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SEISMIC PERFORMANCE OF SINGLE FAMILY DWELLINGS CONSTRUCTED USING BAMBOO-MORTAR COMPOSITE

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ABSTRACT

The use of bamboo as a structural construction material is gaining traction primarily because (i) it is a rapidly growing material and thus sustainable, and (ii) it has many positive engineering attributes such as its high strength-to-weight ratio in tension. One area of recent development has been the use of bamboo-based construction in seismically active regions of India. In this paper the seismic behaviour of one type of bamboo-based construction is examined and validated by calibrating a non-linear numerical model to wall panel experimental results, and then performing multi-record incremental dynamic analysis (IDA) on the full system level model. The response was very reasonable due, in part, to the relatively light weight of the bamboo roof system. Most importantly, the damage to the bamboo-mortar walls during testing, and particularly the eventual failure mechanisms, were consistent with modern engineered materials thus confirming that this type of construction is a viable alternative for seismic regions, particular in developing countries.

Keywords: Bamboo; seismic; structural; housing; seismic performance

1. INTRODUCTION

Bamboo has traditionally been used for a variety of purposes and has recently received renewed attention in many regions of the world due to its speed of growth and therefore sustainability. Forests are being depleted worldwide, particularly in many developing countries, and thus the availability of more traditionally used wood, i.e. dimension lumber, has been reduced. This paper summarizes the method and results of a recent research project whose objective was to demonstrate that bamboo combined with cement-based mortar can

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be used in residential construction in seismic regions, particularly in developing countries.

Bamboo is an eco-friendly material, and thus there is an effort to develop bamboo building technology based on recognized engineering principles in many parts of the world. Bamboo by its very nature is a highly perishable material, thus its use in construction has always been considered temporary, and not surprisingly bamboo is replaced almost every year in much of the rural areas in India and other parts of the world where it has been used. Recently the engineering and material properties of bamboo have been studied exhaustively but its potential as an engineering material has not yet been fully explored. In India, although bamboo is widely used in some regions, it must be emphasized that to date its use has been secondary as a semi load bearing element or as infill material in light-frame wood houses. It is in this context that the bamboo housing technology developed in collaboration with the Timber Research and Development Agency (TRADA) and bamboo-based products developed at the Indian Plywood Industries Research and Training Institute (IPIRTI) are perhaps more significant [1-4]. However, there has been growing interest among engineers and architects to utilize Bamboo as a building and structural material, rather than just non-structural and/or decorative contributions.

Composites have numerous advantages such as their ability to be customized and their high strength to weight ratio. Thus, they are used extensively for novel applications and are replacing many conventional materials like metals, woods, etc, depending, of course, on the details of the application. Composite materials offer some significant advantages to heavier metals in many structural applications due to the flexibility of selecting the fiber reinforcement (e.g. bamboo slivers) and resin matrix to achieve the desired behavior. The reinforcing slivers are the primary load carriers of composite materials with the matrix transferring the load between the slivers to share the load. Selection of optimal thickness of the materials is dependent on the property requirements of the engineered component or assembly.

Over the last two decades IPIRTI has developed cost effective technologies for the manufacture of bamboo-based composites which have now been commercialized. These technologies are not only environmentally friendly but also socio-economically positive in that they have the potential to generate a substantial number of jobs in the bamboo composite manufacturing sector. Use of bamboo composites will lead to reduction of the use of non-renewable building materials, construction waste, and lead to substantial energy conservation. In general, there are four types of bamboo-based building materials that are currently being used in India within this context [5].

1.1 Bamboo mat board [BMB]

BMB is essentially a layered composite consisting of several layers of woven mats in a herringbone pattern, which has excellent internal bond strength, and are resistant to decay, insects and termite attack. They have physical and mechanical properties on par with waterproof plywood and are also fire resistant. Their mechanical properties depend upon the species of bamboo used in the mat, the weaving pattern and the adhesive used for bonding. BMB has high in-plane rigidity and hence high racking strength and is more flexible than equivalent thickness plywood. These properties of BMB can likely be exploited in many engineering applications such as utilizing their deformation properties during earthquakes.

