Seismic Performance of the Amritesvara Temple: Shake Table Test of a Dry Stone Masonry Structure

Vasantha Lakshmi Gudasali, Vijayalakshmi Akella, and B. K. Raghuprasad

Abstract Ancient structures were constructed by considering only vertical static loads. The seismic response of ancient masonry structures depends on their material properties, the geometry of the structure, the types of connections between various structural components, the stiffness of the floors and the strength of the non-structural elements. The rich and diverse architectural traditions across India provide evidence of the structural efficiency and technological skill of Indian craftsmen and builders. Studying the structural behaviour of Indian heritage buildings has national importance. In this study, the seismic vulnerability of the Amritesvara temple was evaluated. Built in 1196 and is located 260.8 km from Bengaluru, India. This study involved a shake table test of the temple. Experiments were conducted at the Earthquake and Vibration Research Centre, Bengaluru. According to the size and payload capacity of the shaking table, a 1:3 scale model was adopted. The model was subjected to various peak ground accelerations from 0.05 to 0.1 g. The dynamic properties of the model were evaluated through the experiments. The experimental results were used for validating the numerical model, which was used to conduct further investigations on the prototype.

Keywords Shake table test · Dry stone masonry structure · Seismic analysis · Heritage building

V. L. Gudasali (✉) · V. Akella
Department of Civil Engineering, K. S. School of Engineering and Management, Visvesvaraya Technological University, Belgaum, India

V. Akella
e-mail: hod.civil@kssem.edu.in

B. K. Raghuprasad
IISC, Bangalore, India

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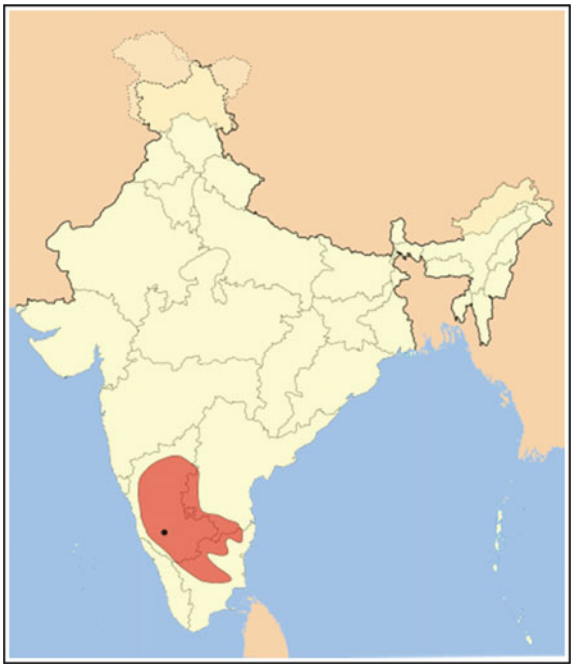

Fig. 1 Map of the hoysala empire

1 Introduction

1.1 Hoysala Architecture

The Hoysala Empire ruled southern India between 1026 and 1343 (Fig. 1) and constructed many large and small temples, including the Chennakesava temple at Belur (1117), the Hoysaleswara temple at Halebidu (1160) and the Kesava temple at Somanathapura (1268). These temple complexes have been proposed to be listed as UNESCO world heritage sites.

1.2 History of Earthquakes in Karnataka

In the present seismic zonation map of India (Fig. 2), Karnataka lies in zones 2 and 3 (i.e., seismically less active to moderately active). A literature survey indicates that 33 earthquakes have occurred in Karnataka from 1828 to 2001 [1]. Karnataka experienced high seismic activity during the 1970s, with five earthquakes occurring in 1971, four earthquakes occurring in 1972 and three earthquakes each occurring in 1970 and 1974. The aforementioned earthquakes had a magnitude ranging from 3.8 to 5 on the Richter scale.

