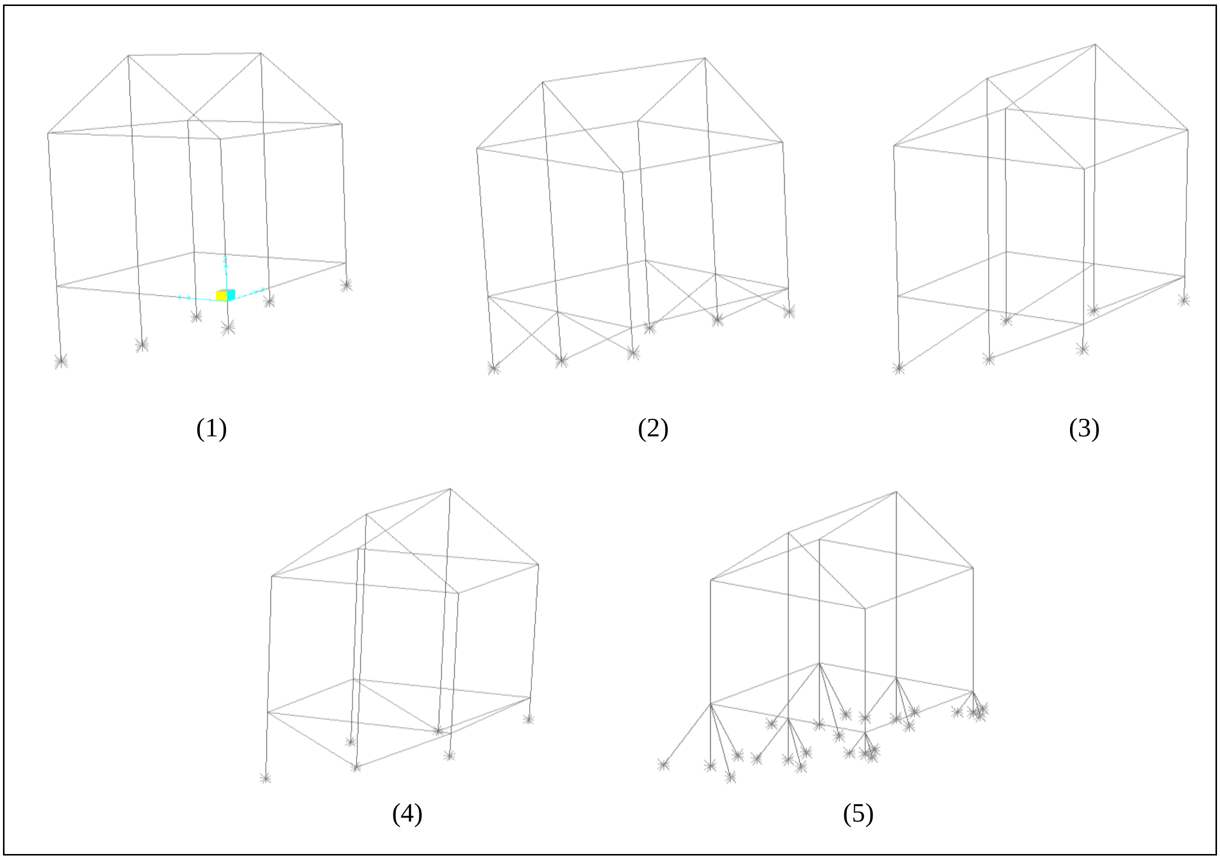


Fig. 6: Different types of stilt systems.

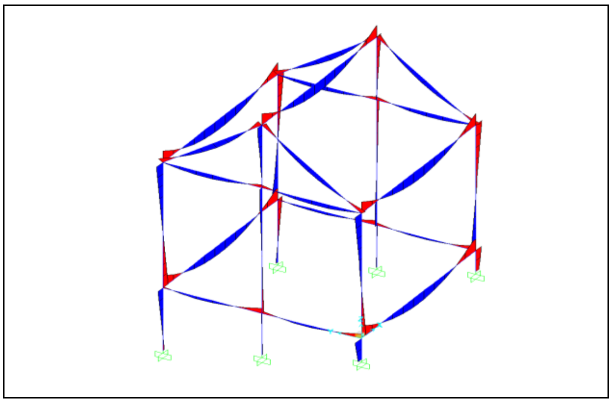


Fig. 7: Nature of BMD under Dead load.

According to the provisions of Clauses 4.4.2 and 4.4.5 in Part 6, NBC 2005, the bamboo is assumed to be under Grade I with outer diameter 60 mm and thickness of 8 mm , as prescribed for structural load bearing members.

5. MODELLING DETAILS

The bamboo house is modelled using frame element as defined in SAP2000, with requisite material properties. As mentioned before, it is assumed that the entire structure is made of bamboo, where walls and floors consist of bamboo mats, which are non-load bearing members. Hence only the beams, columns and stilts are modelled which represent the load bearing members of the house. The support conditions are assumed to be fixed on all sides except in the direction of application of the seismic load in the case of comparison of the displacement of each system. However, for comparison of maximum forces generated in each of the types, the support conditions are taken to be fixed in all directions. A mesh size of .3m is taken for the frame elements after convergence test.