1.2 Bamboo mat veneer composite [BMVC]

In a BMVC, the wood veneers are placed in between the layers of bamboo mats. The properties of BMVC depends on the type of construction in addition to the species of veneer and type of adhesive used. The strength of a panel made using plantation timber is substantially enhanced when made in combination with bamboo mats. BMVC can be used for structural applications similar to plywood.

1.3 Bamboo mat corrugated sheet [BMCS]

Roofing materials such as asbestos cement corrugated sheets (ACCS), corrugated fiber reinforced plastics (CFRP), Corrugated aluminium sheets (CAS), Corrugated galvanized iron sheets (CGIS) which have been used for more than several decades, are being subjected to scientific scrutiny on several counts, including their impact on workers' health and the environment, their energy requirement for manufacture, and a lack of sustainable supply for their raw materials. Therefore, BMCS represent a sustainable and green alternative material and is thus beginning to gain the interest of the building sector as an alternative to these other products. It is made of four or more bamboo mats bonded with an adhesive and pressed in a specially designed sinusoidal platen die. For manufacturing BMCS, bamboo is converted into mats that are hand woven by rural/tribal people, thereby providing employment opportunities within certain regions. BMCS having a size of 1800×950 mm is shown in Figure 1.

Figure 1. 300 mm×950 mm bamboo mat corrugated sheet

BMCS produced in a typical factory would be 2440×1050 mm. The average thickness of BMCS is 3.8 mm, with some slight variation as a result of bamboo sliver thickness. The load bearing capacity of BMCS is comparable to that of ACCS and CGI sheets but superior to ACS. Figure 2 shows the comparative load deflection curves for these different materials. BMCS is water proof and resistant to decay, termites/insects, and fire. The thermal conductivity of BMCS (0.1928 Kcal/m°c) is lower compared to that of ACCS.(0.3422 Kcals/ m°c) and provides better thermal comfort compared to houses constructed from either ACCS or CGIS roofing. These sheets have already been used as roofing material in demonstration houses built using bamboo-based housing technology. Figure 3 shows the IRPITI-TRADA demonstration house in Bangalore, India.

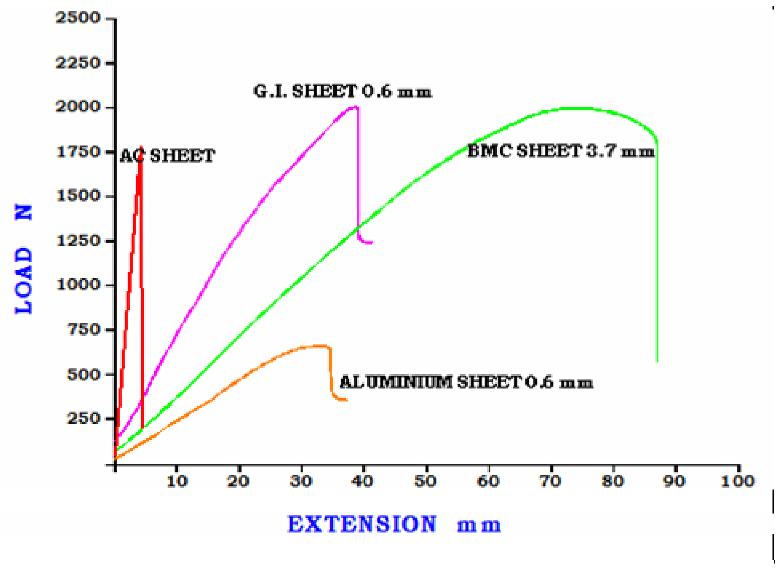


Figure 2. Comparative load-deflection curves

Figure 3. IPIRTI-TRADA demonstration house in Bangalore, India

Bamboo and their composites are gaining popularity as a viable building material for use in seismically active areas because information on the structural and mechanical properties is becoming more available. However, the level of confidence associated with the seismic performance of bamboo-based construction is still currently much lower than steel and concrete construction, and even graded lumber, because significantly less is still known about its behaviour during earthquakes [2]. In this context there is a need for more test data on both components and assemblies developed from bamboo and thus their performance under natural hazards loading should be examined in detail.

