Seismic performance of Bamboo housing– an overview

Jagadish Vengala[1], B. N. Mohanthy[2] and S. Raghunath[3]
[1,] scientist, , [2] Director, [3] Professor
[1,2] Indian Plywood Industries Research and Training Institute (IPIRTI), PB NO 2273, Tumkur road, yeshwanthpur, Bangalore – 560 022 INIDIA, www.ipirti.gov.in, email: contactus@ipirti.gov.in
[3] Professor, Dept. of Civil Engineering, BMS College of Engineering(BMSCE), Bull Temple Road, Bangalore,INIDIA.

ABSTRACT

In India and probably in many bamboo-rich countries, bamboo continues to be used in traditional and rural areas as a cost-effective housing material; Being a naturally grown material, bamboo elements would be an ideal material for vernacular houses in the regions where they are available. Research carried out also has shown that bamboo is an earthquake resistant structural member. This paper presents a summary of the performance of a variety of housing systems where bamboo is used as a predominant structural member and bamboo frame as a predominant structural system, during earthquakes. Ikra type of construction, Bahareque construction in comparison with adobe and Dhajji Dewari constructions were majorly discussed. Since India has large areas falling in the zones of high seismicity, bamboo can play a vital role in appropriate housing and construction owing to its suitability and availability. It is in this context that the bamboo housing technology developed at IPIRTI in collaboration with Timber Research and Development Association (TRADA), U.K. which demonstrated the engineering application of bamboo in housing. In this paper, a shock table facility to evaluate the seismic performance of bamboo based construction, especially the typical IPIRTI-TRADA house has been discussed. The shock table has been designed and fabricated to suit bamboo based housing systems. The IPIRTI-TRADA bamboo house of 2.44m x 2.44m was tested by mounting it on the shock table. It resisted the shocks and showed no signs of any damage/collapse, in contrast to a masonry / concrete structure. The model has resisted major to moderate levels of dynamic forces with minimal damage levels.

Introduction

In India and probably in many bamboo-rich countries, bamboo continues to be used in traditional and rural areas as a cost-effective housing material; however, bamboo does not enjoy official recognition and patronage of contemporary engineers as it is with brick, steel, concrete or timber. There may be several reasons for this situation such as - low durability of bamboo, lack of technical know-how or facilities for preservative treatment, lack of authentic design data on various species, lack of information on design and reliability of jointing techniques and detailing. These factors might have led to resistance in using bamboo in their projects.

Another major reason for not including bamboo in construction projects appears to be due to the difficulty in procuring the right quality (grade) and species required in large quantities as demanded by housing projects, and bamboo not being included in specifications and schedules approved by government agencies. Besides, engineers normally trained in modern building materials like Reinforced Concrete (RC), steel generally hesitate to use natural building materials like bamboo in the absence of specifications and schedules approved by government agencies. Like most vernacular techniques, skill sets needed to sustain such techniques are also depleting rapidly.

Bamboo-based houses are essentially framed systems with a number of elements being joined together to act in unison upon the application of loads, especially lateral loads. There are a number of secondary elements (such as the wall panels) which could alter the overall dynamic response.

Bamboo-based construction system is a traditional construction system not only in India but all over the world. It is considered by many architects as a vernacular construction technique though the history of the bamboo construction technology has given scope to the evolution of a wide variety of joinery details and other structural improvisations. Simultaneously, there has been the development of adequate technology to maintain the material/component from getting deteriorated. Also there have been improvisations in repair and rehabilitation of such structures following post-earthquake disasters.

In different countries there has been development of hybrid construction systems wherein bamboo-based system is synthesized with *adobe* and masonry construction. Even in these structures there have been ample improvisations; however, as always, every earthquake has posed interesting challenges to the traditional users and it appears that there has been improvement after every lesson. This paper presents a summary of the performance of a variety of housing systems where bamboo is used as a predominant structural member and bamboo frame as a predominant structural system, during earthquakes.

Ikra type of housing technology

Traditional construction in Sikkim consists of mostly of typical bamboo houses, known locally as "Assam-type housing" and also known as '*Ikra*' wherein a weed called *Ikra* is extensively used in the walls and the roof of the house. *Ikra* type of housing technology consists of stone masonry walls up to 1m above the plinth and the rest with wooden frame consisting of woven bamboo mat plastered with cement or mud mortar. A typical *Ikra* type housing is shown in Plate 1(Kaushik et.al, 2006 [2]).

Plate 1: *Ikra* type housing (school building at Nandok, East Sikkim)(Kaushik et.al. 2006[2])

The roof generally consists of light-weight materials such as Galvanized Iron (GI) sheets or thatch roof, supported by bamboo/wood trusses, which are laterally connected to the parallel walls. Steel angles and flats with bolts and nails are used to connect the *Ikra* wall to the masonry foundation wall.

The authors reported the performance of these types of houses during moderate earthquakes (reported as Moment Magnitude(M_w)5.3 by U.S. Geological Survey (USGS) and as Local Magnitude

(M_L)5.7 by India Meteorological Department (IMD) that occurred in Sikkim (India) in February2006 and also in September 2011 Sikkim (M6.9) earthquakes. They have given a detailed observation of the structural response as follows:

"These types of houses, constructed on slopes, are susceptible to landslides or slope failure and can be unsafe during strong earthquake ground motion as unequal lengths of posts lead to unsymmetrical shaking. In plains, these buildings are observed to perform the best. In the event of earthquakes, it was observed that no injury was caused due to the falling of debris of *Ikra* walls." They go on to state that "reinforced concrete buildings were severely damaged, during the event."