The structure is subjected to self-weight and earthquake load. The earthquake is applied in the direction of the slope, as this is more critical case than when earthquake is applied transverse to the slope. A simple modal analysis is also defined, in order to find the undamped dominant modes. For application of seismic load, static analysis is used by defining QUAKE loads according to the parameters defined in IS 1893:2002 [30]. The North-east of India lies under Zone V of the seismic map and the parameters are defined accordingly from the inbuilt provisions of SAP2000. Constant damping of 5% is applied over all the modes and analyses are run.

6. VALIDATION OF THE MODEL

According to the material and section properties, the total weight of the Type 1 model comes out to be .5784 KN. This value should be equal to the sum of the reactions at the base nodes if the modelling is done without error. It is seen that the sum of the base reactions is .58 KN, which is almost equal to the weight calculated manually. Hence the model is validated. Secondly, the nature of the bending moment diagram due to dead load and earthquake load is checked, and it has been seen that the nature tallies for all the models. Hence the values can be safely taken for further interpretation. The following figures show the nature of the bending moment diagrams.

7. INTERPRETATION OF RESULTS

A comparative study of the displacement of each type of system under earthquake load is done and the relative results are presented in Table 3.

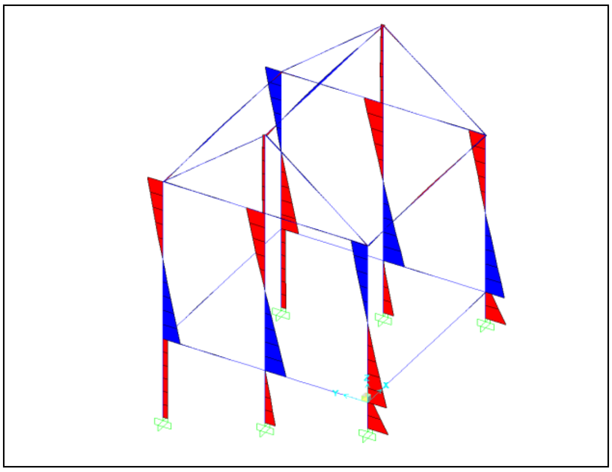


Fig. 8: Nature of BMD under Seismic load.

Table 3. Relative displacement of stilt systems.

Type	T-1	T-2	T-3	T-4	T- 5
Relative displacement (%)	100	40.7	84.4	71.4	88.9
RANK	5	1	3	2	4

From the results it can be seen that the cross bracing system has the least displacement under earthquake whereas the branched system has the maximum, when the house ids built on sloping ground. According to the material taken, the maximum bending stress has been defined as 12.8 N/mm^2. The section is idealized to be an annular section, with outer diameter 60 mm and width of 8 mm. Hence, the maximum bending moment which can be resisted by the section is given by the simple formula:

$$\sigma = \frac{My}{I}$$

where,

σ = maximum bending stress = 12.8 N/mm^2
y = distance of the extreme fibre from the centroid = 30 mm
I = moment of inertia of the section $= \frac{\pi}{64}\,(d_o^4 - d_i^4) =$ 452370.2857 mm^4
d_o = outer diameter of the section = 60 mm
d_i = inner diameter of the section = 44 mm

Using this equation the maximum bending moment is found out to be .193 KN-m.

The major and minor bending moment values, which are obtained from the analyses of the stilt systems in SAP2000, is compared with this threshold value to assess, which of the members fail. It is found that each of the systems do not cross the threshold value in any of its members. However, a comparison is drawn between the systems, on the basis of maximum moment arising in each. The results are tabulated in Table 4.

Table 4. Maximum moment of stilt systems.

Type	Maximum absolute moment (KN-m)	Rank
T- 1	.0094	4
T- 2	.0089	2
T- 3	.0091	3
T- 4	.0088	1
T- 5	.0089	2

As seen from the two tables, Type 2 and Type 4 performs best under the given earthquake load. Considering the variations of results between these two types, we can safely assume that Type 2 i.e. the cross bracing stilt system is most efficient in resisting earthquake forces.

8. CONCLUSION

A lot of simplifications have been done in this study. The model considered is only representative in nature and the earthquake load has been applied as a static load case. Although the results give an insight into the behaviour of the stilt houses, still a lot of fine-tuning is desirable. The model should be built based on an actual case study. As noted from literature, such houses may sometimes have asymmetric shape (e.g. Garo Long house, whose length is significantly more than its breadth) and this factor may play an important role in defining the behaviour of the stilts. Moreover, the seismic load should be applied as a dynamic load, in order to capture the true behaviour of the systems. Hence, future studies are needed incorporating these shortcomings. Nonetheless, the paper is a small step in tapping the huge scope of studies involving quantitative assessment of the vernacular construction techniques, to understand the knowledge of our forefathers and apply them to present scenario for cost-effective and efficient housing systems.

FUNDING

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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