1.4 Bamboo-mortar walls system [BMWS]

In this paper the seismic performance of the fourth type of system, a bamboo-based wall system made up of bamboo and cement mortar, is examined. This is accomplished using a combined experimental/numerical approach. Initially, wall panels are constructed and tested using a reversed cyclic test protocol. Then, the resulting hysteretic response is fit to a nonlinear numerical model and the wall assembly models used to numerically model the full building in a program called Seismic Analysis Program for Woodframe Buildings (SAPWood) [6]. Using the full building numerical model the seismic intensity is scaled to observe the effect of increasing ground motion intensity on the response of the building. Several different seismic masses were also examined to observe the effect of increasing mass on the seismic performance of these bamboo-based structural systems. This increase in mass provided building design variants since the construction is non-engineered which could be representative of larger spans for increased floor space in a building.

2. EXPERIMENTAL PROGRAM

A IPIRTI-TRADA bamboo-based wall system consists of treated bamboo columns. The tops are tied to wooden plates running all through and spaced between columns that are held by a thin wall made of a split bamboo grid/wire mesh plastered with cement mortar. Figure 4 shows a schematic of this type of wall panel including the components making up the wall which specifically included:

1. Three (3) treated bamboo columns, 75mm in diameter spaced at 1.22m and set in a concrete base.
2. A fixed base created for the test panel with a total wall height of 2.2m.
3. A top plate which was a 100×25mm sawn plantation timber fixed to the top of the columns by wood screws.
4. Columns pierced by steel dowels at 150mm on-center.
5. Infill formed from a grid of split bamboo 19x9mm, wired together at 150mm spacing, and wired to steel dowels passing through the columns
6. Thin wire mesh fixed to the outside face of the grid.
7. A 3:1 mix sand-cement mortar applied over the grid to a finished thickness of 50mm.

The second test panel consisted of a 1.22m long panel without a window which is not pictured here for brevity. The larger wall panel having a length of 2.44m with one window was built to simulate, as closely as possible, the type of wall construction employed in the demonstration building in Bangalore. The construction sequence was as follows: Bamboo columns were prepared by drilling the holes every 150mm to accommodate the bamboo split grid of 150mm×150mm between the two columns. Figure 5 shows several photographs highlighting the preparation of the columns.

