Engineering Structures 156 (2018) 480–489

Contents lists available at ScienceDirect

Engineering Structures

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

Degradation laws of hysteretic behaviour for historical timber buildings based on pseudo-static tests

Jinyong Chen[a,b], Tieying Li[a,*], Qingshan Yang[c,d], Xiwang Shi[a], Yanxia Zhao[e]

[a] School of Architecture and Civil Engineering, Taiyuan University of Technology, Taiyuan 030024, PR China
[b] The Institute of Shanxi Architectural Design Research, Taiyuan 030013, PR China
[c] School of Civil Engineering, Chongqing University, Chongqing, China
[d] Beijing's Key Laboratory of Structural Wind Engineering and Urban Wind Environment, Beijing, China
[e] Department of Foreign Languages, Communication University of Shanxi, Taiyuan 030013, PR China

ARTICLE INFO

Keywords:
Historical timber structure
Ultimate state
Hysteretic behaviour
Degradation laws
Full-scale test

ABSTRACT

This paper reports on the pseudo-static tests (PSTs) with a single storey full-scale timber building with architectural details that are prevailing in the Song dynasty, China (A.D. 960–1279). The PSTs were conducted under three levels of vertical load. The force and displacement relationship at selected points in the backbone curves were analysed for the structural stiffness and the accumulated energy dissipation with varying ductility coefficient. The degradation ratios of the bearing capacity, lateral stiffness, and the accumulated energy dissipation of the structure under different vertical loads were obtained. The trilinear backbone curve in PST1 is different from the bilinear relationship in PST2. The stiffness degradation can be modelled with a power function while it is accompanied with a reduced maximum accumulated energy dissipation.

1. Introduction

Chinese historical timber buildings have been developed over the last 2300 years since the period of Warring States at 475 BCE. Due to the effects of natural actions, human factors, and wood aging, only a few buildings have been preserved, and they become an important part of the global historical and cultural heritage. The oldest one is the main hall of Nanchan Temple on Mount Wutai which was reconstructed in the Tang dynasty (A.D. 782) in Xinzhou city, Shanxi, China. The Sakyamuni Pagoda (67.31 m high) of Fogong Temple was constructed in the Liao dynasty (A.D. 1056) in Ying County, Shanxi Province, China.

Over 72% (100 buildings) of existing Chinese historical timber buildings were constructed before the Liao and Jin dynasties (A.D. 907), and they are located in Shanxi Province which has frequent high-intensity earthquakes. Seen from the literatures [1–5], Earthquake is the main natural action to cause damage to timber structures. According to historical records, the Sakyamuni Pagoda has experienced eight earthquakes with a magnitude higher than grade 6 on the Richter scale, and the outer rim of columns in the second storey was found displaced by 450 mm in the last 700 years. This cast doubt on its reliability to sustain similar events in future. It is very important to study the response characteristics of historical timber buildings under horizontal earthquake action, and in particular, the degradation of hysteretic behaviour in multiple earthquakes.

A historical Chinese timber building can be divided into three zones along the vertical direction: stylobate, building body, and the roof (Fig. 1(a)). Stylobates are the structures below the column foot including the stone bases and foundation. The building body refers to that part above the column foot and below the eaves consisting of the column frames and *dou-gong* sets (bucket arches), or storeys (Fig. 1(b)). The roof is above the eaves and is composed of roof trusses and the roof covering. Generally, the column foot is directly placed on the stone bases (Fig. 1(c)).

Studies of historical timber buildings in recent years mainly focus on the column frames and *dou-gong* sets. Previous researches show that the *dou-gong* sets have good energy-dissipating capacity through friction and shear energy dissipation, and their rotational stiffness increases with the vertical load they carry [6–8]. The column frames feature stable energy-dissipating capacity and high ductility, and they fail by the pulling out of tenons from the beam-column connection [9]. It has been observed that a timber building composing of column frames and *dou-gong* sets displays good deformation capability and low energy dissipation under horizontal load, and it can restore its position at rest through cyclic sway motion of its columns [10]. The connection joints of beams and columns in column frames are mostly dovetails which are semi-rigid, and the gaps within these joints affect their bending

* Corresponding author.
E-mail address: 2167429162@qq.com (T. Li).

https://doi.org/10.1016/j.engstruct.2017.11.054
Received 22 December 2016; Received in revised form 15 November 2017; Accepted 22 November 2017