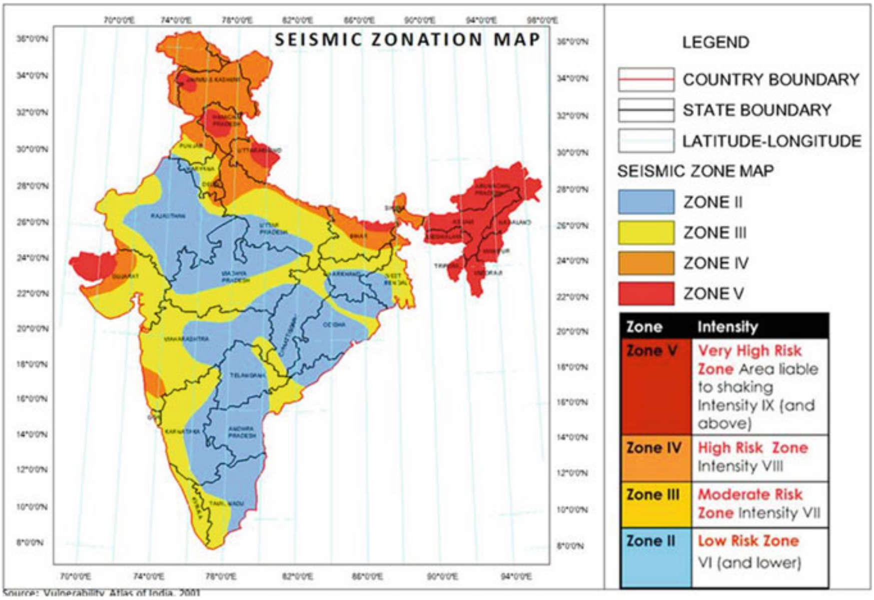

Fig. 2 Seismic zonation map of India

1.3 Literature Review

Analysis of historic masonary monuments by numerical modeling has been carried out by other investigators, few with dynamic characteristics analysis. Benjapon Wethyavivon et al. [2] carried out analysis on Thai historic masonary monuments at the Ayuthaya world heritage site to understand structural behaviour and provide critical information for planning and prioritizing restoration as well as assess their safety. Measured in-situ frequency was found to be 3.9 Hz and 2.3 Hz for 62.1 m high bell-shaped and 31.6 m high corn-shaped structure, respectively. From numerical modeling, the frequency with fixed base is 2.98 Hz and 3.10 Hz whereas with subsoil inclusion it was found to be 1.23 Hz and 2.41 Hz, respectively. The properties considered for modeling are elastic modulus are 3.020 Mpa, poison's ratio is 0.21 and compressive strength is 3.92 Mpa. Jaishi et al. [3] carried out analysis on dynamic and seismic performance of old multi-tiered temples in Nepal. The in-situ measured frequency by ambient vibration test and analytical natural periods were compared. An empirical formula is established to estimate the natural period of vibration for nepalese temples. It was found that the largest period was 0.6 s for the highest tower (21.93 m).

The problem of testing the scaled model and subject them to ground motion tests was addressed by Daniel Ruiz et al. [4] for sixteenth and seventeenth century rammed earth-built churches in the Andean highlands. The purpose of testing the model was to conduct a comparative evaluation of the seismic performance of scaled model of rammed earth-built doctrinal churches, with and without confining reinforcements by wood elements. The displacements were reinforcement by wood elements. The displacements were found to be between 4 and 7.1 mm for unreinforced model and 1.2–1.4 mm with LVDT located at different positions.

A Meher Prasad, Arun Menon et al. [5] worked on seismic vulnerability of south Indian temples, in their effort to protect the monuments from earthquakes as the studies focussing on south Indian temples are not reported in the literature. The temple considered for the study is Ekambaranathar temple in Kanchipuram. Fundamental frequency of the site is estimated to be 3.63 Hz which is closely matching with the fundamental frequency of the mandapam. From FEM analysis using commercially available package ABAQUS 6.6.4 the frequency for 4 pillared mandapam is 3.53 Hz and for 16 pillared mandapam is 3.46 Hz in Y-direction being the first mode. Through ambient vibration the frequency was found to be 3.56 Hz for 4 pillared mandapam and 3.10 Hz for 16 pillared mandapam.