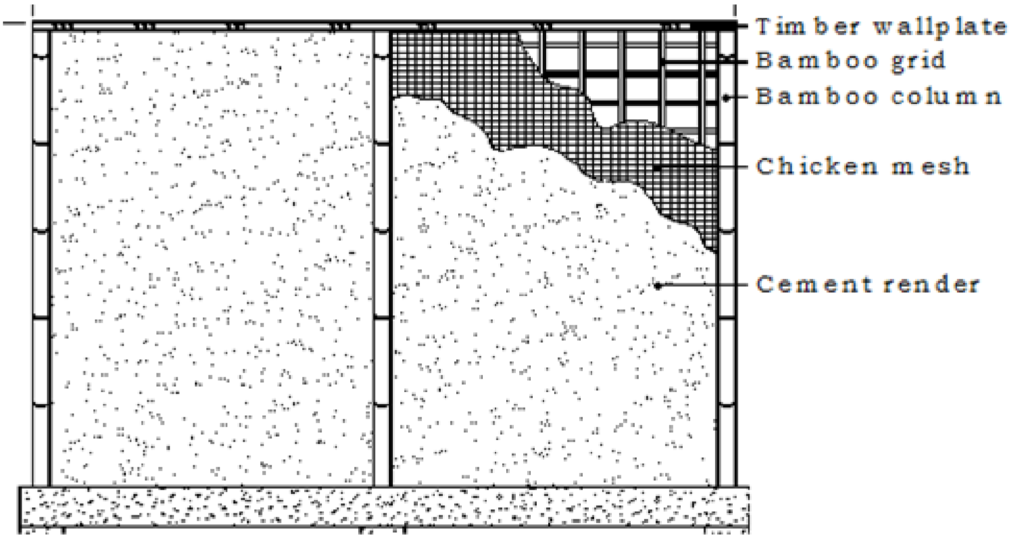


Figure 4. Schematic showing the elements comprising the 2.44m long test panel

Figure 5. Preparation of bamboo top plate for the 2.44m long test specimen

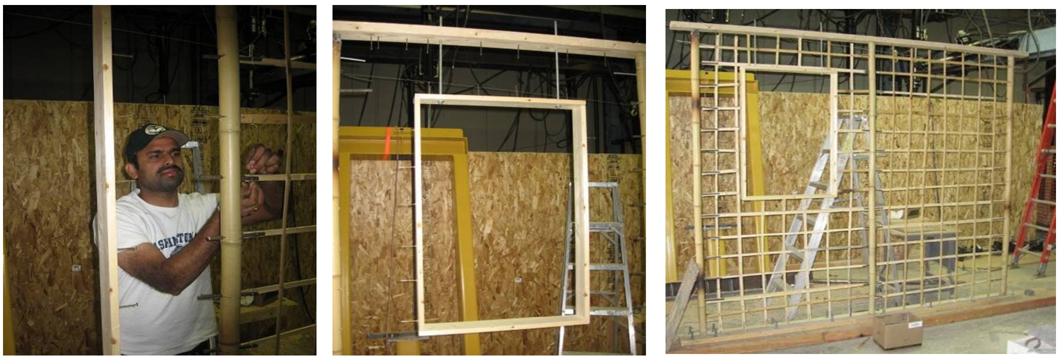


Figure 6. Construction sequence for the 2.44m long test specimen details

The split grid was placed between the two columns using steel dowels inserted and tied using binding wire. Figure 6 shows the preparation of the connections, grid and the window frame. Then cement mortar was applied in two coats to achieve a finished thickness of 50mm.

Figure 7. Completed test specimens curing in place

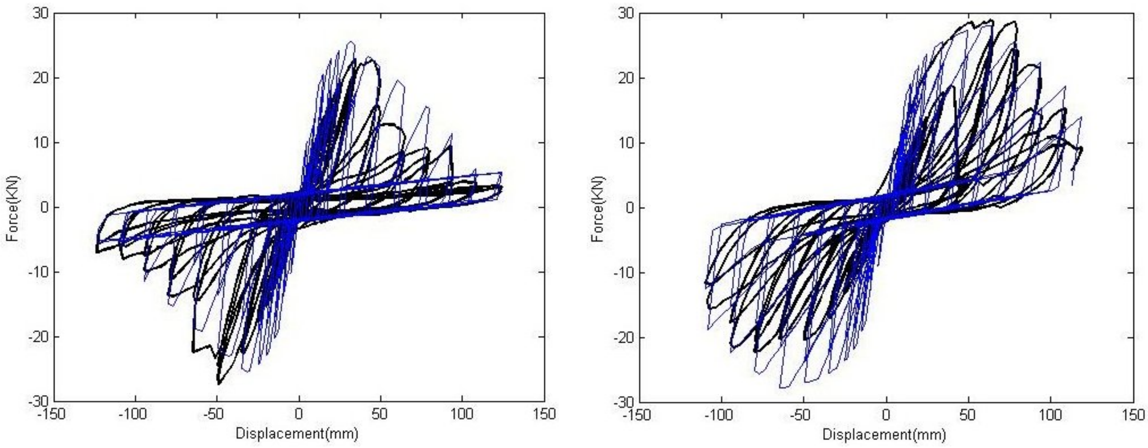
Figure 7 shows the test panels upon completion of the mortar application while they were still curing. The finished wall was cured for 21 days to reach its design - minimum strength. The height of both the test panels above the sill plate was 2.13m. Both the panels were fixed to the ground at each end to provide stability during the cyclic load tests, and to prevent out-of-plane movement. Table 1 presents the test protocol used for both walls, which consisted of reversing the top of the wall back-and-forth in-plane with a hydraulic actuator.

Table 1: Cycles for reversed-cyclic test of wall specimens

Positive cycle (mm)	**Negative cycle (mm)**	**Number of cycles**
5	–5	4
10	–10	4
15	–15	4
20	–20	4
25	–25	4
35	–35	4
50	–50	4
65	–65	4
80	–80	4
95	–95	4
110	–110	4
125	–125	4

3. TEST RESULTS

Figure 8 shows the hysteresis results of the two reversed-cyclic tests which are shown by the bold curves in the figures. Figure 8a are the results of the test on the specimen with the windows and Figure 8b shows the results of the 1.22m long specimen without any windows. Also shown in Figure 8 are the numerical model fits which will be discussed later. As can be seen in both plots of Figure 8 there is significant strength and stiffness degradation for both specimens as they are racked more and more. This is quite typical of concrete (and other) types of walls as they are damaged. However, what is encouraging about the hhysteretic behaviour of the IPIRTI-TRADA bamboo-based walls is their relatively good ductility. For example, the wall without a window opening has approximately 60% to 70% of its original capacity at an inter-story drift of 4%.