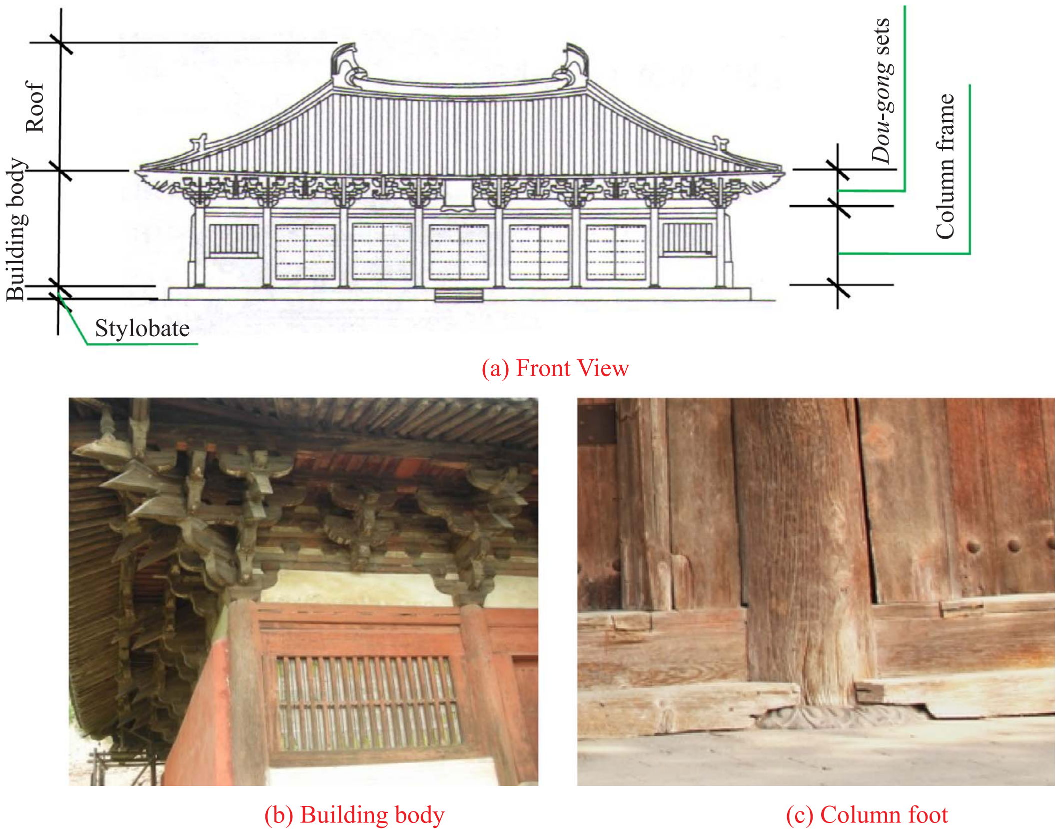

Fig. 1. Components of the Chinese traditional building.

deformation significantly. Moreover, the bending moment and rotation curves show trilinear trends [11–14], and the numerical simulation results on the behaviour of beam-column joints and the *dou-gong* sets are close to the experimental observations [15–18].

Many tests on the static characteristics of timber structures have been reported based on the results from single pseudo-static test (PST) of scaled specimen. These tests cannot reveal the degradation of hysteretic behaviour in the historical timber structures which have been accumulating damage from many earthquakes over hundreds and thousands of years. A single storey full-scale timber building with *dou-gong* sets and four columns has been test in the laboratory. This paper mainly reports on the degradation of the hysteretic behaviour through two PSTs under three levels of vertical load.

The degradation laws of the stiffness and the bearing capacity of the historical timber structure are studied based on results from the two PSTs revealing features of deformation and energy dissipation. These results are reported for the first time and they could provide the needed information on the behaviour of historical timber structures for their structural health monitoring, maintenance and rehabilitation.

2. Full-scale specimen

The full-scale specimen was constructed using *Pinus sylvestris* imported from Russia, and the mechanical characteristics of the wood are shown in Table 1. The specimen models a typical timber structure in Song dynasty of China. The dimensions of structures and components and the connection between components follow the "caifen modular system". The "caifen modular system" is a technical "code of practice" for the construction of historical timber buildings in Song dynasty. The roof of structure is modelled by precast concrete (PC) slabs from experiences gained in previous researches [10,19].

The plan sectional view and south elevation of the model are shown in Figs. 2 and 3, respectively. The dimensions of components of the model are shown in Table 2. The technical terms are referred to Fig. 3. The top of *Sufang* 2 is 54 mm higher than that of *Sufang* 1 in Fig. 3 to ensure that the latter will not be dislocated under earthquake motion, and the PC slabs are placed on the *Sufang* 2 in the southern and northern sides directly on top of the columns. Horizontal forces were transferred between the column bottom and floor, and between the PC slabs and *Sufangs* by friction alone.

Components in this specimen are connected by mortises and tenons or dowels, e.g. the dovetail mortise and tenon are for the column and *lan'e,* and the hasp mortise and tenon are for the *pupaifang*1 and pupaifang2. The connections of column frames and the *dou-gong* sets are shown in Figs. 4 and 5, respectively. The column bottoms are directly placed on the concrete floor without connection. The roof of the specimen was selected to be a pavilion, as shown in Fig. 6 according to the report in *Ying-tsao-fa-shih* (A.D. 1103, Song dynasty) [20], and the PC slabs were designed to match the equivalent weight of the roof.

It should be noted that wood species of the test structure is close to but not equivalent to the timber species in Song Dynasty, but the mechanical properties of wood are close enough. The joints of structure have been modelled according to specifications required in Song Dynasty. The many joints in a wooden structure is commonly acknowledged as a major source of damping of the structure, and yet the test structure only includes the joints forming the timber frame, and the effect of all joints above the eaves of the structure cannot be studied in the tests. The energy dissipation behaviour and damping of the structure studied are only related to the frictional and nonlinear behaviour of these joints under the cyclic loading.

3. Loading configuration and instrumentation

Fig. 7 shows the test configuration including a measuring system, a loading system for horizontal forces, a safety precaution system (only the northern part is shown for clarity) and the PC slabs. Inclinometers