In their observation "one of the typical *Ikra* type housing with two stories in Sikkim, was made of heavy masonry infill walls in the second storey and light weight *Ikra* walls were used in the first storey. Masonry infill walls constructed in the upper stories of such housing are vulnerable to out-of-plane collapse; however, no damage was observed during the September 2011 earthquake shaking."

They also state that "the mud-dung wall plaster becomes brittle during summer and requires maintenance as it comes out during the rainy season. If vertical posts are directly plugged into the ground without foundation, the differential settlement may lead to lateral sway of the house."

They emphasize that, "light mass of walls and roofs, good wall-to-wall connection, flexible connections (bolting, nails, grooves, etc) between various wooden elements at different levels will influence the earthquake safety of the house." *Ikra* houses may not be suitable for construction of higher stories due to possible amplification of ground motion along with the height.

Bahareque type of construction

Bahareque consists of timber vertical elements and horizontal timber, cane or bamboo elements, with mud infill and finished with plaster. Such systems are prevalent in quite a few countries.

In El Salvador, the first type of *bahareque* consisted of small tree branches bonded with clay. Later dwellings were constructed by using a foundation of stones or clay into which vertical wooden posts were inserted. Horizontal rods were attached to the vertical posts and both structural members formed the skeleton of the dwelling. The body of the house was created using bamboo elements with mud infill and covered with plaster (Figure 1) [3]. Wood frames covered by palm fronds constituted the light roof system. It may be noted that this is similar to the IPIRTI-TRADA technology which was developed later.

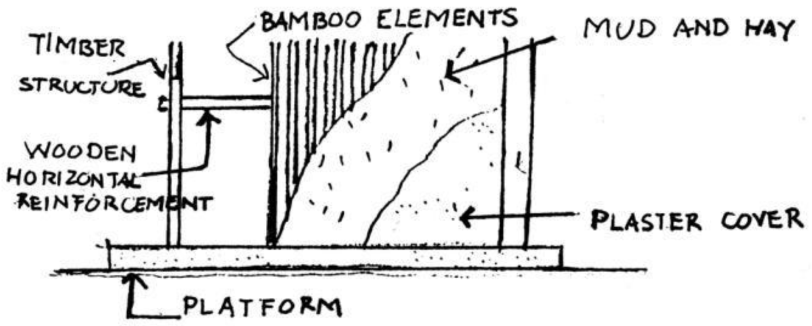
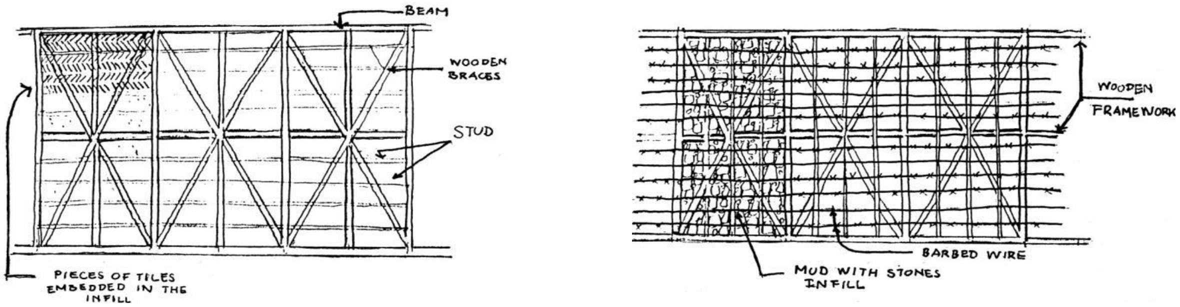


Figure 1: Main components of the *Bahareque* indigenous dwellings
(Moisa y Medrano [4])

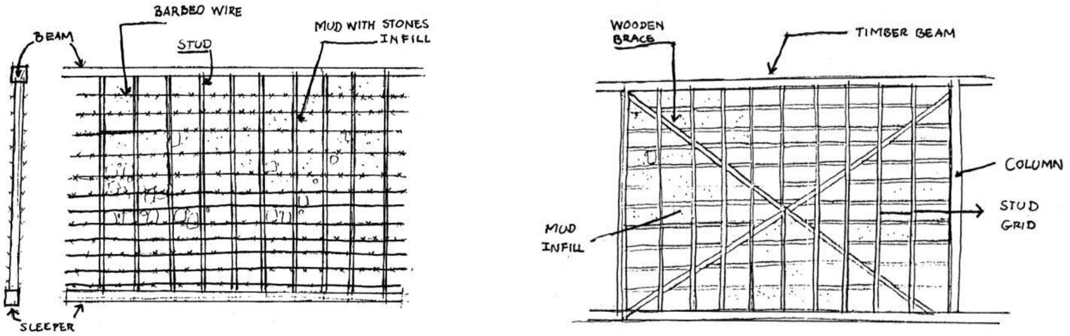
Presently, *bahareque* has some variants (Figure 2). The framework can be made of wooden studs, wooden braces or wooden grid with bamboo strips or barbed wire to provide better infill adhesion. Mud, mud with pebbles or stones, and mud with tile pieces may constitute the *bahareque* infill. To cover the wall, a plaster made of lime or mud is employed. The roof is made of wooden frames and clay tiles.