2 Description of the Amritesvara Temple

The Amritesvara temple is a heritage stone masonry structure that was constructed in the ekakuta style (single Vimana). The temple comprises the sanctum sanctorum, which is also known as the garbhagriha and is where the deity resides; the mandapa, which is a pillared hall provided in front of the garbhagriha for devotees to gather for activities such as chanting and meditation; and the antara, which is a chamber that joins the main sanctuary and the mandapa of the temple. The various components of the temple are illustrated in Fig. 3.

Fig. 3 Various components of the Amritesvara temple

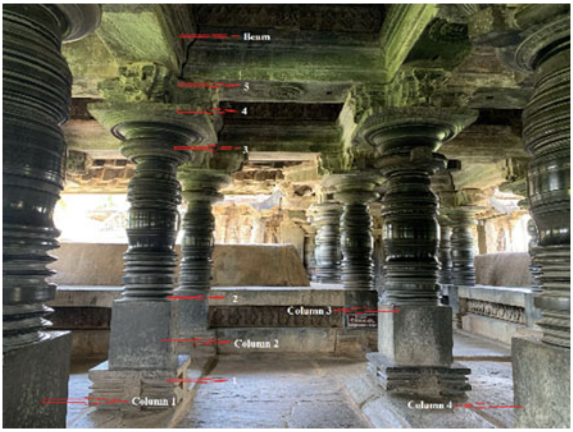

Fig. 4 View of the mandapa at the Amritesvara temple

To study the behaviour of the Amritesvara temple (a heritage structure) under seismic loads, a part of the temple, namely the mandapa (a space frame), was considered. The mandapa consists of four columns, four beams and a dome.

2.1 *Structural System Modelling*

The geometric scaling factor of the model was decided on the basis of shake table dimensions of 1.5 m × 1.5 m. The actual space frame measures 2.92 m × 2.92 m. Therefore, a 1:3 scale model was adopted. The temple columns comprise five table joints. The beams are placed on the capital and are tied using clamps, as observed in the prototype. The dome is placed on the beam without any joints. The joints of the temple column were replicated in the model (Figs. 4, 5, 6 and 7). The column base (pedestal) was fixed to a steel base plate, and this arrangement was assumed to be the fixed condition. The base plate was connected to the shake table by using 20 mm bolts (Fig. 5).

2.2 *Scaling Factors*

Simulation laws were followed when performing geometric scaling. Material used in the prototype and model is the same. Scale factors obtained using modelling principles are specified in Table 1 ($S_i = S_p/S_m$).

Fig. 5 Model of the mandapa of the Amritesvara temple

Fig. 6 Table joints provided in the prototype for different components of the column

2.3 Experimental Setup

The designed components with shear keys (model elements) were assembled on the shake table at the Earthquake and Vibration Research Centre, Central Power Research Institute, Bengaluru (Fig. 8). The provisional assemblage is displayed in Fig. 9. A

Fig. 7 Table joints provided in the model for various elements of the column

Table 1 Scaling factors [6]

Sr. no	Parameters	Scale factor
1	Acceleration (a)	S_i^{-1}
2	Gravitational acceleration (g)	Neglected
3	Time (t)	S_i
4	Linear dimension (l)	S_i
5	Displacement (δ)	S_i
6	Frequency (ω)	S_i^{-1}
7	Modulus (E)	1
8	Stress (σ)	1
9	Strain (ε)	1
10	Poison's ratio (ν)	1
11	Mass density (ρ)	1

fully assembled model of the space frame and the instrumentation are depicted in Fig. 5.

2.4 Seismic Loading Characteristics

Sine sweep tests were conducted on the assembled structure with peak ground accelerations (PGAs) of 0.05 g, 0.075 g and 0.1 g in the X-direction from 1 to 50 Hz at the rate of 1 octave per minute. Figures 10 and 11 display a typical input time history for the sine sweep tests corresponding to PGAs of 0.05 and 0.075 g, respectively.

