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Seismic Testing of a Bamboo Based Building System

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Bamboo grows in abundance in the earth's subtropical and tropical zones, where the majority of earthquake hazards occur regularly. Bamboo is gaining in popularity as an earthquake-mitigating material because engineers are beginning to understand its structural properties. A research project has been taken up to investigate the practical use of bamboo in inexpensive, earthquake-resistant structures. Seismic tests were carried out on a full scale one room bamboo house using tri-axial shaker system to evaluate its adequacy in resisting earthquake loads and to study its performance during earthquake.

1.0 INTRODUCTION

Bamboo is a genus of plants indigenous to Asia and Africa. It has been used as a building material in these regions since prehistoric times. Bamboo is a renewable resource for agro-forestry production and a viable replacement for wood. It is one of the strongest building materials, with a tensile strength that rivals steel and weight-to-strength ratio surpassing that of graphite. It is used to produce flooring, wall paneling, pulp for paper, fencing, raw material for housing, and more. However over time, people started using other materials such as steel and concrete extensively for construction in place of wood and Bamboo.

Bamboo grows in abundance in the earth's subtropical and tropical countries, where the majority of earthquakes occur causing many deaths and injuries and extensive property damage. Over the past two decades, technology has played an increasingly significant role in mitigating hazards that result from earthquakes. Interdisciplinary Research & Development programs are planned in place of conventional discipline-specific theoretical analysis. Considerable research work has gone into Bamboo and is gaining in popularity as an earthquake-mitigating material because engineers are beginning to understand its structural properties.

The level of confidence associated with the seismic analysis and design of Bamboo based construction is much lower than for concrete or steel construction. There is a need for more test data on complete full-scale bamboo based structures to improve the understanding of the state-of-practice of analysis and design. A collaborative project has been taken up jointly by TRADA and CPRI (funded by DFID, UK) with a view to test earthquake resistance capability of bamboo building system. The high performance shake table at CPRI has been utilized for system testing under seismic loading.

2.0 SEISMIC DESIGN

Seismic engineering is one of the most rapidly evolving disciplines in the civil/structural engineering profession. Recent seismic events around the world have provided new insight into the way structures perform when subjected to earthquake related ground motion. These events have focused the attention of government agencies, the scientific community and the general public on safety hazards and

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potential losses associated with structures that perform poorly during earthquakes. As a result, there is growing national emphasis on seismic risk assessment, seismic design requirements for new structures, and seismic retrofit of existing structures. Seismic provisions of building codes have been revised recently.

Scientists have begun to estimate the locations and likelihoods of future damaging earthquakes. Sites of greatest hazard are being identified, and definite progress is being made in designing structures that will withstand the effects of earthquakes.

3.0 SEISMIC TESTING

Due to increased population and growth in construction activities, the risk of earthquake is much higher than before. Hence the safety against earthquakes is strongly required for buildings and other civil engineering structures. To improve our understanding of the response of structures under earthquakes, three approaches could be adopted, i.e., site investigation of earthquake damage, theoretical analysis and structural test. Though the computer and numerical techniques are advanced, the structural testing methods are still the most powerful, basic and determined methods in studying structural seismic behavior, and they provide the foundation for the development of earthquake engineering.

Shaking table can be effectively used for checking structural adequacy of the earthquake-resistant design and to validate the mathematical model of structure, especially to verify the high-rise building by small-scale model. In fact, all kinds of structures can be tested by shaking table testing method so long as the system has enough capacity to carry the specimen.

3.1 Seismic Simulation Tests

The main purposes of carrying out seismic simulation tests are to study the seismic responses of accelerations, displacements and strains at critical locations of structures, to identify the locations of structural crack and the weakness points and to determine the collapse pattern and failure mechanism. Prior to seismic simulation tests, preliminary dynamic tests are conducted on the system to evaluate their dynamic characteristics viz., the natural frequencies, damping ratio and vibration modes etc.,

4.0 SHAKE TABLE TESTS

"Shake" table test is more realistic method of earthquake testing than pseudo dynamic method. The shaking table test is economic, tangible, and reliable validation test to assess the seismic safety and reliability of buildings. Shaking tables are usually square or rectangular stiff planar platforms moved by servo-hydraulic actuators to simulate earthquakes.