Rural construction of bamboo vernacular houses of Ecuador are made almost exclusively with vegetable material, using bamboo poles for most of the structure, *esterilla* for walls and floors, palm leaves or grass for the roof and, where flooding is frequent, timber poles to raise the floor from the ground. The *esterilla* of the walls is left uncovered. The '*esterilla*', is obtained by longitudinally cutting, flattening and removing the softer interior of the bamboo culms, which are then used as boards in walls and ceilings (Plate. 2).



(a) Wooden braces and studs, mud employed as infill

(b) Wood reinforced with barbed wire, pebbles and mud used as infill



(c) Studs reinforced with barbed wire, infill of mud and stones

(d) Wooden columns and stud grids, infilled and covered by mud

Figure 2: *Bahareque* frame work variants (Moisa y Medrano [4])

Plate 2: Bamboo house with *esterilla* in Ecuador (Gutierrez, 2004[5])

The bamboo houses of South America are built almost exclusively with one particular species of bamboo, Guadua angustifolia Kunth. The *esterilla* of the walls is placed in double layers on both sides of the internal timber or bamboo poles, and daubed; originally, the daub was '*cagajón*', a mixture of mud and horse dung but later on, Portland cement replaced *cagajón*. The roof structure is usually made out of bamboo and it is covered with clay tiles. This construction technique is also known as *bahareque*, and has been extensively used in many countries of Latin America [5].

This form of *bahareque* consists of two different procedures for the walls. The first, solid *bahareque* uses spaced horizontal canes or bamboo laths to hold mud, sometimes combined with broken tiles, that fills the interior. The second, hollow *bahareque* places nothing in the interior of the walls and uses a double layer of horizontal bamboo *esterilla* or small-diameter horizontal canes as a supporting surface for the daub, which is applied on both faces.

Hollow *bahareque* is much lighter and drier than the solid, and generates lower inertia forces. If it is plastered with cement mortar, the walls turn into effective structural shear walls.

According to Robledo [6], "the houses where the timber is substituted with *Guadua* in the poles and diagonal bracing of the frame are more than a century old but are in excellent conditions (Plate 3 a)." This shows the capacity of the bamboo *Bahareque* to resist weathering as well as the moderate to strong earthquakes. In the early 20th century, to adapt to the trending construction practices bamboo *bahareque* buildings were plastered with cement mortar (Plate 3 b).

(a) Traditional *Bahareque* building (b) Modern *Bahareque* building

Plate 3: Urban-traditional housing in Antiguo Caldas (Gutierrez, 2004[5])

Behavior of *bahareque* during earthquake

A number of surveys were conducted in San Salvador by different authors during a 1917 earthquake with a magnitude of Surface wave magnitude (M_S) 6.7 and a 1936 earthquake with a magnitude of M_S 6.1 [7, 8]. A number of poorly constructed *bahareque* dwellings were totally destroyed, along with a number of *adobe* houses which suffered collapse or deformation of two walls and the cracking of the other two. *Adobes* are inherently very poor seismically. On the other hand well-constructed *bahareque* houses in general were unaffected except for falling plaster and deformation of the tile roof.

Based on his observations, Levin [9] states that "*bahareque* construction, if well built, is seismically resistant to a remarkable degree." He also states that "the causes of failure are not inherent to *bahareque* but are due to the three remediable factors, which are: (i) lack of structural unity, due to faulty tying of horizontal members to the upright members, especially in the corners; (ii) failure to set the uprights deeply and firmly into the ground; and (iii) excessive weight of the tile roof."

In May 1951, three earthquakes that occurred over two days, caused extensive damage to villages in a small area of eastern El Salvador (Ambraseys et al. [10]). They state that "very few buildings in the most heavily affected area survived. The few *adobe* and *bahareque* houses that did withstand the shocks had been built within two or three years prior to the earthquake." Additionally, these authors further expressed that "*adobe* and *bahareque* deteriorate very rapidly due to the climatic effects and the action of insects and their vulnerability is very much a function of their age."

Rosenblueth and Prince [11] refer to the 1965 earthquake of San Salvador Ms 5.9 and points that "*bahareque* system performed badly due to decayed timber, loose sand present as the subsoil, and high intensities due to near source effects."

The behavior of *bahareque* buildings was reported by Anderson et.al.[12] after San Salvador earthquake of 1986 with a magnitude of M_w 5.7. The *bahareque* construction held up well but failure was often due to structural timber failure caused by rot or damage by insects.

During the series of earthquakes (M_w7.7 and M_w6.6) in January and February 2001, the majority of the damaged houses were *adobe* and *bahareque*, with the *adobe* being the most susceptible type of housing. Lopez et al., [13] reports that "the damage to *bahareque* houses ranged from plaster falling (Plate 4 a), to complete collapse (Plate 4 b)." They have mentioned that "the condition of the structural wood in *bahareque* and the weight of the roof were the two important parameters in the seismic behavior of *bahareque* dwellings."

Following the 2001 earthquakes in El Salvador, there is an almost generalized resistance to re-building house in either *adobe* or *bahareque* due to the poor performance during the previous earthquakes.

