Engineering Structures 159 (2018) 277–285

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Dynamic performance of a multi-story traditional timber pagoda

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ARTICLE INFO

Keywords:
Dynamic performance
Timber pagoda
Shaking table test
Stiffness

ABSTRACT

This paper presents a study on the dynamic performance of a multi-story traditional timber pagoda. A shaking table test was conducted with a 1:5 scaled pagoda model and various excitation intensities. Both artificial and recorded earthquake waves were considered. Ambient excitation test before seismic excitations and white noise excitation tests during the intervals of increasing seismic excitations were conducted to detect the fundamental frequencies and damping ratios of the model pagoda. Equivalent story stiffness was evaluated from the measured inter-story load-displacement hysteretic curves and a lumped mass model was established to determine the dynamic properties of the pagoda during strong excitations. It was found that the pagoda model survived all the input earthquake excitations (up to 0.44g in PGA) with only minor damages. The model frequencies detected after increasing earthquake excitations decreased only by 16% while the damping ratio increased from 1.24% to more than 10%, indicating a good seismic resilience of the pagoda. It was also found that the detected frequencies highly relied on the intensity of the excitations (up to 59% in difference), possibly due to the transition between static and sliding frictions amongst wood members and the recoverable looseness of the mortise-tenon joints.

1. Introduction

Chinese traditional timber structure is one of the oldest structural forms of China and has also been widely adopted in other Southeast Asian countries, such as Japan and Korea. A great many timber palaces, temples and pagodas that were built through history have been preserved and stand as an invaluable legacy to human civilization. Because these historical timber buildings have experienced various degrees of cumulative damage, it is imperative to investigate their structural performance, especially their dynamic performance, to provide a fundamental basis for structural appraisal and strengthening.

Traditional timber structures are distinct from contemporary structures made of concrete and steel. Instead of integral casting, bolting or welding, beams and columns in traditional timber structures are connected by wood-to-wood connections such as mortise-tenon connections and dou-gong connections [1]. Mortise-tenon connections are used for connecting beams and columns. Dou-gong connections, as demonstrated in Fig. 1, are consisted of many layers of small blocks and small size lap jointed beams. Their function is to serve as vertical supports to upper floors and horizontal racking elements (in additional to beam-column wall frames). The stiffness and load-carrying capacities of such connections are often weaker than timber beams and columns due to apparent reasons [2–5]. As a result, such connections play an important role in the structural behavior of traditional timber structures, which are generally featured by small acceleration yet large displacement responses during earthquakes.

Health monitoring studies, often based on ambient vibration tests, have revealed useful dynamic features of traditional timber structures. Typically, the damping ratio ranged from 1.4% to 5.3%, and the natural frequencies, in addition to having a strong correlation with structure height, can apparently be affected by excitation intensities [6–8]. The latter particularly casts a shadow on any structural evaluation results obtained from in-situ ambient vibration tests since they are essentially random in terms of the excitation waveforms and intensities, of which few is comparable to a hazardous earthquake.

The usefulness and indispensability of quasi-static loading tests and shake table tests to studies on seismic performance of traditional timber structures have long been recognized. For example, Seo et al. [9], Suzuki et al. [10], Sui et al. [11], and Li et al. [12] tested single-story mortise-tenon connected timber frames. Fujita et al. [13] tested a five-story timber pagoda on a one-way shake table. Due to the complexity in making and assembling the specimens, these studies were mostly focused on either a small portion of the target structures (e.g., a representative floor), or the entire structures yet with substantially simplified connection and wall frame configurations. This fact really limits the application of their results to practical traditional timber structures, especially multi-story pagodas, whose dynamic performance is highly dependent on the total height and the connection and wall frame behaviors.

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https://doi.org/10.1016/j.engstruct.2018.01.003
Received 18 October 2017; Received in revised form 27 December 2017; Accepted 1 January 2018

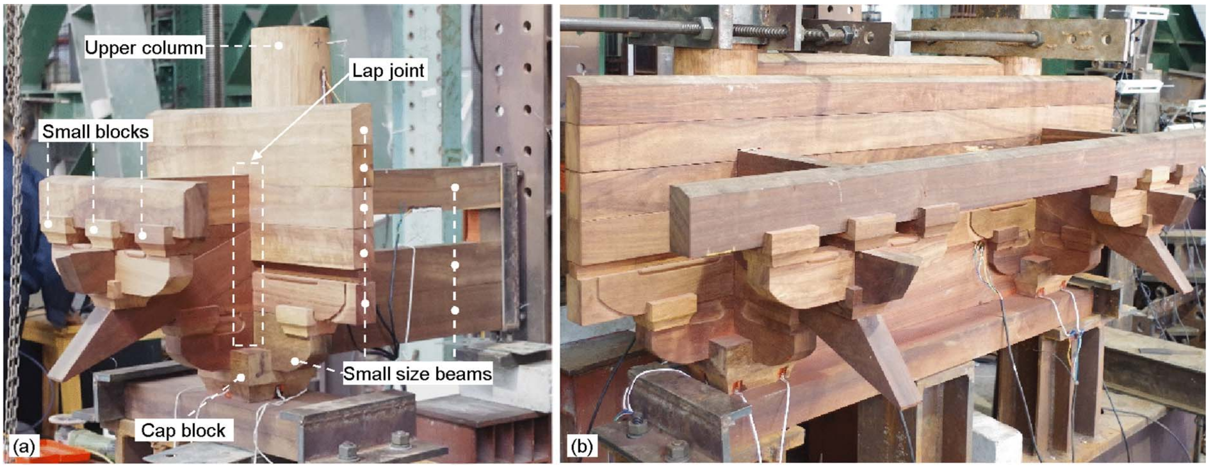

Fig. 1. Dou-gong connections (a) A single dou-gong connection. (b) Dou-gong connections connected with each other.