Specimens of interest are mounted on the table and tests are carried out simulating design or postulated earthquakes. The dynamic behavior of the structure and its damage pattern under earthquake with great magnitude can be reproduced. As a result of this test, the structure is proved to ensure safety, or too weak to resist a destructive earthquake. The weak points of structure are determined, and suggestions and modifications can be put forward, before the construction of prototype structures.

Extensive shake table tests are conducted at many research and academic institutes to study earthquake resistant design of civil engineering structures, such as bridges, dams, and buildings, and to qualify critical equipment like computer control systems, switching relay banks, electrical control panels and nuclear plant cooling pumps and turbines.

4.1 Tri-Axial Shaker System at CPRI Bangalore

Earthquake engineering laboratory housing the tri-axial shaker system with six degrees of freedom, capable of performing a diverse range of seismic qualification test requirements on equipment, sub-assemblies and components as per National/International standards has been established at Central Power Research Institute CPRI, Bangalore in the year 2003. The tri-axial shaker system consisting of a shaking-table is a unique facility that can strictly simulate the earthquake ground motion without any distortion.

The shaking table can vibrate in one axis to three axes with six degrees of freedom. The advanced control system allows the reproduction of earthquake ground motions with high fidelity and little

TABLE I

SALIENT FEATURES OF SHAKING TABLE FACILITIES OF CPRI, BANGALORE

Sl.No	Item	Performance
1	Maximum payload	10 tons
2	Table dimension	3 m × 3 m
3	Exciting direction	*X*, *Y*, *Z* (Simultaneous / Sequential)
4	Degrees of Freedom	Six (3 translatory and 3 rotational)
5	Max. Height of the specimen	10 m
6	Displacement/Max. Stroke *X* & *Y* Direction *Z* - Direction	 ±150 mm ±100 mm
7	Velocity	1000 mm/s (*X*, *Y* & *Z* direction)
8	Acceleration	±1 g (*X*, *Y* & *Z* direction)
9	Maximum specimen channels	128
10	Frequency range	0.1 to 50 Hz
11	Yawing moment	10 ton.m
12	Overturning moment	40 ton.m
13	Actuators Vertical Horizontal	 4 nos. of 170 kN 4 nos. of 120 kN

distortion. Table 1 shows salient features of high-performance shaker system at CPRI, Bangalore.

The seismic qualification tests are being conducted using the tri-axial earthquake simulation system, which features a 10-ton pay load capacity shake table of all-welded steel construction. An advanced control system allows the reproduction of earthquake ground motions with high fidelity.

4.2 Design Spectrum for Shake Table Tests

For choosing suitable earthquake waves or the design spectrum to excite the table for testing the bamboo house, the parameters such as the type soil at site, type of construction, the dynamic behavior of the prototype structure and the appropriate seismic zone are required as design input parameters. The earthquake spectrum is an average smoothened plot of maximum acceleration as function of frequency or time period of vibration for a specified damping for a site-specific condition. These are specified by the appropriate building code.

The design spectrum for testing the bamboo house has been obtained as per the recommendations of IS 1893 (Part1): 2002 titled "Criteria for Earthquake Resistant Design of Structures".

For the purpose of determining seismic forces, the country (India) is classified into four seismic zones i.e Zone II, Zone III, Zone IV and Zone V. The standard specifies the forces for analytical design and design spectrum for testing of structures corresponding to the type of soil at site and damping of the structure. The design horizontal seismic coefficient A_h for a structure is determined by the following expression:

$$A_h = \frac{ZI}{2R}\left(\frac{Sa}{g}\right)$$

For generation of the design Spectrum as per IS : 1893 (part I) 2002, the following factors were considered

Zone factor:	For Zone IV	= 0.24
	For Zone V	= 0.36
Importance factor	I	= 1.00
Response reduction factor,	R	= 1.00
Soil at site		= Soft

For Soft soil sites

$$Sa/g = \begin{cases} 1 + 15\,T, & 0.00 \le T \le 0.10 \\ 2.50 & 0.10 \le T \le 0.67 \\ 1.67/T & 0.67 \le T \le 4.00 \end{cases}$$

The Design acceleration spectrum for vertical motions had been taken as two-thirds of the design horizontal acceleration spectrum as per the codal recommendations. The Design test spectrum for Zone IV and Zone V are shown in Figs. 1 & 2 respectively.