(a) (b)

Figure 8. Hysteresis for the 2.44m (a) and 1.2m (b) specimens

Figure 9. Photographs of failure mechanism for 2.44m long test specimen

In the longer specimen with the window, crushing around the mid-point bamboo column was the first point of major failure as shown in Figure 9. Smaller cracks, typical of racking tests on concrete walls, were observed prior to this major failure. In the case of the 1.22m long walls without a window, failure occurred ultimately as a result of the pullout of the threaded rods that connected the top plate to the bamboo grid inside the wall. This was identified as a potential place for improvement of the system, but was not felt to be critical since good ductility and strength was achieved.

4. NUMERICAL MODELING AND RESULTS

The test results presented earlier provided a means to calibrate a nonlinear numerical model for each wall segment and form a system model for a building by assuming a rigid roof diaphragm and connecting the non-linear springs. This type of modelling is known as a "pancake model" because there is no height associated with the model, only shear/hysteretic springs, and has been used extensively in wood building research over the last decade [see e.g. 6-8]. Each wall segment is represented numerically by a non-linear hysteretic spring which has the ability to degrade in both stiffness and strength, similar to the behaviour observed during testing of the IPRITI-TRADA bamboo-mortar walls. The parameters of the hysteretic model, originally from Folz and Filiatrault [8], is shown in Figure 10.

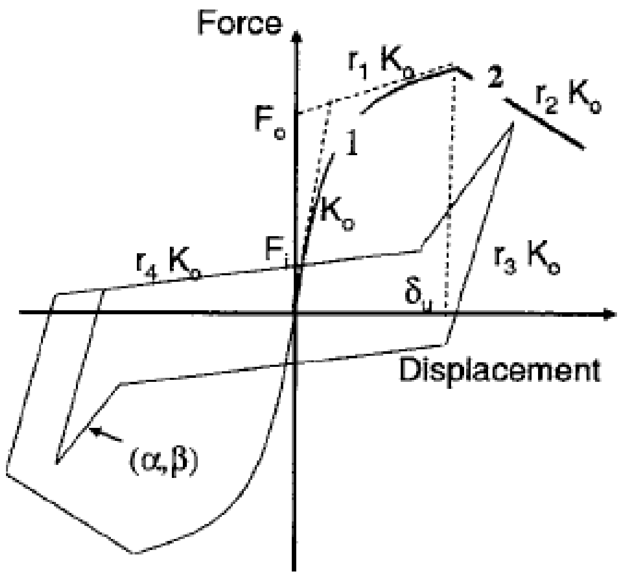


Figure 10. Hysteretic model for a single shear wall

Now, consider a small rectangular building for illustrative purposes as shown in Figure 11. Panel 1, 2, and 5 are modelled using parameters fit to the data from the 2.44m wall with a window, termed wall A. Panel 3 and 4 are modelled using parameters from the 1.22m wall that did not have a window, termed Wall B. The hysteretic parameters for the two types of wall elements are presented in Table 2.