Plate 4 (a) Superficial damage to *bahareque* in Santiago de Maria 13 January 2001 earthquake (Lopez et. al., 2004[3])

Plate 4 (b) Collapse of *bahareque* dwelling in San Agustín (13 January 2001 earthquake) (Lopez et. al., 2004[3])

The failure of *bahareque* to provide adequate resistance and protection during earthquakes in El Salvador has been caused by a number of technical factors related both to the construction of these dwellings and to the lack of maintenance. Lopez et.al., [13] recommends that:

- "The timber to be used must be treated and provided with maintenance."
- "The foundation timber must be placed above the stone masonry foundation with a least height of 0.3m above the ground to protect them from the ground moisture."
- "The spacing of the bamboo or wooden grid must be less than 0.15 m."
- "The infill paste should contain vegetable fibers to increase the strength. The usage of barbed wire on the *bahareque* grid gives more adherences to the infill paste."
- "The plaster cover is to be made of lime to protect the walls from humidity and to provide a neat finish."

In Costa Rica, a timber-framed type of *bahareque* house was developed, with large (2.7 m x 2.4 m) but light prefabricated panels, consisting of small section (25mm x 50mm or 50mm x 50mm) timber frames with a single layer of canes, that were easily transported, manipulated, assembled on top of a continuous foundation and plastered afterwards with 5 cm of cement mortar, resulting in a very light but strong house type (Plate 5 a, b). In a 10- year period, more people came forward and built hundreds of such houses with this technology (Plate. 5 c) [14].

(a) Prefabricated panels (b) Plastered with cement mortar (c) A *bahareque* community

Plate 5: Prefabricated light *Bahareque* housing in Costa Rica (Gutierrez, 2004[5])

In 1990, the University of Costa Rica constructed 13 engineered *Bahareque* wall panels and subjected them to monotonic in-plane load (Plate 6) (Mendoza & Villalobos, 1990[15]). The panels consisted of a timber frame clad in *esterilla* and finally rendered with cement mortar. These tests demonstrated that the load capacity of the wall panels is considerably greater than the seismic load demand from the Costa Rican code.

Plate 6: Monotonic load test on structural *bahareque* (Gutierrez, 2004[5])

Failure occurred by either buckling of the leading stud in compression or a tensile failure of the rear stud. The cement render did not tend to spall, regardless of the use of chicken mesh. Based on the tests conducted, a group of 30 *Bahareque* houses had been built at the site of the epicenter. During the 1991, Limon, Costa Rica earthquake (M_L 7.5), all of them resisted the strong shaking without the slightest damage (Gutiérrez, Handley [16], [17]), even in sites with widespread liquefaction (Plate 7).

Plate 7: Undamaged *Bahareque* house after the 1991 Costa Rica earthquake (Gutierrez, 2004[5])

In 2004, a series of cyclic tests were conducted on similar specimens (Plate 8). This research confirmed the original test results and suggested that the walls had some ductility under cyclic loading. (Gonzalez and Gutierrez, 2003[18])

Based on these tests, it is considered that "these wall panels tend to work compositely, with the cement render taking most of the load as a diagonal compression strut, the wall matrix controlling cracking and out-of-plane buckling and the timber studs taking the vertical tension induced by the diagonal strut."

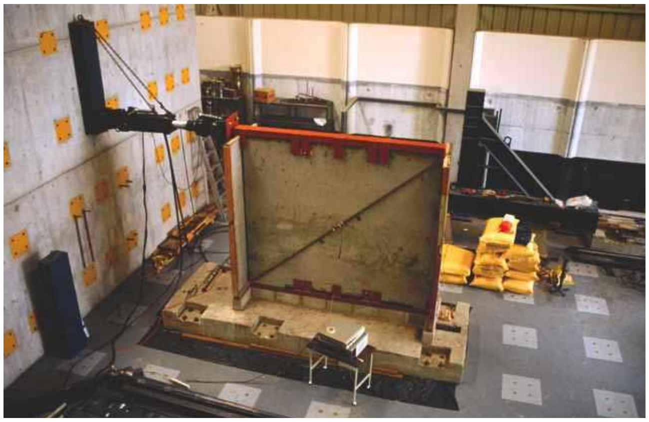


Plate 8: Cyclic load test on structural *Bahareque*, in Costa Rica

(Gonzalez and Gutierrez, 2003[18])

The resulting design effectively eliminated the panels and substituted them with individual bamboo posts placed on top of similar diameter prefabricated concrete cylinders that served as the foundation and raised the bamboo from the ground for the required humidity protection.

The bamboo poles were connected at the top by horizontal bamboo beams, providing the structural integrity. Prefabricated bamboo curtains, made out of laths and flexible wire, were hung down from the beams to the concrete base and joined to the poles. Finally, the walls were plastered with cement mortar. Plate 9 shows the bamboo *bahareque* house with prefabricated poles and curtains.

(a) Bamboo structure (b) Bamboo curtains (c) Finished house

Plate 9: Bamboo *bahareque* house with prefabricated poles and curtains (Gutierrez, 2004[5])

The El Quindío earthquake of 1999 (M_L= 6.2) caused major damage in Armenia and Columbian cities. Many modern masonry and reinforced concrete buildings suffered significant damage, but the vernacular *Bahareque* style of housing fared significantly better (Trujillo, 2007[19]).

Tipping of the structure, collapse of improperly fastened heavy masonry walls, deterioration of timber/bamboo elements and heavy tile roof structure were the main reasons for serious damages to the structures.