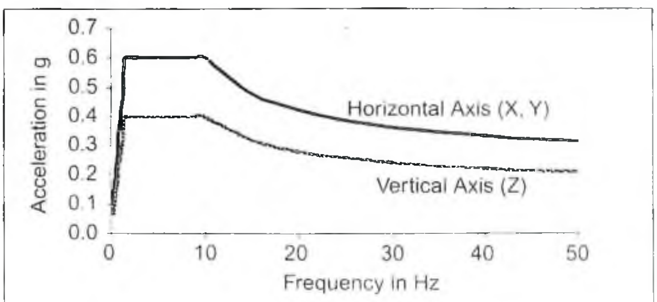

FIG. 1 TEST SPECTRUM FOR ZONE IV

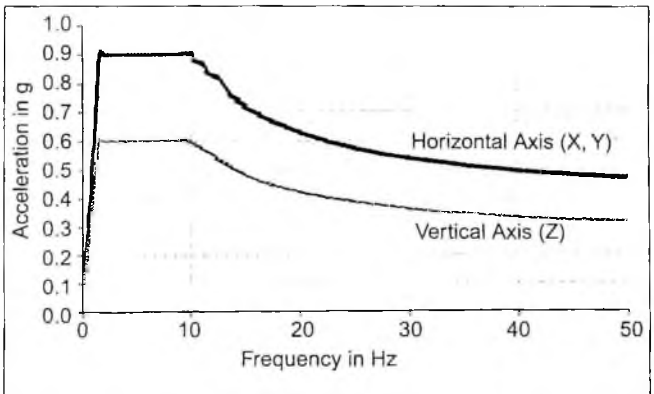

FIG. 2. TEST SPECTRUM FOR ZONE V

5.0 CONSTRUCTION OF BAMBOO HOUSE

It was proposed to test a bamboo house of plan dimension 2.7 m × 2.7 m, the maximum proto type size that can be tested on the seismic table at CPRI. The system consists of suitably preservative treated bamboo columns 80–100 mm diameter spaced at 1.35 m intervals and the top of the column held by wooden top plate. The wall infill comprises of a grid of split bamboo strips. The grids tied together with binding wire are attached to columns through 6 mm dia MS dowels. Walls are plastered for thickness of 50 mm with cement mortar. The roof consists of bamboo mat corrugated sheet composite (BMCS) developed by IPIRTI and supported on bamboo purlins and bamboo trusses with bolted bamboo mat gusset joints. The roof is secured to walls by means of steel angles and bolts. The prototype was constructed on MS steel channel base to facilitate lifting and mounting on the shake table. The walls, the bamboo poles, trusses, windows and door were painted.

6.0 PRELIMINARY DYNAMIC TESTS

In order to obtain the dynamic characteristics of the structure/test specimen such as the natural frequency of different elements of the bamboo house viz., wall panel, roof, truss members, damping ratio, impact tests are conducted on the structure. Hardware necessary for carrying out impulse response testing include Impulse hammer, amplifier, signal conditioner and data acquisition system and a portable computer for running data acquisition and with analysis software. The impulse hammer is required to apply the impact on the specimen such that the impulse consists of a nearly constant force applied over a broad frequency range. For force measurement, an integral quartz force transducer is mounted on the striking head of the hammer head. Accelerometers were mounted on different elements. Upon hammer impact the force and acceleration data are recorded. The test is repeated for atleast 10 times for averaging. Using the "Pulse analyzer", the natural frequencies of individual elements are obtained and the values are tabulated in table 2.

TABLE 2

Sl. No.	Element	Natural Frequency (Hz)
1	Roof	44
2	Front wall	14
3	Side walls	22
4	Rear wall	14
5	Truss	2
6	Door	2
7	Windows	2

7.0 SEISMIC TESTING

The bamboo house constructed on a rigid steel frame was mounted on the seismic table. The weight of the bamboo house was measured 2636 kg. Utmost care was exercised not to damage the test specimen. Preliminary inspection was carried out to locate any distortion or structural failure, if any, in the form of cracks in the walls and deflection in roof trusses. Accelerometers were mounted on identified critical locations. The bamboo house mounted on the seismic table is shown in Fig. 3.

The Bamboo house was mounted on the seismic table and tested for the design spectrum. The primary objective is to measure, quantify and document the building's dynamic characteristics and its responses under seismic loading. The experimental results may help to learn more about the relationship between ground motion and performance of the bamboo house.