Fig. 8 Assembling the model on the shake table

3 Experimental Testing on the Shaking Table

Four accelerometers were mounted on different components of the model (shake table, column, beam and dome), and an infrared linear variable displacement transducer was projected on the part of the dome where the maximum displacement was expected. After assembling the model, the accelerometers were placed on it and seismic testing was initiated. Three shake table tests were performed with PGAs of 0.05 g, 0.075 g and 0.1 g. The PGA was not increased further because the maximum displacement was observed at 0.1 g. The maximum displacement for a PGA of 0.1 g was 20.67 mm. At a PGA of 0.1 g, the column rotated due to torsion (Fig. 12) and the gap between the beams visibly widened at the joints. Therefore, the test was discontinued (Fig. 13).

4 Damping

The logarithmic decrement method was used to determine the damping value of the constructed scaled temple model from the free vibration records collected during the

Fig. 9 Provisional assemblage

Fig. 10 Time history in the sine sweep test when the PGA is 0.05 g

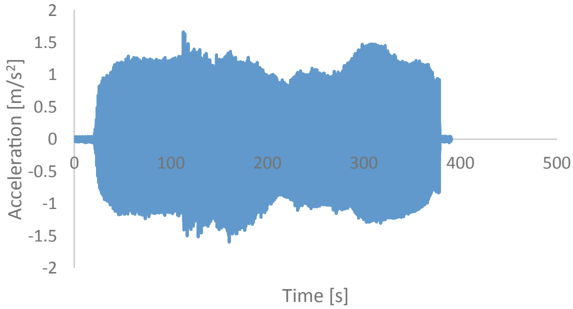

Fig. 11 Time history in the sine sweep test when the PGA is 0.075 g

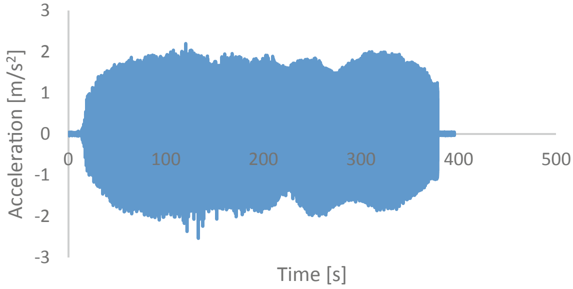

Fig. 12 Rotation of the columns

Fig. 13 Displacement of the beams

shake table test. The damping value was found to be 6%. The structural damping ratio obtained through the experimental process was used for numerically modelling of the scaled temple model. The graph of the free vibration records is displayed in Figs. 14 and 15.

5 Numerical Modelling of the Scaled Temple Model

Considering the details of the scaled temple model, which is a replica of a part of the Amritesvara temple, a finite element (FE) model with joints was designed in ANSYS Workbench 16.0 by using 45 solid elements (Fig. 16). The numerical model consisted of four columns, four beams, one slab, and one dome. The material properties used in the design were obtained by conducting various experiments, such as the uniaxial

