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Flexural behaviour of timber dovetail mortise–tenon joints

Chunchao Chen [a], Hongxing Qiu [a,*], Yong Lu [b]

[a] Key Laboratory of Concrete and Prestressed Concrete Structures of Ministry of Education, Southeast University, Nanjing 210096, China
[b] Institute for Infrastructure and Environment, School of Engineering, The University of Edinburgh, Edinburgh EH9 3JL, UK

HIGHLIGHTS

- Two types of timber dovetail mortise–tenon joints have been studied.
- The moment–rotation relationships and the failure modes have been established.
- A theoretical model is developed to describe the moment–rotation relationship.

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ABSTRACT

A comprehensive study has been carried out on the flexural behaviour of dovetail mortise–tenon joints in timber structures. Two types of the joints have been considered; type 1 represents a joint at the top of a column where the beam tenon may be slid into the mortise from above the column, and type 2 represents a joint below the top of a column where the beam tenon needs to be inserted from the side into the mortise. Relationships of moment vs. rotation and tenon pull-out vs. rotation, as well as the failure modes were obtained from experiments under monotonic loading. Numerical simulation was conducted to examine the deformation states and the stress distributions. On the basis of the experimental and numerical data, a simplified mechanics model has been proposed for the analysis of the moment vs. rotation relationship. Results show that the main failure mode of the dovetail joints is pull-out, and due to the dovetail shape on the two sides of the tenon, the side gaps tend to have a more significant effect than the gaps at the top and the apex. The moment–rotation relationship of the joints has an initial stage of gradual development of nonlinearity, followed by a prolonged yielding phase, and then a descending branch. The moment–rotation relationship may thus be approximated by a trilinear model. Simplified formulas for determining the key points on the moment–rotation relationship have been shown to agree well with the experimental results.

1. Introduction

Timber structures have been the traditional type of buildings in China, Japan, Korea and many other countries for thousands of years. In China, most existing ancient structures are timber structures or timber–brick composite structures. Research on Chinese ancient timber structures started from the 19th century [1,2], but most of the early work was about the structural layout, process and history of buildings. In more recent years scholars all over the world have done much more specific research on ancient timber structures with the method of modern mechanics.

Dovetail mortise–tenon joints connecting beams with columns are widely seen in ancient timber structures [3]. The origin of this joining method is not exactly known, but it was already common in ancient timber structures built in Ming and Qing dynasties in China [4]. The load–deformation behaviour of dovetail joints is very complex, and their rotational stiffness and strength plays an important role in the lateral stiffness, integrity and stability of the whole structure. But in general their strength is lower than that of the adjoining beams and columns. An appropriate analysis of the mechanical properties of the dovetail joints is therefore crucial for a reliable evaluation of the safety of a timber structure.

The behaviour of joints in timber structures has been a subject of some extensive studies both experimentally and analytically. However, as generally recognised [5], the mechanical behaviour of timber joints varies among different practices. Some of the studies on various types of the timber joints are briefly summarised below. The joint rotational stiffness has been a focus of many of these studies.

* Corresponding author.
E-mail address: qiuhx@seu.edu.cn (H. Qiu).

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Chang et al. [5,6] studied the behaviour of continuous and butted Nuki joints with a special interest in the rotational performance of the joints. An initial gap was considered in the joints. Theoretical models were developed to predict the rotational stiffness of both types of joints with gaps.

King et al. [7] conducted experiments on a kind of commonly used beam-to-column connections, with a tenon in the beam and a mortise in the column. They compared prototype and damaged (with material degradation) joints, and developed a three-parameter semi-rigid connection model for the stiffness of the joints.

D'Ayala and Tsai [8] conducted both experimental and numerical studies of the seismic behaviour of timber joints in a special type of timber structures called "Dieh–Dou" in Taiwan. It was also observed that the stiffness of the timber joints played a significant role in determining the overall displacement of the structure.

Chang and Hsu [9] studied the hysteretic behaviour of traditional Go-Dou and stepped dovetail connections, which are usually used to connect frames together and provide out-of-plane stiffness to timber frames. The prediction models for rotational stiffness and the ultimate moment capacity of these two types of joints were established based upon a statistical approach.