This paper takes the advantage of a recently conducted shake table test of a 1:5 scaled seven-story traditional timber pagoda. The pagoda was built following traditional construction techniques in which the fabrication fidelity of wood-to-wood connections as well as the wall frames was kept to the most. Different excitation waveforms as well as intensities of artificial and natural earthquake records were considered. The dynamic characteristics, including the fundamental frequencies and damping ratios, were evaluated by use of ambient excitation and white noise excitation methods before and during the intervals of increasing earthquake inputs. A lumped mass model was also developed after the tests based on the equivalent inter-story stiffness determined from the inter-story load-displacement hysteretic curves. The difference between the results from the three methods was discussed, and the implication of such difference as well as the potential reasons was investigated.

2. Description of the shaking table test

2.1. Model similitude factors

The model similitude of the dynamic performance a scaled structure to the target structure can be fully described by use of three independent factors according to the scaling theory [14]. Considering the capacity and the size of the shaking table in Tongji University, where the test was conducted, the pagoda model was scaled down to one-fifth of a traditional Chinese seven-story timber pagoda. Thus, the dimension scaling factor S_l was chosen as 1/5. Since the model was fabricated with the same material as the prototype pagoda, the scaling parameter of the elastic modulus S_E was equal to 1.0. According to the instrument capacities, the horizontal acceleration-scaling factor S_a was chosen as 2.0. Other scaling factors were then determined via the dimensional analysis, as listed in Table 1.

Table 1
Main similitude scaling factors (model versus prototype) employed in the shake table test.

Physical meaning	Scaling factors	Value
Length	S_l	0.2
Elasticity modulus	S_E	1.0
Stress	$S_\sigma = S_E$	1.0
Acceleration	S_a	2.0
Density	$S_\rho = S_E/(S_a \cdot S_l)$	2.5
Mass	$S_m = S_\rho \cdot S_l^3$	0.02
Time	$S_t = S_a^{-0.5} \cdot S_l^{0.5}$	0.3162
Frequency	$S_f = S_l^{-0.5} \cdot S_a^{0.5}$	3.1623
Damping coefficient	$S_c = S_E \cdot S_l^{1.5} \cdot S_a^{-0.5}$	0.0623

2.2. Model description

The pagoda model had a square plan, as shown in Fig. 2a and b. The total height of the model was 8.7 m; the ground story had a height of 1.45 m, and the story height of the second to sixth stories was 1.05 m. The top story had a height of 1.35 m. Each story of the pagoda had three bays in X- and Y-directions, except for the ground story, which had an additional corridor at the periphery.

The pagoda was consisted of a core frame (with four continuous columns and linking trusses, Fig. 2c) in the central, timber framed shear walls (Fig. 2e) around its periphery, floor joints and panels, and dou-gong connections between the shear walls and the floor joists (Fig. 2d). The core columns were intentionally tilted to the center of the structure with a slope of 0.37%. The trusses were placed underneath the floor and connected to the core columns by mortise-tenon joints. The timber framed shear walls of the 2nd to the 7th story were typically 480 mm tall and were consisted of a cover beam, a main beam, a number of lap-jointed bottom beams, two columns, a lintel beam and infill wood panels, in addition to several adapting members between the beam-column frames and the panels.

African rosewood was used for making of the main structural members. The material properties were obtained from standard material properties tests [15] and are listed in Table 2. All members of the model were scaled down as strictly as possible to one-fifth of the prototype member sizes, the sizes of main structural members were marked in Fig. 2(d) and (e). To simulate the tiles and workloads, a total of 17.5 tons of lead blocks was placed evenly over the overhanging roofs and floor panels following the similitude factors, in addition to the 3.1 ton self-weight of the pagoda. The test setup is shown in Fig. 3.

2.3. Test protocol and measuring schemes

With consideration of the local soil conditions, stiffness characteristic of traditional timber structures and the specified pseudo acceleration response spectrum in Shanghai local seismic code [16], one artificial wave record, SHW2, and two long period natural earthquake records, Kobe and ChiChi waves, were selected for testing. The pseudo acceleration response spectra of the selected seismic waves with unified PGA is presented in Fig. 4.

The waves were further scaled in terms of the time duration and acceleration amplitude considering the prescribed similitude scaling factors and the three seismic hazard levels specified in the Code for seismic design of buildings of China [17]: frequently met 7-degree, fortification 7-degree and rarely met 7-degree. The corresponding peak ground accelerations (PGAs) of the three hazard levels are 0.07 g, 0.2 g and 0.44 g, respectively. Since the pagoda is symmetric about the two