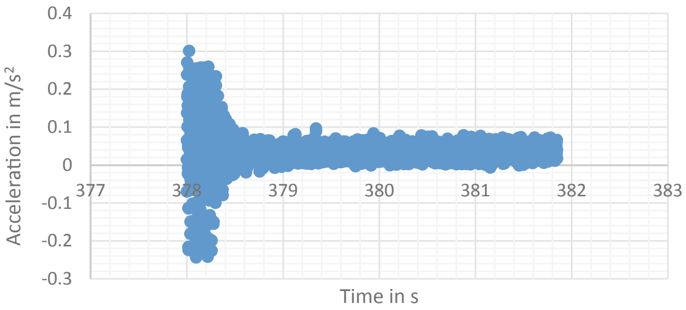

Fig. 14 Free vibration graph

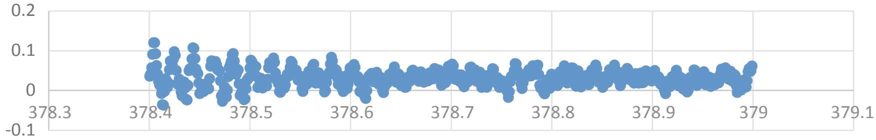

Fig. 15 Enlarged section of the free vibration graph

Fig. 16 FE model of the mandapa

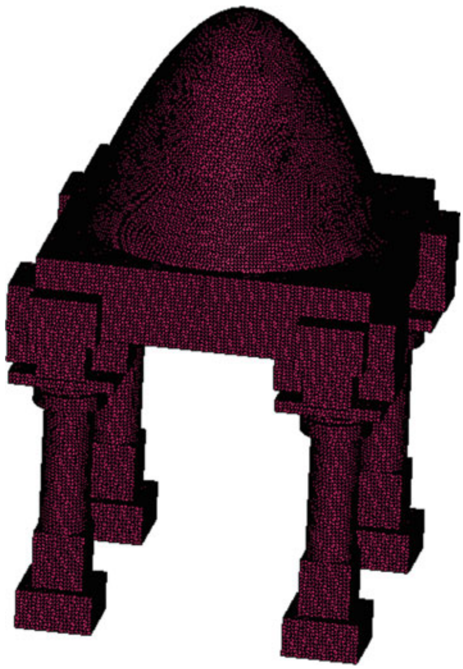

Table 2 Experimental results for the tested samples

Material	Density (kg/m^3)	Compressive strength (MPa)	Young's modulus (MPa)	Poisson's ratio	Tensile strength (MPa)
Soapstone	2798.6	48.88	3354	0.263	7.55

Table 3 Natural frequency obtained from the resonance test

Components	Natural frequency (in Hz)
Dome	3.375
Beam	3.375
Column	2.688

compression test for determining the Young's modulus and Poisson's ratio as well as the compressive strength and Brazilian tests for determining the tensile strength. The obtained results are summarised in Table 2. In the designed model, the building materials were assumed to be homogenous, isotropic and linearly elastic. Constraints were applied to the joints; the base was considered to be rigid; and the domes were designed to rest on the beams.

6 Results

6.1 Natural Frequency

The natural frequencies obtained from the resonance test of the shake table are presented in Table 3. Because the space frame did not act as a single unit, different frequencies were observed for different components of the space frame (Figs. 17, 18 and 19). Table 4 summarises the results obtained from the numerical model for the natural frequency. Table 5 provides a comparison of the natural frequency obtained through experiments and numerical analysis.

7 Conclusion

In the present study, a scaled model of the Amritesvara temple with the Hoysala architecture style was designed, constructed and commissioned. Shake table tests were conducted on the scaled model, and the natural frequency and damping were determined. Furthermore, a numerical model of the constructed scaled model was designed, and numerical analysis was performed. The results from numerical analysis and the laboratory measurements are in good agreement. Thus, the scaled structural model can replicate the behaviour of the real temple model with reasonable accuracy.