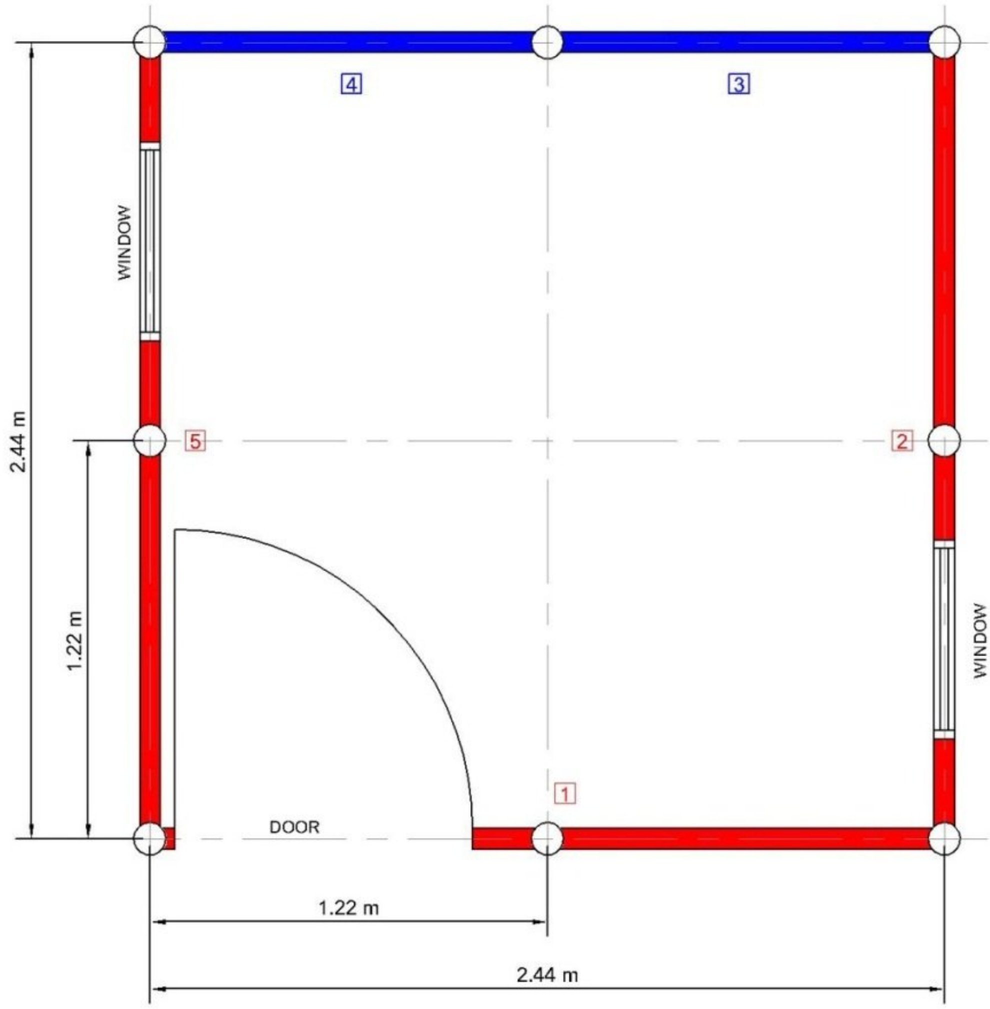


Figure 11. Floor plan for small bamboo-mortar building used in illustrative example

Table 2: Hysteretic model parameters for the two specimens

Wall	K0 (kN/mm)	F0 (kN)	F1 (kN)	r1	r2	r3	r4	Xu (mm)	Alpha	Beta
'A'	2.71	24.5	1.56	0.01	-0.08	1.00	0.01	31.75	0.75	1.20
'B'	2.28	25.1	1.56	0.02	-0.08	1.00	0.02	63.5	0.95	1.18

The small building weighed 2636 kg, so tributary load for the analysis was assumed to be half the wall weight combined with the roof weight. Varying weights of 1000 kg, 1500 kg, and 2000 kg were also considered at roof level as variants of the building. Multi-record incremental dynamic analysis (IDA) [9] was used to examine the behaviour of the bamboo building under increasing seismic intensity for each of these roof weights.