This interest spurred the Colombian Earthquake Engineering Association to conduct research into engineered *Bahareque*, which included a series of racking tests on wall panels using *Esterilla*, chicken mesh and cement render and the results were similar to those obtained in Costa Rica. Following this, the construction manual for seismically-resistant housing using mortared *bahareque* was published (Prieto et. al., 2002[20]), per which some of the new bamboo houses were designed. Even shake table tests were conducted on full-scale, two-storey braced engineered bamboo house and the design complied with the Colombian seismic design code (Plate 10) (Arup and Imperial College, 2013[21]).

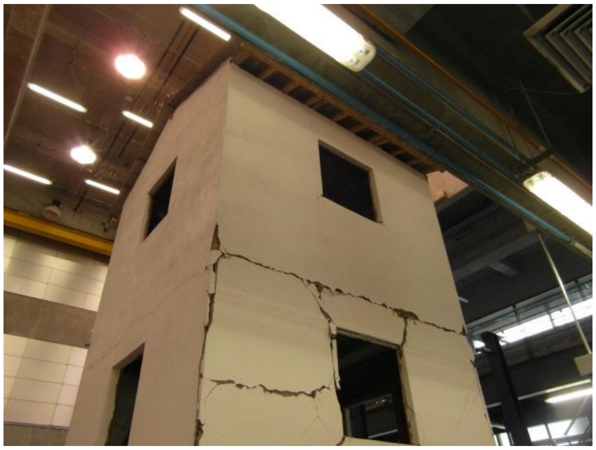


Plate 10: Unidirectional shake table test on two storey house at the University of the Andes, Colombia (Arup & Imperial College, 2013[21])

Replacing timber frame with bamboo frame in *Dhajji Dewari* style of construction

Dhajji is an old Parsi word used to describe patchwork quilts and the same was applied to the traditional building technique of the Kashmir region in India. *Dhajji* construction is made of highly subdivided light timber frames with masonry infill. In *Dhajji*, the energy distribution is through small panels, as opposed to cases like big panels where the energy is highly concentrated. In this construction, there is friction between the mud mortar and the bricks which dissipates the energy and hence helps in reducing the earthquake forces.

The Dhajji Dewari style of construction emerged as a time-tested earthquake resistant technique, indigenously developed through lessons learnt from repeated earthquake disasters over several generations, both in the rural and urban setting of Kashmir which falls under seismic zone V. The work by Aaqib Mir et.al., [22] focused on the revival of the traditional Dhajji Dewari earthquake resistant technique by replacing the timber with bamboo thus making it cost effective and also increasing its strength. Thus, replacing timber with bamboo in Dhajji Dewari is hoped to change the mindset of people who are no longer opting for this technique due to the non availability of timber and its spiraling cost. Six types of frames were tested (Plate 11). Configurations 1 to 3 are bamboo frames with single and double bracing. Configurations 4 to 6 are the timber frames with similar arrangement to that of bamboo frames. The loading system consists of proving ring at the top edge of the frames which records the load applied from a hydraulic jack. Deflections were measured using a dial gauge located at the mid height and top height of the frame. Based on the test results on 6 types of frames (Plate 11) authors could conclude that the joints are the critical locations in these types of traditional constructions. Double bracings increase the strength when compared to single bracings and also strengthening of joints by iron straps increases the load carrying capacity. The lateral load resisting capacity of bamboo frame is ranges from one-and-a-half to three times when compared to that of timber frame. The choice of configuration highly affects the performance of Dhajji in earthquakes. So replacing timber with bamboo is useful both in terms of cost as well as strength in Dhajji Dewari style of construction.

(a) Configuration -1 (b) Configuration-2 (c) Configuration-3

(d) Configuration -4 (e) Configuration-5 (f) Configuration-6

Plate 11 Typical view of six types of test frames (Aaqib Mir et. al., [22])

IPIRTI- TRADA bamboo-based housing system

In India, although bamboo is widely used in some regions, it must be emphasized that its use has been primary as a semi-load bearing element or as infill material in timber framed houses. It is in this context that the bamboo housing technology developed at IPIRTI in collaboration with TRADA, U.K. which demonstrated the engineering application of bamboo in housing. Plate 12 shows the demonstration houses at IPIRTI, Bangalore.

Plate 12: Demonstration house built by using IPIRTI-TRADA technology at IPIRTI, Bangalore; source: author

Bamboo based housing system has very high potential for mass housing, housing in disaster prone areas and for earthquake resistant structures/houses and other applications. The low mass of the bamboo based building is an advantage under earthquake loading as compared to masonry and concrete buildings. Bamboo based housing system offers traditional materials in modern engineering context. The system is suited to either prefabrication or fabrication in situ i.e., all components like infill grids, roof trusses are designed to be prefabricated or prepared on site. Only basic carpentry and masonry tools and skills are required to undertake the construction. The IPIRTI -TRADA Bamboo Housing system differs significantly from conventional bamboo construction practices in many ways viz., [23];

(a) Use of round bamboo as columns, rafters and trusses as main load bearing element,

(b) Use of split bamboo grids/chicken mesh plastered with cement mortar to act as shear walls for transmitting wind loads and to provide overall stability to the structure,

(c) Application of appropriate preservative treatment to bamboo depending on the degree of hazard and service conditions,

(d) Use of Bamboo Mat Board (BMB) as gussets in combination with mild steel bolts for load bearing joints in roofing structure, and

(e) Use of Bamboo Mat Corrugated Sheet (BMCS) as roof claddings.