The design spectrum was fed in to the control system and the appropriate drive files for the eight actuators were obtained. The seismic simulation as per the design spectrum of zone IV and Zone V were carried out on the specimen, the bamboo house. The

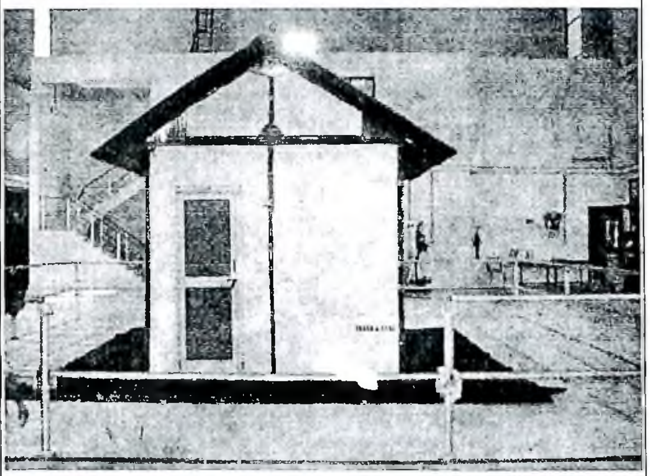

FIG. 3. BAMBOO HOUSE MOUNTED ON SEISMIC TABLE FOR TESTING

duration of the seismic simulation was 30 seconds. The seismic simulation for Zone V was repeated five times to check the fatigue strength of the bamboo house. The acceleration at different identified locations was recorded continuously during simulation. During testing, utmost care was taken to ensure that the test response spectra enveloped the Required response Spectra ie the Design spectra over the entire frequency range of 0.1 to 50 Hz.

8.0 TESTING OF BAMBOO HOUSE FOR KOBE EARTHQUAKE

In was proposed to test the structural adequacy of bamboo house in resisting one of the most severe earthquakes for which the actual time history (strong ground motion) is available. It was decided to play the time history (as shown in Fig. 4) on the seismic table to simulate the Kobe earthquake of magnitude 7.2 that struck the region of Kobe and Osaka in south-central Japan on Tuesday, January 17, 1995 at 5:46 a.m. local time. The duration of strong ground shaking was about 20 seconds. This earthquake caused severe damage over a large area. Nearly 5,500 deaths have been confirmed, with the number of injured people reaching about 35,000. Nearly 180,000 buildings were badly damaged or destroyed, and officials estimate that more than 300,000 people were homeless on the night of the earthquake.

After testing, thorough inspection was carried out to find any structural cracks or structural failure. No visible crack or structural damage observed.

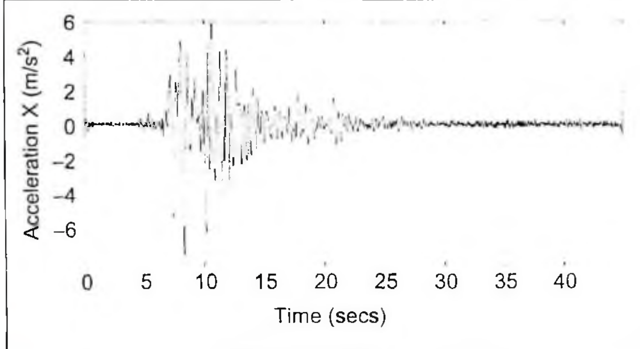

FIG. 4. TIME HISTORY OF KOBE EARTHQUAKE

9.0 CONCLUSIONS

Bamboo housing system developed by TRADA - IPIRTI withstood earthquake intensities as stipulated for Zone 4 and 5 of BIS and KOBE earthquake. The structure did not exhibit any distress or cracks in any part of the building. Joints between bamboo columns and bamboo reinforced cement mortar infill walls remained intact after the test. There were no signs of any damage in the roof structure.

The test clearly establishes the efficiency of bamboo building system and advantages of positive connections between various elements like column, infill wall and roof and high racking strength of infill walls in transmitting horizontal quake forces

Designing structures with bamboo gives the pleasure of working with sustainable materials as well as a natural beauty and grace. The test result clearly proves that the chemically treated bamboo has adequate mechanical strength and is as an efficient earthquake-resistant building material. Further tests are proposed to infill confidence in engineers and planners in utilizing bamboo in construction of safe and economical houses for people in earthquake prone area.

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