Regarding the specific behaviour of dovetail joints, Chun et al. [10] and Yue [11] conducted many experiments to study the flexural behaviour of dovetail joints and derived empirical skeleton curves. Li et al. [12] introduced various assumptions about the failure modes of dovetail joints and subsequently derived the capacity formulas respectively. The failure rotation limits were not provided. Xu et al. [13] developed a moment–rotation relationship of dovetail joints from the perspective of microcosmic relationship of stress–strain, but the formula was very complex and some important parameters needed to be obtained empirically by regression from experimental data. Pang et al. [14] investigated the influence of beam shoulder on the moment-carrying capacity of dovetail mortise–tenon joints by static loading tests. The moment resistance and the failure mode indicated that the beam shoulder significantly affected the performance of the joints. Seo [15] conducted static and cyclic lateral load tests on two Korean ancient timber frames without vertical load. The frames used dovetail joints to connect beams with columns at the column top. The failure modes of the frames were shear failure or bending failure of mortise branches. Despite these studies, however, theoretical research about dovetail joints is still limited.

This paper presents a comprehensive experimental and analytical study on the flexural behaviour of dovetail mortise–tenon joints for beam–column connections. Two types of the joints are considered, representing respectively two different arrangements of the joint positions. Beam–column joint assemblies have been tested to failure under monotonic loading. To assist in the examination of the local stress and deformation distribution in the mortise and tenon, a finite element model has been developed to simulate the joint assembly with details of the mortise and tenon connections. Based on the experiment and numerical simulation, a set of simplification assumptions have been devised with regard to the stress and deformation patterns. Subsequently, a simplified mechanics model has been developed for the analysis of bending moment–rotation relationship of dovetail mortise–tenon joints.

2. Experiment study

2.1. Configurations of the joints

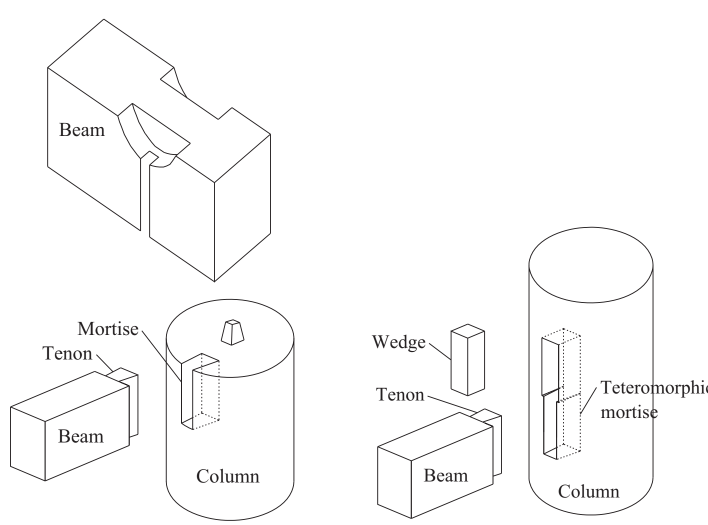
Two types of dovetail joints are considered in the present study, as shown schematically in Fig. 1. The first type (Type 1) has a traditional configuration and the joint is located at the top of the column. The second type (Type 2) is an extended version where the joint is located below the column top.

Because of the dovetail shape of the tenon (the tenon apex is wider than the neck), the tenon cannot be inserted into the mortise directly, so Type 1 configuration has an advantage in that the tenon can be slotted into position vertically from above the mortise. When any other component is subsequently installed on top of the column, such a component will help to hold down the tenon and thus increase the resistance against the rotation of the tenon; otherwise a fixing cap may be required to enable a similar effect.

Type 2 configuration permits a self-contained fixity. The dovetail tenon cannot be inserted directly into the joint in this case, and a wider opening slot needs to be created above the actual mortise to facilitate the installation of the tenon. This effectively renders the mortise to consist of two parts; a wider upper part of right rectangular shape whose width is just enough to allow the passage of the tenon apex, and a dovetail-shaped lower part in which the tenon finally fits. Thus the process of installing the tenon is to firstly bring the tenon into the vertical position through the upper part of the mortise, and then move it down into the lower part of the mortise. Finally a wedge is hammered into the upper part to complete the installation.

2.2. Test specimens

The prototype of the test specimens was made to follow the building practice documented as from Qing Dynasty. Four 1:1.76 reduced-scale specimens were constructed, and these specimens were designated as JA-1, JA-2, JB-1 and JB-2, respectively. Specimens JA-1 and JA-2 were identical Type-1 joints, and specimens JB-1 and JB-2 were identical Type-2 joints. Detailed dimensions of these specimens



(a) Type 1 joint (located right at top of column) (b) Type 2 joint (located below top of column)

Fig. 1. Configurations of the dovetail joints.