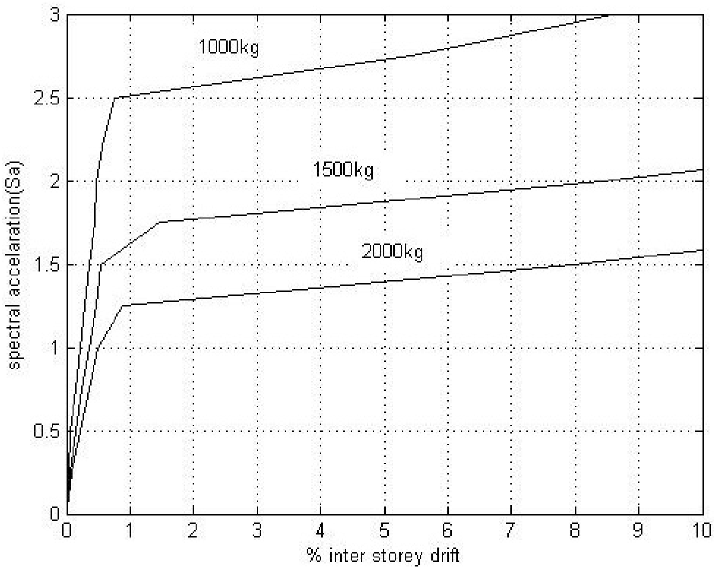


Figure 12. Mean IDA curves for 20 shallow crustal earthquakes for the U.S.

Figure 12 presents the mean IDA curves for a suite of 20 earthquakes that were developed for analysis of light-frame wood structures. Under the lighter 1000 kg roof system one can see from inspection of Figure 12 that excessive inter-story drift does not occur until 2.5g spectral acceleration. The 2000kg roof system, which might represent a larger roof span with additional openings, has excessive inter-story drift at about half that, indicating a fairly linear relationship as one would expect with the mass. In 2001 the Bhuj earthquake occurred in India resulting in numerous fatalities and damage to tens of thousands of dwellings.

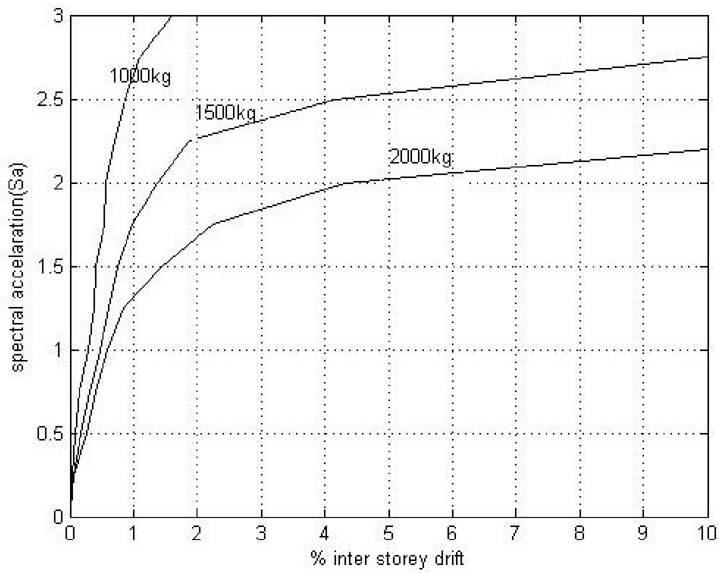


Figure 13. IDA curves for the Bhuj earthquake, India, 2001

Figure 13 shows individual-record IDA curves for the bamboo-mortar buildings for this earthquake. At a roof mass of 1000 kg, the building is performing well in excess of 3g spectral acceleration. Even at double the roof mass, inter-story drifts indicative of failure, i.e. 5%, do not occur until 2g spectral acceleration, indicating that this building would have performed very well during the 2001 Bhuj earthquake.

5. SUMMARY AND CONCLUSION

In this paper, the results of a combined experimental and numerical study to examine the behaviour of bamboo-mortar shear walls and buildings, was summarized. The motivation was that there is increasing interest in use of bamboo-based building products in developing countries but little research into their seismic performance has been completed. Two walls, one with a window opening and one without a window opening were constructed and tested using a reversed cyclic protocol in order to determine the hysteretic response of this type of construction. Then, the hysteretic data was used to calibrate a well-known numerical model to perform non-linear time history analysis. The IDA procedure was used to examine the response of a full structure, albeit small, to a suite of earthquake ground motion records from the United States that was specifically developed to examine the seismic response of wood buildings, and a specific record from the 2001 Bhuj earthquake. The mass at roof level was also varied to examine several building variants. In all cases, the response of the bamboo-mortar buildings was found to be very good, with low drift levels even at seismic intensities significantly exceeding design levels. Based on the experimental and numerical work in this study, it can be concluded that bamboo-mortar buildings are a viable construction alternative in developing countries.

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