Bamboo housing – earthquake-prone areas

Since India has large areas falling in the zones of high seismicity, bamboo can play a vital role in appropriate housing and construction owing to its suitability and availability. Bamboo possesses excellent strength properties, especially tensile strength and is much more flexible than hard wood and concrete materials. For this purpose, it is necessary to develop technological packages, which can be easily adopted for mass housing in such areas. Typical Assam house (Figure 3) has wooden frame with infill plastered bamboo lath and has been found to be effective in resisting earthquakes. A demonstration house (Plate 1.10) was constructed at Mizoram using Latin American earthquake resistant bamboo housing technology [24].

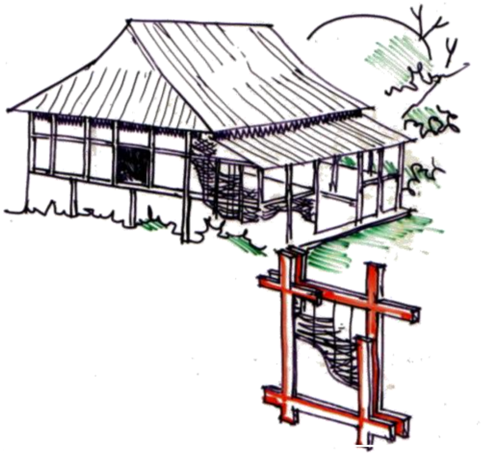


Figure 3: Typical Assam house (Wattle & daub, bamboo lathe infill walls)

Plate 13: Demonstration house at Mizoram, Latin American earthquake resistant housing technology

Seismic performance of bamboo housing

The IPIRTI-TRADA housing system has proven to withstand a simulated earthquake test carried out using the shaking table test facility at Central Power Research Institute (CPRI), Bangalore under the TRADA project.

The bamboo house of 2.7m x 2.7m was tested on shaking table (Plate 14). The mass of the house was 2636kg. A seismic simulation of 30 seconds was carried out on the bamboo house for a design spectrum of zone IV and zone V classification as per IS-1893, 2002 [25].

To test the fatigue strength of the bamboo house zone V design spectrum was repeated for five times. Even Kobe earthquake data was also simulated for the same house. After the test program, the structure did not exhibit any cracks or damage in any part of the building [1]. The testing program needed a sophisticated facility and the perhaps the costs constrained the testing of more models.

Plate 14: Bamboo house under shake table testing at CPRI, Bangalore [1]

To extend the studies on similar and different alternative model houses, there existed the need to go in for a simpler version of the shaking table, such as a shock table in which it is possible to study the progressive failure of the structure in a methodical manner.

Shock table tests have become quite popular in recent times where many scaled masonry models have been tested [26, 27]. Shock table is a simple version of the shaking table, which is a horizontal table over which the building model can be built and subjected to controlled base shock. The shock table can be used to simulate the cumulative effects of ground induced vibrations by subjecting it to a series of base impacts/ shocks. The intensity of the shocks can be controlled by using a pendulum impacting device.

Shock table tests carried out at Indian Institute of Technology (IIT), Roorkee, [28], Indian Institute of Sciences (IISc.), Bangalore[29], Nirma university (Ahmedabad) [30] and at BMSCE (Bangalore) [26, 27], have shown ample examples wherein the failure modes of building models are reproduced almost exactly as those observed during earthquakes. It is also possible to study the progressive failure patterns, which help a great deal in identifying the critical seismic detailing aspects.

Seismic evaluation of bamboo housing using shock table studies

IPIRTI-TRADA bamboo housing system, as stated earlier, is a building system consisting of skeletal frames and a number of panels. The skeletal frame itself consists of a number of joints, in addition to the panels attached to it. The entire structure takes on an enclosed form which is actually specified to be tied to the plinth of the foundation supporting the system. Seismic evaluation of such a system is indeed quite complicated. There are a number of parameters which influence the lateral load response under dynamic loads. Generally, shaking table tests are preferred to evaluate the seismic performance of such buildings, especially when the soil-structure interaction is in-significant. Shaking table test facility is quite sophisticated and obviously cost-wise prohibitively expensive. A shake table test was indeed conducted [1] on a similar bamboo house model and no damage had been assessed, since the test was conducted for an earthquake input to which the model responded effectively. Apparently, the dynamic loads were not magnified to the levels required to cause crack/failure patterns. Thus, from the point of view of damage assessment, the shaking table test proved to be in-conclusive. Shock table test is an effective alternative to shake table tests, especially to subject building models to intensive damage levels with minimal sophistication, though with certain de-merits.

A shock table test facility allows the comprehensive damage assessment of low-rise structures such as the bamboo based house, under lateral dynamic loads. The major advantage of a shock table test is that progressive cracks/failures can be controlled and monitored to a great extent. One can almost precisely identify the series of local failures which can influence and contribute to the overall dynamic response. Shock table tests can also be used to provide a systematic comparison of the dynamic response of geometrically identical buildings. The crack patterns and failure modes can be demonstrated quite effectively.

In this particular investigation, a shock table was designed and fabricated specifically for the purpose of evaluating light-weight bamboo building models. The model was subjected to base impacts significant enough to cause damages much more than the ones reported in the shaking table test conducted at CPRI, Bangalore.