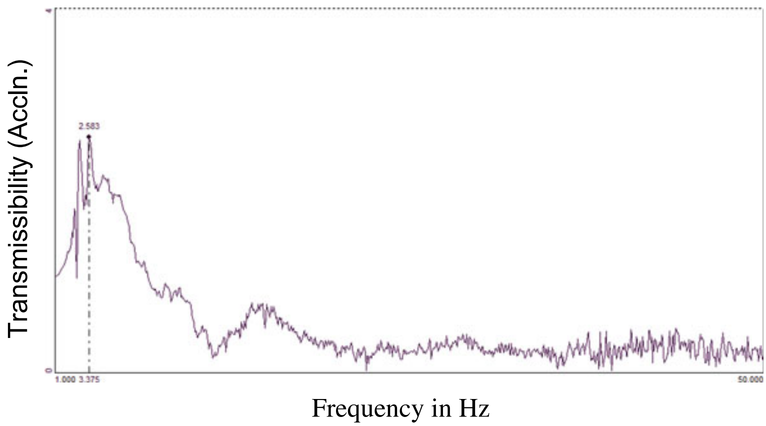

Fig. 17 Transmissibility graph for the beams

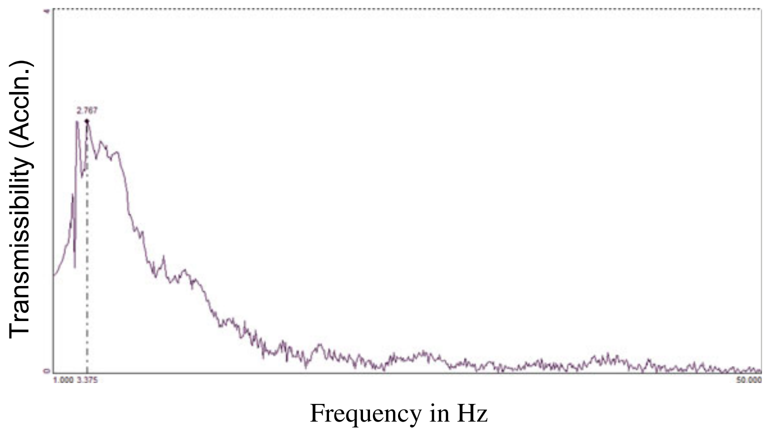

Fig. 18 Transmissibility graph for the dome

In conclusion, the scaled temple model is a valid and qualified model that can be used for further experimental investigations. The numerical results indicated that the vulnerability of the mandapa is mainly due to a lack of suitable interconnection between structural members.

In the experimental tests, the columns were rotated and hairline cracks were observed. Moreover, the gap between the beams at the joints visibly widened. This behaviour suggests that the beam and column behaved independently during the testing, as indicated by the obtained results. Thus, the experimental results also indicate that the vulnerability of the mandapa is primarily due to a lack of proper interconnection between structural members.

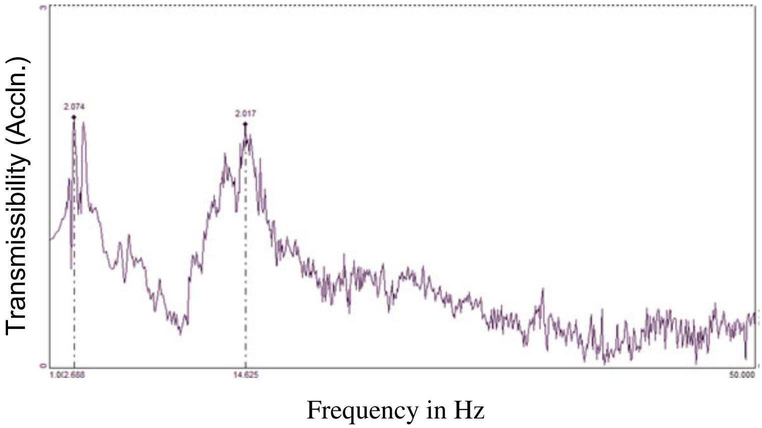

Fig. 19 Transmissibility graph for the column

Table 4 Results obtained from the numerical model of the scaled temple

Modes	Mode of vibration	Natural frequency (in Hz)
1	Transition in X	2.561
2	Transition in Y	2.568
3	Torsion	3.505
4	Transition in X	12.134
5	Transition in Y	12.954

Table 5 Comparison of the fundamental frequencies obtained through experimental and numerical analysis

Modes	Frequency obtained through shake table testing in Hz	Frequency obtained through numerical modelling in Hz
1	2.688	2.561

This study conclusively proves that torsion is the primary mode of vibration of the temple structure, and the temple structure may collapse during future earthquakes, even those of relatively low magnitude.

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