Construction of shock table

A shock table was constructed specifically for the purpose of testing full-scale bamboo house models at IPIRTI, Bangalore by the author. The shock table is a framed platform assembled with Indian Standard Medium Beam (ISMB)-150 and Indian Standard Medium Channel (ISMC)-150, interconnected through welded joints. The underneath of the table is fitted with grooved wheels, mounted on bearings on two sides of the shock table so that it allowed the motion of the shock table in only one direction. The shock table measured 3.05 m x3.66 m and weighed 6400 N. The grooved wheels were supported on rails made of inverted T-section. These two rails were anchored to the rigid concrete foundation and the base concrete. The table could be set into motion through pendulum impacts on one side and rigid rebound beam on the opposite side of the table facilitated the reverse motion. The length of suspended pendulum is 1.6m from the centre of the hinge to the centre of the hammer weighing 4000 N. Figure 4 shows the layout of the shock table. Plate 15 shows the shock table facility at IPIRTI, Bangalore.

The shock table can be subjected to a series of controlled base shocks using a pendulum impacting device for different angle of releases starting from 5 degrees to 50 degrees at an interval of 5 degrees. The response of the shock table can be observed and monitored using accelerometers mounted at various locations which are in turn connected to a high speed data acquiring system. Plate 16 shows the arrangement at the point of contact for the measurement of contact duration.

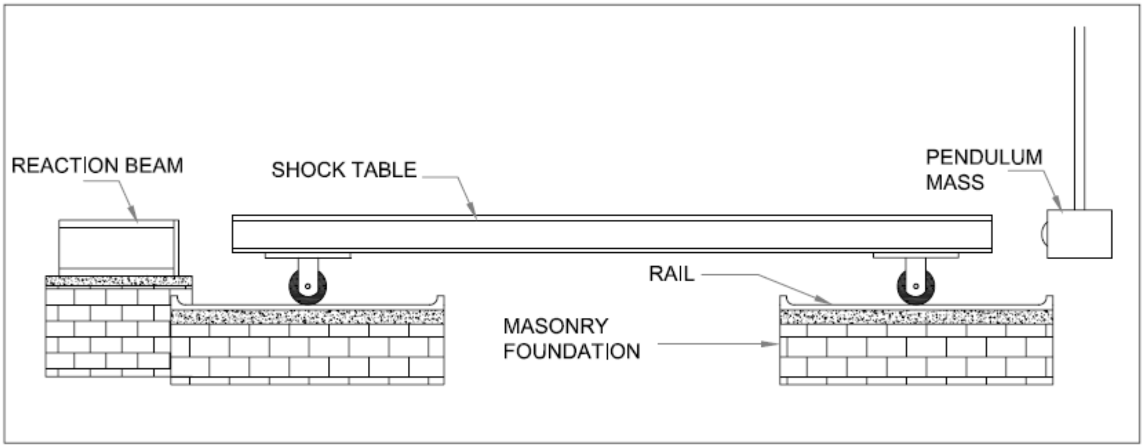


Figure 4: Schematic diagram of shock table

Plate 15: Shock table at IPIRTI

Plate 16: Arrangement at the point of contact for the measurement of contact duration

Test program of model and observations

The bamboo house built using the IPIRTI-TRADA, technology was tested to evaluate the preliminary damage patterns and structural adequacy. The prototype house of 2.44m x 2.44m was made using split bamboo grid and wire mesh, plastered with cement mortar for walls, with bamboo columns providing support. The ceiling was made of light bamboo mat corrugated sheets developed by IPIRTI. The total mass of the house worked out to be 2.7 tons. This prototype house was made by mounting it on the shock table and a series of base shocks were delivered through a simple pendulum device. A series of base shocks varying the angle of release of the pendulum from 15 to 40 degrees with an interval of 5 degrees were applied with the help of the 400kg pendulum mass.

The test program consisted of 15 shocks given to the shock table. Various parameters of the shocks are presented in Table 1. The performance of the 2.44m x 2.44m full-scale IPIRTI-TRADA building model is described below. The total cumulative energy imparted after all the tests was 13236 N-m. Figure 5 gives the test setup and Plate 17 shows the bamboo house during testing.

Shocks and physical response of the building

i) Shock 1, 2 & 3: Pendulum angle 20^0: The table was subjected to three shocks with an angle of 20^0. There was no damage after the three shocks. Hair line cracks were observed near the door portion of the bamboo house.

ii) Shock 4, 5 & 6: Pendulum angle 25^0: The table was subjected to three shocks with an angle of 25^0. Hair-line cracks were observed at the top of the wall on the pendulum side. However there were no signs of significant distress observed in any portion of the house.

iii) Shock 7, 8 & 9: Pendulum angle 30^0: The table was subjected to three shocks with an angle of 30^0. Hair line diagonal cracks were observed on the wall panel next to the door.

iv) Shock 10, 11 & 12: Pendulum angle 35^0: The table was subjected to three shocks with an angle of 35^0. Hair line cracks were a little extended at all the places mentioned above.

v) Shock 13, 14 & 15: Pendulum angle 40^0: The table was subjected to three shocks with an angle of 40^0. Cracks were observed on both inside and outside portions of the house as mentioned in Figure 6(a) to (c). Only outside portion cracks were visible as shown in Figure 6.

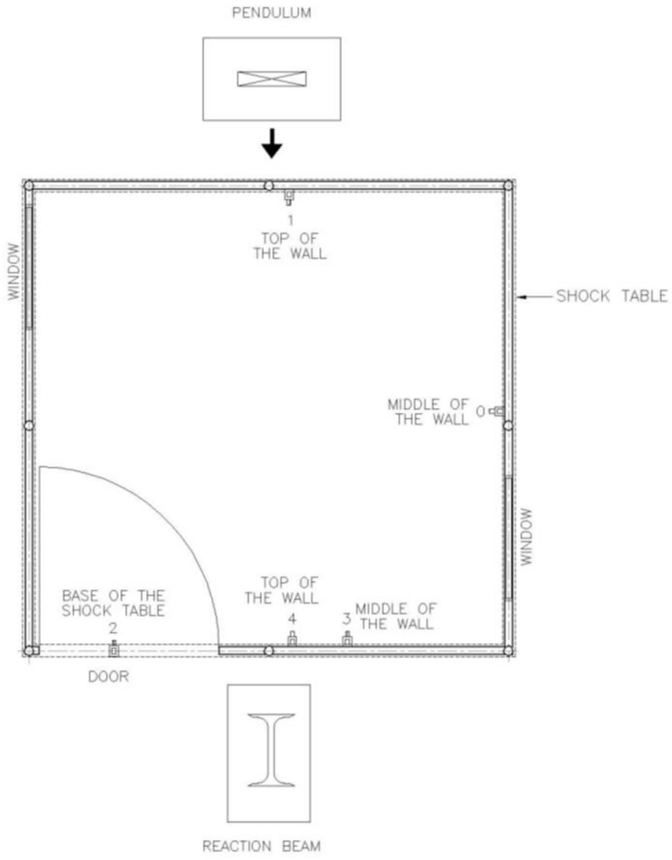


Figure 5: Test set-up and accelerometer positions; model-1

Plate 17: Bamboo house model during testing

Table 1: Details of shocks imparted on house Model-1 using pendulum

Shock No	Pendulum angle (deg.)	Peak velocity of pendulum (m/s)	Energy of Impact (Nm)	Cumulative Impact Energy (Nm)	Remarks
1	20	1.38	378.6	378.6	Hair line cracks were observed near the door portion of the house model
2	20	1.38	378.6	757.2	
3	20	1.38	378.6	1135.8	
4	25	1.720	588.2	1724.0	Hair-line cracks were observed at the top of the wall on the pendulum side
5	25	1.72	588.2	2312.2	
6	25	1.72	588.2	2900.4	
7	30	2.05	841.1	3741.5	Hair line diagonal cracks were observed on the wall panel next to the door
8	30	2.05	841.1	4582.6	
9	30	2.05	841.1	5423.7	
10	35	2.38	1135.4	6559.1	Cracks were little extended at all the places
11	35	2.38	1135.4	7694.5	
12	35	2.38	1135.4	8829.9	
13	40	2.71	1468.9	10298.8	After the test program, it was observed that cracks shown in Figure 5.7 were observed both inside and outside portions of the walls
14	40	2.71	1468.9	11767.7	
15	40	2.71	1468.9	13236.6	

Figure 6(a): Front side crack pattern of Bamboo house

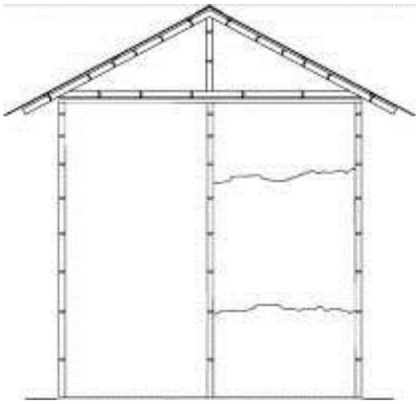


Figure 6 (b): Outside crack pattern of bamboo house on pendulum side

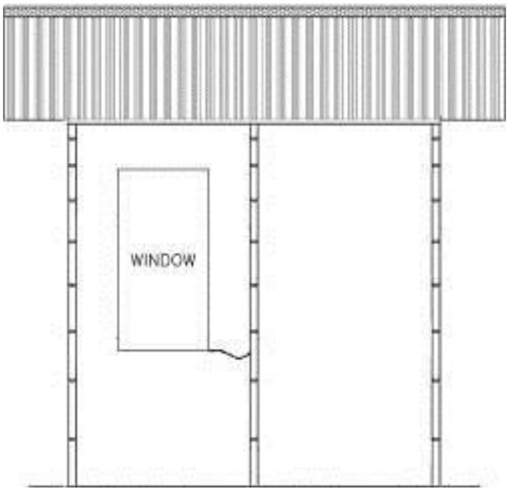


Figure 6(c): Outside crack pattern of side wall

Figure 6: Crack patterns observed for model-1

After the last set of three shocks with an angle of 40^0, the cracked portions were observed even in the inside portion of the house model. However the cracks were clearly visible only on the outside portion of the walls. After the test program, the prototype resisted the shocks and showed no signs of falling apart. Thus it can be stated that the model has met the objectives of resisting major to moderate levels of dynamic forces with minimal damage levels. Thus it could be stated that the model had met the objectives of resisting moderate levels of dynamic forces with minimal damage levels. The author is involved in carrying out the further experiments on this.

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